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EUROPEAN ORGANIZATION FOR EXPERIMENTAL PHOTOGRAMMETRIC RESEARCH

Proceedings of the

OEEPE – WORKSHOP
on
AUTOMATION
IN DIGITAL PHOTOGRAMMETRIC PRODUCTION

Marne la Valée, 22–24 June 1999
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I-27100 Pavia

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Department of Geoinformatics
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P.O. Box 6
NL-7500 AA Enschede

Ir. F. A. HAGMAN
Survey Department of the Rijkswaterstaat
Postbus 5023
NL-2600 GA Delft

Prof. Ø. ANDERSEN — Norway
Norges Landbrukshøgskole
Institutt for Kartfag
P. O. Box 5034
N-1432 Ås

Mrs. E. MALANOWICZ — Poland
Head Office of Geodesy and Cartography
Department of Cartography and Photogrammetry
ul. Wspólna 2
PL-00-926 Warszawa

Mr. J. A. RODRIGUEZ SANCHEZ — Spain
Centro Nacional de
Informacion Geográfica
General Ibáñez de Ibero 3
E-28003 Madrid

Mr. J. HERMOSILLA
Instituto Geografico Nacional
General Ibáñez de Ibero 3
E-28003 Madrid

Prof. J. TALTS — Sweden
National Land Survey of Sweden
S-80182 Gävle

Prof. K. TORLEGÅRD
The Royal Institute of Technology
Dept. of Geodesy and Photogrammetry
S-10044 Stockholm 70

Mr. C. EIDENBENZ — Switzerland
Bundesamt für Landestopographie
Seftigenstrasse 264
CH-3084 Wabern

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Ministry of National Defence
General Command of Mapping
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Dikimevi
TR-06100 Ankara

Col. E. BAYBALI
Ministry of National Defence
General Command of Mapping
MSB
Harita Genel Komutanligi
Dikimevi
TR-06100 Ankara

Mr. K. J. MURRAY — United Kingdom
Ordnance Survey
Romsey Road
Maybush
Southampton S016 4GU

Prof. Dr. I. J. DOWMAN
Dept. of Photogrammetry and Surveying
University College London
Gower Street 6
London WC 1E 6BT

SCIENCE COMMITTEE

Prof. K. TORLEGÅRD
The Royal Institute of Technology
Dept. of Geodesy and Photogrammetry
S-10044 Stockholm 70

EXECUTIVE BUREAU

Mr. C. M. PARESI
Secretary General of the OEEPE
International Institute for Aerospace Survey
and Earth Sciences
350 Boulevard 1945, P. O. Box 6
NL-7500 AA Enschede (Netherlands)

Ir. J. TIMMERMAN
Smaragdstraat 20
NL-7314 HG Apeldoorn

OFFICE OF PUBLICATIONS

Dr. P. HANKE
Bundesamt für Kartographie und Geodäsie
Richard-Strauss-Allee 11
D-60598 Frankfurt am Main

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Norges Landbrukshøgskole
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Institut Géographique National
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2, Avenue Pasteur
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F-94165 Saint-Mande

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Proceedings of the

OEEPE - WORKSHOP
on
AUTOMATION IN
DIGITAL PHOTOGRAMMETRIC PRODUCTION

(with numerous figures and tables)

Marne la Vallée, 22-24 June 1999

Editor: O. Kölbl

Preface

In the last years we have observed great changes in photogrammetry. Automatic procedures of digital photogrammetry have been introduced in practice and caused a considerable increase in productivity. This increase in productivity was very important in order to counterbalance the outsourcing of photogrammetric work in cheap-labor countries. The classical photogrammetric restitution has also obtained concurrence by other airborne sensors like laser altimeter for the DTM determination or kinematic GPS and INS for aerotriangulation. Furthermore, the first digital imaging systems for aerial photography are appearing on the market.

An essential part for the automation of the photogrammetric processes has been achieved by the different manufacturers; most of the workstations for digital photogrammetry allowing a large automation of the working process used in Europe comes from the firms Intergraph, LH Systems and Zeiss. Furthermore, the firm Inpho in Stuttgart has achieved important development work. Within these firms we have also observed great changes. Helava merged with the photogrammetry of Leica to form LH Systems two years ago and the photogrammetry section of Intergraph and that of Zeiss are forming a joint venture under the name Z/I Imaging.

In order to give practicians a survey of all this development, OEEPE organised a workshop from 22 to 24 June 1999 on the topic 'Automation in Digital Photogrammetric Production'. This workshop took place in Champs-sur-Marne (Cité Descartes), part of Marne-la-Vallée near Paris in the new premises of the Ecole Nationale des Sciences Géographiques (ENSG). A similar workshop was organised three years ago in Lausanne. Once again a very close partnership was achieved between manufacturer and user. This was largely facilitated by the manufacturers' willingness to use for the demonstrations unified test material concerning automatic aerial triangulation, automatic DTM determination and the elaboration of orthophoto and image mosaics. These presentations by firms were complemented by lectures given by users who shared their experiences with these various systems. In the present OEEPE publication, an attempt has been made to highlight the current status of photogrammetry. Again, we tried to transcribe all discussions in order to transmit to the reader not only the lectures but also a picture of the various critical aspects. In this context the discussions on logistic aspects are of special interest. Unfortunately, it was not possible to reproduce the text of the manufacturer demonstrations, but the reader is referred to the lectures in the last part of the booklet where the various tools are presented in detail.

I feel very much obliged to the representatives of the manufacturers (Tobias Heuchel Inpho, Mustafa Madani Intergraph, Scott Miller LH Systems, Christoph Dörstel Zeiss) for their excellent collaboration. An important contribution was also made by the chairpersons, José Colomer, Yves Egels, Christian Heipke, Raphaële Héno, Alain Dupéret and Thomas Kersten. Very special thanks are due to Patrice Denis, ENSG/IGN, for the enormous organisational work and Mrs Grujard, secretary of the symposium. The transcription of the discussions has been done by Mrs M'Kenzie ENSG and Grégoire Ramuz has prepared the proceedings for printing. We are also specially grateful to the German “Federal Agency for Cartography and Geodesy” for the printing of the proceedings.

Lausanne, October 1999 O. Kölbl

Executive Summary
of the

OEEPE Workshop on
Automation in Digital Photogrammetric Production

From June 21 to 24, OEEPE (European Organization on Photogrammetric Experimental Studies) organized a workshop entiteled **“Automation in Digital Photogrammetric Production”** in Champs-sur-Marne, in the new premises of the University of Geographic Sciences of IGN.

The OEEPE is concerned with the development of effective and efficient digital photogrammetric production lines, including standardization (guidelines for the production processes and standards for the various products), optimization and financial and logistic aspects. To be successful, this development needs to be done through close co-operation with manufacturers and users. The workshop should serve as a platform to discuss issues related to the optimization of digital photogrammetric production lines.

Main objectives of the workshop

- Establish a discussion platform between users and manufacturers on the tools for digital photogrammetry;
- contribute to a better understanding and use of the working tools for digital photogrammetry and help to elaborate standard guidelines for the various working processes;
- optimize the use of photogrammetric tools in production and contribute to the development of efficient digital production lines;
- consider the related financial and logistic aspects;
- work out standards for the various products such as orthophotos in digital and analog form.

The following manufacturers were invited to participate to the Workshop with demonstrations:

- LH-Systems
- Z/I Imaging (Zeiss and Intergraph)
- Inpho Stuttgart

Digital photogrammetric equipment from these vendors is currently largely used in Europe. Consequently a lively dialog was established between vendors and users as various contributions were also given by enterprises using this equipment in daily production.

Furthermore DVP, Virtuoso and Erdas participated in discussions and in the exhibition.

The workshop was intended for practitioners of digital photogrammetry who wanted to improve their working methods and were interested in establishing close contacts with the vendors. On the whole, 160 persons from 25 different countries participated. During the workshop, the different topics were introduced through lectures given by experienced photogrammetrists and vendors were invited to give demonstrations on standardized test material. Ample time was reserved for discussions.

Main topics of the OEEPE Workshop:

- **State of the Art of Digital Cameras** (Y. Egels)
- **Digital Scanners** (O. Kölbl)
- **DTM Elaboration, Practical Experiences** (A. Dupéret)
- **Automatic Aerial Triangulation: Practical Experiences** (Th. Kersten, Ch. Heipke)
- **Orthophoto Production** (O. Kölbl)
- **Logistics, Management and Financial Aspects** (R. Héno, J. Colomer)

The main objectives of the different sessions and the contributions are listed below; an attempt is then made to provide a short overview of the main results and to outline the conclusions. All contributions will be printed, together with the transcription of the discussion. The text will also be available on the web site of the Institute of Photogrammetry of the Technical University of Lausanne under: http://dgrwww.epfl.ch/PHOT.

State of the Art of Digital Cameras (Chairman: Y. Egels)

Objectives

- Presentation of the current developments in digital cameras, their advantages in comparison with film cameras, specific performance of the different electronic image capturing systems (CCD-line elements, CCD-frame matrix and photo multiplier), reflections on the characterization of image quality (MTF, tone and colour reproduction, image noise).

Contributions

State of the art of digital imaging systems (B.Dierickx, IMEC, Belgium)

Digital aerial cameras, possibilities and problems (R. Sandau, LH-Systems Switzerland)

IGN’s digital camera (C. Thom, IGN, France)

Digital aerial survey for network planning (practical experiences with 3-lines camera) (L. Renouard, ISTAR, France, and F. Lehmann, DLR-Institute of Planetary Exploration, Germany)

Main Results

The first lecture given by B. Dierickx analyzed the obtainable image quality with electronic image sensors compared with photographic films. He predicted that the CMOS technology will also replace the CCD technology in the high end and will slowly reach the capacity of photographic films, also for large formats.

Nevertheless, manufacturers are already involved in the development of digital photogrammetric cameras. There are two systems in direct competition. The 3-line camera which is currently being developed by LH-Systems in collaboration with the DLR (Deutsche Gesellschaft für Luft- und Raumfahrt); and the frame camera on which important development work is done by IGN, a line which is also preferred by Zeiss respectively Z/I Imaging. The 3-line camera has the advantage that one can use much larger image formats; one currently tests an engineering model with a sensor array of 12,000 pixels but the functioning model should show an array of 20,000 pixels. On the other hand, the digital frame camera currently shows sizes of only 4,000 x 4,000 pixels. However, the number of pixels gives only limited information on the real optical resolution. Under ideal conditions, the pixel resolution allows one to determine directly the modulation transfer function and the image resolution as described by B. Dierickx. However, optics and then the eventual post-processing of the images can substantially affect the optical quality. The success of the 3-line camera will consequently depend largely on the quality of the stabilization of the camera. If it is possible to largely correct the pitch and roll movements of the airplane, then a very efficient system should emerge. However, the technical requirements for the stabilization (GPS and INS) call for considerable efforts. On the other hand, the technical effort for the frame camera is very modest and allows the use of relatively small survey planes, although with the disadvantage of a relatively small image format.

Both systems are currently still limited by the speed of the data registration. With the frame camera (4000x4000 pixels) one can get an image every 4 seconds. For similar limitations, it is not currently possible with a line camera to get a pixel resolution on the ground higher than 30x30 cm. Which means that for a flying speed of 200 km/h during the flight mission, one requires about 1/200th of a second to read and register one complete array.

The French firm ISTAR (cf. contribution L. Renouard) has already had practical experience with the use of the 3-line camera. This firm uses a prototype, also developed by DLR. The camera is used for the elaboration of city models as they are required by telecommunication. In this case, one has to elaborate the DTM and to model the houses, orthophotos are also required. The image correction and DTM elaboration is done largely automatically; but the post-treatment of the data and the editing requires about 6 hours – 2 days per km^2. The precision obtained is indicated to be within ± 1 m.

Digital Scanners (Chairman: O. Kölbl)

Objectives

- Presentation of the current performances of photogrammetric scanners (strengths and weaknesses, scanning of negatives), advantages of drum scanners, advantageous in comparison to the use of digital cameras

Contributions

Quality evaluation and tests with DSW200, DSW300, SCAI, OrthoVision (M. Baltsavias, ETH-Zürich, Switzerland)

Colour reproduction in photogrammetric scanner (O. Kölbl, EPF-Lausanne, Switzerland)

Archiving of digital image data (L. Rosentaler, University Basel)

Main Results

Without any doubt, photogrammetric scanners have reached a very high standard. The most important achievements of the last years are certainly the incorporation of devices for the treatment of uncut rollfilm and unsupervised scanning of a whole serie of photographs. The DSW300 of LH-Systems as well as the SCAI Scanner (Z/I Imaging) offer this possibility. Many improvements have also been made in order to increase the geometric precision (cf. also article by M. Baltsavias concerning the progress from the DSW200 to the DSW300). The dynamic range has been extended to about 2D due to the progress made in the sensor technique. However, checking the Modulation Transfer Function of the digitised images gives the impression that the quality of digital images is considerably below original images. Also, the colour reproduction of the scanned images shows certain deviations which can however be corrected purely numerically to a certain extent (cf. article by O. Kölbl).

The archiving of data remains a great problem of digital photogrammetry. According to Lukas Rosenthaler, Switzerland, there is no real long-term solution available for this task. Great institutions like NASA have had the misfortune to lose a certain amount of their data, in this case all numerically registered image data from the first-generation satellite. The rapid changes in technology and the limited stability of the digital storage media were mainly responsible for this problem. He only can advise to plan for a copying cycle of all digital image data, at least every two years if one has in mind to build up an image archive, and he currently recommends DLT as data media, as the magnetic traces of this media are in the direction of the tape which makes them relatively insensitive to mechanical interference.

Automation in Photogrammetric DTM Elaboration (Chairman: A. Dupéret)

Objectives

- Principles of matching techniques (feature-based matching, area matching, least square matching), editing and filtering of automatic derived DTM data, experiences in practice and performance of automatic DTM derivation in comparison to laser measurements.

Contributions

Principles of image matching (P. Julien, IGN, France)

IGN's new semi-automatic process to generate contour lines (A. Dupéret, ENSG/ IGN,France)

Vendor's demonstration with standardised images in terms of preparation of the correlation, data checking and data editing (Intergraph, LH-Systems, Zeiss).

DTM derivation at the Ordnance Survey Ireland (M. Cory, Ordnance Survey, Ireland

DTM derivation with Match T (T. Blaudet, A.P.I., France)

DTM determination by laser scanning: an efficient alternative (B. Petzold, LVA Nordrhein-Westfalen, Germany).

Main Results

The automatic DTM derivation from aerial photographs is a research area that has been intensely dealt with for about 2 decades. Meanwhile, this technique is facing competion from laser scanning but also from the 3-line camera. The most important software products currently used in Europe in practice are those of LH-Systems (Socet Set) and Match-T. The latter is integrated in the Intergraph ImageStation (Clix and Windows) as well as in Phodis (Zeiss). For the DTM derivation for topographic requirements, the Socet Set of LH-Systems is mainly used. The contributions by A. Dupéret (IGN France) and M. Cory (OS Ireland) showed the efficiency of the LH-System software in production, allowing an improvement of productivity by a factor of about 3 compared to the plotting of the contour lines on an analytical plotter with the same quality requirements. However, the preparation of the data and the successive editing requires much experience.

Automatic Aerial Triangulation (Chairmen: T. Kersten, C. Heipke)

Objectives

- Show the efficiency and difficulties of automatic aerial triangulation (problems on point transfer due to scale changes, height differences, texture), demonstrate the possibilities for quality control and discuss the optimal work flow.

Contributions

Summary of the results of the OEEPE/ISPRS Test (Ch. Heipke, Uni Hannover and K. Eder, TU München, Germany)

Vendor's demonstration with standardised images in terms of the preparation of the aerotriangulation and the quality check (Inpho, Intergraph, LH-Systems, Zeiss).

Results of digital triangulation using different software packages (HATS/Match-AT/Phodis-AT) (T. Kersten, Swissphoto, Switzerland)

Automated triangulation in Nordic terrain – experiences and challenges with Match AT (Anne Urset, Blom Kart AS, Norway and Ivar Maalen-Johansen, Dept. of Mapping Sciences, Agricultural Univ. of Norway)

Digital Aerotriangulation for map revision with Match AT (Ch. Kaeser, SFIT, Switzerland)

Experiences in digital triangulation with Phodis AT (B. Masala, Cabinet Philippe Rollin, France)

Digital Aerotriangulation with HATS (T. Kersten, Swissphoto, Switzerland)

Main Results

Great progress has been made in the last two years in the area of automatic aerial triangulation. At the past workshop, about two years ago, the only experiences available were done on the ImageStation of Intergraph with the ISDM software package. This software package allows semi-automatic processing, meaning that the operator has to choose the tie points but can use a module for the automatic point transfer to the neighboring images. Very often, however, point transfer is done purely manually. Nevertheless, this method has led to a considerable rate of production. It was indicated that an operator is able to handle up to 60 images and even more per day in this way.

Today, practicians essentially have a choice between the 3 following procedures :

- HATS by LH-Systems,
- Match-AT by Inpho also as stand-alone version but also integrated in the Image Station,
- Phodis-AT by Zeiss or integrated in the UNIX station of Z/I Imaging.

Manufacturers as well as practitioners have reported on these three software packages. All procedures have shown high efficiency and satisfying results. However, all procedures also show certain weaknesses. For the detection of blunders, it is important that the process of the automatic point transfer be densely coupled with a numerical control over the algorithm of the block adjustment. All manufacturers are working intensively on this aspect. However, these modules have not yet been introduced in practice. A user-friendly procedure for the correction of blunders is also important. In this respect, the ImageStation with the module ISDM which allows for simultaneous monitoring and measurement of up to 12 images or 6 images and 6 enlargements offers a considerable advantage. The control of the connection of the images, in particular with images on neighboring strips is also still problematic. Users of LH-Systems and Match-AT software have written special control software for this objective. According to explanations given by Scott Miller of LH-Systems, this problem will be solved with the next NT version of HATS, with the help of the ORIMA block adjustment program.

The efficiency of automatic aerial triangulation is also characterised by the fact that many institutions which have digital workstations use only digital procedures for aerial triangulation, even if the plotting is done on analytical plotters. However, some problems might result from the transfer of the orientation elements coming out from the bundle block adjustment, due to the use of special parameters.

Orthophoto Production (Chairman: O. Kölbl)

Objectives

- The input data for orthophoto production, exchange of orientation parameters, DTM/DSM quality and representation
- Radiometry, scanning problems and image quality, radiometric colour enhancement, dodging and homogeneity
- Mosaicking, printing techniques, standards for orthophotos

Contributions

Some aspects of digital orthophoto production (U. Weidner, Hansa Luftbild, Germany)

Automation of computation of ortho-images (D. Moisset, IGN, France)

Vendors demonstration on mosaicking (Helava, Intergraph, Zeiss)

Remarks on the quality control of digital orthophotos (M. Wiggenhagen, Institute for Photogrammetry, Germany)

Principles of printing technique, (R. Raychoudhury, Hewlett Packard)

High quality printing with Cibachrom (M. Gubler, Switzerland)

Main Results

Digital workstations have doubtlessly been most widely used in orthophoto production; today, these documents are practically exclusively produced by digital techniques. Consequently, the different manufacturers have invested heavily in software tools for orthophoto production. In an overview lecture, Weidner (Hansa Luftbild Germany) stated that the rather complex chain of production requires a combination of different products for the proper rectification, computation of the mosaics, optimal tone adaptation and final output for the printing of the images. The manufacturers (Intergraph, LH-Systems and Zeiss) showed important new developments during their demonstration, in particular for tone adaptation and image enhancement. The uniform task concerning the combination and adaptation of colours of 4 aerial photographs of medium quality was demonstrated by the manufacturer in a convincing manner.

Currently, the German Standardisation Committee (DIN) is elaborating standards for orthophotos; however, this publication might not be available before 1 or 2 years.

One of the standard reproduction techniques for the printing of orthophotos is without any doubt the HP-DesignJet (Hewlett-Packard). The representative of the firm explained the principle of digital printing technique and concentrated mainly on the inkjet technique. Standard resolution of the 2000 and 3000 series as well as of the series 1000 is 600 dpi for colour printing. Intensive work is being done on a further refinement of the colour resolution. The 2000 and 3000 series have been especially developed for the graphic industry, allowing the use of dye and pigment colours. The latter are very resistant to light and it should be possible to store them for an unlimited period of time. Meanwhile, photo plotters on photo material still provide an alternative to inkjet plotters for high quality requirements (presentation Gubler).

A complete chain of software packages for orthophotos production up to the driver for printing is delivered by Intergraph. In particular for the output for printing, many other firms prefer foreign products. Postscript is definitely an upcoming general standard in this respect.

Logistics, Management and Financial Aspects (Chairpersons: R. Héno, J. Colomer)

Objectives and Themes of Discussion

- Major bottlenecks in digital photogrammetric workflows
- Running production workflows in an heterogeneous environment
- Translators, standards
- Development tools: libraries, macro languages, documentation
- Workflow management tools
- Migration/upgrading: protecting the investment - hardware /software/ data
- Maintenance, availability, reliability, training

Contributions

The automation, integration and optimization of a digital photogrammetric production environment" (T. Kersten, N. Chuat, W. O'Sullivan, Swissphoto, Switzerland)

Logistics and system integration, experience of France Ingénierie Topographie, digital photogrammetry integration and production optimization (G. Toth and D. Lenne , FIT, France)

Financial aspects/economics of tenders (J. Piedfort, Switzerland)

Logistic problems at ICC (M. Torre, T. Magarinof, J. Colomer, ICC, Spain)

General discussion: "Advances since Lausanne 1996" (update of the list of requirements, major breakthroughs, issues still pending, etc. (R. Héno, IGN, France and J. Colomer, ICC, Spain)

Main Results

Digital photogrammetry poses considerable logistic problems. Already, the enormous amount of data which are yielded by the image data, the necessity to have as many operations as possible to run as batch processes and to load the operator with a minimum of data manipulation require a very rigorous organisation of the data management. These logistic aspects were presented in contributions by T. Kersten (Swissphoto, Switzerland), G. Toth (FIT, France), as representatives of private offices and Margarita Torre (Institute of Cartography of Catalonia, Spain) representing a national topographic mapping institution. Also of interest concerning data management are the overview diagrams regarding the system configuration at ICC and the diagrams of the various working processes given in the ahead-mentioned paper. Furthermore, the various logistic and management problems were dealt with in an extended discussion; the main topics have been summarised by R. Héno and J. Colomer in an overview paper.

Already for image storage, one has to state that questions on the image format and the possible data compressions have only been partly solved. Without any doubt, TIFF has imposed itself largely as a standard but it remains open whether the data should be archived in a compressed form. The problems of the long-term storage of all technical data concerning image registration, flight mission and data restitution also remain open.

For large companies, it is also of great interest whether the image and project data of the various processes can be handled on a central image server. It has been clearly stated that current network technology and the efficiency of the storage media are not capable of providing sufficiently rapid data access. In particular, the access to the mass storage devices still considerably limits the speed of image processing, much more than the computation capacity of the processors.

Another question which was not completely clarified concerns display technology. It is true that the various automated processes of image treatment allow one to achieve a high performance. However, the image quality as it is presented on the monitor to the operator does not by far reach the same standard as a high-quality optical observation system in an analytical plotter. It is true that the digital plotting systems are accepted very easily by young operators; however, the detail recognition remains below the standard of an analytical plotter.

It is evident that training, technical assistance as well as the exchange of experiences are of the utmost importance for such a complex matter as digital photogrammetry in a production environment. It is understood that manufacturers, the various training institutions, but also practitioners are making great efforts in this field. Nevertheless, the costs for the introduction of a digital workstation in a production environment are considerable and it takes a long time to obtain a more or less optimal use. In this field, it would be important to enhance the efforts especially on the manufacturer's side.

In an overview lecture concerning the financial aspects J. Piedfort in particular showed the extremely large variations of prices, especially in international tenders. Generally, the wish has been expressed to introduce a certain ethic when working out tenders and to avoid ruinous and unrealistic low bids. It is understood that no real solution has been found thus far in this field.

Conclusions

The workshop obviously did not succeed in providing an answer to all questions still open. It did however show the general tendencies and demonstrated the great progress made in digital photogrammetry. Digital photogrammetry is a mature technique mainly in the field of process, which can be largely automated, like aerial triangulation, orthophoto production and also the derivation of precision DTMs. With respect to plotting, it was less evident whether digital workstations are preferable, due to the low degree of automation.

List of Participants

Organisation Committee

KÖLBL Otto (Chairman)	ECOLE POLYTECHNIQUE FEDERALE GR Ecublens CH - 1015 Lausanne Switzerland otto.koelbl@epfl.ch
DENIS Patrice	ENSG 6 & 8, avenue Blaise Pascal Cité Descartes F - 77455 Marne-la-Vallée Cedex 2 France patrice.denis@ensg.ign.fr
GRUJARD Isabelle	SFPT 6 & 8, avenue Blaise Pascal Cité Descartes F - 77455 Marne-la-Vallée Cedex 2 France sfpt@ensg.ign.fr
COLOMER José L.	INSTITUT CARTOGRAPHIC DE CATALUNYA Parc de Monjuic E - 08038 Barcelona Spain colomer@rcc.es
DUPERET Alain	ENSG 6 & 8, avenue Blaise Pascal Cité Descartes F - 77455 Marne-la-Vallée Cedex 2 France alain.duperet@ensg.ign.fr
EGELS Yves	ENSG 6 & 8, avenue Blaise Pascal Cité Descartes F - 77455 Marne-la-Vallée Cedex 2 France egels@ensg.ign.fr
HEIPKE Christian	UNIVERSITÄT HANNOVER Institut für Photogrammetrie und Ingenieurvermessungen Nienburger Strasse 1 D - 30167 Hannover Germany Heipke@ipi.uni-hannover.de
HENO Raphaële	IGN SIT 2, avenue Pasteur F - 94165 Saint-Mandé Cedex France
KERSTEN Thomas	SWISSPHOT VERMESSUNG AG Dorfstr. 53 CH - 8105 Regensdorf - Watt Switzerland thomas.kersten@swissphoto.ch

Lecturers (persons already mentioned above are not listed here)

BALTSAVIAS Emmanuel	INSTITUTE OF GEODESY AND PHOTOGRAMMETRY ETH CH - 8093 Zürich Switzerland manos@geod.ethz.ch
BEGNI Gérard	Président SFPT ENSG – 6–8, avenue Blaise Pascal Cité Descartes – Champs sur Marne F - 77455 Marne-la-Vallée cedex 2 France
BLAUDET Tristan	ALPES PYRENEES IMAGES 20, rue Paul Helbronner F - 38100 Grenoble France
CORY Michael	ORDNANCE SURVEY IRELAND Phoenix Park IRL - Dublin 8 Ireland mcory@si.ie
DIERICKX Bart.	IMEC Kapeldreef 75 B - 3001 Leuven Belgium dierickx@imec.be
DÖRSTEL Christoph	Z/I IMAGING GmbH Postfach 1166 D - 73442 Oberkochen Germany doerstel@zeiss.de
EDER Konrad	TECHN. UNIVERSITÄT MÜNCHEN Arcisstr. 21 D - 80290 München Germany konni@photo.verm.tu-muenchen.de
FRITSCH Dieter	UNIVERSITÄT STUTTGART Instit. für Photogrammetrie Geschwister-Scholl-Str. 24(0) D - 70174 Stuttgart Germany dieter.fritsch@ifp.uni-stuttgart.de
JULIEN Patrick	IGN DT / SR 2, avenue Pasteur F - 94165 Saint-Mandé Cedex France
KACZYNSKI Romuald	INSTITUTE OF GEODESY AND CARTOGRAPHY Jasna 2 / 4 PL - Warszawa 00 950 Poland Rom@igik.edu.pl

KÄSER Christoph	SWISS FEDERAL INSTITUTE OF TOPOGRAPHY Seftigenstrasse 264 CH - 3084 Wabern Switzerland christoph.kaeser@lt.admin.ch
MAALEN - JOHANSEN Ivar	AGRICULTURAL UNIV. OF NORWAY Depart. of Mapping Sciences P.O. Box 5034 N - 1432 Aas Norway ivar.maalen@ikf.nlh.no
MADANI Mostafa	INTERGRAPH CORPORATION Mailstop IW17C4 USA - Huntsville AL 35894 - Alabama msmadani@ingr.com
MAGARIÑOS VARO Antonio	INSTITUT CARTOGRAPHIC DE CATALUNYA Parc de Monjuic E - 08038 BARCELONA Spain antoniom@rcc.es
MASALA Bernard	CABINET PHILIPPE ROLLIN BP 28 19, rue Albert Chabanon F - 13448 Marseille Cantini cedex France cabinet.rollin@wanadoo.fr
MILLER Scott	Vice Président Photogrammetry LH SYSTEMS LLC 10965 Via Frontera USA - CA 92127 San Diego - California scott.miller@lhsystems.com
MOISSET Didier	IGN DC DEV / Projet Ortho2, avenue Pasteur F - 94165 Saint-Mandé Cedex France
PETZOLD Bettina	LANDESVERMESSUNGSAMT Nordrhein - Westfalen Muffendorfer Str. 19-21 D - 53177 Bonn Germany petzold@lverma.nrw.de
PIEDFORT Johan	JOHAN PIEDFORT PHOTOGRAMMETRIE Rue Saint-Martin 22 CH - Lausanne 1003 Switzerland

POULIT Jean	IGN 2, avenue Pasteur F - 94165 Saint-Mandé Cedex France
RAYCHOUDHURY Rana	HEWLETT-PACKARD BCD Software Lab Barcelona Division Avenida Graells, 501 E - 08190 Sant Cugat Del Valles Spain rana@bpo.hp.com
RENOUARD Laurent	ISTAR Les Espaces de Sophia Bâtiment F 80, route des Lucioles BP 282 F - 06905 Sophia Antipolis Cedex France Renouard@istar.fr
ROSENTHALER Lukas	UNIVERSITY OF BASEL Scientific Photography Lab. Schützenweg 61 CH - 4123 Allschwil Switzerland rosenth@foto.chemic.unibas.ch
SANDAU Rainer	Prg Manager ADC LH SYSTEMS GmbH Heinrich Wild Strasse CH - 9435 Heerbrugg Switzerland rainer.sandau@email.leica.com
SPILLER Rudolph	Z/I IMAGING GmbH Postfach 1166 D - 73442 Oberkochen Germany spiller@zeiss.de
THOM Christian	IGN DT / SR 2, avenue Pasteur F - 94165 Saint-Mandé Cedex France
TORRE ALLOCERA Margarita	INSTITUT CARTOGRAPHIC DE CATALUNYA Parc de Monjuic E - 08038 Barcelona Spain margat@rcc.es
TOTH Gabriella	F.I.T. 59, avenue de Paris F - 95230 Soisy / Montmorency France G. toth@fit-topo.fr
URSET Anne	Project Manager BLOM KART AS Høyörhtenveien 13B N - 1055 Oslo Norway au@blom.no

WALD Bruce	President and CEO LH SYSTEMS LLC 10965 Via Frontera USA - CA 92127 San Diego California bruce.wald@lhsystems.com
WEIDNER Uwe	HANSA LUFTBILD GmbH Elbestr. 5 D - Münster Germany weidner@hansaluftbild.de
WIGGENHAGGEN Manfred	UNIVERSITÄT HANNOVER Institut für Photogrammetrie und Ingenieurvermessungen Nienburger Strasse 1 D - 30167 Hannover Germany wigg@ipi.uni-hannover.de

Participants (persons already mentioned above are not listed here)

ABU RAGHEB Nader	Head of Leica Dept. AL-TEWEFIK AUTO & EQUIPMENT Gardins Str Amman Jordan Nader@al-tewfik.com.jo
AGNARD Jean-Paul	UNIVERSITE DE LAVAL Département des Sciences Géomatiques G1K 7P4 Sainte-Foy Quebec Canada jean-paul.agnard@scg.ulaval.ca
ALEITHE Wolfgang	ING. BÜRO GEOCAD GmbH Hoyerswerdaer Strasse 20 D - 02906 Kreba Germany W.Aleithe@geocad.de
ANDERSEN Oystein	AGRICULTURAL UNIV. OF NORWAY Dept. of Mapping Sciences N - PO Box 5034 1432 Aas Norway ikfoa@ikf.nlh.no
ARRANZ JUSTEL Jose Juan	MAPLINE S.A. E - Serrano, 228 Madrid Spain jjarranz@retemail.es
BALLESTERO GARCIA-ASENJO Ernesto	Ingeniero tecnico topografo MAPLINE S.A. E - Serrano, 228 Madrid Spain mapline@retemail.es
BARBACANNE Edmond	IGN SPCN 2, avenue Pasteur F - 94165 Saint-Mandé Cedex France
BAUDOUIN Axel	Ass. Prof N.T.N.U. Faculty of Social Sciences N - Dragvoll 7491 Norway axel.baudouin@sv.ntnu.no
BAZILLE Pierre	CNERTA 26, boulevard Docteur Petitjean F - 21 000 Dijon France p.bazille@educagri.fr
BECIRPAHIC François	IGN SPCN 2, avenue Pasteur F - 94165 Saint-Mandé Cedex France

BELGUED Youssef	Student ENSEEIHT / LIMA 2, rue Camichel F - 31071 Toulouse Cedex 7 France y.belgued.alcatel@e-mail.com
BIDO Irena	DLR Rudower Chaussee 5 D-12489 Berlin Germany Irena.bido@dlr.de
BOBERG Anders	ROYAL INSTITUTE OF TECHNOLOGY Department of Geodesy and Photogrammetry S - Stockholm Sweden abg@geomatics.kth.se
BOLDO M.	Auditeur libre IGN France
BOULIANNE Michel	UNIVERSITE DE LAVAL Département des Sciences Géomatiques G1K 7P4 Sainte-Foy Quebec Canada michel.boulianne@scg.ulaval.ca
BRANDT Steffen	DEUTSCHE STEINKOHLE AG DG Geoinformationsbearbeitung Gleiwitzer Platz 3 D - 46236 Bottrop Germany Steffen.brandt@dg.deutsche-steinkohle.de
BRAY Colin	ORDNANCE SURVEY IRELAND Phoenix Park IRL - Dublin, 8 Ireland cbray@Osi.ie
BRIND’AMOUR Martin	DVP GEOMATIC SYSTEMS Inc 8389 av. Sous le Vent Charny, PQ G6X 1K7 Quebec Canada martin@dvp.ca
CAMPAGNE Philippe	Auditeur libre IGN France
CHUAT Nathalie	SWISSPHOT VERMESSUNG AG Dorfstr. 53 CH - 8105 Regensdorf - Watt Switzerland nathalie.chuat@swissphoto.ch
COULOMBE Jacques	DVP GEOMATIC SYSTEMS Inc 8389 av. Sous le Vent Charny, PQ G6X 1K7 Quebec Canada Jacques@dvp.ca

CRAWFORD David	SDS 3, Hope Street Bo'ness GB - West Lothian EH510AA Scotland U.K. dc@sds.co.uk
CZAKA Thomas	SWISS FEDERAL INSTITUTE OF TOPOGRAPHY Seftigenstrasse 264 CH - 3084 Wabern Switzerland thomas.czaka@lt.admin.ch
da SILVA Celeste	Geographic Engineer IPCC Rua Artilharia UM, 107 P - 1070 Lisboa Portugal Celeste@ipcc.pt
da SILVA Irineu	Regional Manager LEICA BRASIL Rua Sta Ifigénia, 89 01207-001 Sao Paulo Brasil leicabr@ibm.net
DE GRAEF Jan Bertha Walter	FLEMISH LAND AGENCY Staatsbaan 148 B - 3460 Bekkevoort Belgium cgrit@tin.it
DE JONG Jan	Manager International Consultancy KADASTER Waltersingel 1 NL - 7314 NK Apeldoorn The Netherlands 101553.2240@compuserve.com
de LAPORTE Karin	WSL-LI Zuercherstrasse 111 CH-8903 Birmensdorf Switzerland
de MAN Guy	EUROSENSE Nerviërslaan, 54 B - 1780 Wemmel Belgium info@eurosense.be
DEPOND Jean-Marc	ALPES PYRENEES IMAGES 20, rue Paul Helbronner F - 38100 Grenoble France
DONNENWIRTH Christian	CONTINENTAL HIGHTECH SERVICE 370, avenue Napoléon Bonaparte F - 92500 Rueil Malmaison France info.chs@wanadoo.fr

DOWMAN Ian	UNIVERSITY COLLEGE LONDON Dept. Geomatic Engineering GB - Gower Str. London WCIE 6BT U.K. idowman@ge.ucl.ac.uk
ECKARDT Andreas	GERMAN AEROSPACE CENTER Deutsches Zentrum für Luft- und Raumfahrt (DLR) Rudower Chaussee 5 D - 12489 Berlin Germany andreas.eckardt@dlr.de
EDEL M.	Auditeur libre IGN France
FAVE M.	Auditeur libre IGN France
FLEURY Benoît	ISTAR Les Espaces de Sophia Bâtiment F 80, route des Lucioles BP 282 F - 06905 Sophia Antipolis Cedex France Fleury@istar.fr
GACHET Roland	Auditeur libre IGN France
GENTILI Guiseppe	COMPAGNIA GENERALE RIPRESEAEREE SPA Via Cremonese N. 35 / A Fontana I - 43010 Parma Italy cgrit@tin.it
GEVREY Sylvain	Directeur LH SYSTEMS EURL 86, avenue du 18 juin 1940 F - 92563 Rueil Malmaison France sylvaingevrey@compuserve.com
GODONE Franco	Service CNR IRPI Str. delle Cacce 73 I - 10135 Turin Italy f.godone@irpi.to.cnr.it
GRABMAIER Karl	ITC P.O. Box 6 NL - 7500 AA Enschede The Netherlands grabmaier@itc.nl
GROSSER Martin	TOPSCAN GmbH Münstertrasse 19 D - 48565 Steinfurt Germany grosser@topscan.de

GRUSSENMEYER Pierre	ENSAIS Polytechnicum de Strasbourg 24, boulevard de la Victoire F - 67084 Strasbourg Cedex France Pierre.Grussenmeyer@ensais.u-strasbg.fr
GUT Daniel	Ing. retired Leica Heerbrugg Av. Ruchonnet 41 CH - 1003 Lausanne Switzerland
GVOZDANOVIC Tomaž	Tech. Director DFG CONSULTING Divovarnisua 8 SLO - 1000 Ljubljana Slovenia dfg.consulting@spiua.unistar.si
HANQUINET Christine	IGN Abbaye de la Cambre, 15 B - 1000 Bruxelles Belgium jvo@ngi.be
HEUCHEL Tobias	INPHO GmbH Smaragdweg 1 D - 70174 Stuttgart Germany tobias@inpho.de
HEYNE Wolfgang	LH SYSTEMS GMBH Heinrich Wild Strasse CH - 9435 Heerbrugg Switzerland Wolfgang.heyne@email.leica.com
HOSCHTITZKY Hans	ITC P.O. Box 6 NL - 7500 AA Enschede The Netherlands Hoschtitzky@itc.nl
JAAKKOLA Juha	FINNISH GEODETIC INSTITUTE Geodeetinrinne 2 FIN - 02430 Masala Finland juha.jaakkola@fgi.fi
JADBANE Abdel	Erdas Ingenier Products ESRI France 21, rue des Capucins F - 92190 Meudon France ajadbane@esrifrance.fr
JANSSENS Katleen	FLEMISH LAND AGENCY Staatsbaan 148 Gulden - Ulieslaan 72 B - 1060 Brussel Belgium Katleen.janssens@vlm.be

JOUANNET Daniel	GEOMETRIC Rue Montespan 5 F - 91024 Evry Cedex France JGeometric@aol.com
JUD Sillie	Z/I IMAGING GmbH Postfach 1166 D - 73442 Oberkochen Germany jud@zeiss.de
KAARTINEN Harri	FINNISH GEODETIC INSTITUTE Geodeetinrinne 2 FIN - 02430 Masala Finland Harri.kaartinen@fgi.fi
KAMPER John	DANISH NATIONAL SURVEY AND CADASTRE Rentemestervej 8 DK - 2400 Copenhagen NV Denmark jk@kms.dk
KIRWAN Richard	Director ORDNANCE SURVEY IRELAND Phoenix Park IRL - Dublin 8 Ireland
KOEHLER Gerd	HESSISCHES LANDVERMESSUNGSAMT Schaperstrasse 16 D - 65195 Wiesbaden Germany g.koehler.la@hlva.hessen.de
KOHLHOFER Gerald	BEV Krotenthallergasse 3 A - 1080 WIEN Austria gkohlhofer@bev.gv.at
KOLBUSZ John	Programmer KLT Associates Inc. 200 Corporate Place USA - Peabody, Massachussetts 01960 USA john@kltassoc.com
KOPF Didier	CARL ZEISS OBERKOCHEN 1, impasse des saules F - 67118 Geispolsheim France
KOROLITSKI Jean-François	IGN DPE 2, avenue Pasteur F - 94165 Saint-Mandé Cedex France

KREILING Walter	AVIOSOFT Büntstr. 27 CH - 9442 Berneck Switzerland kreiling@aviosoft.ch
LATARGET Sylvain	IGN SPCN 2, avenue Pasteur F - 94165 Saint-Mandé Cedex France
LAUGIER Olivier	Erdas Technical Engineer ESRI France 21, rue des Capucins F - 92190 Meudon France olaugier@esrifrance.fr
LE BLANC Serge	SPOT IMAGE / Direction commerciale 5, rue des Satellites F - 31030 Toulouse Cedex 4 France Serge.Le-Blanc@spotimage.fr
LE YHUERIC Yann	SYSECA 66-68, avenue Pierre Brossolette F - 92247 Malakoff Cedex France
LITHOPOULOS Eric	APPLANIX CORPORATION 550, Alden Road, Unit 12 Markham Ontario Canada Elithopoulos@applanix.com
LOFFET André	EUROSENSE Nerviërslaan, 54 B - 1780 Wemmel Belgium info@eurosense.be
LÖFLATH Ulrich	HAUMANN Beratende Ingenieure Ingolstädter Strasse 12 D - 80807 München Germany Haumann.ingenieure@t-online.de
MALANOWICZ Ewa	HEAD OFFICE of GEODESY and CARTOGRAPHY PL - Wspolna 2 Warsaw Poland emalanowicz@gugik.gov.pl
MALLET Isabelle	IGN SIT 2, avenue Pasteur F - 94165 Saint-Mandé Cedex France
Mc GILL Andy	ORDNANCE SURVEY IRELAND Phoenix Park IRL - Dublin, 8 Ireland cbray@Osi.ie

MONVOISIN Philippe	Professeur de Photogrammétrie ESTP 28, avenue du Président Wilson F - 94234 Cachan Cedex France mvsn@estp.fr
NEUMANN Klaus	Z/I IMAGING GmbH Postfach 1166 D - 73442 Oberkochen Germany neumann@zeiss.de
NICOLETTI Antonio	INTERGRAPH CORPORATION Mailstop IW17C4 USA - Huntsville AL 35894 Alabama
NILSEN Barbi	AGRICULTURAL UNIV. OF NORWAY Dept. of Mapping Sciences PO Box 5034 N-1432 Aas Norway ikfbn@ikf.nlh.no
NIZEYIMANA Egide	PENNSYLVANIA STATE UNIVERSITY 101 Land and Water Research Building USA - University Park PA 16802 USA Exnios@psu.edu
NOLETTE Clément	UNIVERSITE DE LAVAL Département des Sciences Géomatiques G1K 7P4 Sainte-Foy Quebec Canada clement.nolette@scg.ulaval.ca
NONIN Philippe	ISTAR Sophia Antipolis F - 06560 Valbonne France nonin@istar.fr
PAPELARD M.	Auditeur libre IGN France
PHEM Sokhon	ITC P.O. Box 6 NL - 7500 AA Enschede The Netherlands phem@itc.nl
PLIETKER Berthold	LANDESVERMESSUNGSAMT MECKLENBURG-VORPOMMERN Lübecker Strasse 289 D - 19053 Schwerin Germany
POULAIN Eric	DGA CTA / GIP / CEGN 16 bis, avenue Prieur de la Côte d'Or F - 94114 Arcueil Cedex France epoulain@ctme.etca.fr

POYMBROECK Nadège Van	Student CEA BP 12 F - 91680 Bruyeres Le Chatel France vanpuymb@ldg.bruyeres.cea.fr
RABADI Jamil	ROYAL JORDANIAN GEOGRAPHIC CENTRE PO. Box 20214 11118 Amman Jordan rgc@amra.nic.gov.jo
RAVAT Christian	Direction technique THOMSON-CSF/DETEXIS 1, bd Jean Moulin 78852 Elancourt France christian.ravat@detexis.thomson.csf.com
REDWEIK Paula Maria	F.C.U.L. UNIVERSITY OF LISBON R. Ernesto Vasconcelos C1 3° P P - 1700 Lisboa Portugal Predweik@ptrol.cc.fc.ul.pt
REISS Peter	BAYER. LANDESVERMESSUNGSAMT Postfach 22 00 04 D - 80535 München Germany Peter.Reiss@blva.bayern.de
REULKE Ralf	GERMAN AEROSPACE CENTER Deutsches Zentrum für Luft- und Raumfahrt Rudower Chaussee 5 D - 12489 Berlin Germany ralf.reulke@dlr.de
ROHRBACH Arthur	Vice President, General Manager LH SYSTEMS GmbH Heinrich Wild Strasse CH - 9435 Heerbrugg Switzerland arthur.rohrbach@compuserve.com
SAKS Tauno	Chief of Cartography Department ESTONIAN MAP CENTRE Mustamë tee 33 EW - Tallinn Estonia taunos@ekk2.estpak.ee
SALAMEH Khalil	ROYAL JORDANIAN GEOGRAPHIC CENTRE PO. Box 20214 11118 Amman Jordan rgc@amra.nic.gov.jo

SASSOR Andrea	LH SYSTEMS Gmbh Gontermannstrasse 46 D - 12101 Berlin Germany
SCHELSTRAETE Daniel	ECOLE NATIONALE DES SCIENCES GEOGRAPHIQUES 6 & 8, avenue Blaise Pascal Cité Descares F - 77455 Marne-la-Vallée Cedex 2 France daniel.schelstraete @ensg.ign.fr
SCHROTH Ralf	HANSA LUFTBILD GmbH Elbestr. 5 D - 48145 Muenster Germany schroth@hansaluftbild.de
SCHULZ Bernd-Siegfried	BUNDESAMT FÜR KARTOGRAPHIE UND GEODÄSIE Richard Strauss Allee 11 D - 60598 Frankfurt am Main Germany schulz@ifag.de
SHEARS Jonathan	ERDAS INTERNATIONAL Telford House GB - Fulbourn Cambridge CB1 5HB UK jshears@erdas.co.uk
SHEMDIN O.H.	ELECTRONIC MAPPING Inc. PO Box 1109 USA - La Canada CA 91012 USA elecmap@aol.com
SIDLICHOVSKY Pavel	LAND SURVEYING OFFICE Kostelni 42 CZ - Prague Czech Rep. sidlich@zupha.cz
SIMAN-TOV Ofer	OFEK AERIAL PHOTOGRAPHY Ltd New Industrial Zone PO Box 8065 Netanya Israel ofek-gis@netvision.net.il
SIMMONS Greg	SIMMONS MAPPING (UK) Limited 5 West Street GB - Axbridge Somerset BS26 2AA UK
SMART Anthony	ORDNANCE SURVEY Romsey Road GB - Southampton SO16 4GU U.K. asmart@ordsvy.gov.uk

STOJIC Mladen	Product Manager ERDAS Inc. 2801 Buford Highway, NE USA - Atlanta, Georgia 30329-2137 USA mstojic@erdas.com
SURACE Luciano	COMPAGNIA GENERALE RIPRESEAEREE SPA Via Cremonese N. 35 / A Fontana I - 43010 Parma Italy fotogram@vlm.be
TABOR Mark	CSCS ORDNANCE SURVEY Romsey Road GB - Southampton SO16 4GU U.K. Mtabor@ordsvy.gov.uk
TALTS Jüri	NATIONAL LAND SURVEY OF SWEDEN S - 80182 Gävle Sweden talts@lmv.lm.se
TARRAGA Emilio	Auditeur libre Université de Valence
VALGEPEA Jelena	ESTONIAN MAP CENTRE Mustamë tee 33 EW - Tallinn Estonia leenav@ekk2.estpak.ee
VIVIER Benoît	IGN SIT 2, avenue Pasteur F - 94165 Saint-Mandé Cedex France
VÖGTLE Thomas	UNIVERSITÄT KARLSRUHE Inst. f. Photogrammetry Englerstr. 7 D - 76128 Karlsruhe Germany voegtle@ipf.bau-verm.uni-karlsruhe.de
WICHERSON Remko	RIJKSWATERSTAAT Kanaalweg 3B NL - 2600 GA Delft The Netherlands R.J.Wicherson@Mdi.rws.minvew.nl
WILD Dietmar	INPHO GmbH Smaragdweg 1 D - 70174 Stuttgart Germany dietmar@inpho.de

WILD Emil	Manager C & B TECHNIC GmbH Silcherstr. 1 D - 71706 Markgröningen Germany CuB-Technik.Wild@t-online.de
ZAMOLO Isabelle	Auditeur libre IGN France
ZIEMANN Hartmut	HOCHSCHULE ANHALT (FH) F 35 Postfach 2215 D - 06818 Dessau Germany hziemann@vw.hs-anhalt.de

Opening and Welcome Addresses

Chairman

O. Kölbl

Welcome address by the General Director of IGN-France

J. Poulit,
General Director of IGN-France

Dear colleagues, I would like you to join me for a minute of silence in honour of Mrs Vera Kölbl who died ten days ago. Ladies and gentlemen please stand-up.

<< A minute of silence >>

Dear Otto, please accept my sympathy and moral help for that distressing event.

Despite that, dear Otto and dear colleagues,

It is my pleasure to welcome you here in Marne-la-Vallée in the premises of the Ecole Nationale des Sciences Géographiques. This building was inaugurated by the President of the French Republic, Mr Jacques Chirac in Octobre 1997. During his visit, he had a chance to learn about photogrammetry. He even sat down in front of a stereo plotter, put the special glasses on and saw on the screen and in stereo the displayed stereopair. The visit was scheduled to last few minutes but the magic of geographic information together with the highly spectacular show we made turned it twice longer than planned. And the security was upset for such a long standing at the same place.

At that time I was just nominated director general of Institut National of France, the French National Mapping Agency. So it was for me a great privilege I was able to make the visit with the president!

As you probably know IGN-France is in charge of producing the reference information necessary to geographically describe our country. It therefore masters all the technology for doing so. From a fleet of 4 planes to the printing facilities, including, geodesy, photogrammetry and cartography, IGN-France is organised in a way to efficiently produce the products requested by the society including not only the public administrations but also the private sector and the general public. IGN-France is requested to self finance 50% of its activity. In order to fulfil such an undertaking the institute developed a strategy which is two fold: identification of synergy of the civilian, military and international requirements on the one hand, innovation on the other hand.

Innovation implies that IGN-France undertakes research in the field of geographic information and operates partnerships with the private sector organization enabling to offer new products and services as well as improving its production methods and processes.

Which are the products and services IGN-France is now offering. First of all, maps. IGN-France is in charge of covering the entire country with maps ranging from the one to twenty five thousands to the one to one million. They are useful for hiking, riding and driving. Only fifteen per cent of general public spontaneously know IGN-France. We just entered a programme of advertisement in order to raise this ratio specially with regard to the range of products useful for the car drivers and tourists. Innovative processes are now operational to create maps at various scales from the digital geographic information we now produce. Income from map selling range a stable one hundred and twenty million francs per year.

Second is the production of geographic databases which are generic in a sense they offer an information platform for adding value. Such products are useful for professionals in their day to day work connected to space and for value adding companies offering new services to users. Larger in size and to be terminated by year two thousands and five, BDTopo® is covering the needs usually met by maps at one to ten thousands. First completed, the BDAlti® provides the contour lines for the entire country. Second to be completed, BDCarto® addresses smaller scales (one to one hundred thousands) while Georoute® meets the requirements implying a sound knowledge of the road network needed by end-user systems such as in car navigation systems, fleet management or geomarketing.

Recently in this area we innovated quite a lot! We entered contractual agreements with several private companies which provides added value on top of our generic databases. We are also experimenting a phoning service to users allowing them to know how long it may take to go from the place they are to the place they want to reach. A business plan demonstrated that even if we target 10% of the professional users of cellular telephones, that activity could generate about twenty to thirty million French francs per year (three to five million Euros).

In collaboration with the French administration responsible for the cadastre, we are undertaking studies into geo-referencing the French cadastre. Progress in the mentality is so rapid that IGN-France will market BDParcellaire® the database providing the geometry of all the 5 million parcels owned in France! This database production area provide an increasing incomes ranging eighty millions Frances in 1998.

In order to be able to produce maps and databases, IGN-France, as all NMAs, requires to install geodetic and levelling reference frameworks, acquire aerial photographs, create orthophotos. These also are products available to the users. A service on the Internet is operational whereby you can order aerial surveys. This service may be soon extended to on line delivery of data. We just enter a programme of covering the entire country with one meter orthophotos in a five year interval. This programme is quite innovative as it will enable to market a triptych for any area in France composed of BDTopo®, orthophotos and BDParcellaire®.

Last but not least, all this expertise is offered on the French and international markets. On the French market, IGN compete with the private sector in call for tenders in an open competition. This activity generates another eighty million francs. In the world market, through our subsidiary, IGN France International, we operate wherever a National Mapping Agency or other public or private bodies require our skills and knowledge. In average 10% of our commercial income comes from international activities.

This wide range of activities and the requirements for being innovative and cost effective justify the existence of four laboratories. I will list them in the alphabetical order, that order being luckily suitable for the workshop!

COGIT is in charge of research in the field of geographical information models and GIS (in its wider sense). Key words in this area is conceptual modelling, data and system interoperability, generalisation and cartography.

LAREG skills are in geodesy and reference framework. Its main focus is on spatial geodesy, participating in the definition of European and world reference systems. It skills cover DORIS, the French satellite positioning system, GPS GLONASS and the emerging GALILEO. It is also preparing the advent of active geodetic positioning network.

LOEMI is one of the two laboratory concerned with this workshop. It is the one which developed the digital camera on which IGN France is placing much hope. You will learn about its performance and the way we intend to operate it for our production. I have already had the region Ile de France flown over. The digital camera with its capacity of directly creating digital images will be the last link in the chain to be digital enabling a full digital production line from the photograph to the master plates via databases!

MATIS is the second laboratory highly concerned with the workshop. Its main goal is to enable automatic extraction of geographical objects such as buildings or roads from images, either photographs or scanned analogue maps. Results currently available will generate significant costs savings when they will be turned operational.

Having looked at the workshop programme, I would like to stress the importance of the topics you are going to discuss. Through the results presented by my staff, you will reckon how much technical innovation will be instrumental for future growth of geographic information business. Automation in digital photogrammetric production bears the seeds for that innovation. While computers will be in charge of extracting geometry from images, probably the most boring stuff to do, operators will have more time available for adding attributes and links enabling the user to geo-reference its own information and operate spatial analysis. They will more confronted with the essence of geographic information and its usage. I also recognise the importance for you to bring together your experiences and compare operational solutions.

As you are probably aware, I am currently president of CERCO (comité Européen des Responsables de la Cartographie Officielle) the place where the heads of the European national mapping agencies meet. I have been approached by Otto Kölbl, currently OEEPE president, to discuss the role OEEPE can have in co-ordination of the requirements of the National Mapping Agencies. I have advocated the following role for OEEPE:

OEEPE should encourage mutual presentation of production methods and strategies in the European National Mapping Agencies,

OEEPE should identify topics and undertake timely studies of mutual concerns with regard trends in production processes such as bench-marking industrial tools, identification of requirements for new tools,

OEEPE should enable European co-operation between university, the NMAs and the industry in order to stimulate an European industrial answer to present and future requirements for operational tools.

From within CERCO, OEEPE may get inputs for a research and development agenda from a managerial perspective. I will propose the creation of a CERCO working party on research and development where the R&D responsible in each NMA would get together to reciprocally present their R&D programmes and to identify the areas where co-operative work would significantly improve each other's efforts. That working party would be instrumental to study how OEEPE would assist in such an endeavour. I am convinced that NMAs experts have much to gain in discussing among their pairs on practical issues of geographic information production and services. This very workshop is quite instrumental to that purpose.

Dear colleagues, I will stop here that too long an opening speech. Therefore it is time for me to leave the floor for the discussions themselves to happen. I wish you a fruitful and successful meeting, I hope it will be a milestone in automating the digital photogrammetric production. I look forward to receiving positive echo and building an efficient network of scientists in the field of automation in digital geographic information.

Welcome address

G. Begni,
President of the French Society
of Photogrammetry and Remote Sensing

Mr. President, dear colleagues,

Acting as chairman of SFPT, I am very pleased and honoured to have been invited to say a few words of introduction and welcome to the present OEEPE symposium.

Co-operation between SFPT and OEEPE is quite natural, since we are both addressing similar scientific and operational issues from different perspectives.

As you all know, two delegates represent each country in the OEEPE Steering Committee. As far as France is concerned, one of them is presented by IGN, the second one by SFPT. I am very pleased to have been one of them for several years, followed by my colleague, Mr. Alain BAUDOIN.

One of the common points of interest between SFPT and OEEPE is automation and standardisation of research results. To achieve such results first on a national basis, SFPT promotes the dialog between all actors in the field of photogrammetry: academic and applied research, education and training (we are here in ENSG, a very active and supportive SFPT member), public organisations (such as IGN and CNES, also very supportive), small, medium and large companies (it is worthwhile to be noted that our Vice-President is the chairman of a small company).

Beyond fostering national synergies, international co-operation is a major issue and a priority for SFPT. Our activities are open to any country or organisation willing to participate.

We are a member of ISPRS, and develop strong interactions with this international Society. Two joint workshops are organised this year, in co-operation with IGN and CNES. We have bilateral co-operation with "sister" associations in Europe. For instance, in 1998, RSS and SFPT held a joint symposium entitled "RSS'98 – Developing International Connections", with bilingual sessions. We are also discussing with several "sister" associations about ideas of European concerted actions under the EARSeL umbrella. EARSeL and other European associations such as EURISY are indeed important partners for SFPT. But obviously, when it turns to European collaboration in such technical issues as photogrammetric research and applications, OEEPE is our natural partner.

We are indeed very pleased to have brought our modest contribution to the present workshop. We do believe it will be very successful, and will pave the way to new initiatives and co-operative work.

Thank you for your attention.

Objectives of the Workshop

O. Kölbl
Opening address of the President of the OEEPE
and Director of the Workshop

Mister General Director of IGN, Mister President of the French Society of Photogrammetry, Ladies and Gentlemen,

It is a pleasure to welcome you to the OEEPE Workshop on “Automation in Digital Photogrammetric Production” here in Champs-sur-Marne.

We are here on the new Academic Site of Paris, the new “Quartier Latin”. The University of Civil Engineering and Geomatics, the Ecole Nationale des Ponts et Chaussées and the Ecole Nationale des Sciences Géographiques are located in that building. It is a special coincidence that the current Director of the Institut Géographique National, Mister Poulit, was at the time in charge of the planning of this site.

I have the pleasure to open this Workshop as one of the organisers of this event. It was a joint task with Mr. Patrice Denis, who is in charge of the Workshop secretariat and the Chairpersons of the sessions, Mrs. Hèno, Mr. Egels, Mr. Kersten, Mr. Duperet, and Mr. Colomer. I must also mention Mrs. Grujard, who was in charge of all administrative aspects. I can assure you that this workshop has been in preparation for two years and required several preparatory discussions. I am very grateful to Mrs. Veillon, head of the department of photogrammetric production, who offered to house this Workshop at the site of the IGN, the National mapping agency of France.

I open this Workshop also as President of OEEPE, or "Whepy" as it was called by a colleague from the United Kingdom. OEEPE stands for European Organisation of Experimental Photogrammetry Research. The aim of OEEPE is to improve and promote methods, performance and application of photogrammetry by mutual co-operation in carrying out, investigation and research, particularly of an experimental and application-oriented nature. The OEEPE is a pan-European organisation established in 1953 in Paris. Its members are European Countries and affiliation requires a governmental decision. OEEPE currently has 16 member countries. OEEPE is managed by a Steering Committee, mainly composed of representatives of the national mapping agencies and academics. Each country may delegate two members to the Steering Committee, who are in general a representative of the national mapping organisation and a professor of photogrammetry of the national university. In this sense OEEPE is very special since planning of the activities is done jointly between practicians and academics, a procedure which has formed out to be very fruitful.

It is true that only some of the principal actors in photogrammetry are present in this organisation; industry and private offices are missing. I am not yet sure how this could be changed concerning the Steering Committee; however, we are happy that it was possible to integrate the principal actors in photogrammetry, meaning industry private enterprises, the National Mapping Organisations and Academia, within this Workshop.

Of course, we must be aware that an important part of research, especially applied research, is done by industry. There was a time when we hoped that a university institute could develop its own modules for image matching and the derivation of a DTM, and we know some that had considerable success. However, meanwhile, we realised that the automation of the various photogrammetric processes is very demanding and only software tools enabling thorough visualisation of the results, possible post editing and particularly a rigid quality control will have a future.

So we are in a way back to the situation when industry developed the good old photogrammetric instruments like analog plotters or analytical plotters. When the famous analog Plotter Stereoplanigraph C5 or the Poivillier B were appearing on the market, then it became unthinkable to develop one's own plotter as an amateur. However, the proper application needed a long period of development. It was not by chance that the ingenious industrialist Otto von Gruber then founded the Photogrammetric weeks in the thirties, which are still organised every 2 years, now in Stuttgart. The main problem at that time was to develop the necessary procedures for an efficient application of photogrammetry for topographic mapping. Now we are back to this situation; the tools are more or less here but how can they be used efficiently? How can we ensure when doing aerial triangulation that all images are properly tied together and that no gaps will remain between adjacent strips leading to unacceptable block-deformations? The same problem arises for automatic DTM derivation. In 90% of cases we get excellent results, but we have to guarantee that the height specifications are respected all over the working areas.

The OEEPE is concerned with the development of effective and efficient digital photogrammetric production lines, including standardisation (guidelines for the production processes and standards for the various products), optimisation and financial and logistic aspects. To be successful, this development needs to be done through close co-operation with manufacturers and users. The Workshop should serve as a platform to discuss issues related to the optimisation of digital photogrammetric production lines.

As main objectives we have defined:

1. Establish a discussion platform between users and manufacturers on the tools for digital photogrammetry;
2. Contribute to a better understanding and use of the working tools for digital photogrammetry and help to elaborate standard guidelines for the various working processes;
3. Optimise the use of photogrammetric tools in production and contribute to the development of efficient digital production lines;
4. Consider the related financial and logistic aspects;
5. Work out standards for the various products such as orthophotos in digital and analogue form.

It is not clear whether all that can be achieved within the 3 days, but let us take as a goal that we want to make a substantial contribution to these 5 objectives. 3 days are short and the technology is still changing rapidly. We had already organised a Workshop with similar objectives some 3 years ago. Conditions were somewhat different. Digital photogrammetry was on the point of being used in practice, although the degree of automation was quite different. Full automatic aerial triangulation was not yet available and automatic DTM generation was mainly used for othophoto production. Today, the degree of automation is much more advanced and digital workstations impose in practice. Many aspects, which were presented 3 years ago, have changed. And even today, it is not always easy to give statements that are still valid when the next release arrives. Nevertheless, in order to give a rather complete picture of the state of the art, we wrote down all discussions last time. We will try to do things in a similar way for this Workshop. This is not an easy task and needs considerable editing. It might also lead to some misunderstandings. Last time I sent the discussions only to the manufacturers for a review, in order to avoid severe mistakes. I hope you agree that we proceed this time in a similar way. The time available for the writing is very limited and the manuscript for printing has to be ready in autumn.

I am very grateful that the principal manufacturers of digital photogrammetric equipment were prepared to participate to this Workshop. We are aware that it is easy for a manufacturer to show the strong points of his systems in public, even in the presence of competitors; things might however be different if weak points are discussed. However let us be aware that we are all in the same boat. We need good digital systems and the manufacturers want to bring out good systems. But they need information on the experiences with their system. They also need feed back on the advantages and deficiencies of their system. Moreover all this is affected by the fact that the market is quite limited. Therefore I would like to ask that we search mainly for a partnership between users and manufacturers during this Workshop.

Another important aspect is to realise that modern photogrammetry is not always easy to handle. I still remember in 1968 at the Congress of Lausanne, when I saw the Santoni V analog plotter for the first time. It was a wonderful instrument with a lot of possibilities, but I think 5 minutes of explanation were sufficient to understand how to handle the instrument, although maybe not to understand all the specialities of the system.

Today the training is much more demanding and for example to use all the editing tools for a DTM efficiently, the operator needs considerable experience and routine including good stereo vision. Training is becoming essential; the user has to interfere when problems arise. It is no more possible to say "it was just the system". The user has to supply reliable results and he has to know how to handle the system. It is much more demanding today than in the past. Of course, the manufacturers will have to supply the training and in some cases, it might even cost more than the software.

This workshop is also intended for discussions. The good and the bad points as well as various experiences will be written down. I am grateful to the manufacturers who are present; they represent the principal firms whose products are already introduced into the market and the mapping organisations. They are, in alphabetic order:

Inpho Stuttgart,
LH-Systems,
Z/I Imaging (Zeiss Intergraph).

They are our main partners and will introduce themselves. I would also like to welcome all the colleagues, the users of the instruments, and wish you all a successful meeting.

Vendor's View

B. Wald
President & CEO
LH Systems, LLC

It is my pleasure to have this opportunity to address the opening of the OEEPE meeting here at the IGN School in Marne la Vallee. As President & CEO of LH Systems it is my pleasure to provide some introductory and brief comments on the expectations that I and my colleagues have for the program, or said another way, the 'vendor perspective'.

As a short introduction to my company, LH Systems was formed in June 1997 as a joint venture between Leica and GDE Systems. Both parents of the joint venture have undergone corporate identity changes. The Leica Geosystems entity is now a stand-alone company under the ownership of Investcorp of the United Kingdom. At some of the near term, Leica Geosystems may elect to float its shares on the open market through a classical IPO; initial public offering. GDE Systems and its immediate parent, Tracor, were purchased through a friendly tender of the shares, by Marconi North America; part of the GEC Ltd. group. Changes from this side of our parent's house continue with Marconi to become part of the British Aerospace (BAe) group in the next few months, once regulatory approvals are obtained in the UK, EU and USA. Both parents of LH Systems have strong traditions and continued interest in a variety of products and services relative to spatial information.

Simply speaking, LH Systems is a company that designs, manufactures and distributes systems for the acquisition, processing and maintenance of precise information from imagery; historical we referred to being in the 'photogrammetry and aerial camera business'. Our heritage comes from our famous product brands including Wild Heerbrugg, KernSwiss, Leica and Helava.

I am somewhat humbled by the diverse technical subjects being discussed during this week's program, including papers and activities offered by my LHS colleagues, customers and professional staff from other industry companies. My short discussion this morning will not address any technical issues, but another issue which has a great impact on our business, you and your organizations; the issue relates the paradox between technology advances and people.

In today's' global economies with readily available tools on Websites, email, fax, Internet, intranet, extranet, ecommerce and cell phones, we have tried to put great productivity tools in the hands of our employees. Theoretically this provides us a better ability to communicate and from the vendor view, support our customers in over 65 countries. During my travels around the globe, I always try to take the opportunity to ask our customers about their needs. On most occasions, I hear complaints (or should I say constructive criticism!) on the speed of software, support of certain data or image file formats, new versions of software or requirements for specific feature and functionality.

In addition, and this holds true for most countries, I also hear bigger and increasing need for ‘qualified people’. I would like to discuss this morning, what I call the paradox of HIGH TECH, HIGH TOUCH.

I can’t claim ownership of this phrase and quite honestly, I can’t even remember the first time I heard the phrase sticks with me everyday in the management of LH Systems. Despite all of our collective efforts and investment in research and development, we have substantially improved the price performance of the photogrammetric process, but not nearly to the extent whereby we can eliminate the human element in the process….the people. We have the HIGH TECH, but still need the HIGH TOUCH.

HIGH TOUCH also comes in the form of training and education. It is appropriate to raise this issue as we convene for this week’s program here in Marne la Vallée, the impressive home of the IGN School. This is not my first visit to this venue. I had the opportunity to visit here last year and was extremely impressed, not only with the physical facilities, but the range of courses in the curriculum, the geographic diversity of the student body and the commitment to excellence by offering relevant courses with outstanding teaching professionals and the latest technology. IGN has addressed the HIGH TOUCH side of the equation, along with the HIGH TECH. But have others? In almost every country, with both private and government sector customers, there are a general lack of technician level personnel to operate systems, manage networks and projects. Although the overall size of the geomatics ‘industry’ has growth tremendously in the last ten years, the number of organizations or institutions providing quality and relevant training has decreased. Again, the paradox of HIGH TECH, HIGH TOUCH.

LH Systems has begun to attack this issue on several fronts. We have established several scholarship programs to try to stimulate academic interest in our business. These type programs address higher level research and development, but on a basic level increase aware to attract university level people to the industry. In addition, we have provide funds to several organizations, such as MAPPS in the U.S. to help develop recruiting programs to attract technician level employees to the industry. In North America, there is a severe shortage of trained operators for analytical and digital workstation systems. Many larger private sector companies and government organizations have been forced to develop their own recruiting and training programs to supplement vendor programs. Again, we seem to be doing an adequate job on many technical and systems productivity fronts; the HIGH TECH, but we are doing poorly on the HIGH TOUCH side.

Don’t misunderstand me, the technical developments in the digital world have opened up some new application markets and also provided some degree of automation which no longer requires the same type of technician necessary for analog or analytical instruments. To put this into perspective, in 1990, a typical customer would have had to invest over 500’000 ECU to have instruments for DTM generation and orthophoto production. There are now products on the market for less than 5’000 ECU that can provide similar results, with higher production throughput. In less than ten years with the HIGH TECH, we’ve been able to reduce capital investment costs per workstation by over 50%, but we have not yet been able to achieve automation to the point to eliminate the people part of the equation….the HIGH TOUCH. Automated feature extraction is still a dream and not a reality.

With eCommerce, FTP sites, Websites and email, the ability to provide users with better quality and timely support has been one of our business goals. Again, HIGH TECH at its best. Wider bandwidths on networks are giving us the ability to more around gigabyte files, that a year or two ago would have frustrated the best of us. At the same time, the permutations and combinations of systems, data flows and sources of data, have lead to a complexity never seen before in the industry. We have found that despite the HIGH TECH tools available to support our customers, there is an increasing need for a consultative approach to customer support. A real HIGH TOUCH approach which at some times make it necessary to understand the customers specific project needs, sources of data, and production workflow, before having the ability to support the workstation operator or production supervisors. From a vendor perspective, that despite the increase automation in the 'mapping processes', we must invest more than ever in the HIGH TOUCH to support our customers.

It is unlikely in my lifetime that we'll see the fully autonomous or automatic extraction of precise information from imagery. Substantial progress has been made with computer based automation, particularly as we move farther into the digital product life cycle. Despite this movement, we still find we can't dispense with the 'artificial intelligence' provide by the human being sitting at the workstation. Great HIGH TECH, but still the need for HIGH TOUCH.

In closing to my short remarks, it is my expectation and I believe an expectation also shared by my many colleagues from LH Systems in attendance this week, that we need to increase our efforts, as a company and as an industry, to address the human element of the business and not just the technical features and functionality of systems for image acquisition, image processing or image maintenance. I would hope that during the course of this week's program we all might find the time to begin to explore some of the issues to balance the HIGH TECH and the HIGH TOUCH. From my personal point of view, this is not a just a vendor problem, but we also submit that our customers and educational institutions must share an equal burden (or opportunity) to consider how we continue to address the need to attract, recruit and retain qualified people in our industry.

We share this burden as the trend is clear in the HIGH TECH business throughout the world, that there is no longer a clear distinction between vendors and customers. The situation is quite common that a customer can not only be a customer, but also a co-developer, a competitor or an information source. Consider the extreme example of Microsoft these days. Microsoft received 400'000 requests to beta-test Windows 2000…..free testing by 400'000 customers. At normal rates, this 'testing' would have cost Microsoft over $20 Million U.S. This is not a traditional vendor and customer relationship and in our industry, we find many situations whereby the roles of each party of not as clear as before.

I hope you all find this week productive and I congratulate Otto Kölbl and his group for putting together an interesting program and being held at a first class. I would also like to thank Jean Poulit, Director General of IGN and his staff for their hospitality in offering the school for the OEEPE program.

Part 1

State of the Art of Digital Cameras

Chairman

Y. Egels

Presentation of the current developments in digital cameras, their advantages in comparison to film cameras, specific performance of the different electronic image capturing systems (CCD-line elements, CCD-frame matrix and photo multiplier), reflections on the characterization of image quality (MTF, tone and colour reproduction, image noise).

Electronic Image Sensors vs. Film: Beyond State-of-the-Art

B. Dierickx
IMEC, Belgium

Summary

In this paper we compare the theoretical performance limitations of electronic image sensors and film. Both systems have completely different border conditions and technology limitations, which makes a practical comparison impossible. Therefore we consider idealized pixels and idealized film, neglecting all technological limitations. The result is a set of scaling rules for the performances of film and image sensors.

1 Introduction: trends in electronic image sensors

A trend exists to replace film in many applications by electronic image sensors.

Large area, high resolution image sensors can be built around CCD or CMOS image sensors developed for video, still picture or astronomical applications. The size of the CCD is apparently only limited by the silicon wafer size. Philips has demonstrated a full wafer, 9000 x 7000 pixel, image sensor.

A recent trend is the shift of the "high end" CCD technology to the mainstream CMOS technology to build image sensors. CMOS image sensors appear in all low-end applications (monitoring, security, toys, and multimedia), but also start to replace CCDs in their own high-end domains. The main asset of CCD is still the image quality, but recent improvements of the CMOS technology and design methodologies have resulted in CMOS sensors with near-CCD performance. Moreover, as CMOS is the technology of microprocessors, ASICs and memories, it is *straightforward* to add functionality or *intelligence* to the image sensor.

Standard sensors with larger resolutions

In the coming years we will see a wave of low price image sensors developed for specific large volume markets, as digital picture, digital video and scanners. Due to the market demand the image formats will be converging to certain standards, both for pixel numbers and image diagonals. One can expect pixel numbers well above the "VGA" (640×480 pixels) or video (PAL/CCIR 575×767 pixels). High resolution will remain a *driving force*. Acceptable digital pictures will require 1300×1000 to 3000×2000 pixels, and more if the market demands. The existence of these sensors will trigger a number of applications that previously did not exist, or that could only be handled by film.

Small pixels

A second and more important driving force is the camera dimension, thus system price. As the MTF of the optics should not dominate the resolution, the effective lower limit pixel size, and in fact the "typical" pixel size, will be about 5 μm. Focal plane formats will be smaller than the present 35mm and APS formats.

The main drawback of small pixels is their lower light sensitivity. For a given relative aperture or F-number, the amount of photons received by the pixel is proportional with the pixel area. In typical shot noise limited situations the dynamic range will thus vary with the pixel size. This will jeopardize the use of these volume produced sensors for demanding short exposure time applications.

Custom designed image sensors can solve this dilemma. Both in CMOS technology and CCD technology it is possible to design application specific sensors, excelling in certain properties that are not available in off the shelf components. Think about sensors with large pixel size and large sensitivity, large image formats, sensitivity to non-visible wavelengths, image processing on chip (smart sensors), very low power or very high speed, etc.

Increasing the image size or the pixel size is a key towards a higher sensitivity. This is *almost* equivalent to the increase of grains size and negative size for film.

2 Comparing the basic sensitivity in film and pixels

It is not straightforward to compare the performance of film with the performance of electronic image sensors.

Neither electro-optical detectors nor photographic film are ideal. It is not feasible to compare both systems while including all practical parameters and limitations. In the sequel we will assume idealized cases for both. *We assume that all technological limits are solved, or that fundamental laws of physics are the only limit to the performance.*

We compare the theoretically most sensitive silicon pixels with the fastest possible silver halide film. We must assume 100% fill factor (FF) and 100% quantum efficiency (QE), and noise dominated by optical shot noise.

Quantum efficiency of pixels and grains

For *pixels* this situation is not far from reality, as several CCD and CMOS sensors today reach 50% QE*FF, and are shot noise limited except for a small residual noise of 5 to 50 electrons in the dark. In a similar way we must assume that film will in the limit consist of 100% efficient grains, covering exactly 100% of the area.

The light detection mechanism in grains differs fundamentally from pixels. In order to define a latent image in a grain, several Silver ions must be neutralized by the absorption of light quanta. At maximum QE, 3 light quanta will create 3 silver atoms, the minimum required to create a latent image in a grain ("*3 photon grains*"). In practice tens of photons are required, and the QE for film is much less.

As a third possibility we consider photochemical detection where in the limit a single photon can create a reaction in an elementary grain or molecule ("*1 photon grains*").

Pixel area

The pixel ultimately collects a signal and a noise expressed in “electrons”. The photographic system collects a signal and noise expressed in “black grains”. For film, a pixel must be defined as an arbitrary square area with a given number of grains. For an objective comparison we calculate grains and electrons back to the input signal expressed in “photons”.

3 Performance criteria

3.1 Sensitivity

We need a generic *light power vs. transmittance* relation of photographic film in a form that can be compared to the *light power to voltage* response of electronic devices. For simplicity we assume

- that there is a constant number of grains per unit area
- all grains have the same effective cross section and sensitivity.
- grains have a perfect contrast.
- the probability of a grain to be activated during the exposure time is a good approximation of the resulting film transmittance T.
- The generation of an electron in a pixel requires the conversion of 1 photon. The creation of a latent image in a grain requires 3 photon conversions.

1 or 2 photons cannot activate a silver halide grain. This creates a non-linear behavior for the probability that a grain remains white, expressed by a cumulative Poisson probability:

$$T = \text{probability\_white} = \sum_{p=0,1,2} \frac{\exp(-n) \times n^p}{p!}$$

where n is the average number of photons that hit a grain during the exposure time. The transmittance T is equal to this probability if the grain contrast is 100%.

Alternative, photo-chemical conversions might require only on photon per conversion. In that case:

$$T = \text{probability\_white} = \exp(-n)$$

In image sensors or pixels

the output signal is a voltage that is practically a linear function of the amount of collected electrons. Photons generate electron-hole pairs by direct band transitions. This principle is highly linear also at very high light intensities. As one photon can generate ideally 1 electron-hole pair, in theory the quantum efficiency reaches 100%. Exposure can be defined as an amount of light power, per unit area per unit time. Exposure is thus equivalent to a “number of photons per pixel”.

The transmittance versus exposure relation of film

The signal of a film is not a voltage but a transmittance. We assume that film transmittance, or better: the number of developed grains, can be measured to an arbitrary accuracy, e.g. in an ideal scanner.

The probability for a grain to turn black is related to the exposure time or to the light intensity in a non-linear way. Here also, consider the "exposure" as the average number of photons that "hit" the surface of an equivalent pixel area. We normalize exposure to 1, where the number of photons equals the total number of grains.

In practice films are a combination of slower and faster film layers, or mixtures of larger and smaller grains, in order to obtain a wider exposure latitude, at the expense of a lower average contrast (a lower dT/dExposure).

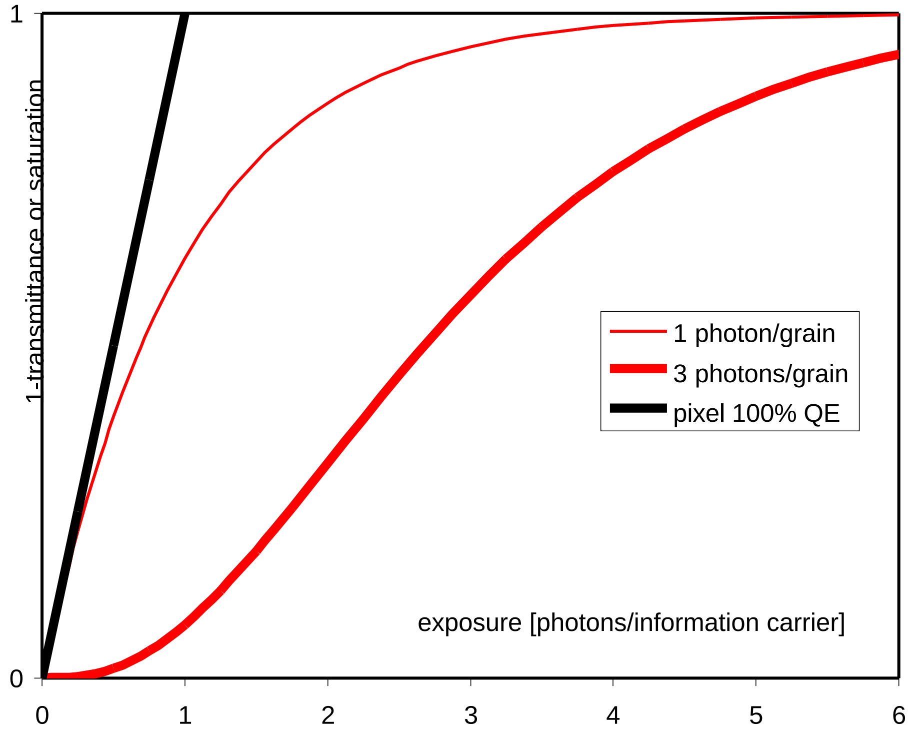

Fig. 1 – Transmittance vs. Exposure or Charge versus exposure for

- Film with grains reacting on 1 photon
- Film with grains requiring 3 photons
- An ideal pixel with 100% QE

y-axis: 0=dark, 1=saturation, all information carriers are used
x-axis: 0=no light, 1=1photon per information carrier

<table>
<tr><th>Silver halide film</th><th>Silicon image sensor pixels</th></tr>
<tr><td>Pixels are arbitrarily defined as square areas with a constant average number of grains/area</td><td>A regular array of pixels</td></tr>
<tr><td>Grains have 100% contrast, are contiguous, do not overlap, and all have the same (diffraction limited) size.</td><td>100% fill factor</td></tr>
<tr><td>100% QE, but 2 cases:
• 1 photon activates a grain
• 3 photons activate a grain</td><td>100% quantum efficiency</td></tr>
<tr><td colspan="2">Signal response and sensitivity</td></tr>
<tr><td>If one photon activates a grain
At high exposures:
Transmission = exp(-n)
For low exposures:
Transmission = 1- n
where $n = \left(\frac{\#\,photons \times QE}{\#\,total\_grains} \right)$
$\#\,black\_grains = \#\,total\_grains \times \left[1 - \exp\left(\frac{-\#\,photons \times QE}{\#\,total\_grains} \right) \right]$
for low exposures:
$\#\,black\_grains = \#\,photons \times QE$</td><td rowspan="2">Linear response:
Signal = C^t * Exposure

#electrons = #photons×QE</td></tr>
<tr><td>If 3 photons activate a grain
$Transmission = \sum_{p=0,1,2} \frac{\exp(-n) \times n^p}{p!}$
for low exposures:
Transmission = 1- $n^3/3!$</td></tr>
</table>

3.2 Linearity

Linear response and explicitly non-linear responses in electronic image sensors

Electronic image sensors typically integrate the photo current of a photodiode during a certain integration time or exposure time, which is converted to a voltage on a capacitance.

As the integration capacitance is linear, the photo current to voltage response is typically linear to within 1% over the useful (or used) output range.

A linear response (figure 2, curve 2) has an advantage for subsequent absolute photometry, or for calibration. Two possible shortcomings of the linear response are

- The differential signal to noise ratio is high at the extreme of the range, and very low near the dark. It does not make use of the fact that shot noise is lower in the dark.
- The dynamic range of the sensor is limited: the signal response for intensities outside the linear range (over exposure) suddenly drops to zero.

Alternative systems to increase the dynamic range have been devised for electronic image sensors:

- Logarithmic response (figure 2, curve 4). The voltage response is the logarithm of the light intensity. Such a response can be implemented in a fairly elegant way in CMOS image sensors. The main advantage of this system is that many orders of magnitude of illumination levels can be compressed on the available output range. The dynamic range easily goes beyond 120 dB. The price to pay is the poor differential sensitivity, i.e. the differences between nearby grey levels are strongly attenuated. It may be noted that the human eye also exhibits an approximately logarithmic light sensitivity.
- The gamma corrected response (figure 2, curve 3). The apparent brightness of cathode ray tubes in television screens is a non-linear function of the video signal amplitude. Empirically one has found that this can be pre-corrected in the camera by the transformation $V \rightarrow V^{0.45}$. This overall intensity to voltage law happens to amplify the contrast in the dark part of the image, which have lower shot noise, and attenuates the shot noise rich, bright parts.
- The bi-linear response. In order to acquire a large dynamic range of scene intensities on a limited voltage range, one often combines two or more linear response images with different exposure time into one. The effect is a response as in figure 2, curve 5.

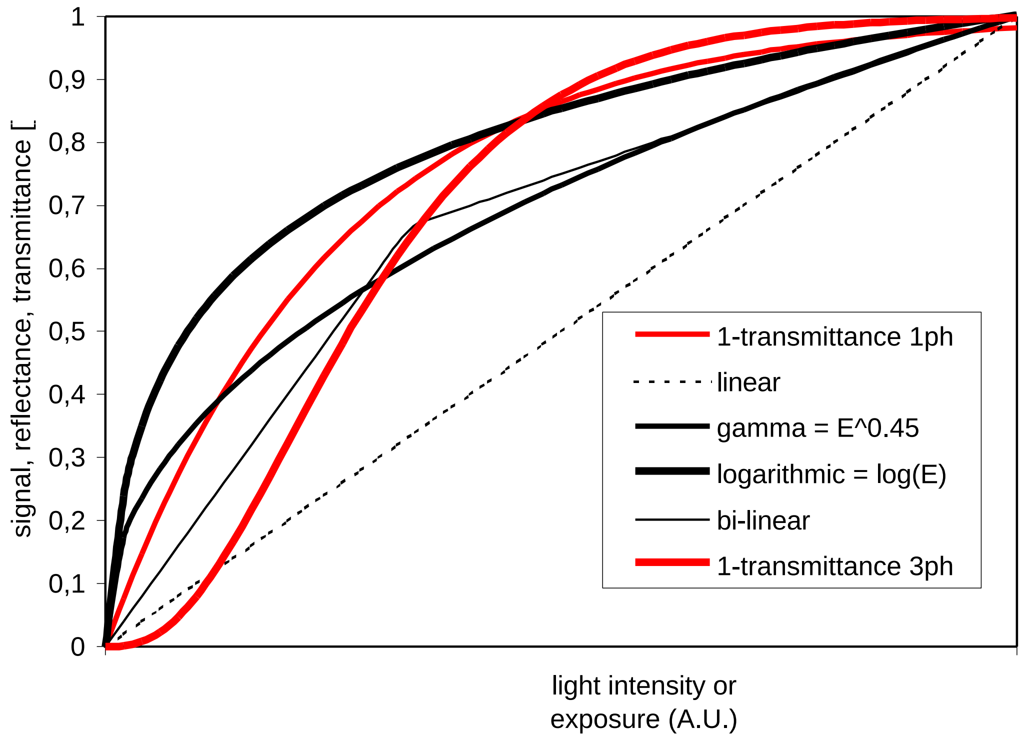

Fig. 2 – Qualitative comparison of electronic and photographic responses

1. Transmittance for 1 photon grains
2. Ideal linear response image sensor
3. Response of a gamma corrected image sensor
4. Logarithmic response image sensor
5. Bi-linear response image sensor
6. Transmission for 3 photon grains

Systems, which are assumed to be linear, need only correction for a possible dark signal and bias in addition to the relative sensitivity variation over the detector.

Linearity is a useful property if absolute intensities are required. However, for relative contrast measurements, the ideal response is the logarithmic response. For a fixed amplitude of the noise, the signal to noise ratio expressed in units of light intensity, is constant. Thus a certain relative contrast yield the same signal difference, both for a dark scene as for a bright scene.

The non-linear transmittance vs. exposure behavior of film is favorable in the sense that it responds strong medium exposure parts of the image; at very high exposures, the signal in the film is faint, but at least there will be a signal. It has an extended dynamic range compared to a linear response sensor. At low exposures however the response of a pixels or of 1-photon film is superior.

The technique of combining material with different speeds into one film extends the useful dynamic range of film, but at the same time it reduces the low light sensitivity. This disadvantage is not present with electro-optical detectors.

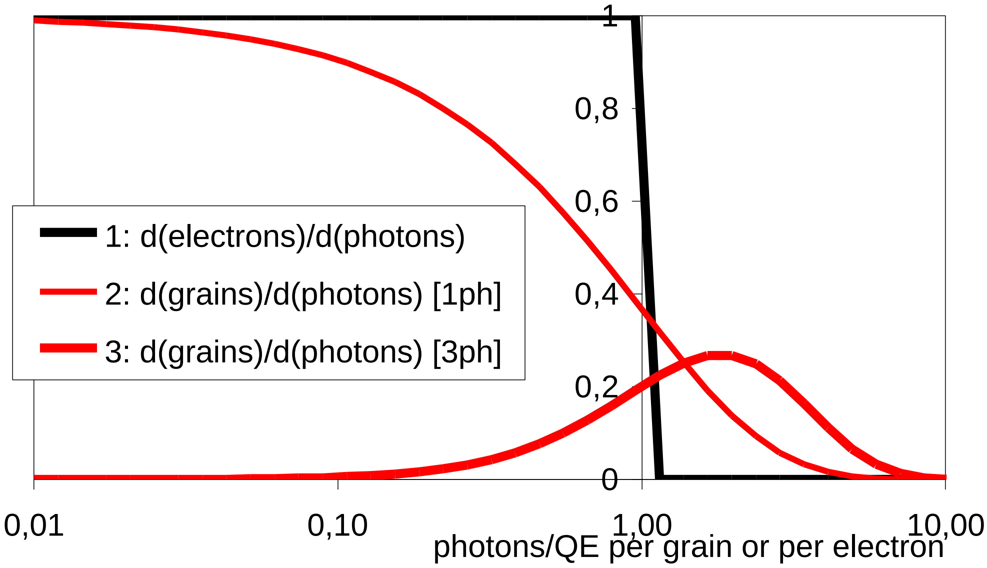

Fig. 3 – Derivative of response versus exposure for
(1) pixels, (2) 1-photon grains (3) 3-photon grains

3.3 Noise

In order to compare film and pixels, we scale the noise to the input signal, i.e. number of photons. Noise in this context is only *temporal noise*. Spatial noise or fixed pattern noise in electronics image sensors can be calibrated. In film spatial noise (granularity) cannot be distinguished from temporal noise.

In the following derivation, the prefix "#" stands for "number per equivalent pixel per exposure time". The physical noise source is essentially photon shot noise.

Noise, expressed as # noise photons	
Film	***Pixels***
Noise is the RMS of #black_grains. We assume that scanning (counting) the grains in a film can be done without additional noise $\#noise\_grains = \sqrt{\frac{\#black\_grains \times \#white\_grains}{\#total\_grains}}$ for low exposures: $\#noise\_grains = \sqrt{\#black\_grains}$	Only temporal noise counts. Noise is composed of "dark" base level read noise (neglected here) and shot noise: $\#noise\_electrons =$ $\sqrt{\#electrons}$

A noise measurement in terms of number of grains can be converted to noise in the amount of photons by the straightforward relation $\frac{\#\text{noise\_photons}}{\#\text{noise\_grains}} = \frac{\partial\#\text{photons}}{\partial\#\text{black\_grains}}$ • for 1 photon activated grains $\#\text{noise\_photons} =$ $\frac{1}{QE} \times \sqrt{\frac{\#\text{black\_grains} \times \#\text{total\_grains}}{\#\text{white\_grains}}}$ for low exposures: $\#\text{noise\_photons} = \sqrt{\#\text{black\_grains}} / QE$ • If more than 1 photon is required the activate a grain, the #noise_photons becomes infinite at low exposures	neglecting the base level electronic read noise: $\#\text{noise\_photons} =$ $\sqrt{\frac{\#\text{photons}}{QE}}$

3.4 S/N ratio

The Signal to Noise ratio is calculated with both signal and noise in the same working point. The S/N ratio stands for the ability to discriminate a certain relative contrast in an object with the size of a pixel.

$$\text{Signal to noise ratio} = \frac{\#\text{photons}}{\#\text{noise\_photons}}$$

In a pixel

$$\sqrt{QE \times \#\text{photons}}$$

In film (equivalent pixel), with 1 photon activated grains

$$\sqrt{QE \times \#\text{photons}} \times \frac{\sqrt{\alpha}}{\sqrt{\frac{1-\exp(-\alpha)}{\exp(-\alpha)}}}$$

where $\alpha \equiv \frac{\#\text{photons} \times QE}{\#\text{total\_grains}}$

For 3 photon activated grains the analytical form of the S/N ratio as a function of exposure level is complicated (see figure 3)

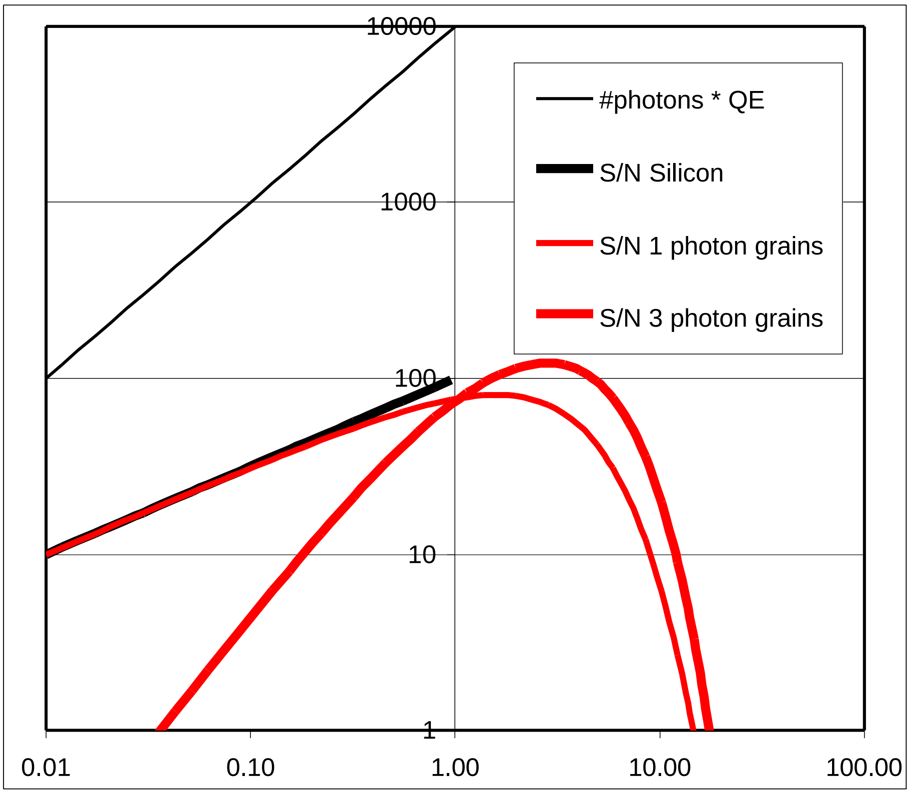

Fig. 4 – Signal to noise (S/N) ratio for film and silicon versus normalized exposure (#photons*QE/#total_grains or #photons*QE/#max_electrons). The maximal number of information carriers (grains or electrons) per pixel is 10000.

In the figure 4 the evolution of the signal to noise ratio with the illumination level is plotted, both for idealized film and for idealized Silicon pixels. For pixels the S/N grows as the square root of the number of detected photons (#photons*QE). Beyond saturation a linear Silicon detector has no response, while film keeps some S/N up to a factor 10 overexposure. 3-photon sensitive grains have a significant response only in a range of a factor 10 above and below the normalized exposure.

For the same maximum number electrons or grains per pixel, the S/N of film and pixels behave mostly in the same way. The effect of QE does not appear in the S/N *ratio*,

For sake of comparison, the S/N has been calculated for a pixel with a capacity of 10000 electrons or 10000 grains. In reality CCD and CMOS pixels can handle much more: 20000 to 100000 electrons for pixel sizes between 5 and 10 um, while (high speed) film has much less grains for the same equivalent area. Film must compensate its lower QE compared with Silicon by reducing the number of grains per unit area.

3.5 Dynamic range

In this context the S/N ratio is defined as the ratio between signal and noise, in the same operating point.

Dynamic range is defined as the ratio between the (lowest) noise in the dark and the maximum signal. This ratio is much higher than S/N, as the noise in the dark is free of shot noise. Depending on the context, several types of definitions are being used. In order to avoid ambiguous interpretations between film or pixels, let us define dynamic range as: *the full dynamic range is the factor, expressed in light intensity, between the high and low points where S/N = 1.* The equivalent pixel area is a parameter.

For the cases in figure 3, the dynamic range is

- For the linear pixels: equal to the max. number of information carriers per pixel
- For the 1-photon grain film: about 10 times the number of information carriers per equivalent pixel area.
- For the 3-photon grain film: a few times the square root of this number of information carriers per pixel area.

In image sensors the read noise defines the practical low noise limit. The dynamic range is then simply proportional to the maximum number of information carriers per pixel.

The dynamic range can be greatly extended for pixels, by using deliberately non-linear responses as in figure 2. Mixing grains of various sizes and speeds, and increasing the number of grains per unit area extends the dynamic range of film.

3.6 MTF and image sharpness

The MTF of pixels is fixed by and limited by the pixel geometry. The MTF of abruptly delineated pixels always has a zero crossing at the so-called *Nyquist limit*, this is the spatial frequency for which exactly 1/2 line pair fits in a pixel. Beyond this frequency the spatial information is corrupted by *aliasing* artifacts. The MTF of the point spread function of a square pixel behaves as a *sin(line_pairs)/line_pairs* function.

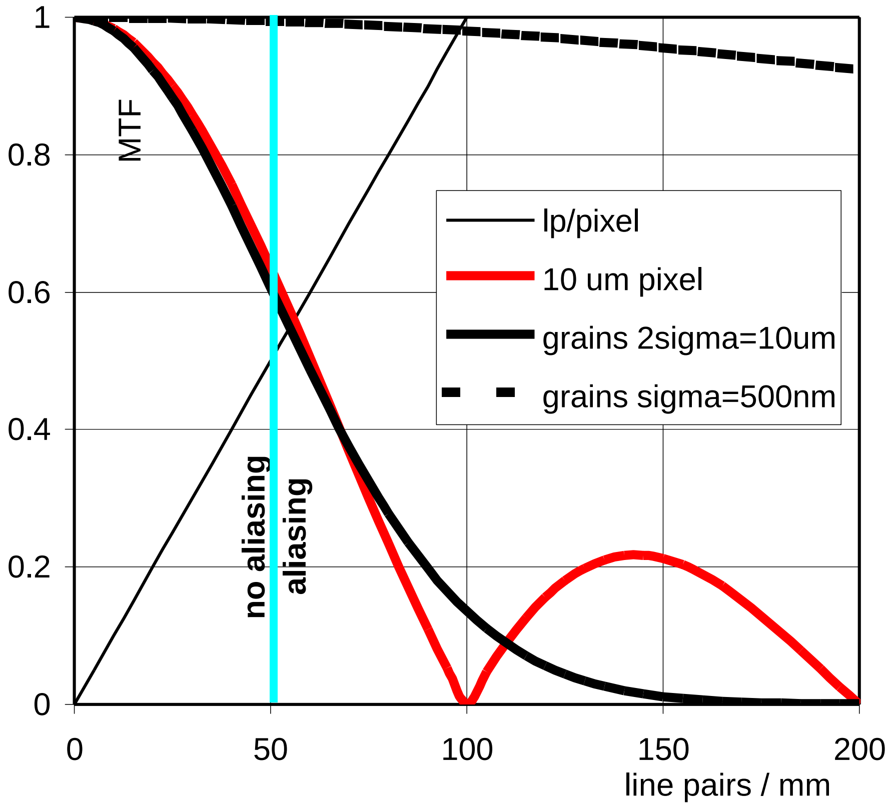

Fig. 5 – Comparison of the MTF of a 10 μm square pixel and the MTF of a Gaussian spread function with 2σ = 10 μm. In dotted lines the diffraction limited MTF for an arbitrarily small grain.

In film the point-spread function is a superposition of spatially extended randomly placed grains. The MTF is always positive, but decays as the spatial wavelengths become shorter than the grain's optical cross section. This is approximated by a Gaussian point spread function. In figure 5 the MTF of a 10 μm pixel is compared with the MTF of a Gaussian spread function with 2σ = 10 μm. Aliasing does not occur in film.

As an effective pixel can consist of many optically small grains, the MTF of film can easily outperform the MTF of pixels. In that case we assume that the MTF of grains is diffraction limited with a spread function sigma of about 500nm. In this type of idealized film, the sharpness can persist down to the optical grain size.

The price to pay for this advantage is the reduced S/N ratio per *effective* pixel. Small features can indeed be discriminated. One can define e.g. effective pixels with 1 um size. The number of grains in the pixel is then very low, as is the attainable S/N ratio for the discrimination of this feature.

3.7 The product of MTF and S/N

Let us use as a final criterion the S/N ratio of the detection of small features: the product of the MTF as a function of line pairs/mm × the maximal S/N for an equivalent square pixel containing 1 line pair.

For this criterion, film will outperform pixel arrays. When we neglect the possibilities of interpolations and super resolution, pixels cannot “see” or localize features smaller than the pixel pitch. Film will be able to see and localize features down to the grain size, even if larger equivalent pixels of grains are required to obtain a good S/N ratio.

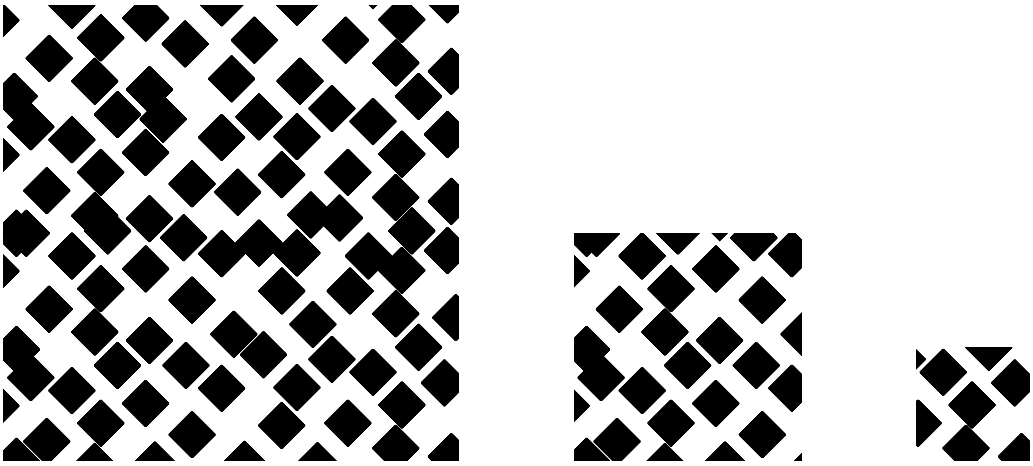

Fig. 6 – The idea of equivalent pixels of various sizes in film with a constant # grains per unit area. The size of equivalent pixels can be as small as a few grains.

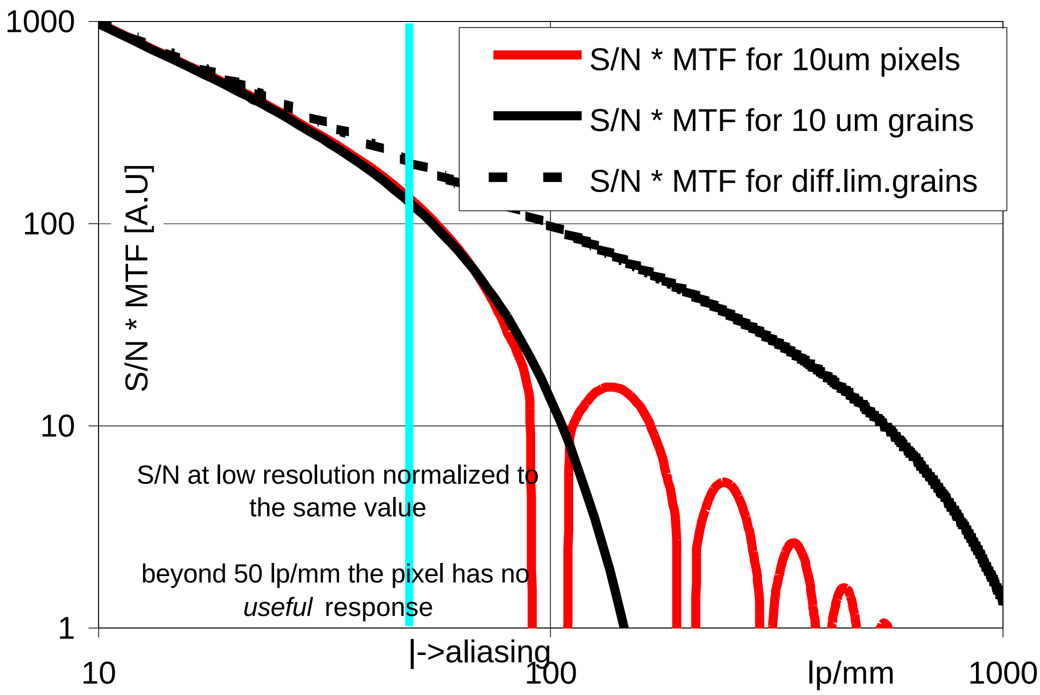

Fig.7 – S/N*MTF for pixels and film, for a given optimal illumination level. Ideal pixels or film is assumed, with the same S/N for large features

The graph in figure 7 compares ideal film and ideal pixels with the same numbers of information carriers per unit area, which will results in a similar maximal S/N for large features. For film we include two cases: the optical cross section of grains is diffraction limited to 1um and to 10 um. The first case assumes ideal minimal diffraction low F-number optics and small grains in a thin film. The second case assumes that the film is thick or that grains are larger, or that we use optics that is just sufficient for the 10 um pixels.

The graph is valid for one idealized case with as much as possible similarity between pixels and film: film and pixels have the same number of information carriers per unit area – in reality this number is much lower in film.

Noises in this respect are RMS noises. In a minimalistic approach one will need a S/N of 1 to be able to detect a feature, a “noise equivalent feature”. Such feature can be thought as a square or spot with the dimensions of ½ line pair.

Ideal square pixels can detect contrasting line pairs to nearly the Nyquist spatial frequency. Moreover, because of the danger of aliasing, the image must be spatially filtered, causing a drop in S/N. Still, the S/N is much higher than 10.

Ideal film, with the same number of information carriers per unit area, and with an optical point spread function comparable to the pixel size, can detect these line pairs far beyond the same Nyquist limit, to the level where the S/N*MTF drops below 1. Aliasing does not occur in the film itself, but can be introduced at the moment of scanning.

Ideal film with a diffraction limited 1 um point spread can detect 100% contrasting line pairs down to 2 times the diffraction limit.

3.8 Contours of equal S/N in saturation/exposure space

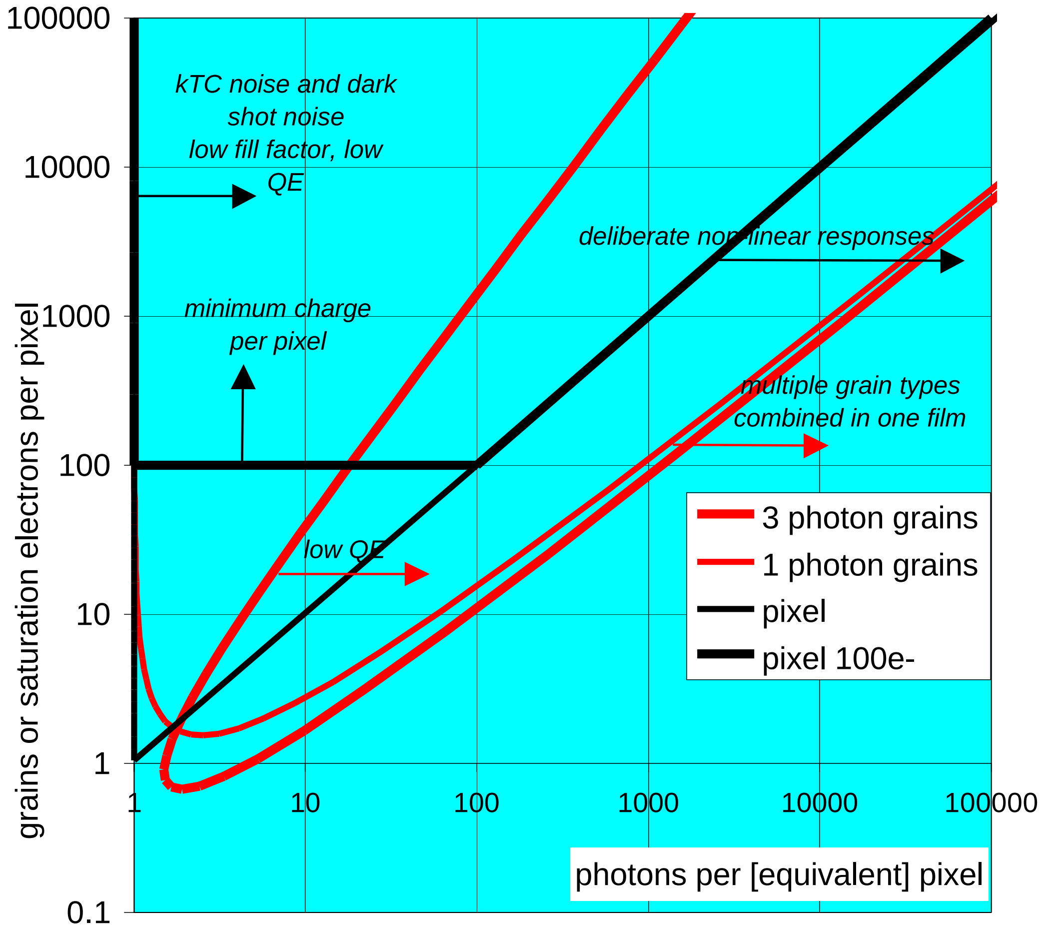

Fig. 8 – Contours for S/N = 1 for ideal film of pixels. Higher S/N is obtained above/right of these contours.
x-axis: *exposure*, expressed as photons per pixel
y-axis: *saturation* expressed as the (max) number of information carriers per eq pixel
a. film with ideal grains needing 3 photons
b. film with ideal receptors needing 1 photon
c. the perfect pixel
d. the same pixel, but assuming that the minimum charge per pixel is always higher than 100 electrons
Arrows indicate the shift of the contours for non-ideal pixels or film.

Figure 8 illustrates the low light level operation range of the ideal film and pixels. Pixels are designed with a certain saturation charge, or maximal number of electrons. Film is designed with a number of grains per unit area. For the same equivalent pixel area, figure 8 compares pixels and film, for their low light level performance. The low light limit is arbitrarily defined where the *S/N =1*, for the operation of a single equivalent pixel.

Film and pixels can reach in principle nearly the same low light level performance, but in film one must sacrifice the number of grains per pixels, thus the dynamic range or S/N ratio of small features. For pixels the light sensitivity does in theory not depend on the saturation charge – in practice the dependence does exist.

1-photon grain film outperforms 3-photon grain film in all respects.

Curve 8d shows a pixel with a practical constraint. In practice a photodiode will at least contain a few 100 electrons, but this has no implications for the performance.

For the low light level operation, the left parts of the contours are relevant. The high light level operation limit is the right part of the contour. The dynamic range is in principle the distance between the left and right edge of the contour.

The dynamic range can be extended in the high exposure direction almost indefinitely by several techniques both in pixels and in film.

4 Conclusions

We summarize the behavior of non-existing ideal film and ideal pixel arrays, for a number of performance criteria.

For a given equivalent pixel size:

The sensitivity increases

- proportionally with the fill factor and quantum efficiency of the grains,
- inversely proportional with the number of grains or with the maximum number of electrons per unit area or per equivalent pixel.

No other factors play a role! The hypothetically highest possible film or pixel sensitivity is reached with (equivalent) pixels containing 1 electron or grain, having a 100% fill factor and maximal QE.

- For pixels not even the maximum number of electrons plays a role, as for 100% QE and 100% fill factor every photon is effectively detected. A high dynamic range is not in contradiction with a high sensitivity.
- For film however large grains are necessary for 3 photon sensitive grains. Larger grains are thus more sensitive than many small grains, and the quest for higher sensitivity *is in contradiction with* a high S/N ratio per equivalent pixels area.

The exposure to reach the maximal S/N ratio

is reached near the saturation exposure level, thus:

- proportional to the maximal number of electrons per pixel, or the number of grains per equivalent pixel area, and
- to 1/QE and 1/fill factor and other optical attenuations or losses.

The exposure to reach a given minimal S/N ratio

- is inversely proportional to QE, fill factor and other optical attenuations or losses, and
- to the electronic read noise or other noises *if these are larger than the shot noise*. These other noise sources tend to increase with the number of information carriers.

For film, the relation between S/N and exposure is much steeper than for pixels.

The longest possible exposure time

- In silicon, dark current limits the exposure time. Exposures of a few seconds up to a few minutes at room temperature are possible.
- For film this limit does not exist or occurs only at very high temperatures.

Linearity of the optical response

Integrating silicon sensors can have a nearly perfect linearity depending on details in the circuit implementation. Deliberate non-linear behavior is possible

The linearity of film is bad. A linear response can be obtained by software post-processing.

The S/N behavior

If the noise is dominated by shot noise, the S/N ratio is generally equal to the square root of the number of converted grains or generated electrons. For high exposures, the S/N of film saturates, and falls back at about a factor 10 overexposure. For Film there is no distinction between temporal and spatial noise. The S/N includes granularity.

The maximal obtainable S/N

- is proportional to the linear pixel size, thus to the root of the maximum number of information carriers, and
- degraded by other noise sources that are not mentioned in the idealized cases: electronic read noise, cosmetic defects, non-uniformity.

For film obtaining a high S/N is in contradiction with obtaining a high sensitivity. For a high S/N one needs a high maximum number of grains or electrons per pixel; for a high sensitivity this number must be low. High speed film must have large grains.

A high QE is of course beneficial for both properties.

The same contradiction exists to a minor level in pixels, or in film that needs only 1 photon for a conversion.

The exposure range; extending the exposure dynamic range

- A linear response Silicon sensor abruptly ceases operation beyond the saturation level. Various schemes exist to extend the exposure range towards larger times, while *maintaining the sensitivity* at low exposures and sacrificing the S/N ratio only at higher exposures.
- Ideal single speed film tolerates about a factor 10 over exposure (compared to silicon sensors). The exposure latitude is normally extended by combining multiple speed grains into one film. This sacrifices QE and thus sensitivity for all exposure levels.

The MTF behaves as

pixels have a hard limit at 1/2 line pair per pixel, above which the signal can be corrupted by aliasing. The theoretical MTF of the silicon pixels degrades by diffusion of electrons between nearby photo diodes.

Film has no aliasing limit. The MTF is limited by the optical cross section of the grains. Degradation of the MTF can further be caused by light scattering in the film.

100% constrasting line pairs can be detected down to

- for pixels: slightly less than 1/2 line pair per pixel;
- for film: limited by the optical point spread function of the grains, or by blurring in the film.

Discussion

State of the Art of Digital Imaging Systems
B.Dierickx, IMEC, Belgium

Kölbl (EPFL, Switzerland):
What are the possibilities of reading up more on this topic of digital imaging system. Are there any textbooks or any other literature available? I had a lot of difficulties in finding an expert on the subject; is this a special science?

Dierickx (IMEC, Belgium):
I had the same problem. There are some very good books on the topic of electronic imaging and probably some on chemical imaging but the combination is very rare. Even if chemical imaging is an old science or maybe because of this, I had to contact specialists on silver bromide films at an Agfa factory, close to my university. I found there are only very few specialists. So perhaps it is time to write a book on this topic.

Digital Aerial Sensors: Possibilities and Problems

P. Fricker, R. Sandau and A. Stewart Walker
LH Systems GmbH and LH Systems, LLC

Abstract

The case for airborne digital sensors is compelling. The transition from analytical to digital photogrammetry is well advanced and the dividing lines between photogrammetry and remote sensing grow increasingly blurred. One of the advantages of direct digital data capture in the air is the possibility of capturing multispectral data as well as panchromatic. Between modern film-based aerial mapping cameras with their extremely high resolution and, at the other end of the spectrum, the forthcoming high-resolution satellite sensors, the market for new airborne devices is large and uncontestable.

Two technologies are available as the basis for airborne digital sensors – linear and area array CCDs. The performance of the latter is insufficient to offer swath widths and resolutions comparable to film cameras. The most promising alternative appears to be linear arrays, arranged in a triplet on the focal plane, one forward-, one nadir- and one backward-looking. When combined with GPS and INS systems, this configuration provides geometric performance that enables the same photogrammetric operations to be performed on the workstation as with scanned film imagery. Moreover, multispectral CCD lines can also be placed on the focal plane, providing data tractable by image processing techniques from remote sensing, with the additional advantages of geometrically correct sensor modelling, stereo imagery and accurate geocoding.

A development project between LH Systems and the German Aerospace Centre has resulted in a functioning three-line sensor. An engineering model has flown successfully and a production model is scheduled for market introduction in summer 2000.

1 Introduction

LH Systems' announcement at the end of 1998 that an engineering model of their forthcoming airborne digital sensor had flown suggests that a genuine alternative to the familiar aerial film camera is imminent.

Other than as a producer of stereoscopes, LH Systems and its predecessor Leica were never active in image interpretation. Yet this new sensor will have multispectral lines on the focal plane: it will be capable of generating precise, geometric information about the surface of the earth, but will also produce data amenable to proven remote sensing techniques. It will further soften the demarcation between photogrammetry and remote sensing and accelerate the decline of the photo laboratory, as digital image data can be transferred from the aircraft directly to the workstation.

The debate about airborne versus spaceborne imagery rages on. The highest resolution applications, with ground pixel size in the one centimetre to one decimetre level, are likely to remain the province of the film camera, but there is a huge, pent up demand for top quality, multispectral information in the gap between this and the one meter and coarser resolutions offered by the satellite operators. Both spaceborne and airborne sensors have their advantages and the most likely scenario for the future will be an increased emphasis on data fusion as users select the sensors most likely to provide their information in each case and rely on their workstation software to use all the data together. Undoubtedly, the two types of data will be complementary rather than competitive.

2 Airborne digital sensors – the requirements

To have any chance of an impact in a market place spoilt for decades by high performance film cameras, an airborne digital sensor must provide:

- Large field of view and swath width.
- High resolution and accuracy, both geometric and radiometric.
- Multispectral imagery.
- Stereo.

The first requirement, however, seems to rule out area CCD arrays, because readily available models in early 1999 are spring 4Kx4K pixels or less, whereas a linear array of 12,000 pixels is readily available, requiring only one third as many flight lines. Considerable research work has been done in Germany since the 1970s, which has demonstrated the suitability of three panchromatic lines on the focal plane, with additional multispectral lines near the nadir. This obviates the need for multiple area arrays to provide a wide field of view and a multispectral capability (Figure 1).

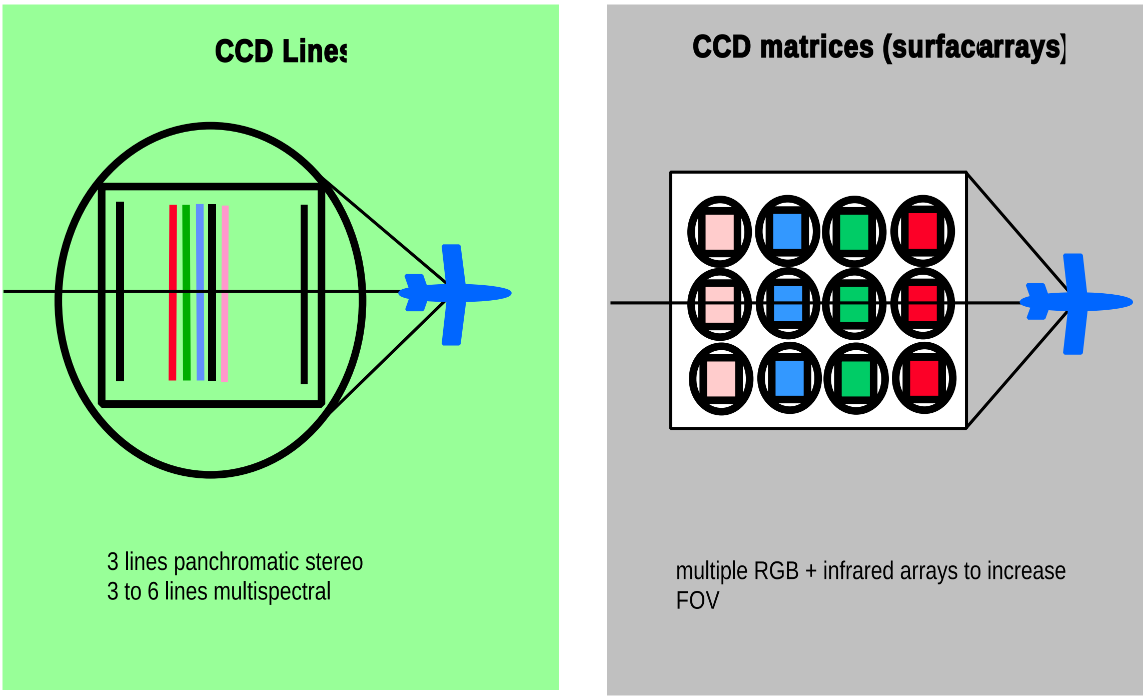

Fig. 1 – The alternatives: The left-hand diagram suggest how the focal plane could be populated using the three line principle: three panchromatic lines give the geometry and stereo, whilst additional lines, their sensitivity controlled by filters, give the multispectral information. In the right hand diagram, multiple area array CCDs and lenses are required to provide both the same ground pixel size and multispectral range as the three-line approach.

3 Three-line scanner approach

The three-line concept results in views forward from the aircraft, vertically down and looking backwards (*Figure 2*). The imagery from each scan line is assembled into strips (*Figure 3*). The characteristics of relief displacement in the line perspective geometry of the strip approach *vis a vis* the conventional central perspective geometry are indicated in *Figure 4*.

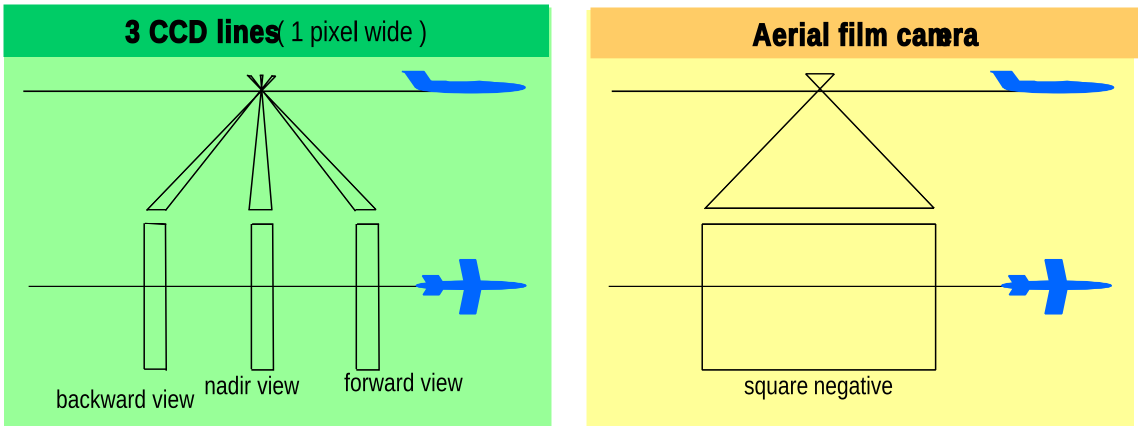

Fig. 2 – Basic geometric characteristics of three-line digital sensor and film camera.

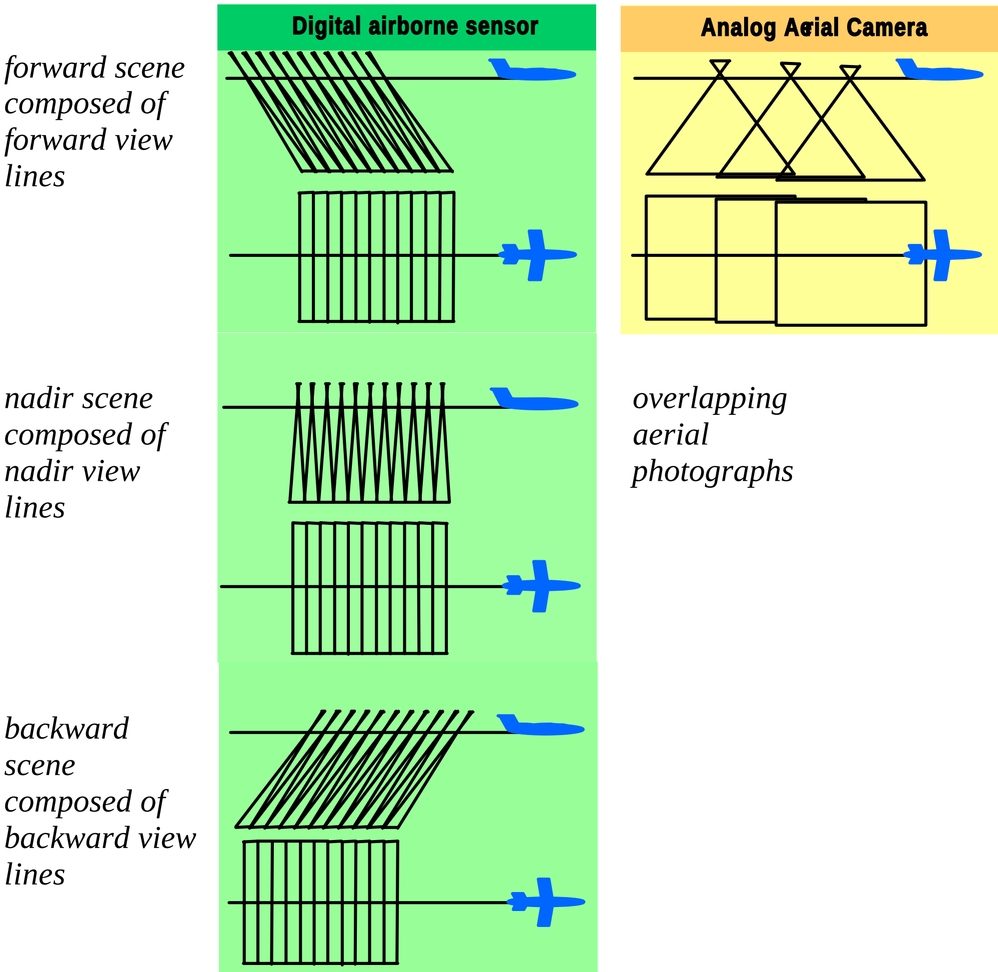

Fig. 3 – Comparison of the acquisition of scenes by three-line digital sensor and film camera.

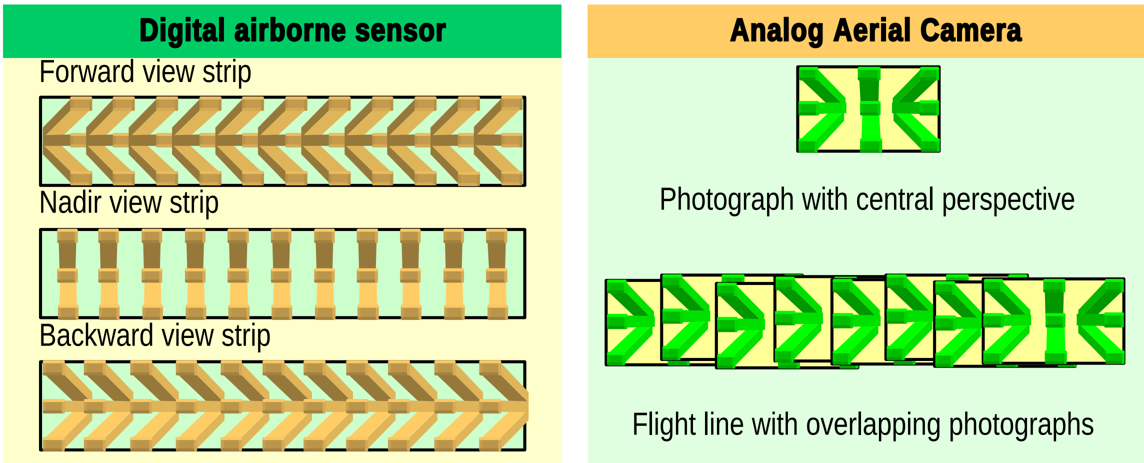

Fig. 4 – Effect of terrain relief on the imagery showing the line perspective geometry of the three-line imagery on the left and the familiar central perspective geometry of the film photograph on the right.

The angles between the incoming information to the three-lines are, of course, fixed. With three lines there are three possible pairings for stereoscopic analysis – strips 1 and 2, 2 and 3, and 1 and 3. With film cameras, the parallactic angle is a function of principal distance and airbase. Moreover, every object appears on all three strips, whereas on film imagery only 60% of the area of any one photograph is in a triple overlap.

4 Image processing

The raw imagery looks bizarre, owing to the linear arrays imaging widely varying strips of terrain owing to aircraft tilts and terrain relief (*Figure 5*). Tilts can be compensated by adjusting each individual scan line for the attitude of the aircraft, using data from the airborne GPS and INS units carried on every fight. An initial rectification using these data is essential even to view the imagery. Thereafter, operations such as triangulation, DTM measurement, orthophotos and feature extraction continue in the usual way. Automated processes, such as point measurement for triangulation and DTM extraction, can be based on triplet matching using the three strips.

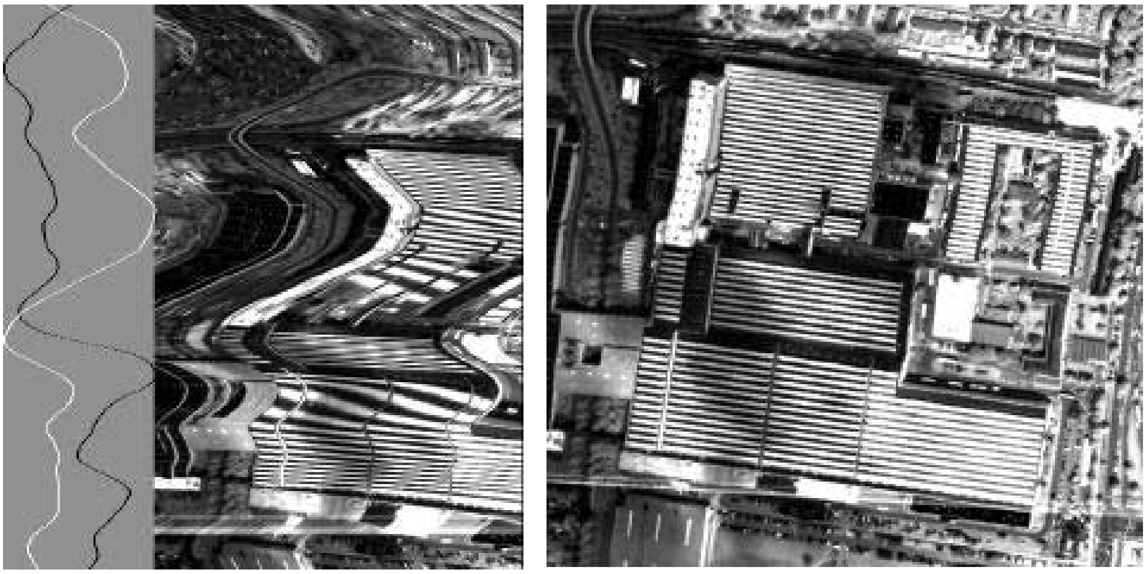

Fig. 5 – Imagery acquired by the WAAC sensor from DLR. The flight direction was from top to bottom. The left-hand image is raw and has been supplemented by curves representing the roll (white line) and pitch (black line) behaviour of the aircraft. The right hand image has been rectified and looks similar to a conventional aerial photograph.

A particularly interesting feature is that owing to their positions on the focal plane, combined with the aircraft and terrain variations, the colour lines image slightly different parts of the earth’s surface. Thus full rectification is required, i.e. orthophotos, before the colour bands can be properly registered and transformed into colour composite images suitable for analysis by off-the-shelf remote sensing packages.

5 Engineering model and technical co-operation

The complexity, cost and difficulty of developing and manufacturing a novel airborne digital sensor ruled out “going it alone”. In early 1997, shortly before LH Systems was formed, Leica Geosystems reached a technology agreement with Deutsches Zentrum für Luft- und Raumfahrt (DLR), the German Aerospace Centre in Berlin. This provided for long term co-operation, with joint development by both parties and assembly by Leica Geosystems. DLR’s experience in this area is unparalleled. Amongst a host of intricate and impressive achievements in both airborne and spaceborne technology, it made historic progress with sensors based on the three-line approach (*Table 1*), for example the WAOSS (Wide Angle Optical Stereo Sensor, built for the unfortunate Mars-96 mission) [1], WAAC (Wide Angle Airborne Camera) [2] and HRSC (High Resolution Stereo Camera) [3]. The technical and performance data of WAOSS and WAAC are summarised in *Table 1.* This expertise complemented well Leica Geosystems’ abilities in optics, mechanics and electronics, together with its deep appreciation of customers’ requirements acquired through decades of producing aerial film cameras. It was natural that the agreement between the parties be transferred to LH Systems quite soon after its formation.

Tab. 1 – Technical and performance data of Wide- Angle Optoelectronic Stereo Scanner (WAOSS) and Wide- Angle Aircraft Camera (WAAC)

	WAOSS	**WAAC**
Focal Length, f	21,7 mm	21,7 mm
FOV (Across the Track)	≤80°	≤80°
Optics	Spitmo- Russar-96	Spitmo- Russar-96
Number of CCD- Lines	3	3
Spacing of CCD's	10,1 mm	10,1 mm
Convergence Angle	25°	25°
IFOV (Quadratic)	3,23 x 10^{-4} rad	3,23 x 10^{-4} rad
Elements per CCD- Line	5184	5184
Elements Spacing	7 µm	7 µm
According to Platform Height	Hn = 250 km	H = 5 km (v = 200 km/h)
Swath Width (Nadir CCD)	420 km	8,4 km
Min Ground Resolution – in Line Direction – in Trajectory Direction	 80 m 80 m	 1,6 m 1,6 m
Dynamic Range	11 Bit	11 Bit
Radiometric Resolution	8 Bit	8 Bit
Spectral Channel – Nadir – Forward, Backward	 470...670 nm 580...770 nm	 580...770 nm 470...670 nm
Data Compression Factor	2...20	2...20
Data Compression Method	DCT- JPEG	DCT- JPEG
Output Science Data rate	100...500KBit / s	100KBit / s...24MBit / s
Physical Dimensions	L:373 x B:190 x H:218 mm	L:285 x B:190 x H:202 mm
Mass	8 kg	4,4 kg
Power	18 W	15W

6 Practical Conclusions

The features of the film and digital approaches are compared in *Table 2*. LH Systems has chosen the three-line scanner approach for the reasons given above. The engineering model has flown (*Figure 6, Table 3*) and work is proceeding towards the production model, which will have at least 20,000 pixels in each line, faster integration times and multispectral bands. This is on schedule for launch at the ISPRS Congress in Amsterdam. The formidable technical challenges can be met. Perhaps the real hurdle will by then have moved: photogrammetrists will learn to work with imagery that is strikingly different in appearance from the film case and is processed using unfamiliar sensor models. They will be able to share data with the remote sensing community and for the first time create deliverables with both the depth of information accruing from image understanding of multispectral images and the geometric fidelity of photogrammetry.

Tab. 2 – Features of aerial film camera and airborne digital sensor

Characteristic	**Aerial film camera**	**Airborne digital sensor**
Flying time	20% less	–
Photo lab	Yes	No
12-bit in-flight sensing	No	Yes
8/10-bit scanning	Yes	unnecessary
Data volume	20-50% less	–
Pre-processing	No	Yes
GPS	Yes (optional)	Yes
INS	unusual	Yes
Projection centres	interpolated (few)	interpolated (many)
Ground control points	Yes, but hardly any with GPS	Yes, but hardly any with GPS
Tie point matching	few – between images	many

Fig 6 – The engineering model of LH Systems' airborne digital sensor, which was successfully flown in late 1998.

Tab. 3 – Specifications of the Engineering Model

General

Principle	3 line CCD stereo sensor
Pixels per CCD Line	12,000
Pixel size	6.5 µm
Dynamic range	12 bit (raw data mode)
Radiometric resolution	8 bit
Normalisation mode	8 bit linear or non-linear
FOV (across track)	52°
Focal length	80 mm
Swath at 10000' flying height (3,100 m)	3,000m (1,9 mi) and 25 cm ground pixel size
Stereo angles	17°, 25°, 37°
Recording interval per line	1.2 ms
Filter range (at λ50)	Panchromatic, 465nm – 680nm

Power

Input voltage	28 Vdc or 220 Vac/50 Hz	
Consumption / average (peak)	Engineering Model	600 W (1000 W)
	Mass Memory System	600 W (600 W)
	ASCOT	80 W (180 W)

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Discussion

Digital Aerial Cameras, Possibilities and Problems
R. Sandau, LH Systems, Switzerland

Heipke (University Hannover, Germany):

I have two questions, one regarding the image quality you get once you use a three-line camera. In your paper there is a comparison between the raw image and the processed image. If you take the raw image, it has to undergo some resampling which will result in a degradation of the image quality; can you comment on that? The second question concerns the orientation: are you going to release the interior orientation including the parameters and the exterior orientation model so that the image can also be processed by somebody else?

Sandau (LH Systems):

Perhaps your first question: the images that we deal with in that paper are from the very first flight and they are not really representative of what we have seen here in our April flight, so I should maybe change them and put better quality images in the paper. This was not a properly calibrated camera and it was just the first shot. We flew under the clouds, it was a hazy, cloudy and rainy day and turbulence were so extreme that it was very difficult to correct all effects. The second point is: sure we thought of developing a complete system, which is a camera system combined with SocetSet, but it will be an open system file format which can be fed into all the other available systems like Phodis etc. So it is open to post-processing on different platforms. But what we are preparing is a complete solution from the camera to the SocetSet solution.

The IGN Digital Camera System

Ch. Thom, J-P. Souchon
Institut Géographique National, France

Abstract

The latest progress of IGN's project on digital cameras, that has begun in 1991, are described. The features of the present prototypes are presented. The results of the first tentatives of use of digital images in IGN production lines are given, either in colour with an orthophoto on the city of Rennes, and in panchromatic with a survey over the city of Saumur for the production of IGN's BDTOPO®. The trends of the project are then briefly assessed.

1 Introduction

The superior quality of directly digital images is now firmly established (Thom, 97), and the questions are now first to obtain from the industry a viable acquisition system, and second to integrate this new kind of data into the existing geographic information production processes.

The IGN's digital camera project, already described in (Thom, 97), resulted in the production of some prototypes of digital aerial camera, either color or black and white, and made it possible for us to focus on the second point as soon as the previous year (1998), leaving the first for the industrials to solve.

2 The cameras' features

Let us briefly review the features of the prototypes we used for our work:

Features	Color Camera	B&W Camera
Sensor manufacturer	Kodak	
Pixel size	9 microns	
Sensor size	3072x2048	4096x4096
Antiblooming protection	yes	no
Digitization	8 MHz, 12 bits	8 MHz, 12 bits
Signal/Noise	300	300
Dynamic range	2000	3000
Minimum period between shots	1.4 s	3.8 s
Minimum ground pixel size (in stereo, 60 % overlap, Plane speed=80m/s)	15 cm	20 cm

Features	Color Camera	B&W Camera
Storage type & capacity	2 Hard Disks, 10MBytes/s, 20 GB, extensible (hot removable)	
Forward motion compensation	Electronic, up to 22mm/s, accuracy : 1 pixel	Electronic, up to 22mm/s, accuracy : 1/2 pixel
GPS interface for date and position of shots, integrated in header of images	Yes	
Lenses	- 30 mm, 1/500s min. (Schneider Distagon) - 40 mm, 1/500s min. (Schneider Distagon) - 50 mm, 1/1000s min. (Schneider Super-Angulon PQS) - 80 mm, 1/1000s min. (Schneider Planar)	
Number of available prototypes	2	2
Real time display of images	Yes	

The color is obtained in the color CCD by putting small filters of different primary color in front of each pixel, following a special pattern. A pixel then sees only one color, the others having to be interpolated from their neighbours. Since the colour filters are far from perfect, and the sensitivity of the sensor different in each spectral band, some colorimetric processing and sensor calibration are also needed to obtain a good resulting colour. A good amount of work has been invested in this field to achieve satisfactory results.

Many points of minor importance have also been lastly improved, in the electronics to ease the production of the camera, and improve the dynamics, and in the software, particularly in the user interface to make the system operable by IGN's planes usual staff.

3 The surveys realised

Since the survey over Le Mans in black an white and in colour that we described during the PHOWO 97, two main surveys have been flown : one in panchromatic over the city of Saumur, for the production of the BDTOPO®, and one in colour over the city of Rennes, to produce an orthophoto.

3.1 The SAUMUR survey

It has been realised in June 98. An area of 30x20 km has been surveyed, in 9 axis, at a ground pixel size of 67 cm. The camera used was the panchromatic 4k x 4k. The along track overlap was 70 %, the across track overlap 20 %. The flight altitude was 3800 m and traditional photographs have been taken every other axis, for comparison purpose, and in security. At that time, only a 50 mm lens was available, leading to a very poor base over height ratio of 0.2. A B/H ratio of 0.4 was nevertheless achievable thanks to the 70 % overlap, skipping one image to form the stereo pairs. Unfortunately this feature was not used during the plotting of the survey.

The work on this survey is not yet fully completed. It has been for the moment used to:

- Test the automatic tie points measurement of some commercial software, with mixed results.
- Plot a stereo pair. Several problems have been detected:
    - ♦ particularly for the display of the image, the linear dynamics of the raw image being too contrasted for a CRT display,
    - ♦ a resampling of the image at an equivalent of 50 cm ground pixel size have been done to get nearer the usual value of 40 cm,
    - ♦ the poor B/H ratio has led to a bad altitude determination,
    - ♦ the blooming of some areas made it impossible to plot some objects and even in some cases relatively large area.
- Test an automatic DTM measurement software, with good results even in very uniform areas.

To conclude, it seems that some developments are still needed to make the use of this kind of images in the present production line easier, especially with commercial softwares.

3.2 The RENNES survey

It has been realized in September 98. An area of 11x10 km has been surveyed, in 15 axis, at a ground pixel size of 30 cm. The camera used was the 3k x 2k colour. The along track overlap was 70 %, the across track overlap 20 %. The flight altitude was 1700 m and traditional photographs have also been taken every other axis. The 50 mm lens was also used. It is the highest resolution survey realized at this time at IGN with a digital camera. It is also the biggest in term of number of images : 1068 shots were taken...

The digital images were used to produce a orthophoto of the urban area, the traditional to produce a DEM to be used to construct a 3D city model, with the colour images mapped on it.

To overcome the problems arising from the high number of images, many new techniques, still at the research level at IGN, have been used:

- Automatic production of a photoindex with computation of approximate image position, to initiate the
- automatic tie points determination (a total of 4144 points).
- Use of the new aerotriangulation program TopAero-PC, with only 70 ground control points taken on a previous traditional survey at the 1/30000 scale.
- Rectification and mosaicking with the process used for spatial images, at the IGN-Espace department, in Toulouse.

This work has been very interesting, because it has proved that the use of (relatively) small images was a surmountable problem, given the adequate automatic tools. It has also brought a lot of information:

- The human part in the whole process is relatively small, and will be even smaller in the future, limited in fact to the pointing of the ground control points, and to a small number of digital data manipulation.
- The process of tie points determination (produced by the MATIS Laboratory at IGN) is very successful. The quality is excellent, with an rejection ratio during aerotriangulation of only 0.65 %, and residuals of 0.2 pixel RMS.
- The number of ground control points is not proportional to the number of images. For a traditional survey of this size, a total number of 2000 control points would have been used. Actually, only **70** have been used...
- The excellent quality of automatic measurements shows also that no significant geometrical systematism is present in the image. It confirms that CCD arrays are geometrically very stable and very accurate, and that no on the pixel basis geometrical calibration is necessary. For this work, the camera system (CCD+lens) was calibrated using only a radial model.
- The mosaicking process showed that the radiometric quality was such as no adaptation was necessary between adjacent images along track. Between tracks, a slight difference is sometime visible, depending on the nature (in fact the 3D texture) of the ground. These are bi-directional reflectance effects, and are not caused by the camera.
- The most surprising difficulty was to find the good parameters (gamma correction,...) to adapt the linear response of the camera to the eye of the customer, which is used to photographs.
- The fact that the sensor is a mosaic of colored pixels leads to small colored artifacts, when contrasted linear details are sub-parallel to the axis of the sensor. With this ground pixel size, this problem seems not very important for a visual use of the image. For more sophisticated uses, like DEM or building extraction, or different scales, it might reveal a problem.

4 Camera development perspectives

Two axis of development are considered:

First, it is planned to assemble and synchronize from two to four cameras. This work will lead to the construction of two new camera systems:

- A true colour camera, with three colored and maybe one NIR channels. With this camera system, real colour images, without the artifacts caused by the colour mosaicking, will be produced. With the NIR channel, the remote sensing applications will be accessible, with a highest geometrical resolution than with the spatial imagery, and with a good radiometric quality, unattainable with aerial photography.

- A wide field panchromatic camera, by tilting the axis of the cameras in different directions. This will reduce the flight costs by increasing the system swath.

Second, it is considered to order from KODAK a new class of sensor, a 4k x 4k with antiblooming capacity and blue enhancement, and maybe even a 4k x 4k colour sensor based on the same technology as the 3k x 2k. The present sensors are relatively insensitive in the blue spectral range. It causes a poor response in the shadowed areas for the panchromatic sensor, and a bad signal to noise ratio in the blue channel for the colour sensor. With this new technology, these problems will be solved, together with those caused by the blooming. The increase in size for the colour sensor will lead to a better swath and then to an improvement of the flight cost.

5 Surveys planned for 99

The production of a digital orthophoto in colour over the whole Ile de France region (about 150x100 km²) with a ground pixel size of 1 m, plus the urban parts of this area with a ground pixel size of 50 cm has been decided this year. The flights have started the 26th of May. It will amount at about 20000 images of 18 Mbytes and represents then about 360 Gbytes of data (+240 Gbytes for raw data).

A survey with the future multichannel camera is scheduled for the autumn 99 / spring 00 over the Bassin d'Arcachon, near Bordeaux, for a remote sensing application.

An area around the city of Amiens has been equipped with landmarks to provide a test zone for various applications (aerotriangulation, building extraction , etc.). This area will be flown during multiple surveys, at different ground pixel sizes, to constitute an image data base to help customers to choose the ground pixel size for their application, the notion of scale having no meaning anymore in digital imagery.

It will also be flown with the future wide field camera to acquire some images to develop the software that will mosaic the partial images into a big one, and to measure the geometrical stability of the mount in normal flight conditions.

6 Conclusion

The good quality of the images produced by IGN digital camera, in colour and black and white, has convinced customers, inside and outside IGN, to order surveys, despite the overcost due to the small size of the sensor. New automatic tools have been proved necessary, developed and used to overcome the problem of the number of images.

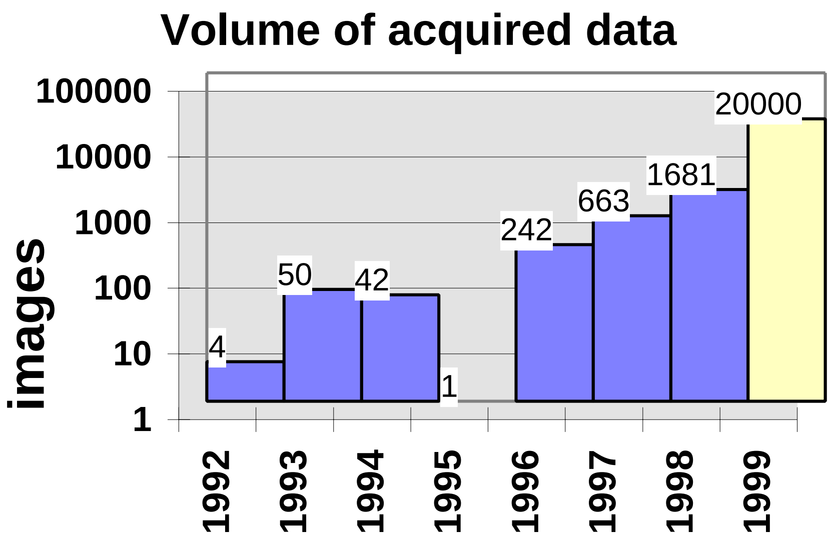

Figure 1

In parallel to this start in production, the development of new camera systems is undertaken to obtain a wide field and a multichannel colour camera that will reduce the flight costs, and yet increase the image quality. The radiometric ability of the camera will allow it to aim at remote sensing applications.

As it is shown in the fig. 1, the use of digital camera is really now taking off. The digital cameras leave the status of "research instrumentation" and get into the field of devices used to produce real geographic information.

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Digital Aerial Survey Data for Telecoms Network Planning: Practical Experience with a High-Resolution Three-View Stereo Camera

by L. Renouard*, Istar, France
and F. Lehmann**, DLR, Germany

Abstract

DLR and Istar have joined forces to apply space technologies to the acquisition and processing of a new kind of stereo aerial survey data. Image data are acquired using the High-Resolution Stereo Camera (HRSC), based on an instrument developed for the 1996 Russian Mars mission, and processed using software developed to produce digital terrain models and orthophotos from satellite imagery. Practical experience acquired to date suggests that these technologies have the potential to revolutionize aerial surveying and photogrammetry, with RF network planning expected to prove a major early application.

Background

DLR developed the HRSC for the 1996 Russian Mars mission, then a modified version for airborne remote sensing. The HRSC airborne camera is the first to combine high resolution, photogrammetric accuracy, all-digital acquisition, and multispectral stereo.

One of the challenges associated with the operational use of the HRSC camera is how to process the massive volumes of data. In late 1998, Istar first processed HRSC data using its Spot3D software suite. These tests showed that Istar could meet the processing requirements and handle the large volumes of data. The tests further demonstrated the processed data's considerable potential for meeting geographic information needs in general and telecom operators' network planning requirements in particular.

This success and the scale of the potential applications prompted DLR and Istar to set up a joint programme to acquire and process HRSC mapping data, formally announcing their decision in May 1999.

* Laurent Renouard (Ph.D.), founder and General Manager of Istar, a private French company based in Sophia Antipolis.
E-mail: renouard@istar.fr

** Frank Lehmann (Ph.D.), Head of Earth Observation Section , DLR Institute of Space Sensor Technology and Planetary Exploration, Berlin, Germany.
DLR (*Deutschen Zentrum für Luft-und Raumfahrt e.V.*) is the German national aerospace centre.
E-mail: Frank.Lehmann@dlr.de

Technological partnership

The partnership between the DLR's Institute of Space Sensor Technology and Planetary Exploration, headed by Prof. Dr. Gerhard Neukum, and Istar of France is governed by a three-year agreement covering cooperation and R&D. Both partners see the programme as an essential component of their long-term strategies.

This programme represents a major technological and industrial breakthrough in remote sensing and aerial photogrammetry as it combines a new sensor and proven expertise in 3D digital image processing and software. Istar's Spot3D software suite is currently one of the few capable of processing HRSC imagery to yield 3D digital models and true 25-cm orthoimages on a large scale. These products are expected to attract strong interest from companies requiring large-scale precision urban models for the optimization of point-to-point and point-to-multipoint networks, including micro-cellular networks.

Data acquisition system

Extensive testing has demonstrated that the HRSC system is ideal for photogrammetric and general remote sensing applications in that it combines high resolution, satellite quality imaging, with the flexibility of an airborne platform. It has been shown to be thoroughly operational. Advantages over film-based airborne cameras include:

- quick access to digital data,
- high radiometric resolution,
- 5 stereo/photometric bands,
- 4 multispectral bands from blue to near IR.

Advantages over new-generation satellite systems (Ikonos, OrbView, etc.) include:

- high resolution (< 1 m),
- flexible flight plans and acquisition strategies,
- cloud-free imagery viewed from nadir,
- stereo as a nominal mode,
- large coverage.

The HRSC features linear arrays, each comprising 5,184 charge-coupled device (CCD) detectors. Nine CCD arrays, mounted in parallel in the instrument focal plane, acquire successive scanlines as the aircraft flies over the terrain. Five arrays acquire panchromatic stereo and photometric imagery while the four remaining arrays are fitted with filters to acquire multispectral imagery. The camera is extremely sensitive to variations in light intensity, allowing aerial mapping to continue under a wide range of weather conditions.

Whereas the geometry of satellite-based imaging instruments is ensured by the regularity of the platform's trajectory over the terrain, the HRSC system uses a precision position and orientation system (POS) to compensate for platform motion. Another key consideration is the camera's mechanical and thermal stability, which ensure that it remains perfectly calibrated under normal operating conditions.

Aside from the camera proper, the HRSC data acquisition system comprises:

- Sony 32-Mbyte/s digital tape recorder,
- Applanix precision position and orientation system (POS) combining an inertial navigation system and differential GPS,
- Zeiss gyrostabilized platform.

At an airspeed of 250 km/h (70 m/s), the camera acquires data at 7 Mbytes/s (5,184 pixels/scanline x 450 scanlines x 3 views). Each tape holds 50 Gbytes, or 2 hours' acquisition time, and it takes just 5 minutes to change tapes in flight.

The camera's three viewing angles (–19°, 0° and +19°) result in forward, nadir and backward views (see Fig. 1). For a survey altitude of 6,000 m, the pixel size is 24 cm and accuracy 20 cm rms in x and y and 30 cm rms in z. The instrument can be flown higher for increased coverage, at the cost of resolution, or lower for increased resolution.

In addition to the along-track overlap provided by the camera's forward, nadir and backward views, Istar has adopted a data acquisition strategy guaranteeing 50% sidelap between adjacent strips. The resulting multiple redundancy of the data gathered during each survey contributes to improved stereo processing and more reliable checking and correcting of anomalies.

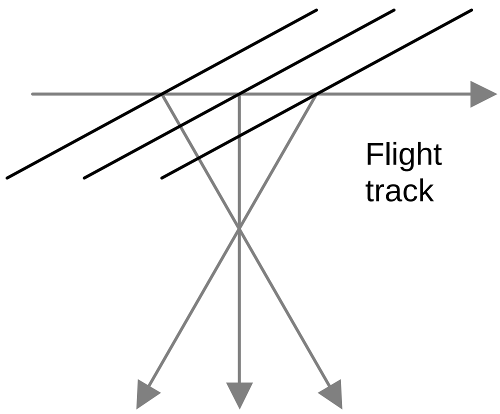

Fig. 1 – Acquisition of forward, nadir and backward views by HRSC camera

Fig. 2 – HRSC airborne data acquisition system

Position and orientation system

Aside from the camera’s mechanical and thermal stability, one of the most critical aspects of the entire airborne HRSC concept was to incorporate a very-high-performance position and orientation system (POS) for motion compensation. After reviewing various products, the design team opted for a complete subsystem by Applanix of Canada.

The Applanix POS comprises an inertial measurement unit, a dedicated computer, and an embedded GPS receiver. By using DGPS data to calibrate inertial sensor errors in real time, the system maintains the dynamic fidelity of the inertial solution while removing long-term systematic drifts from inertially derived position and orientation.

The POS uses an inertial navigation algorithm and a Kalman filter to compute real-time position (latitude, longitude, altitude) and orientation (roll, pitch, heading). The algorithm combines inertial and DGPS data to generate a blended solution combining the best characteristics of each.

The nominal sampling frequency of 200 Hz results in an absolute accuracy over 2 to 4 hours of 20 arc-sec or about 20 cm in x, y and z at 6,000 m. Relative accuracy over 10 seconds (between acquisition of forward and nadir views) is 4 arc-sec or about 4 cm in x, y and z, again at 6,000 m.

Data processing

Since 1988, Istar has steadily developed and expanded its core skills in digital terrain modelling and geographic data packages. Today, the company offers industrial-scale facilities and the capacity to process huge volumes of 3D image data on a routine basis.

In 1995, Istar focused its energies on the special needs of telecoms operators. The company quickly went on to launch a range of map products (satellite image maps, orthoimages, ClutterMaps, linear network maps, etc.) and custom data packages tailored to this market's specific needs.

To meet the needs of clients requiring higher resolution, Istar also began processing digitized aerial photographs acquired using conventional photogrammetric cameras. This work enabled the company to further refine and expand its core skills in digital terrain modelling and geographic data packages.

Following the success of the first tests on HRSC data in late 1998, Istar developed the following five-step process for industrial-scale processing:

1. Read and preprocess HSRC output to generate radiometrically corrected "raw" imagery.
2. Resample strips (i.e. forward/nadir/backward views and adjacent views) using POS data to obtain views in epipolar geometry.
3. Correlate stereo images to obtain one DSM per stereopair, then merge the resulting DSMs to obtain a DSM on a 1-metre grid.
4. Resample raw imagery using DSM to obtain true 25-cm orthoimages.
5. Manually edit DSM, depending on client's needs, to obtain a digital terrain model and/or building vector database.

The first step uses software developed by DLR. Steps 2 to 5 are performed by Istar using its own facilities, software and methods. Step 5 involves optional labour-intensive tasks tailored to the client's needs. Note that, in contrast with conventional stereo-photogrammetry, and with the one exception of step 5, all data processing is fully automatic, which is to say, without human photointerpretation.

An idea of the data volumes can be gleaned from the fact that a ground area of 200 km^2, generates 32 Gbytes of HRSC data input plus 3.2 Gbytes for the DTM and the true orthoimage. For those familiar with satellite imagery, the correlation of 200 km^2 of HRSC imagery represents about 100 times the processing required to correlate a Spot stereopair covering 60 x 60 km^2.

Key data processing steps are illustrated in sections 3.1 to 3.4 below.

Read and preprocess HSRC output

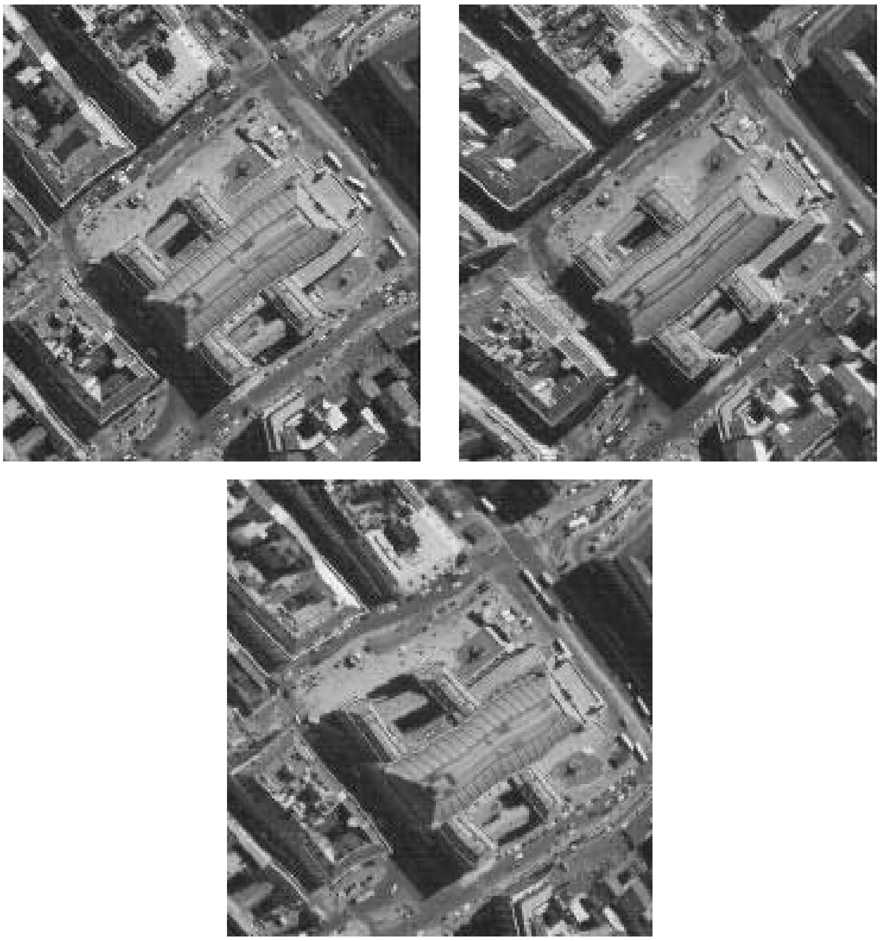

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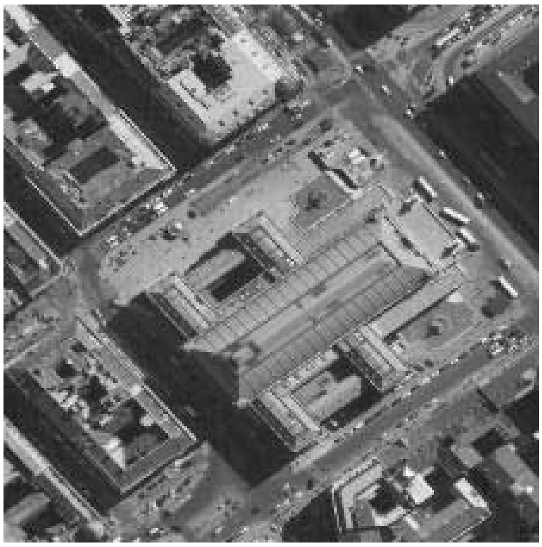
Fig. 3 – Radiometrically corrected “raw” imagery: Forward, nadir and backward views

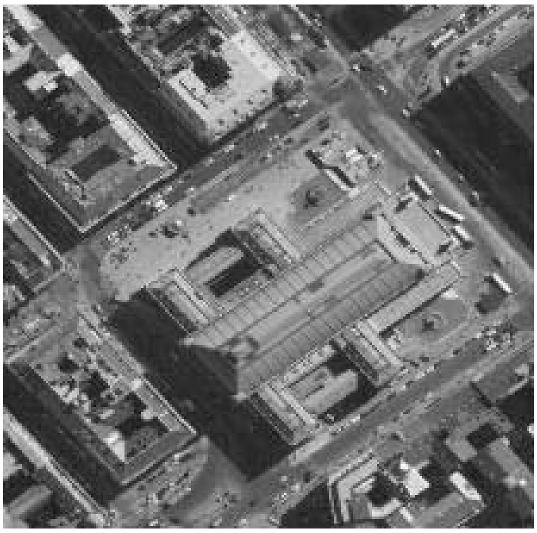
In the past, the photogrammetrist’s main aim was to obtain distortion-free imagery. Today, DLR and Istar propose distorted HRSC views plus precision POS data for distortion correction by motion compensation. The feasibility of this approach hinges on:

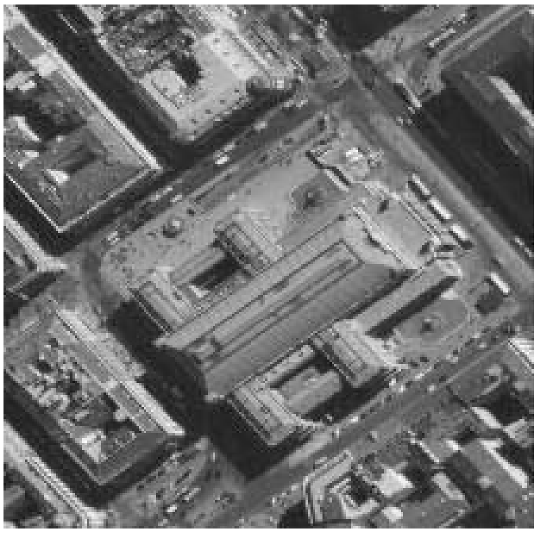
a) the geometric quality and stability of the HRSC camera,

b) the accuracy of the Applanix POS.



Forward view Nadir view





Nadir view Backward view

Fig. 4 – Images are resampled to obtain views in epipolar geometry as input of the correlation algorithm

Correlate stereo images and merge resulting DSMs

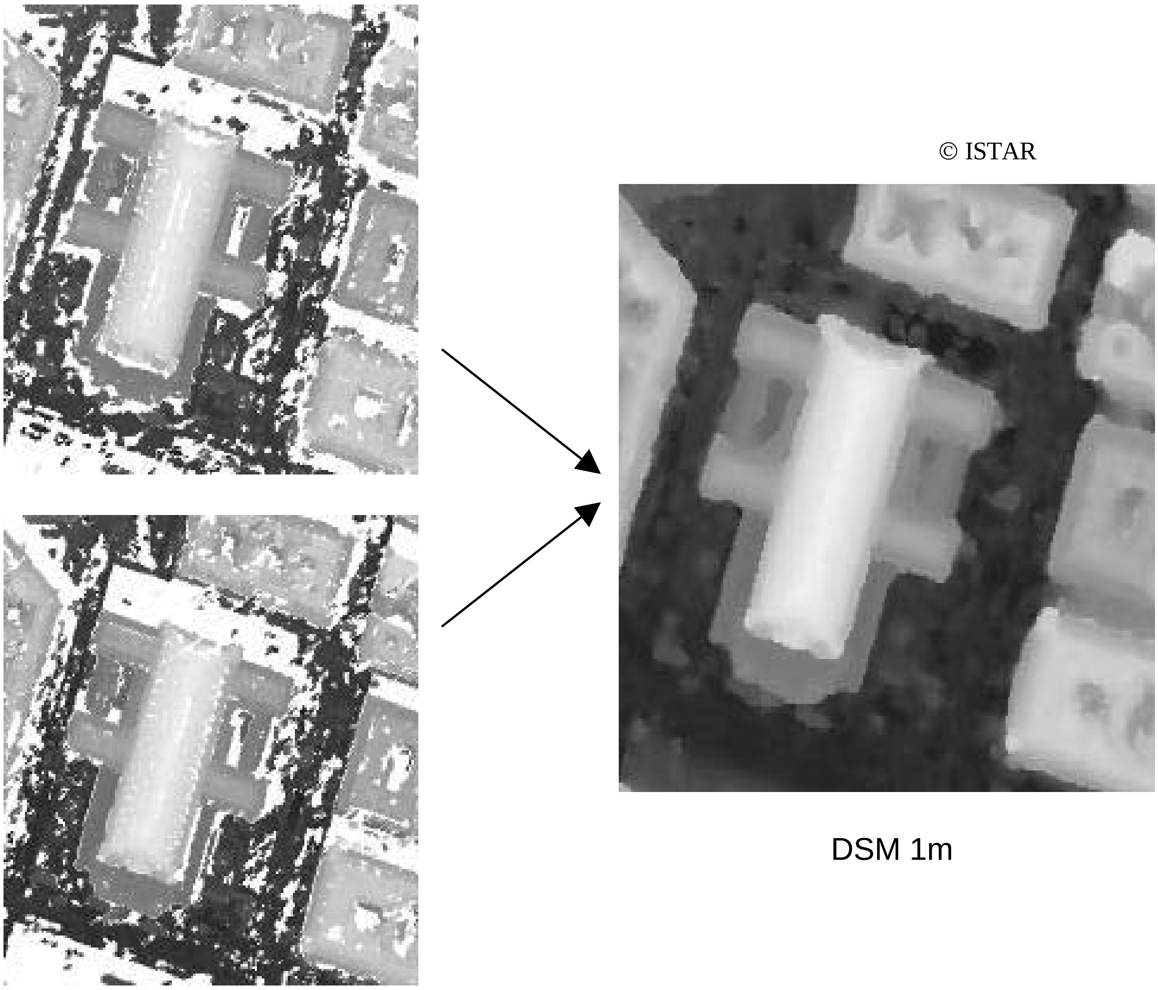
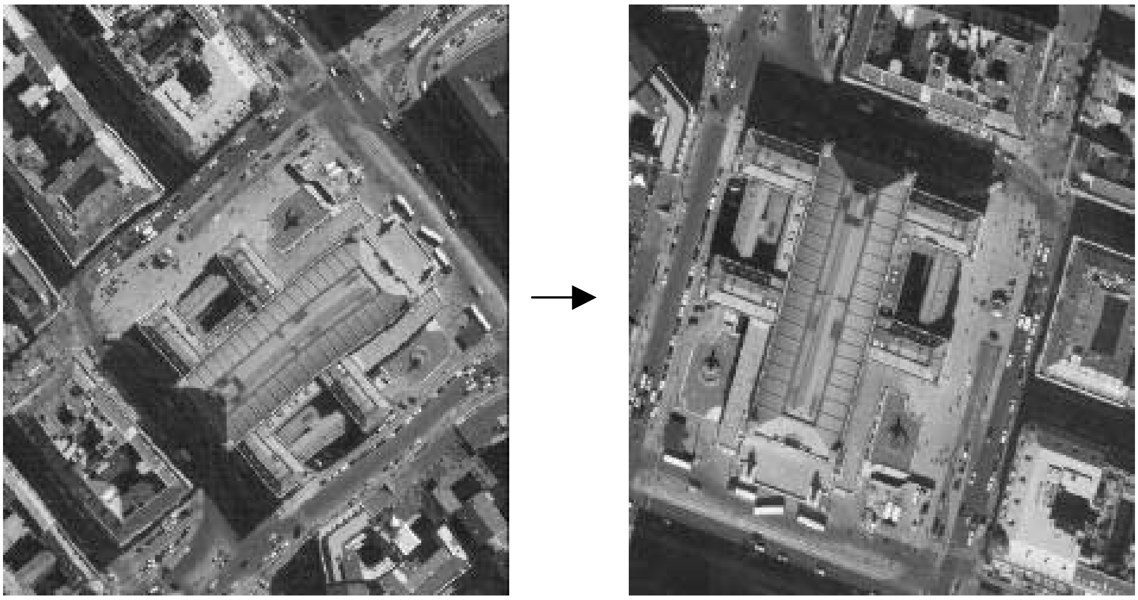


Fig. 5 – Stereo views in epipolar geometry are correlated. The output consists of unit DSMs which are merged to obtain a 1m grid DSM

Resample raw imagery to obtain true orthoimage



Raw imagery   True Orthoimage, 25cm

Fig. 6 – Raw imagery is resampled using the DSM to obtain a true 25-cm orthoimage. Left-hand image is aligned as scanned by the HRSC camera during flight; right-hand image is aligned with North up

This process is slightly more complex than conventional orthorectification in that ground-level surfaces (roads, fields, etc.) are rectified at ground elevation while roofs are orthorectified at roof elevation, thus ensuring the precision planimetric positioning of all features, irrespective of height.

Istar processes HRSC data using:

- its own Spot3D software suite,
- a Sony 8-Mbyte/s recorder for data entry,
- a cluster of 25 Sun workstations for data processing.

This system is in place and fully operational with further developments planned for the near future. An additional 1-Terabyte mass storage system and server for data archiving is planned for early 2000. The workstations provide the processing power while the mass storage system and server paves the way for Intranet access in the near term and Internet access in the medium term.

To process an HRSC survey of a city covering 200 km^2 takes about 50 hours using 25 Sun workstations, giving Istar a production capacity is about one city per week.

Data acquisition campaigns and future plans

In early 1999, DLR and Istar decided to survey 43 cities in 12 European countries between April and September 1999.

Fig. 7 – Perspective view of Lisbon, Portugal (Resolution: 0.5m)
Main alignment, from top: *Avenida da Liberdade, Praça do Marquês de Pombal, Parque Eduardo VII*. Note excellent 3D representation of the central monument.

Additional campaigns will be organized when DLR makes two additional cameras available in the fourth quarter of 1999:

- HRSC-A offers a resolution of 25 cm at 6,000 m and stereo imaging in five panchromatic bands plus four multispectral bands (blue, green, red and near IR),
- HRSC-B offers a resolution of 1 m at 6,000 m and stereo imaging in three panchromatic bands plus two multispectral bands (B1 and B2).

HRSC-A will be used to acquire 25-cm 3D data of city centres while HRSC-B will acquire 1-m-resolution data of suburban areas and city environs.

In 2000, DLR and Istar will use the HRSC-A camera to acquire imagery of 100 cities in Europe and the United States producing DSMs on grids from 2 to 5 m with an rms accuracy of 1 m. Products will include building vector databases and true 25-cm orthoimages in colour or B&W.

The wider-angle HRSC-B will be used to survey selected areas totalling 500,000 km^2 in Europe and the United States and produce DSMs on 5-m grids with an rms accuracy of 2 m. Products will include true 1-m orthoimages (panchromatic or multispectral).

R&D

As soon as the partners began acquiring operational experience with the HRSC camera and Istar software, they identified areas in which efficiency could be further enhanced by setting up R&D projects under the DLR/Istar partnership. Projects now in progress concern:

- Multiple GPS base stations: Using differential GPS to provide ground control points (GCPs), the current system requires one GCP within 30 to 50 km of each GPS base station. Using multiple GPS base stations, anticipated performance is one GCP within 200 km of each base station, provided airborne GCP receiver and base station can see the same GPS satellites.
- Automatic vectorization of buildings using DSMs to reduce the cost of generating building vector databases. In dense urban areas, manual generation of building vector databases requires around 8 hours work by a trained operator per square kilometre.
- Colour orthoimagery: Removal of colour "echo" effects produced by moving objects (road vehicles, trains, aircraft) as a result of the fact that different spectral bands are acquired at slightly different times.

Conclusion

Istar and DLR have successfully transferred new know-how in imaging instrument design and data processing from satellite-based remote sensing to conventional photogrammetry. These efforts will continue apace with the deployment of two additional HRSC in Europe and in United States. In 2000, DLR and Istar will conduct two major surveys, one covering 100 cities, the other selected regions of interest totalling 500,000 km^2. The resulting products expected to prove highly attractive to telecom operators and others engaged in planning and deploying mobile telecommunications networks.

Discussion

Digital aerial survey for network planning
L. Renouard (ISTAR, France)

Lithopoulos (Applanix, Canada):
I have two questions: how do you see yourself competing with laser scanners which do a similar application for telecommunications?

Renouard (ISTAR, France):
I have understood that laser scanning today is a new technology that allows one to model buildings but does not provide the imagery as yet.

Lithopoulos (Applanix, Canada):
My second question is, why do you use the DLT tape technology, which is only about half the speed of a new tape technology coming up?

Renouard (ISTAR, France):
Even if the digital camera seems to be a big machine and an expensive system, it is not a big deal compared to the costs of an aircraft flight.

Heipke (University Hannover, Germany):
Can you elaborate more on the DTM technique and building extraction? You mentioned it was a semi-automatic and manual process. How does it work in detail? Do you have to touch every building and how fast or how slow is it?

Renouard (ISTAR, France):
I have to admit that the process is rather slow; you do one square kilometre in 1-2 days. We subcontract the job to partners in different countries. This is a burning issue of course, and we have 3 PhDs charged with reviewing our processes and to make it quicker and easier.

Part 2

Digital Scanners

Chairman

O. Kölbl

Presentation of the current performances of photogrammetric scanners (strengths and weaknesses, scanning of negatives), advantages of drum scanners, advantages in comparison to the use of digital cameras.

Quality Evaluation of the DSW200, DSW300, SCAI and OrthoVision Photogrammetric Scanners

Emmanuel P. Baltsavias [*], Christoph Kaeser [**]

[*] Institute of Geodesy and Photogrammetry, ETH-Hoenggerberg, Zurich [**] Swiss Federal Office of Topography, Wabern,

Abstract

Geometric and radiometric investigations performed with the DSW200, DSW300, SCAI and OrthoVision photogrammetric scanners are presented. These tests were performed within the period August 1996 to June 1999 and in most cases involved testing of more than one scanner for each model. The tests were performed in close cooperation with the companies LH Systems, San Diego, Carl Zeiss, Oberkochen and Swissphoto Vermessung AG, Regensdorf. The scanner performance evaluation was carried out using good quality test patterns and accurate processing methods. The test patterns were identical or very similar for all scanners and the analysis of the results identical. The geometric tests included global geometric errors, misregistration between colour channels, determination of the geometric resolution and in some cases local geometric errors and geometric repeatability. The radiometric tests included investigations of noise, linearity, dynamic range, spectral variation of noise, colour balance and artifacts. After a brief description of the scanners, the above investigations, analysis and results are presented. The majority of the tests have been already published in detailed papers on the DSW200, DSW300 and SCAI. Thus, here only a summary of the major results will be given, while unpublished results on the radiometric performance of the new Kodak CCD of SCAI and the OrthoVision will be presented in more details. The results show that an improvement of the scanner performance since 1996 has been achieved and that the differences between scanner models but also between scanners of the same model can be significant, while in some cases the performance, both geometric and radiometric, is poor and does not allow a full exploitation of the accuracy potential of digital photogrammetry.

1 Introduction

Scanners are an essential part of softcopy photogrammetric systems. The main use of scanners today is definitely in the digitisation of aerial images. The main applications that increase the need for digital aerial data are (i) orthoimage generation, (ii) automated aerial triangulation (AT) (iii) automated DTM generation, (iv) generation and update of digital feature databases, and (v) the integration of digital data, particularly DTMs, orthoimages and derived products, in GIS. Since every subsequent processing step builds upon the scanned imagery, the analysis of scanner accuracy and performance is of fundamental importance. Several problems that have been observed in digital photogrammetric procedures, like poor interior orientation and aerotriangulation results, as compared to results with analytical plotters, errors in DTMs (stripes etc.), and various radiometric artifacts and poor image quality, are occasionally (especially in the past) caused by insufficient geometric and radiometric scanner performance.

An overview of photogrammetric scanners is given in Baltsavias, 1999. Related work on tests for evaluation of the above scanners include geometric and radiometric evaluation of the DSW200 (Miller and Dam, 1994, Baltsavias et al., 1997), DSW300 (Baltsavias et al., 1998), Zeiss SCAI (Baltsavias and Kaeser, 1998), and OrthoVision (Honkavaara et al., 1999), radiometric characteristics of SCAI (Waegli, 1998), and colour reproduction and image sharpness of various scanners (Koelbl, 1999).

2 Overview of tested scanners

An overview of the scanners is given in Table 1. DSW200 was replaced by DSW300 in 1996 and the latter by DSW500, which has quite some differences to DSW300 especially in the illumination and the CCD chips, in July 1999. The Kodak sensor of the SCAI has been used since autumn 1998. The old SCAI models were using a Thomson THX7821 3-linear colour CCD with 8640 elements, which was replaced by the Kodak sensor due to various problems (see Baltsavias and Kaeser, 1998). The Zeiss SCAI is also sold by Intergraph under the name PhotoScan TD. Differences to SCAI are the host computer (Intergraph TDZ 2000 with Pentium III, only Windows NT), software JPEG compression and the scanner software. A ScanServer with dual processors and RAID disk subsystem is also offered. OrthoVision was produced by XL-Vision but the scanner department of this firm was bought in autumn 1997 by ISM, Vancouver, and the scanner is since then sold under the name XL-10. More details can be found for the DSW300 in Dam and Walker (1996), LHS (1999), the SCAI in Mehlo (1995), Vogelsang (1997) and Zeiss (1999), and the XL-10 in ISM (1999). DSW300 and SCAI are tightly coupled to complete digital photogrammetric systems of the firms LHS, and Zeiss, Intergraph respectively, while XL-10 is coupled to ISM’s DIAP but also sold with Autometric’s Softplotter. These four scanner models are, together with the Vexcel VX 3000+/4000 and Wehrli RM-1/2, the ones that are currently used more extensively in the professional practice.

The DSW models employ area CCDs, the SCAI and OrthoVision trilinear colour CCDs. XL-10 uses 3 optically butted trilinear CCDs (i.e. 9 CCD lines in total) to scan the whole image in one swath. This requires very precise mounting and calibration, very good image focusing and quality optics, high bandwidth for the A/D converter (ADC) and electronics or slower scan speed (if one ADC is used) or alternatively more ADCs and electronics (if multiplexing of the signal from the CCDs is to be avoided). SCAI needs for scanning several swaths, and the DSW several image tiles. The DSW and XL-10 have moving stage and stationary sensor/illumination, while the SCAI employs the opposite principle. All scan colour in one pass, but DSW makes at each image tile a sequential colour acquisition through rotating filters, while SCAI and XL-10 grab the R, G, B channels simultaneously.

3 Tests, test patterns and test procedures

The acquisition of the test scans was performed as follows. DSW 200 was tested during the period 1995–1997 at different sites (Leica Unterentfelden, Swissphoto Vermessung AG) using four different scanners. DSW 300 was tested in December 1997 at LH Systems in San Diego using two different scanners. SCAI was tested once at Carl Zeiss Oberkochen in August 1996 (termed SCAI 1), another SCAI was tested in spring 1997 at the Swiss Federal Office of Topography (called SCAI 2), and the latter scanner, but with the new Kodak CCD, was tested at the same site in June 1999 (SCAI 3). OrthoVision 1 was tested in August 1996 at the firm Geosystems in Germany. OrthoVision 2 was an independent test performed at the Finnish Geodetic Institute (see Honkavaara et al., 1999) with 29 and 33 scans of the geometric and radiometric test patterns respectively from July 1996 to November 1997. A new scan programme was installed end of January 1997. The information on test patterns and procedures below does not refer to the OrthoVision 2 tests. In the latter tests a similar grid plate (23 x 23 grid points, 10 mm spacing, 1 µm accuracy) and the same grey scale as below were used (however, we do not know whether the grey scale was calibrated).

For the geometric tests, mainly two glass plates were used (for the DSW300 two additional grid plates for comparison). One high precision réseau glass plate came from Rollei, which has been produced by Heidenhain, with a 2 mm grid spacing (116 x 116 crosses), 200 µm cross length, 15 µm line width, and an accuracy of the reference cross positions better than 1 µm. The second grid plate (called ETH plate) was a custom one produced by a Swiss company specialising in high precision optical components (IMT) with a 1 cm grid spacing, 187.5 µm line width (25 x 25 crosses) and an accuracy of ca. 2 µm. To determine the scanner resolution, a standard USAF resolution pattern on glass produced by Heidenhain was used. The radiometric performance was mainly checked by scanning a calibrated Kodak grey level wedge on film (21 densities with density step of approximately 0.15 D; density range ca. 0.05 D–3.05 D). The densities were determined by repeated measurements (4 to 15) using a Gretag D200 microdensitometer with a resolution of 0.01 D. Two similar grey scales were used (after the loss of the first one).

Table 1 – Photogrammetric scanners (for the newest status, especially on throughput, host computer and price, consult the manufacturer).

Brand / Model	**LH Systems / DSW 300** [1]	**Zeiss / SCAI**	**ISM / XL-10**
Mechanical movement	flatbed, moving stage	flatbed, stationary stage	flatbed, 1-D moving stage
Sensor type	digital Kodak Megaplus 4.1I 2029x2044 CCD (960^2 - 1984^2 active)	Kodak trilinear colour CCD, 10,200 pixels (5,632 active)	Kodak trilinear colour CCDs, 3 optically butted, 3 x 8,000 pixels
Scanning format x/y (mm)	265 / 265	275 / 250	254 / 254
Roll film width/length (mm/m) Motorised transport	35 - 241 / 152 manual, automatic	245 / 150 manual, automatic	241 manual, automatic
Scan pixel size (µm)	4 - 20 base resolution (and multiples of 2, other in software)	7 - 224 (in multiples of two, and 21 µm)	10 - 320 (in multiples of two)
Radiometric resolution (bit) (internal/output)	10 / 8 or 10	10 / 8	10 / 8
Illumination	Xenon arc, liquid pipe optic, integrating sphere	Fan-cooled, halogen, 250 W, diffuse, fiber optic	daylight, fluorescent lamp
Colour scan passes RGB simultaneously?	1 no	1 yes	1 yes
Density range	3D	0 - 3D	0.1 - 2.4D
Geometric accuracy (µm)	2	2	< 3
Radiometric accuracy (DN)	1 - 2	±1.5	
Scanning throughput [2] **and/or speed**	1.7 MB/s (12.5 µm, colour) 1.3 MB/s (12.5 µm, B/W) max. 100 mm/s	0.45 MB/s (14 µm, B/W) max. 4 MB/s (7 µm, colour) max. 38 mm/s	0.73 MB/s (20 µm, colour) 0.37 MB/s (20 µm, B/W) max. 35 mm/s
Host computer/ Interface	Sun Ultra 10, 30, 60 / fast 32-bit wide SCSI-2	UNIX SGI /fast SCSI-2 Pentium II, Windows NT/SCSI	Dual Pentium, Windows NT
Approximate price (US$)	145,000 / 125,000 with / without roll film	138,000 incl. roll film	95,000 incl. roll film

[1] DSW 300, apart from enabling roll film scanning, is similar to the older DSW 200 with differences in scanning stage and electronics, and more precise servos.

[2] The throughput also depends on the host (which changes frequently), the scanner/host interface and the output image format.

All scans were with the minimum scan pixel size, if not otherwise mentioned. In all cases except for the DSW200, the grid plates were scanned in colour to check the geometric misregistration between the colour channels. The grey level wedge was scanned (except for DSW200) in B/W and colour, with the minimum pixel size (with linear and logarithmic LUT) and double this pixel size (only with linear LUT) to check the effect of the LUT, the spectral properties of the noise, the colour balance and the effect of pixel size on the radiometric performance. The wedge was masked with a black carton to avoid stray light.

The pixel coordinates of the grid crosses were measured by fully automatic Least Squares Template Matching (LSTM). An option of the algorithm that reduces the influence of dust and other noise on the cross measurement was used. The accuracy of LSTM, as indicated by the standard deviations of the translations, was for these targets 0.02–0.05 pixels. Matching results with bad quality criteria (low crosscorrelation coefficient etc.) were automatically excluded from any further analysis. In addition, the matching results of all crosses with large errors were interactively controlled. However, smaller errors (e.g. 5–6 μm) due to dust could have remained in the data set.

The geometric tests performed include:

1. Global geometric tests

For this purpose an affine transformation between the pixel and the reference coordinates of all crosses was computed with three versions of control points (all crosses, 8 and 4, the latter two versions simulating the fiducial marks used in the interior orientation of aerial images).

2. Misregistration errors between the channels

Such errors were checked by comparing pairwise the pixel coordinates of the channels (R-G, R-B, G-B).

3. Geometric resolution

It was determined by visual inspection of the scanned resolution pattern, i.e. the smallest line group that was discernible was detected, whereby it was required that the contrast between lines is homogeneous along the whole line length.

For some scanners, e.g. DSW300, additional aspects were tested like local geometric errors of the individual image tiles (due to lens distortion), short- and mid-term repeatability, and stability and robustness with respect to using different grid plates and different scanner calibration values.

The radiometric tests include:

1. Estimation of the noise level, linearity, dynamic range and colour balance

This was done by determining the mean and standard deviation for each density of the grey level wedge. In previous tests it has been noticed that the grey level wedges of our film, especially for the high densities, are not homogeneous, i.e. they are lighter towards the borders. There is also a very small decrease in the grey values across each density rectangle as one goes from low to darker densities. To avoid the influence of such inhomogeneties on the computed grey level statistics, only the central region of each wedge was used (the same region for all wedges and test scans, independently of the scan pixel size). In addition, in previous tests when scanning with small pixel size a corn pattern was sometimes visible. To reduce the effect of such dark corn and also of dust etc., grey values that are outside a specified range are excluded from the computation of the statistics. The range is computed for each grey wedge as (mean ± 3 x standard deviation), whereby the minimum and maximum allowable range is 4 and 20 grey values respectively. The minimum range is used to avoid excluding too many pixels in high density wedges with small standard deviations due to saturation. The linearity was checked by plotting the logarithm of the mean grey value of each wedge (and for logarithmic LUT, simply the mean grey value) against the respective calibrated density. These points should ideally lie along a line and be equidistant. The dynamic range is determined as follows. Firstly, the minimum unsaturated density is selected. Then, the maximum detectable density "i" is determined using the following conditions:

(a) $M_{i+1} + SD_{i+1} + SD_i < M_i < M_{i-1} - SD_{i-1} - SD_i$, with M and SD the mean and standard deviation of the wedges and "i" increasing with increasing density (i.e. the distance of the mean grey value of a detectable density from the mean values of its two neighbouring densities must be at least equal to the sum of the SD of the detectable density and the SD of each of its neighbours),

(b) $SD_i > 0.1$ (to avoid cases when other conditions, especially condition a), are fulfilled but the signal is in reality saturated and therefore has a very small SD), and

(c) $\mathrm{nint}\,(M_i) \neq \mathrm{nint}\,(M_j)$, with "j" any other density except "i" (i.e. since grey values are integer, the mean grey value value of a detectable density must differ from the mean grey value of all other densities).

The colour balance was checked by comparing the linearity plots of the R, G, B scans and the mean values of each density.

2. Artifacts

Some of the above mentioned scanned patterns, and other scanned B/W and colour films, were very strongly contrast-enhanced by Wallis filtering. This permits the visual detection of various possible artifacts such as radiometric differences between neighbouring tiles, "electronic" dust, etc. However, the quantification of radiometric errors was always performed using the original images.

4 Summary of geometric and radiometric results

In the following, a summary of the performed geometric and radiometric tests will be given (only for the tests marked 1 above). More details can be found in the respective references of Section 1. For each scanner, multiple results are presented, using the same scanner model but different scanners, in order to check variations in their performance. The OrthoVision 2 results are listed here because they differ significantly from our results with the OrthoVision 1. In all tests, except the ones referring to the OrthoVision 2, the same test patterns, scan options and analysis methods have been used. In all results, the individual results are mean values of up to 29 scans. The geometric errors have been estimated using an affine transformation between measured and reference values of calibrated glass plates having an accuracy of 1–2 μm and a grid spacing of 2 or 10 mm, using all grid points as control. The pixel coordinates were measured automatically, e.g. with Least Squares Template Matching in all tests except OrthoVision 2. When only 4 or 8 points are used as control, the geometric errors increase compared to those in Table 2.

As it can be seen from Table 2, the differences between scanner models are significant. Differences between scanners of the same model can also be substantial, as the results of DSW200 and OrthoVision reveal. Newer, more mature scanners like the DSW300 and the SCAI show a better homogeneity. OrthoVision 2 showed larger errors in the y (scanning) direction. The errors in this direction showed a barrel effect. The use of the new scan programme did not influence the results. Figures 1 and 2 show some results of the geometric tests for SCAI, DSW200 and DSW300.

Table 2 – Mean geometric errors of various scanner models and scanners.

Scanner model / scanner	**RMS x (μm)**	**RMS y (μm)**	**Max. absolute x (μm)**	**Max. absolute y (μm)**
DSW200 / 1	3.4	5.1	9.7	16.6
DSW200 / 2	1.8	2.5	6.8	8.7
DSW300 / 1	1.8	1.4	7.0	5.3
DSW300 / 2	1.3	1.4	5.3	5.2
SCAI / 1	2.2	2.1	6.1	7.4
SCAI / 2	2.3	2.1	8.1	6.6
OrthoVision / 1	7.5	7.0	26.8	17.9
OrthoVision / 2	1.3	2.2 [1]	4.1	7.6

[1] In the first 6 scans, the RMS in scan (y) direction was higher, between 3.2 and 4.3 μm, and the maximum absolute errors too. Then, a second scanner calibration led to improved results.

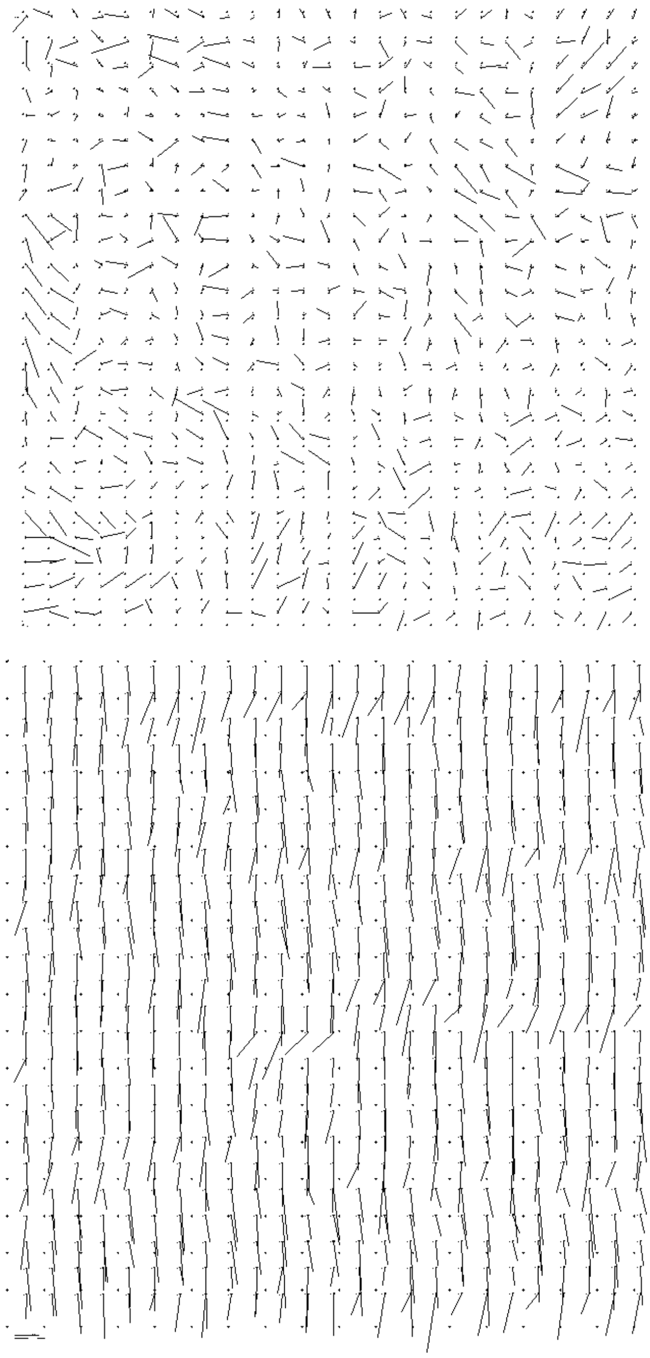


Fig. 1 – Top: Residuals of an affine transformation with the ETH plate and SCAI 2, showing local systematic errors which were quite stable in short term. Image scanned in 7 swaths from top to bottom. Bottom: pixel coordinate differences between green and red channel of SCAI 1 showing a clear constant shift in y (scan) direction, due to a fabrication error of the Thomson CCD.

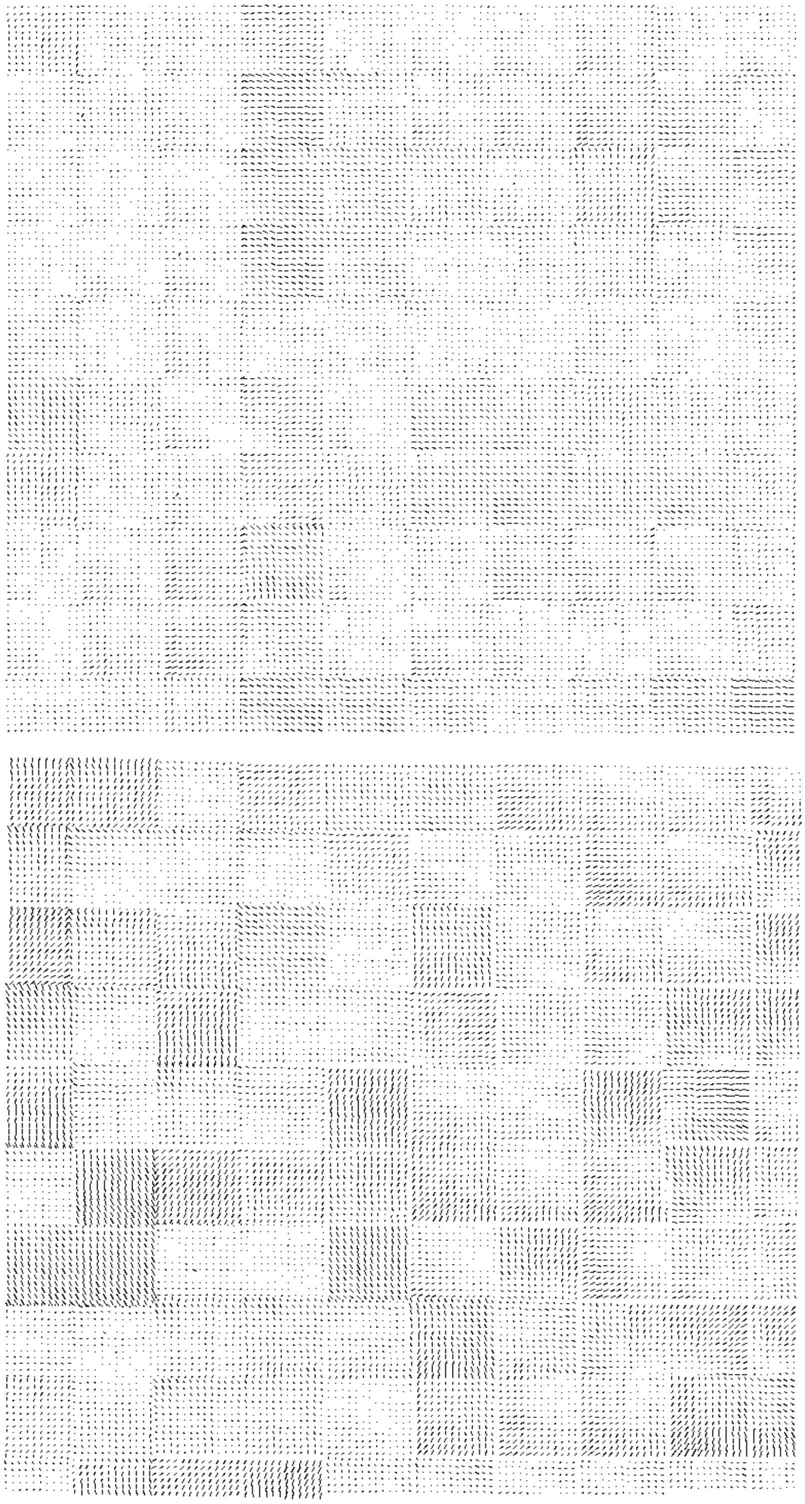


Fig. 2 – Residuals of an affine transformation using the Rollei plate: Top, DSW300; Bottom one of the best results for the DSW 200. Note in the latter case the very visible image tiles.

Table 3 – Radiometric performance of various scanner models and scanners.

Scanner model / scanner	Dynamic range	Mean noise (DN)	Scan pixel size (µm)	Used LUT
DSW200 / 1	0.05D–1.9D	1.1	12.5	linear
DSW200 / 2	0.05D–1.44D / 0.05D–1.75D	2.9 / 1.9	12.5 / 25	linear
DSW200 / 3	0.05D–2.2D	1.9	12.5	logarithmic
DSW300 / 1	0.05D–1.95D	1.2 / 0.9	12.5 / 25	linear
DSW300 / 2	0.05D–2.16D	4.3	12.5	logarithmic
SCAI / 1	0.2D–1.28D / 0.35D–1.75D	2.3 / 2	7 / 14	linear
SCAI / 2	0.05D–1.75D / 0.05D–1.95D	1.3 / 1.1	7 / 14	linear
SCAI / 3	0.2D–1.58D / 0.2D–1.75D	2.2 / 2	7 / 14	linear
SCAI / 4	0.2D–1.66D / 0.2D–1.83D	3.8 / 3.2	7 / 14	logarithmic
OrthoVision / 1	0.2D–1.44D	1.6 [1]	10	linear
OrthoVision / 2	–	6%–7% of mean grey value	20	linear?

[1] In the 0.2D to 1.7D range that was unsaturated, the mean noise was 2.5 grey values.

Table 3 gives a summary regarding the dynamic range and the noise (standard deviation of homogeneous areas). In all cases, except of DSW200 / 1, the results are mean values of multiple scans, sometimes in colour. For OrthoVision / 2 only the densities 0.05D to 1.7D were checked. In this test, the noise is given as % of deviation from the average grey value of each density. 33 scans were performed with two different program versions. For both program versions the low densities (0.05–0.35D) showed a deviation of 2%–6% from the average value. For the higher densities (1.4D–1.7D), the deviation was 6%–14% for the old program and 8%–17% for the new one. The average deviation for all densities was ca. 6% and 7% with the old and the new programs, respectively. Although the average grey values of each density were not published, it is obvious that the low densities have too high noise. All tests of Table 3 are from different scanners except DSW200 / 2 and / 3, DSW300 / 1 and / 2, and SCAI / 3 and / 4, which were identical but using different LUTs. SCAI / 3 was the same scanner as SCAI / 2 but with the new Kodak sensor, instead the Thomson linear CCD.

In SCAI / 1 and SCAI / 3 scans with both 7 and 14 μm scan pixel size, the low densities appeared with a lot of corn, which increased the noise and decreased the dynamic range. The fact that the corn was almost equally visible also in the 14 μm scan is due to the fact, that with SCAI the real pixel size in scan direction is less than the nominal one (by ca. 50%, i.e. a 14 x 14 μm^2 pixel is in reality 14 x 7 μm^2). This corn really exists in the film, but it is peculiar that it did not appear in the SCAI / 2 scans. This could be due to lower exposure time (ET) in these scans (the standard deviation of the grey values, i.e. the corn visibility, increases linearly with the exposure time; this contradicts to the fact that with longer ET the signal-to-noise ratio should increase; the SCAI 2 test was performed with 1.7 ms ET, the SCAI 3 with 1.5 ms, so the ET does not explain why no corn was visible with SCAI 2) or due to scanning with emulsion up, which would defocus the scan and again decrease the standard deviation (such an error is, however, very unlikely). Also OrthoVision / 1 with 10 μm scan pixel size showed a similar effect but to a lesser extent, while with the DSW the corn was not visible. Thus, our interpretation is that these Kodak grey scales are not homogeneous enough for tests with small scan pixel size. Either, the pixel size should be increased (e.g. around 30 μm) but then this pixel size will not correspond to the one used in practice, or more homogeneous test patterns, preferably on film, should be used. All DSW scanners used the Kodak KFA 2000 x 2000 pixel sensor, but however different versions of it (at least 3 different ones). The results of DSW 200 /2 and / 3 were very atypical among the four DSW200 scanners that were tested, but are listed here, to indicate the differences that can occur. Apart from the sensor, some differences among the same scanner models were due to software changes, especially regarding the radiometric calibration. In most of the tests, the lowest density (0.05D) was to a large extent saturated but not totally. The performance (noise, dynamic range) was generally better for the R, then B/W, then G, and then the B channel, whereby the difference between the first three was often small. The average grey values of each density and the linearity were similar for the R, G, B channels, with the exception of OrthoVision 1, while no tests using R, G, B were performed for the OrthoVision 2. Use of a logarithmic LUT increases the maximum detectable density and the dynamic range, but at the expense of losing grey values in the bright areas and significantly increasing the noise of the high densities, where the signal-to-noise ratio is the lowest.

Figure 3 shows the grey value linearity for the R, G, B channels and a linear LUT for DSW300, OrthoVision 1 and SCAI 2. It is obvious that for high densities there is no good linearity and the scanner can not discriminate these grey values. OrthoVision 1 in particular shows a poor performance in these densities. The colour balance seems good in all 3 scanners, with slightly worse performance for SCAI 2 and high densities. However, as Table 6 shows (see mean grey values) the colour balance with the OrthoVision 1 is not good, with differences between the 3 channels up to 30 grey values (differences were large in the 0.2D–1D range).

The published results for DSW200, DSW300 and SCAI can be summarised as follows:

DSW200: The major problems of DSW200 refer to the geometry. The mean RMS values for the R, G, B scans were 1.7–3.7 μm in x, and 2.3–5.5 μm in y. The mean maximum absolute errors were 6.7–10 μm in x and 8.2–20.7 μm in y. The major error sources are vibrations, mechanical positioning accuracy and the related scanner calibrations (stage and sensor). Vibrations and electronic errors are random, and even the mechanical positioning errors vary within a few hours. There are significant error variations between different DSW200 scanners. The errors are always larger in y, and increase as we go from blue to green to red channel. The differences between colour channels (ignoring a random line shift of one of the CCD camera models) can amount up to 6 μm. The biggest problem are the maximum errors that affect whole tiles.

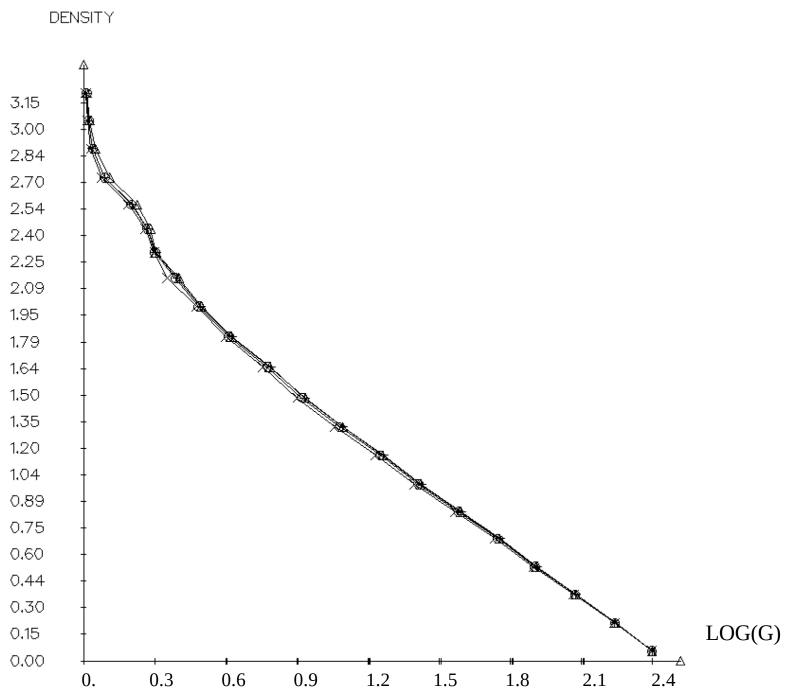
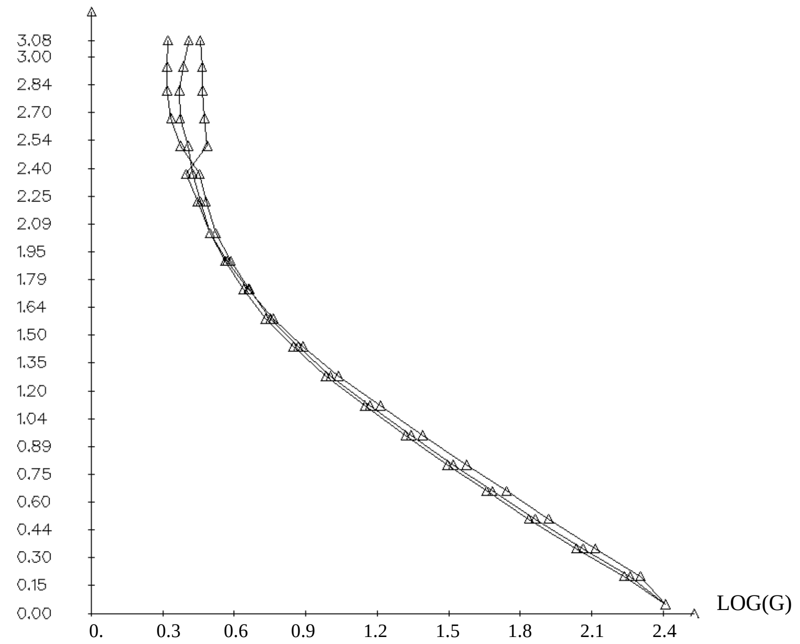


Fig. 3a – Grey scale linearity, linear LUT, DSW 300, 12.5 μm



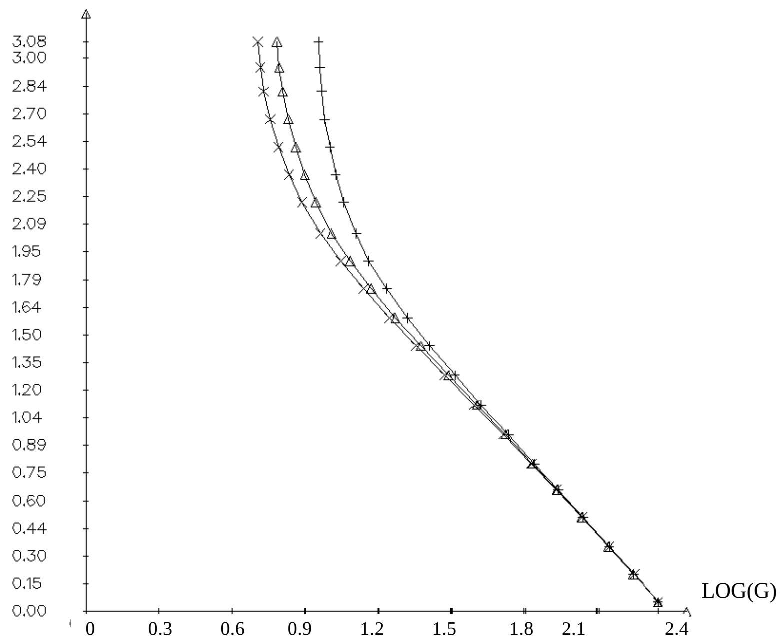


Fig. 3b and 3c – Grey scale linearity, linear LUT , OrthoVision 1, 10 µm (Top),
SCAI 2, 14 µm (Bottom)

These tile shifts have serious effects on subsequent operations with aerial images like interior orientation, aerial triangulation, DTM, orthoimage generation etc. Regarding the radiometric errors, the noise level for 12.5 µm scans was ca. 3 grey levels for the DSW200 / 2 test, but in most older tests was rather 2 grey levels. The dynamic range lies between 0.1–0.2D and 1.6–1.9D for 12.5 μm scans. The difference in dynamic range and noise level between colour channels is small. The blemished pixels (defect CCD pixels) are very few and do not constitute a problem. Dust is a more serious problem and can lead to "electronic" dust, if the radiometric equalisation procedure of the sensor elements is not improved. The histograms showed spikes (grey values occurring more often that their neighbours) in the dark grey values.

DSW300: With respect to the geometric accuracy, the RMS was 1.3–1.9 μm and the mean maximum absolute error 4.5–8 μm. Lens distortion contributes to this error by an RMS of 0.7–0.9 μm (a priori calibration of the lens distortion and application of appropriate corrections could remove this error and lead to even more accurate results). The errors are bounded, i.e. on the average the 3 sigma (99.7%) values are 3 RMS, and the maximum absolute error 3.7 RMS. The co-registration accuracy of colour channels was about 1 μm, i.e. better than the geometric accuracy, as it should be. The short and medium term repeatability was very high. With a linear LUT, the radiometric noise level is 1 and 1–1.5 grey values for 25 and 12.5 μm scan pixel size respectively, and a logarithmic LUT, 3.5–5 grey values. The dynamic range is 2D/2.16D for linear/logarithmic LUT with a very good linear response up to this value. One of the major remaining radiometric problems is dust. In both geometric and radiometric tests no significant differences between R, G, B and B/W scans has been observed.

SCAI: Regarding the geometric accuracy the RMS was 2–2.3 μm and the mean maximum absolute error 6–8.1 μm. The errors are bounded, i.e. the maximum absolute error is 2.7–3.6 RMS. Local systematic errors were observed with both SCAI 1 and 2 probably mainly due to temporally stable x-, y-positioning errors and to a lesser degree calibration errors and vibrations. The co-registration of colour channels is very good in x, but in scan direction there is a constant shift from one CCD line to the next one of ca. 1 μm due to fabrication inaccuracies. The shift between R and B channels is ca. 2.5 μm, i.e. more than the geometric accuracy of the scanner, and with high resolution scans creates wrong colours at sharp edges. The short term repeatability was very high. Both scanners had similar geometric accuracy values but one was better in x-direction, the other one in y. The radiometric noise level with SCAI 2 is 1–1.6 and 0.9–1.3 grey values for 7 and 14 μm scan pixel size respectively. The dynamic range is 1.6–1.9D and 1.75–2.05D for 7 and 14 μm respectively with a good linear response up to these values. There were no significant differences between R, G, B channels with respect to geometry but their radiometric noise and dynamic range was different, with B clearly showing a poorer quality, and G being only slightly worse than R. Quite some artifacts and electronic noise problems causing systematic local errors up to 5 grey values and larger that the noise level of the scanner were observed. The most important are vertical stripes due to different CCD sensor element response because of inaccurate radiometric calibration, and echoes due to cross-talk between the 3 CCDs. The effective y-pixel size can be smaller than the nominal one by 10% (exposure times > 4.5 ms) and up to 50% (exposure times < 4.5 ms).

5 Detailed results with OrthoVision

Since the tests with OrthoVision 1 are unpublished, some additional details of this test will be presented here. In Table 4 it is shown that the results are similar for all 3 colour channels. Both RMS and maximum absolute errors are very large. The x-direction is a bit worse than the y-one in the RMS and much worse in the maximum absolute errors. With 4 control points the bias (mean values) are also high. Table 5 shows the pairwise differences of the pixel coordinates of the colour channels. The differences are large, especially in the x-direction and particularly for the Blue-Red. However, the mean values are very low, which indicates that there is no error in the manufacturing of the trilinear CCDs, e.g. the pairwise distance between the 3 colour linear CCDs is accurate and an integer multiple of the pixel size. However, the pixel differences will not indicate mounting errors between the 3 trilinear CCDs, which do exist as Figure 5 (left) shows. Figure 4 shows that the errors differ for the 3 trilinear CCDs, they are locally very systematic and increase towards the borders of each trilinear CCD. The differences between the colour channels clearly increase towards the borders of the lens and point outwards. These errors indicate that the lens does not have good achromatic properties.

Table 4 – OrthoVision. Statistics of differences after an affine transformation (in µm)

# of control /check points	Statistics (Scan dir. x)	Red channel	Green channel	Blue channel
600 / 0	RMS x	7.7	7.5	7.4
	RMS y	6.9	7.0	7.1
	max abs. x	27.4	26.8	26.3
	max abs. y	17.2	17.5	18.9
4 / 596	RMS x	8.3	8.0	7.9
	RMS y	10.0	10.0	9.8
	mean x	–1.7	–1.5	–2.0
	mean y	3.3	3.4	2.7
	max abs. x	29.2	28.4	27.7
	max abs. y	20.2	21.1	21.6

Table 5 – OrthoVision. Statistics of pairwise differences between colour channels (in µm).

# of comparison points	Statistics (Scan dir. y)	Green - Red	Blue - Red	Blue - Green
600	RMS x	1.9	4.9	3.2
	RMS y	0.9	1.5	0.9
	mean x	–0.1	0.1	0.2
	mean y	–0.2	0.1	0.3
	max abs. x	4.0	11.1	8.0
	max abs. y	3.5	4.3	2.9

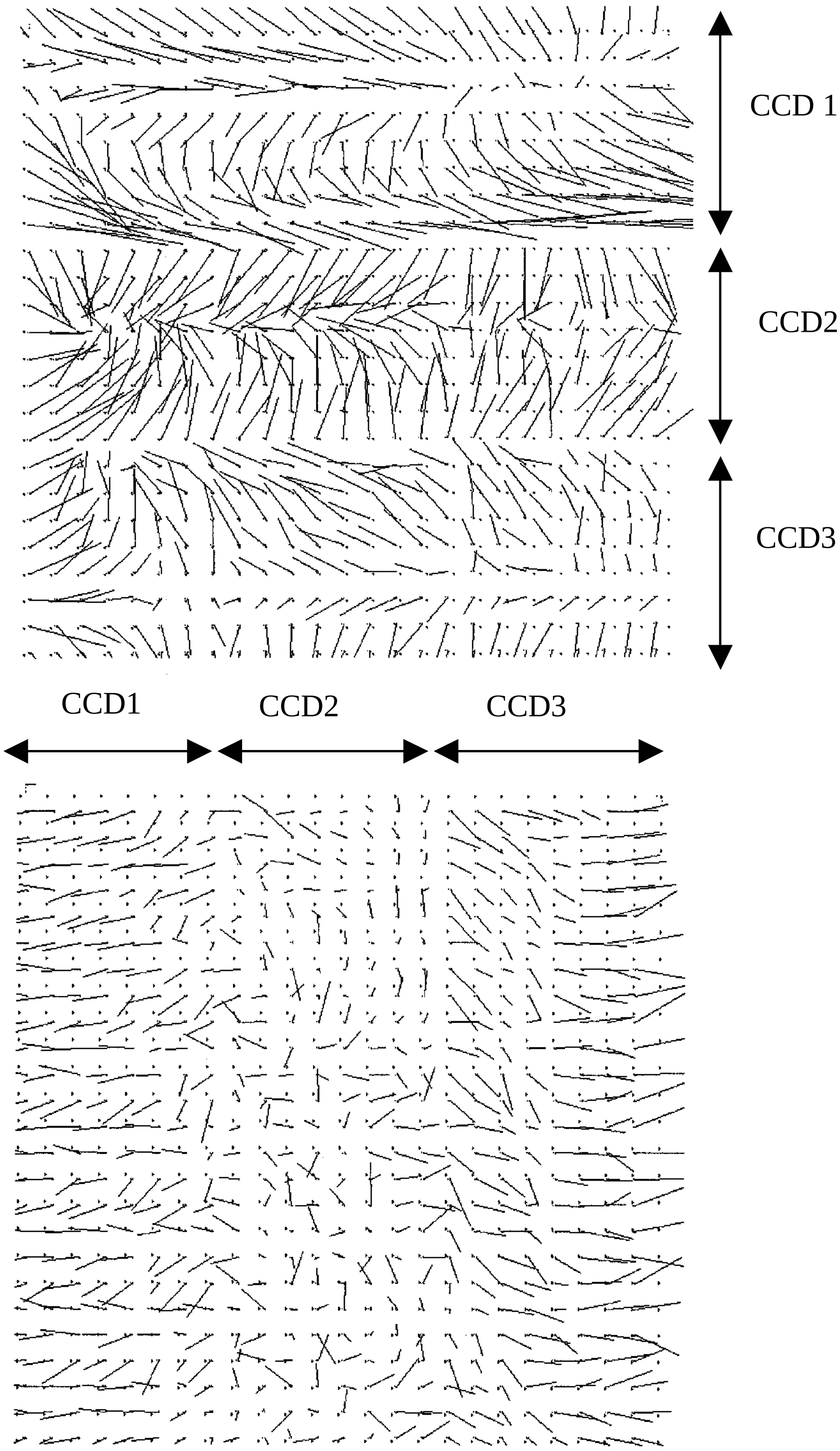


Fig. 4 – OrthoVision 1. Top: residuals of affine transformation (red channel) with scan direction to the left. Bottom: differences of pixel coordinates between green and red channel with scan direction to the bottom.

Table 6 shows the radiometric results with the grey scale. The lowest density is saturated. The noise for the low densities is quite high. The maximum detectable density is marked in italics.

Table 6 – Radiometric tests with grey scale wedge, OrthoVision, 10 μm, linear LUT.

Density	Red channel		Green channel		Blue channel	
	Mean	**St.D.**	**Mean**	**St.D.**	**Mean**	**St.D.**
0.05	255.0	0.3	255.0	0.2	255.0	0.5
0.2	181.5	5.3	200.9	5.7	171.2	5.5
0.35	114.6	4.7	129.0	5.3	107.0	5.1
0.51	72.0	3.9	82.0	4.9	67.5	4.4
0.66	47.2	3.0	54.1	4.1	44.5	3.6
0.8	32.0	2.2	36.5	3.2	30.2	2.6
0.96	20.9	1.6	23.5	2.2	19.8	2.0
1.12	13.7	1.2	15.3	1.6	13.0	1.4
1.28	9.0	0.9	9.9	1.3	8.6	1.0
1.44	*6.3*	*0.7*	*6.7*	*1.0*	*6.0*	*0.8*
1.59	4.6	0.7	4.8	0.9	4.4	0.7
1.75	3.6	0.6	3.6	0.7	3.4	0.6
1.9	2.8	0.6	2.7	0.7	2.6	0.6
2.05	2.3	0.5	2.1	0.6	2.1	0.5
2.22	2.0	0.4	1.8	0.5	1.9	0.4
2.37	1.8	0.4	1.5	0.6	1.7	0.5
2.52	1.4	0.5	2.1	0.5	1.5	0.5
2.67	1.2	0.5	2.0	0.5	1.4	0.5
2.82	1.1	0.4	1.9	0.4	1.3	0.5
2.95	1.1	0.4	1.9	0.5	1.4	0.5
3.09	1.1	0.5	1.9	0.6	1.6	0.5
Mean St. D.		1.4		1.7		1.6
Mean St. D. (0.51–1.44D)		1.9		2.6		2.3

Figures 5 and 6 show geometric and radiometric differences between neighbouring trilinear CCDs. They also show quite a lot of stripes both vertical, common in linear CCDs, and horizontal ones.

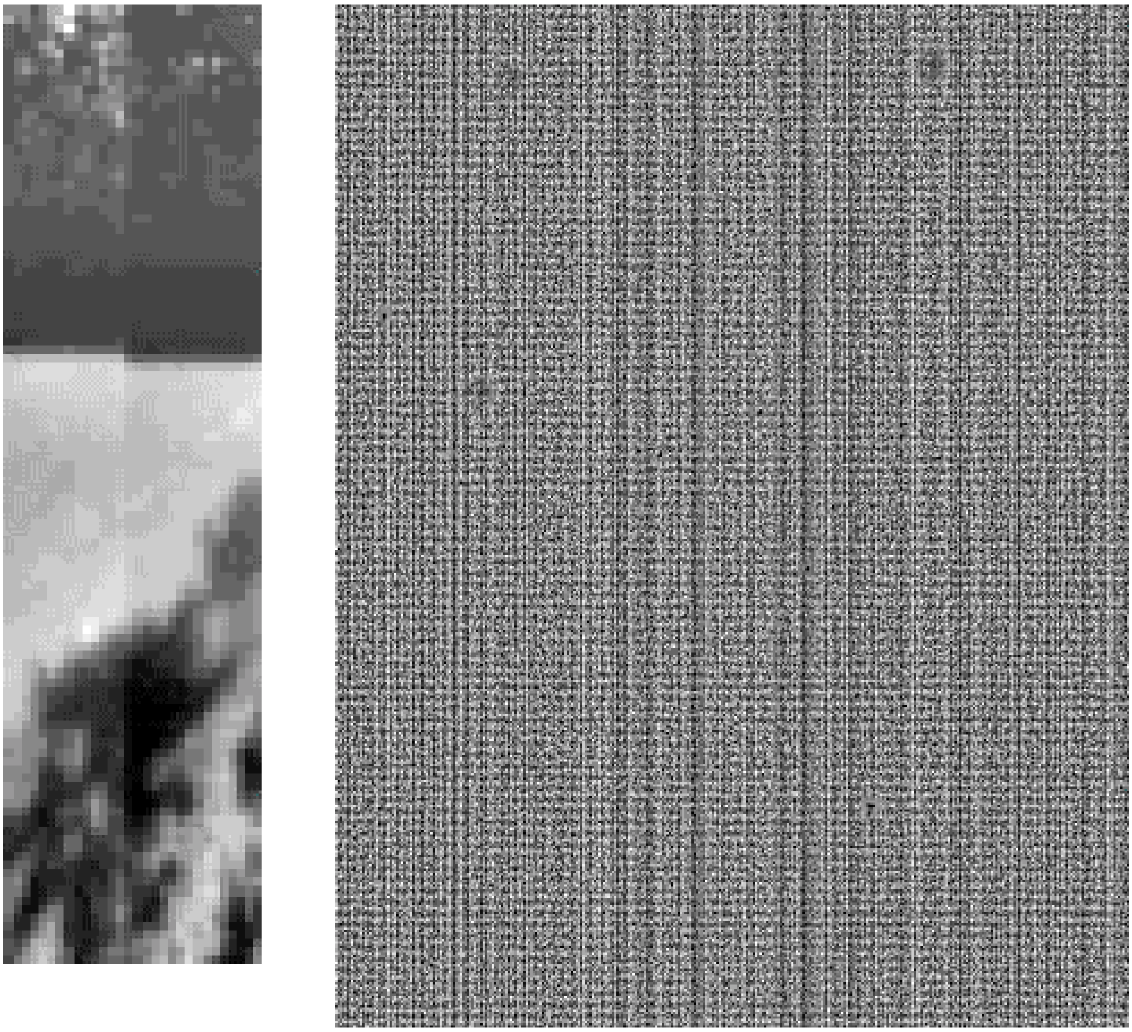


Fig. 5 – Left: geometric shift (1 pixel) between neighbouring trilinear CCDs. Right: vertical and horizontal stripes (empty glass plate, green channel, contrast enhanced). Max. mean differences between neighbours: columns (3 grey values), rows (1.1 grey values). Max. mean difference in whole image: columns (11.3 grey values), rows (2.7 grey values).

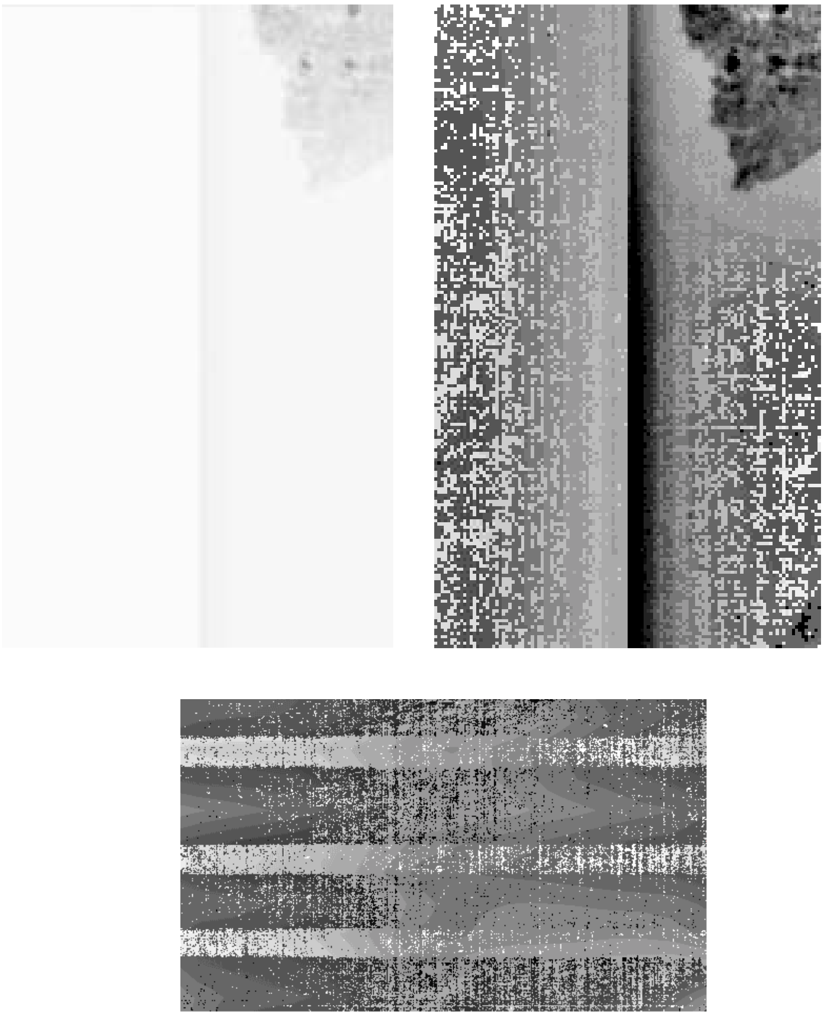
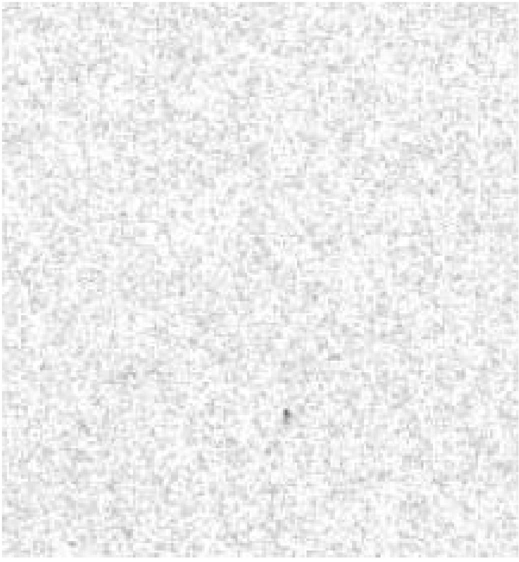


Fig. 6 – Top: Radiometric differences between neighbouring trilinear CCDs, B/W aerial image. Left, original (differences of 10 grey values); right, contrast enhanced. Bottom: wide horizontal strips, blue channel, contrast enhanced.

6 Results with the new Kodak CCD of SCAI

The grey scale was scanned with 7 and 14 µm, in B/W and colour. For B/W, both a linear and logarithmic LUT was used. The number of pixels per channel and density were 73,000 (14 µm) and 292,000 (7 µm). Many pixels were excluded from the test due to film corn (see Figure 7), e.g. for linear LUT in densities 0.21–0.69 D, 10%–43% for 14 µm, and 19%–53% for 7 µm ; for logarithmic LUT in densities 0.84–1.32 D, maximum 7% for 14 µm, and maximum 15% for 7 µm. Still, remaining pixels showing corn have led to high standard deviations (noise). Table 7 shows the results for the B/W scan with linear LUT. The results for the red channel were almost identical, and the ones for the green and blue very similar and only slightly worse. The numbers in italics show the maximum detectable density. The noise and the dynamic range are similar as with SCAI 1 but worse than the SCAI 2. However, this was due to the film corn, and as mentioned above, better more homogeneous test patterns should be used before drawing any definite conclusion with respect to noise and dynamic range of the new CCD. Figure 8 shows the linearity of the new CCD for 7 µm, linear LUT, B/W, R, G, and B scans. A comparison with Figure 3 (bottom) shows that the new CCD has a better colour balance.



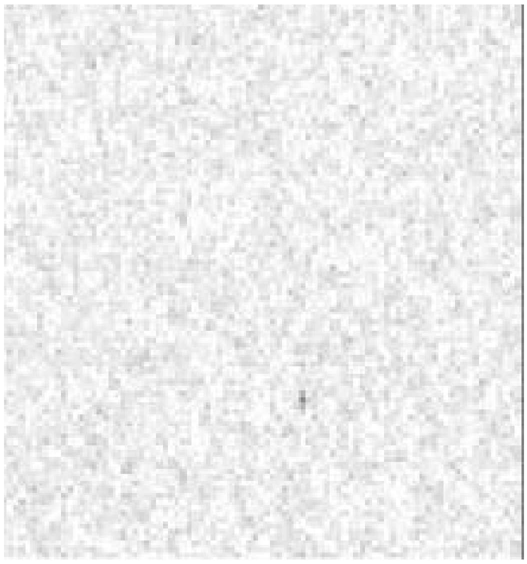


Fig. 7 – Corn in 2nd density (0.21 D), linear LUT, B/W scan: left 7 µm, right 14 µm

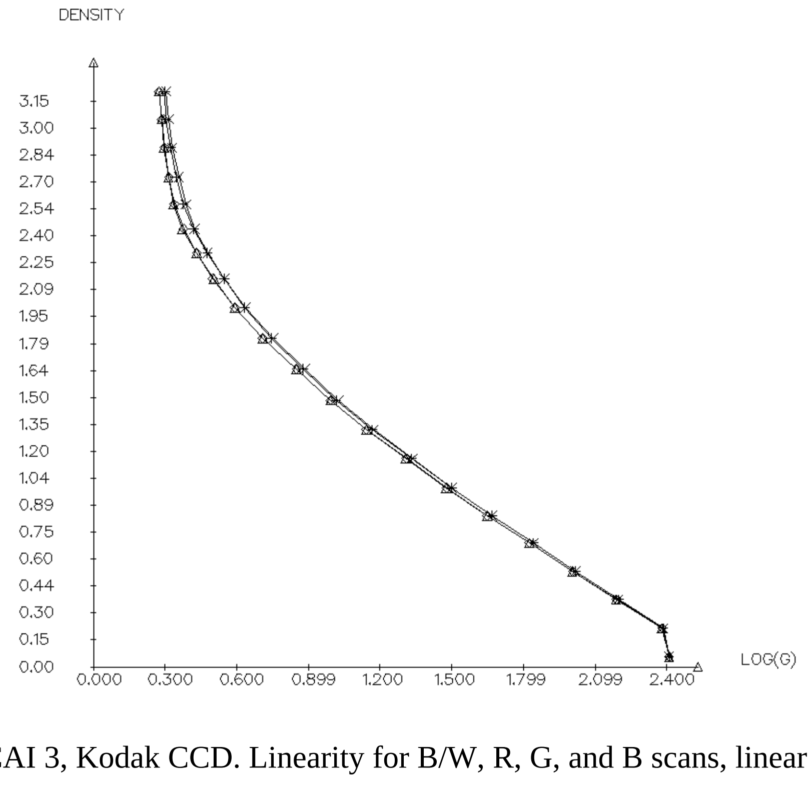


Fig. 8 – SCAI 3, Kodak CCD. Linearity for B/W, R, G, and B scans, linear LUT, 7 µm

Table 7: SCAI with Kodak trilinear CCD. Radiometric tests with grey scale wedge, linear LUT, B/W scan.

Density	**7 µm**		**14 µm**	
	Mean	**St.D.**	**Mean**	**St.D.**
0.05	255.0	0.0	255.0	0.0
0.21	238.3	5.9	239.2	5.7
0.38	152.3	5.8	153.1	5.7
0.53	99.7	5.7	99.8	5.5
0.69	65.6	5.4	65.8	5.0
0.84	43.4	4.9	43.5	4.3
1.0	28.9	4.0	29.0	3.4
1.16	19.3	3.1	19.2	2.4
1.32	12.8	2.2	12.8	1.7
1.49	8.8	1.6	8.8	1.3
1.66	6.1	1.1	6.0	0.9
1.83	4.1	0.9	4.0	0.7
2.00	2.9	0.7	2.9	0.5
2.16	2.2	0.6	2.2	0.4
2.31	1.7	0.5	1.7	0.5
2.44	1.3	0.5	1.3	0.5
2.58	1.2	0.4	1.1	0.3
2.73	1.1	0.4	1.0	0.2
2.89	1.0	0.3	1.0	0.2
3.05	0.9	0.4	1.0	0.2
3.20	0.9	0.4	0.9	0.3
Mean St. D.		2.1		1.9
Mean St. D. (0.53–1.49D)		3.8		3.4

The geometric misregistration between the colour channels was checked by scanning with 7 µm a razor blade, with the blade edges parallel to the CCD lines. Measurement of The upper and lower blade edges were measured at the same pixel (x-position) with LSTM. The y-coordinates (line number) for the R, G, B channels were:

– upper edge: 394.86 / 394.81 / 394.81 ; max. difference 0.29 µm (0.04 pixel)
– lower edge: 3528.15 / 3528.16 / 3528.09 ; max. difference 0.43 µm (0.06 pixel)

Also the grey level statistics in a 100 x 3 pixel stripe along the horizontal edges, above and below them were computed (see Tables 8 and 9). The edge width was 1 pixel. For the given edge contrast, a 0.1 pixel shift between the channels would cause ca. 8 grey levels shift of the mean for the blade edge. According to this criterion, the values of Tables 8 and 9 show a maximum shift between red and blue channel of ca. 0.1 pixel or slightly more, i.e. ca. 0.7 μm. In any case, the results are much better than the ones of the Thomson CCD, where the shift between the red and blue CCD line was 2.5 μm.

Table 8 – Grey level statistics for upper edge.

	Bright Background		**Blade Edge**		**Dark Background**	
	mean	**stand. dev.**	**mean**	**stand. dev.**	**mean**	**stand. dev.**
R	255	0	116.9	102.1	1.3	0.46
G	255	0	121.4	100.6	1.7	0.48
B	255	0	125.1	99.9	1.8	0.42

Table 9 – Grey level statistics for lower edge.

	Dark Background		**Blade Edge**		**Bright Background**	
	mean	**stand. dev.**	**mean**	**stand. dev.**	**mean**	**stand. dev.**
R	3.6	0.49	127.6	96.9	255	0
G	3.2	0.41	121.8	97.1	255	0
B	2.6	0.55	117.5	94.5	255	0

7 Conclusions and outlook

Since 1996 there were quite some changes and improvements with the DSW300 and the SCAI, while for the XL-10 much less is known, but still since 1996 no major change of this scanner was announced. Generally, the scanner performance and functionality has improved, while their price has stabilised, unfortunately at still high levels. Major changes include roll film scanning, better software, faster scan throughput and some improvements in their radiometric quality. One can talk of second generation film scanners with more functionality, better performance, and less costs in comparison to their predecessors. Significant differences between scanners with respect to geometry, radiometry, and software exist. Scanners are extremely sensitive and complex instruments, and a very high number of errors due to hardware, firmware or software parts may occur. Thus, topics like proper calibration, environmental and maintenance conditions, as well as careful and simple design, good quality components including those from third parties, and intelligent and robust image processing software are a must.

A geometric accuracy of 2 μm RMS is feasible and sufficient, as it is in most cases less than 0.25 pixel, which is less than the accuracy that can be achieved in aerial triangulation, DTM and orthoimage generation etc. Larger local systematic errors of 7–8 μm size may occur and need to be better modelled and compensated for. The radiometric accuracy is 1–2 grey values in the best case. Artifacts create larger systematic errors and should be reduced (stripes, electronic noise, electronic dust). The dynamic range is still low (1.5–2.2D). A good geometric and radiometric balance between the colour channels is possible. Improved performance in the blue range is possible today with new CCD technology, but such sensors have not been exploited yet in the photogrammetric scanners. Tests for colour reproduction (especially relative accuracy) are still rare and need to be performed.

Future developments should be expected in the sensors (more pixels, better radiometric performance), quantisation with more bits, faster scans, and extended software functionality (especially with respect to automation, speed and ease-of-use, e.g. automatic density control, on-line display in overview (prescan) image of effect of radiometric parameter settings, automatic film detection in roll film scanning, image processing like edge and contrast enhancement, digital dodging etc.). The radiometric performance and the dynamic range should be improved by a careful selection of sensor and electronics, intelligent calibration but possibly also slower scans, frame averaging and cooling. An optimal setting of the LUT and reduction from more to 8-bits will also lead to a better quality image.

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Reproduction of Colour and of Image Sharpness with Photogrammetric Scanners Conclusions of the OEEPE Scanner Test

O. Kölbl
Ecole Polytechnique Fédérale – Lausanne

Abstract

The article analyses the reproduction of colour on various photogrammetric scanners and develops a concept for colour correction. The test shows that the scanned images show considerable colour deformation in comparison to severe colour extraction filters. Furthermore, the resolving power of the scanners is analysed using the Modulation Transfer Function.

1 Introduction

Scanning of photographs is a key operation in photogrammetry, but also in many other disciplines of image processing, as in particular in the printing industry. The photographic film still plays a key role in image registration, due to its high performance in terms of image sharpness, colour reproduction and its dynamic range. Digital cameras are slowly coming up on to the market but do not yet provide the efficiency of film cameras. The only field where they have largely replaced the film cameras is in television, but even the film industry still uses the classical film cameras for movie production. Consequently, aerial film cameras will still play a key role for image registration for the next 5–10 years and scanning decisively influences the product quality of digital photogrammetry.

In 1993, OEEPE set up a Working Group with the task of analysing the photogrammetric scanners. The objective of the Working Group was to analyse the different scanners and to elaborate recommendations for scanning and testing of scanners. A set of test images (test patterns and aerial photographs) were chosen and sent to various manufacturers. The plan was then to analyse the test material at various research institutes. However, the test scanning took a considerable amount of time as there was only one test set available. The test set included original negatives and it did not appear appropriate to use duplicates for scanning. Meanwhile, the partners in the research institutes made their own experiments, and there was no response when the test material was sent out some 15 months ago. Research priorities and objectives have changed too rapidly and other tests have been performed. Therefore, the article is limited to the analyses done by the Photogrammetric Institute of Lausanne University. It is being presented on the occasion of the Workshop on “Automation in Digital Photogrammetry” in June 1999 in Paris as one of the contributions to the scanner session. In this way the presentation is rounded off by other articles and the hope is to contribute in this way to a general understanding of image reproduction by scanners without pretending that it was possible to achieve a complete picture of the initial goals. The objective of this article is to draw the attention to the problem of colour reproduction and image sharpness of photogrammetric scanners.

The author of the article is very grateful to the following firms which participated in the scanner test:

Agfa, Mortsel, Belgium with the Agfa Horizon Plus,

Helava, San Diego USA with the DSW200,

Intergraph, Huntsville USA with the PS1,

Wehrli & Assoc, Valhalla USA, with the RM1,

Zeiss, Oberkochen Germany with the SCAI.

2 Considerations on the image quality of aerial photographs

As mentioned earlier, standard aerial cameras and aerial films are still the most important tool for image acquisition. Electronic cameras are as yet far from achieving the overall efficiency of film cameras, if one considers the information quantity, the speed of registration or the dynamic range, although in some fields as image noise or image sharpness, the electronic devices might already show a superiority. It is not very easy to enumerate the information content of an aerial photograph. In the most simple case, one could take an image resolution of maybe up to 100 lines per millimetre. In order to reproduce a target of such a fine resolution properly, we would need a pixel size of at least 1/3 of the resolution, that means 3 µm [1]. A colour photograph of 230 x 230 mm would then easily fill 10 Gbytes, even after image compression 1–2 Gbytes might remain. Of course, practice in digital photogrammetry is quite different and it might be important to discuss the effective image quality in more detail. In the following, we concentrate on image resolution and in particular MTF, granularity and dynamic range and colour reproduction.

2.1 Image resolution of aerial photographs

The image resolution of aerial photographs is commonly characterised by the resolution of lines per millimetre. As already explained above, this would lead to extremely small pixel sizes and consequently to large quantities of image data. In order to obtain more realistic data quantities we should take into consideration that the image resolution is defined as the “cut-off frequency” of the modulation transfer function (MTF). The MTF informs on the contrast reduction of a sine wave pattern for the various frequencies. Within OEEPE, various studies have been made in order to determine the MTF of aerial photographs, for it is understood that the camera and the film limit the image quality (cf. 2,3). A study by the author [4] published in 1986 already gave the MTF curves reproduced in figure 1. One recognises that, for a frequency of 50 lines per millimetre, up to 40% of the contrast are still reproduced; newer cameras might even give better results. However, there is hardly a response for 100 lines per millimetre. Converting this into the requirements of the pixel size, we realise that we should use a pixel size of 5–7 µm in order to convert the complete image information into numeric form. A somewhat larger pixel size might be tolerable for colour film as its resolution is somewhat lower.

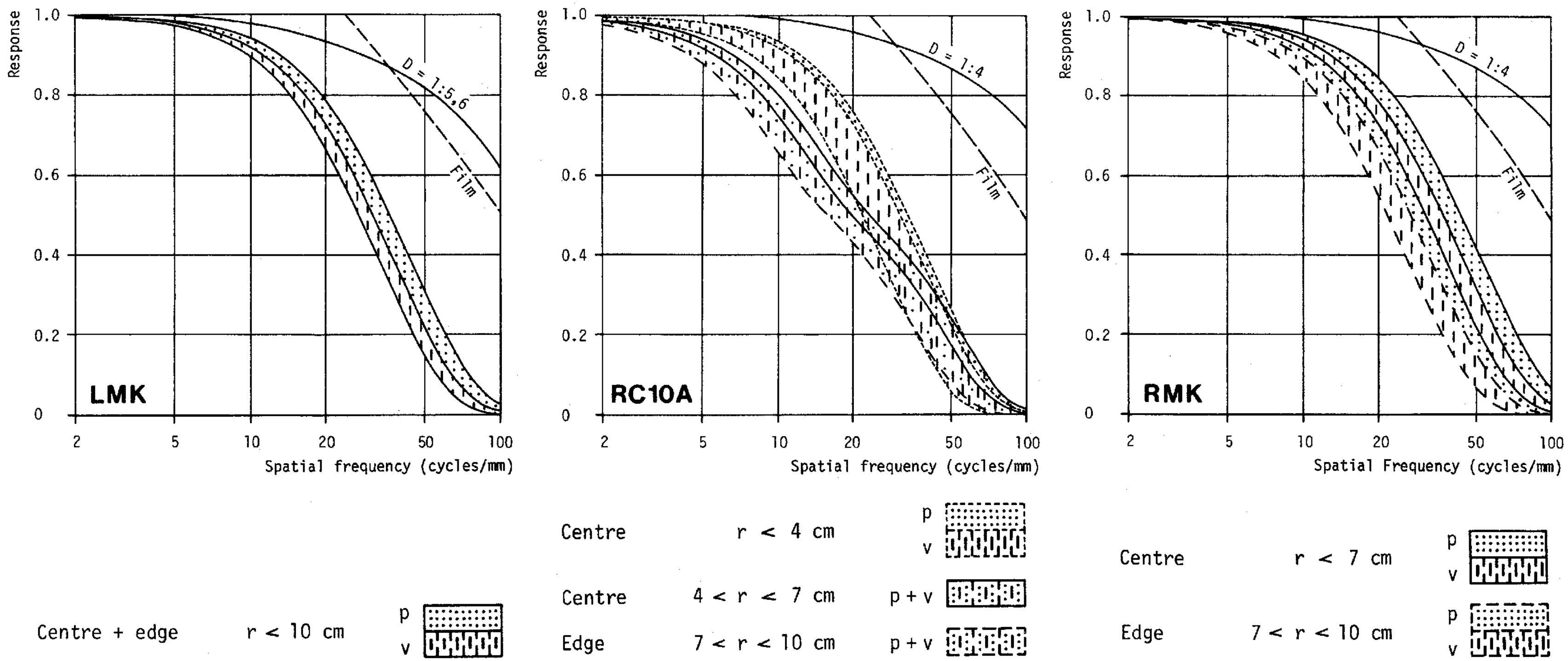


Fig. 1 – Modulation transfer functions determined under flight conditions with the Panatomic-X film for the different cameras. The graph also shows the MTF of the film (Film) and the MTF limited by diffraction of the aperture (D).
p = perpendicular to flight direction; v = in flight direction.

2.2 Granularity of the photographic emulsion

The granularity of aerial films is rather closely related to the image resolution. Granularity is an important criterion for the selection of a film; a fine graininess of the emulsion generally gives a high resolution. The granularity of the emulsion is carefully analysed by the manufacturer. In the Kodak data book of aerial films, the "Diffuse Root Mean Square Granularity" is indicated. This granularity is measured on a microdensitometre with diffused illumination. A homogeneously exposed film probe is scanned with 12x optical enlargement and a circular window of 48 µm. The standard deviation of the density value multiplied by 1000 is given. For example, the granularity of the Kodak Plus-X film is between 26 and 28, the one of the Panatomic X film is 9 for a photographic density of 1. For the Agfa film Pan 150PE the corresponding values of the granularity lies between 17–25 for a circular aperture of 50 µm. Consequently one has to expect an image noise of ±0.017 to 0.025D when working with a quadratic pixel size of 45x45 µm (conversion from circular aperture to a quadrate one). For a pixel size of 10x10 µm, one should expect primarily an image noise of ±0.075 to ±0.1D, that means values 4 to 5 times larger than the initial ones. In this case, one supposes that the grey value of neighbouring pixels are not correlated. However, if one assumes that the width of the spread function of the scanners corresponds to the pixel size of the assumed 10x10 µm, a smoothing of 50% has to be taken into consideration. Consequently, image noise should be only ±0.035 to 0.05D; the corresponding tolerance values for Panatomic X film would amount to only ±0.02 D.

2.3 Dynamic range of aerial photographs

According to the above-mentioned publication of OEEPE [3], one can also get an overview of the current density range of aerial photographs. In general, black and white films have less contrast than colour films. In this study signalised points have been observed with a background density varying between 0.2-2.0D using Panatomic X film of Kodak, whereas a range of 0.3-3.5D was obtained for IR colour film. Consequently, a density range of about 2.5D is to be required from scanners for black and white films whereas for colour films a density range of 3.5D is needed.

2.4 Reproduction of colour

For colour reproduction, the film must be sensitised to the 3 spectral bands corresponding to blue, green and red, or for false colour films for green, red and the near infrared; furthermore, the layers have to be equipped with colour dyes allowing for colour mixture according to the principle of subtractive colour mixture. That means that the colour dyes yellow, magenta and cyan have to be used. It is understood that the colour sensitivity and the colour reproduction of photographic films might show slight deviations or, in the case of the infrared false colour film, even quite fundamental variations. As mentioned for scanning, it is essential to extract the 3 layers of the colour film in an optimal way. The final desired colour reproduction of the scanned image can then be influenced by appropriate look-up tables or other means. Fig. 2 shows the colour sensitivity of a typical aerial film and the transparency of the colour dyes for general information.

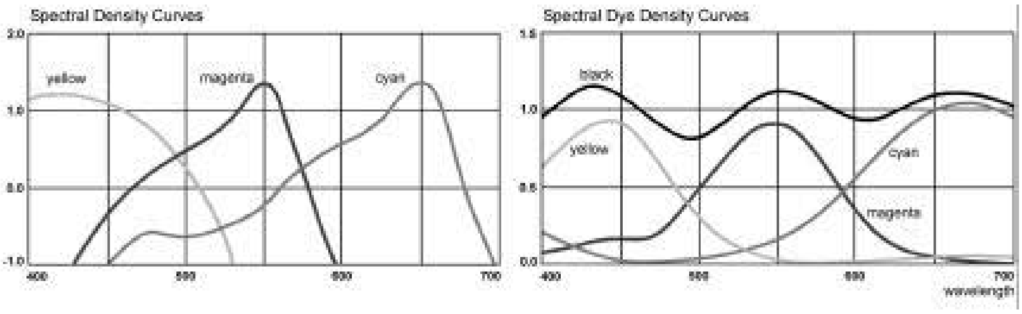


Fig. 2 – Spectral sensitivity and transparency of a typical aerial film used in photogrammetry (Kodak Aerochrome MS Film 2448). Taken from *Kodak Data for Aerial Photography*, 1982.

3 Requirements in the scanning process

Already in the first section we have indicated the high requirements in scanning. It is important that the high image quality can be conserved during the scanning. In detail, we can list the following criteria:

Geometric precision

In general, one should obtain a geometric precision of about ±1–2 µm during the scanning process.

Image noise

The image noise of the photographic images is largely defined by the granularity of the film; the scanning process should not noticeably accentuate the image noise, which would mean that the noise of the scanner should be inferior to ±0.03D (logarithmic density) over the whole dynamic range.

Dynamic range

The dynamic range covers up to 2.5D for black-and-white photographs and up to 3.5D for colour images. It is important that the image noise remains within the mentioned noise of the aerial photographs over this whole dynamic range. This is a requirement which, for most of the scanners used in photogrammetry, can only be respected for a density range from 1.0 to possibly 1.5D.

Resolution

Depending on the film type, one obtains a geometric resolution of up to 50-100 lines/mm. In consequence, one should scan aerial photographs with a pixel size of up to 3–7 µm, depending on the effective image quality. The lack of sharpness of the scanner or the spread function should not noticeably exceed the chosen pixel size.

Colour reproduction

The colour reproduction of the scanner should correspond to the colour dyes of the film which would mean that the filters of the scanner should largely correspond to standard extraction filters of the colour film.

4 Constructive elements

Manufacturers of photogrammetric instruments have developed specific scanners for aerial photographs, in parallel to the printing industry. The main objective of these specific scanners is to guarantee a high geometric precision of ±0.001 to 0.002 mm for a standard format of original 23x23 cm film documents and to cope with the high image resolution of the original images. It is understood that high dynamic range of the scanner, low image noise and good colour reproduction would also be desirable. Contrary to the printing industry, the fidelity of tone reproduction is of minor importance, whereas appropriate image enhancement in terms of colour and grey tones is much more important in order to assure a good object recognition. Effects of image disturbance like haze or poor image contrast must in any case be corrected.

4.1 General set-up

The set-up of a scanner is heavily influenced by the photodetectors used (cf. fig. 3). Photomultipliers can only be used as individual elements but show a very high response time. Most of the scanners working with photomultipliers are drum-scanners. In this case, the film is mounted on a rotating drum. The photodetectors are generally mounted outside of the drum and scan the image line by line. The transparencies are illuminated by a light source mounted inside the drum. In order to keep the heating as low as possible, one generally uses directed light, very often even laser illumination. This type of scanners allows one to obtain high performance in terms of resolution and dynamic range. The disadvantage is however that the film must be mounted on a drum.

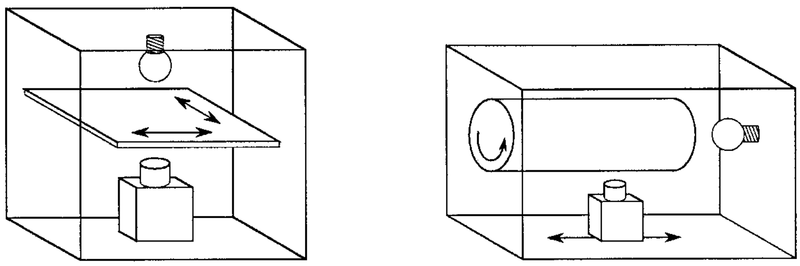


Fig. 3 – Sketch of a flat-bed scanner (left) and of a drum scanner (right).

Mounting the film between glass plates protects it far more. This is however only possible with flat-bed scanners. In this case, the film is mounted on a motor-driven cross carriage. The alternative is of course moving the illumination and the photo detector. The illumination can be diffused or directed; one generally uses line sensors or matrix sensors as detectors.

4.2 The illumination system

The illumination system also plays an important role for image reproduction. It is useful to distinguish between directed and diffused illumination (see also fig. 4).

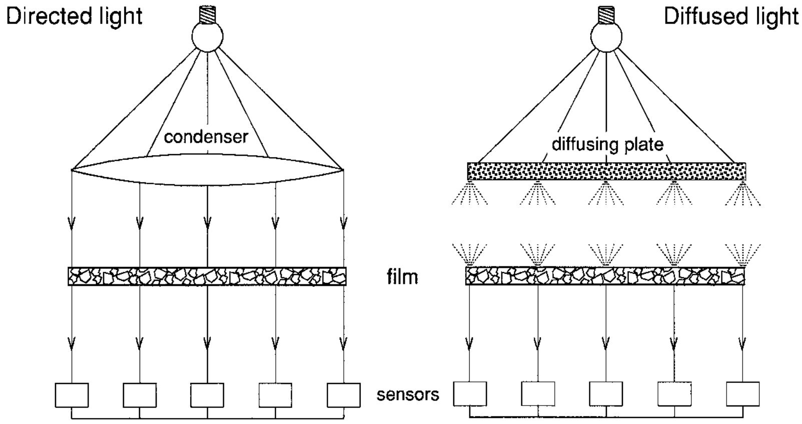


Fig. 4 – Illustration of an illumination system with directed light by a condenser (left) and with diffused light by a diffusing plate (right).

The **directed** illumination uses a condenser for enlarging a more or less punctual illumination source and images this light source into the aperture of the projection lens. An advantage of this type of illumination is the economic use of the light energy, requiring only lamps with a rather modest heat radiation. In order to reduce even further this heat radiation, one can use fibre optics for the transmission of the light to remote the light source. Strongly directed light provokes a very small optical opening angle and consequently increases the depth of field of view. An optical system with direct illumination might also be less sensitive to small effects of defocusing. On the other hand, light is rather coherent and will provoke diffraction effects on the film.

Diffused light is obtained when using milk glass for diffusion. This can be done by putting milk glass directly onto the photographic film or by using fluorescent light tubes which have a strong diffusing effect. More refined possibilities include the use of the "Ulbrichtkugel" or of a light channel. The "Ulbrichtkugel" is an empty sphere which is coated on the inside with magnesium dioxide. Light is introduced laterally and escapes through a very small opening. This opening should not exceed 1/50 of the sphere diameter [2].

It is remarkable that current optical enlargers generally use only diffused illumination, whereas older instruments such as the famous photogrammetric rectifiers were generally equipped with Fresnel lenses as condensers. Many of the photo enlargers built today are equipped with a light channel. Very often, photogrammetric plotting instruments also use diffused light in order to achieve a more pleasant illumination.

In sensitometry, directed or diffused light plays also an important role. The quotient of the transparency measured between parallel light and diffused light is designated as the Callier quotient and is proportional to the graininess of a film. Kodak recommends using only diffused light for the measurements of the graininess, as the corresponding measurements of directed light are not properly defined.

4.3 Colour separation

The reproduction of colours by photogrammetric scanners requires the use of colour extraction filters. In most cases the scanning is done sequentially for the 3 colours red, green and blue. Many recent scanners now also have different sensors for the 3 colours and this means that only one path is required for the reproduction of colour images. Obviously, the spectral photometric transparency of the filters is defined by the colour hues of the film. For Kodak films, special Wratten filters are designated for the colour extraction. These are filters which are in general very narrow in order to assure proper colour separation (see fig. 2 and 5).

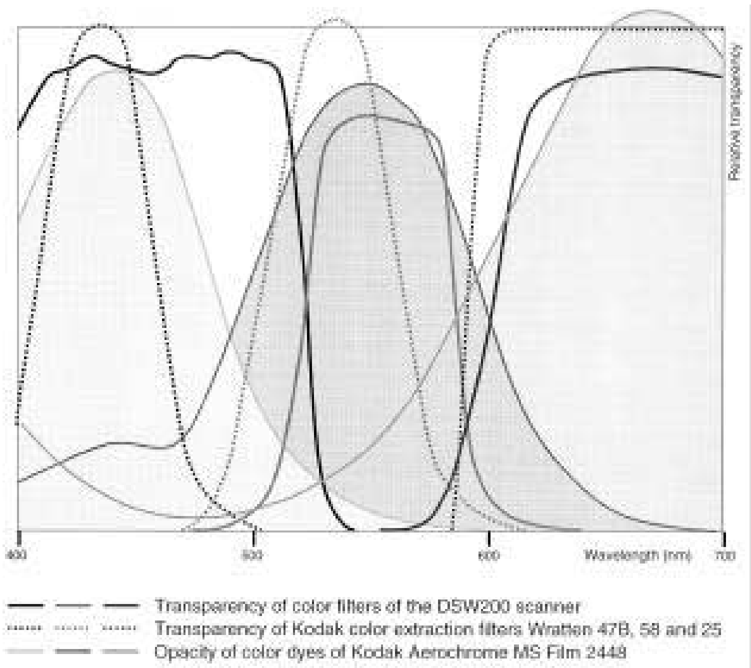


Fig. 5 – Transparency of the colour filters of a typical photogrammetric scanner (DSW 200) in black, compared with the opacity of the colour dyes of a Kodak aerial film (grey surface) and the transparency of the Kodak extraction filters (dotted). One realises that the blue filter of the scanner is much too wide, whereas the other filters more or less fit.

For practical work, these narrow filters have a considerable disadvantage as a lot of light is absorbed, thereby slowing down the process of scanning. Consequently, many scanners use interference filters and larger transparencies, especially in the blue band, for better use of light energy and balancing the low sensitivity of photosensors in the blue spectra.

5 Analysis of the colour reproduction

As earlier mentioned, when working with colour aerial photographs, one is in general not as strict as in printing industry regarding colour fidelity. Furthermore, one is aware that haze considerably degrades colour reproduction; even worse, one very often prefers false colour photographs instead of true colours as they give more information. All this might explain why colour reproduction has not yet been really analysed in photogrammetry. The Kodak colour table Q60 was part of the scanning set, which will be analysed in the following. This table is not calibrated and it was necessary to determine the "true values" by densitometre measurements. The results of this comparison are shown numerically and in the form of a simplified colour triangle. Numerical colour correction is also dealt with.

5.1 The Kodak colour transparency and its calibration

In the following we concentrate on the use of the Kodak Ektachrome colour table Q60, which was part of the scanning set. This transparency gives an efficient tool for testing colour reproduction. It includes batches which are only transparent in one of the 3 bands (red, green, blue) and transparency in the other bands is below 1%. Furthermore, the transparency contains batches with mixed colours and also a grey wedge.

For the evaluation of the scanning results, we referred to density measurements of the colour table as "calibrated values". In fact, Kodak does not supply a calibration of the transparency. For the density measurements we used the Macbeth Densitometre equipped with Standard AA Filters. These filters correspond to the colour extraction filters of colour films and have a rather narrow band (cf. fig 2). It is understood that the density values were converted into transparency values and then multiplied by a factor 400 in order to get values comparable to the size of the pixel values (cf. table 1).

5.2 Comparison of the scanner data with the calibrated values

The next question which has to be raised, is whether the measured pixel values of the scanners are proportional to the transparency of the film. Although the theory of CCD sensors suggests such a relation, it is more realistic not to rely on this relation. Consequently, it is important to establish a proper relation between the scanner data and the transparency measured by the densitometre. This relation was established with the help of the grey wedge integrated into the test table. We decided to use a piecewise interpolation for the data conversion, in order to correct all irregularities. In this way, all colour values have been adapted to the transparency values of the densitometre measurements.

Table 1 shows a direct comparison of the measurements between the densitometre measurements and the converted scanner values. We realise that many of the scanners give rather low values for saturated colours:

- DSW : blue band, deviation up to 50% of the measured values,
- SCAI: red band, deviation up to 30% of the measured values,
- PS1: green band, deviation up to 30% of the measured values.

Similar deviations are found in the mixed colours cyan, magenta and yellow.

An explanation of this effect can be found in the bandwidth of the colour filters. The transparency of the DSW colour filters was measured with a EGG spectral photometer (cf. fig. 5). It shows that the blue filter has a much larger transparency than the standard extraction filter used in the densitometre. When calibrating the response of the scanner on a grey wedge supplying white light, we obtain much more light than when measuring a blue colour batch, which only uses a narrow part of the blue filter. This illustrates the fact that the filter is too large and also measures a part of the green band of the colour film. Most probably, the same explanations could be given for the green filter of the PS1 or the red filter of the SCAI scanner; however, the filter curves are not available for these scanners. In order to establish a proper balance, it is understood that one should not consider only the filter curves, but has also to take into consideration the spectral sensitivity of the photo sensors and the spectral repartition of the light source.

5.3 Numerical correction of the colour deviations

Photogrammetric Scanners are normally equipped with facilities for the correction of the grey values according to well-defined calibration procedures. In the same sense, one can devise a procedure for the colour correction, an approach which is already quite usual in the printing industry. In order to achieve such a colour correction formula, we simply used a 3^{rd}-order polynom in which we entered the pixel values of the 3 measured channels. The coefficients of the polynoms were determined by overdetermination with the help of a normal equation. In this way the pixel deviations were reduced from 15 to 20 pixel values to about 3 pixel values (cf. table 1).

This correction formula can be applied to successively scanned colour images. Currently tests are still being carried out to analyse the efficiency of this procedure and to optimise the correction equation.

Table 1 – Densitometric values of the various colour patches of the Kodak Ektachrome colour table Q60. The left part gives the converted densitometric values and the right section shows the corresponding values derived from digital images. One realises that there are systematic deviations and the differences are shown in the lower part of the table. The last two rows of the table give the standard deviation of the differences of 84 patches and the residuals after colour correction.

Patch	Densitometre			Scanner			Scanner PS1			Scanner SCAI		
	red	gree	blue	red	gree	blue	red	gree	blue	red	gree	blue
E12	84	210	192	88	193	187	76	199	184	97	197	185
L12	11	132	163	14	113	153	11	124	152	24	115	153
E13	210	63	142	201	67	103	214	84	139	178	72	130
L13	136	4	53	139	7	24	161	15	54	98	8	45
E14	241	210	52	220	207	77	229	191	56	224	212	59
L14	215	156	3	211	161	14	206	128	7	214	163	7
E16	205	60	34	195	64	36	207	69	39	174	68	36
L16	121	3	1	119	0	2	139	7	3	88	6	3
E17	86	175	52	90	163	73	80	150	52	98	165	56
L17	8	68	2	11	59	7	8	46	3	15	58	3
E18	78	63	142	77	62	106	77	75	133	76	67	128
L18	3	5	63	1	0	30	6	11	52	4	6	49

	Differences								
E12	- 4	17	5	7	11	7	- 14	13	6
L12	- 3	20	10	0	8	11	- 12	17	10
E13	9	- 4	39	- 4	- 21	3	32	- 9	12
L13	- 4	- 3	29	- 26	- 11	- 1	38	- 4	7
E14	21	3	- 25	13	19	- 5	17	- 2	- 8
L14	4	- 5	- 11	9	28	- 4	1	- 7	- 4
E16	10	- 3	- 2	- 2	- 9	- 5	31	- 8	- 2
L16	1	3	- 1	- 19	- 4	- 2	33	- 3	- 1
E17	- 5	12	- 21	6	25	- 0	- 12	10	- 5
L17	- 3	9	- 6	0	22	- 1	- 7	10	- 1
E18	1	2	36	1	- 12	9	2	- 4	14
L18	2	5	34	- 2	- 6	11	- 1	- 1	14

σ resid. before adj.	7.6	8.5	20.1	9.7	15.2	6.5	19.3	8.6	8.1
σ resid. after adj.	2.9	2.4	5.3	3.1	3.4	3.0	3.2	2.2	2.6

5.4 Presentation of the colour values with the help of the colour triangle

The above-mentioned pixel deviations are in principle numerical values and it is not easy to imagine the effective colour shift. In order to analyse colour hues, one normally uses the colour triangle. For better understanding, some basic notions of the colour co-ordinates are recapitulated here.

The absolute colour co-ordinates (X,Y,Z) are computed by definition as an integral of the spectral eye sensitivity ($x(\lambda)$ for red, $y(\lambda)$ for green and $z(\lambda)$ for blue), the spectral illumination intensity $E(\lambda)$ and the spectral sensitivity $\tau(\lambda)$ of the film.

$$X = \int_{0.4}^{0.7} \bar{x}(\lambda) E_c(\lambda) \tau(\lambda) d(\lambda)$$

$$Y = \int_{0.4}^{0.7} \bar{y}(\lambda) E_c(\lambda) \tau(\lambda) d(\lambda)$$

The 3-dimensional "Absolute" co-ordinates are difficult to present; furthermore, the light intensity is in this case unimportant and the co-ordinates can be normalised by introducing relative colour co-ordinates (x,y).

$$x = \frac{X}{(X+Y+Z)} \qquad y = \frac{Y}{(X+Y+Z)}$$

That would mean that the pixel values themselves are not sufficient for the computation of the colour co-ordinates and we have to take into consideration the spectral light intensity of the screen or the colour hues of the printer pigments. However, we are not interested in absolute values here and we want to interpret the possible relative colour shifts. For this purpose we can simple use the 3 pixel values or better the pixel values converted to the transparency of the film as X,Y.Z and compute the relative colour co-ordinates:

This conversion also allows us to present the colour shift with respect to the initial colour values resulting from the densitometre measurements of the colour table (cf. fig. 6). One realises that, according to our measurements e.g. on the DSW, green is shifted to blue and appears more "smaragde"; on the PS1, blue is strongly shifted to green and appears "sapphire", whereas on the SCAI the saturation is insufficient.

However, the correction of the colour values discussed above seems to eliminate all these deviations and we observe only larger vectors for the extreme values which could even be corrected.

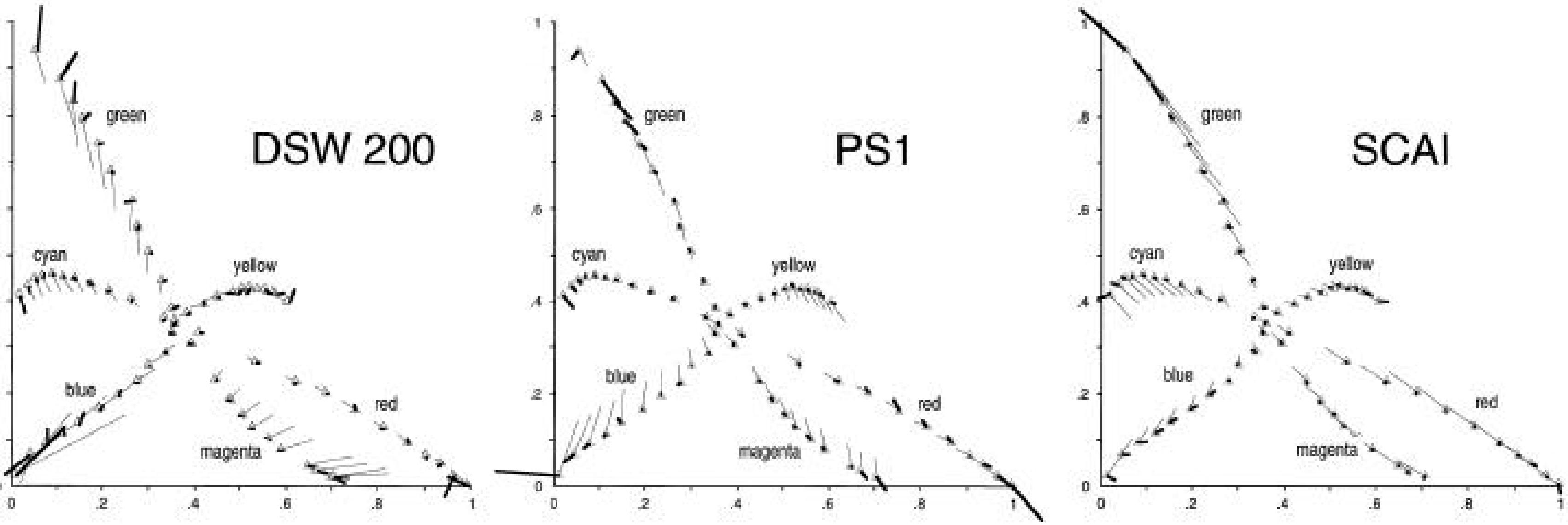


Fig. 6 – Representation of the colour deviations of the Kodak Colour transparency Q60 digitised on various scanners. The deviations are shown in comparison to density measurements done with the Macbeth densitometre (thin lines : comparison of original measurements, thick lines : after polynomial adjustment). The extreme values could be further corrected by more refined mathematical models. The diagram shows that colour deviations can be largely corrected.

6 Image resolution

There has already been much discussion on image resolution and very often the pixel resolution is considered as a limiting factor. However, when analysing the reproduction of small objects in photographs, like signalised points, one realises that the cut off frequency is not at all decisive, whereas the loss of contrast for larger frequencies is much more important. This loss of contrast is given by the modulation transfer function (MTF). In order to determine the MTF, one should know the object function and of course the image function, which are in any case given by the digitised image. By computing the Fourier transforms, one can then determine the spread function or its Fourier transformed, the modulation transfer function. By some simplifications, the modulation transfer function can also be deduced from the contrast reduction of a rectangular pattern, a way which was chosen here.

Figure 7 shows a reproduction of the resolution target (lower part) as negative. A density profile was determined with the software tools of ISI of the ImageStation by Intergraph. One recognises that the contrast diminishes with the increasing frequencies and the signal vanishes with frequencies of about 50 lines/mm.

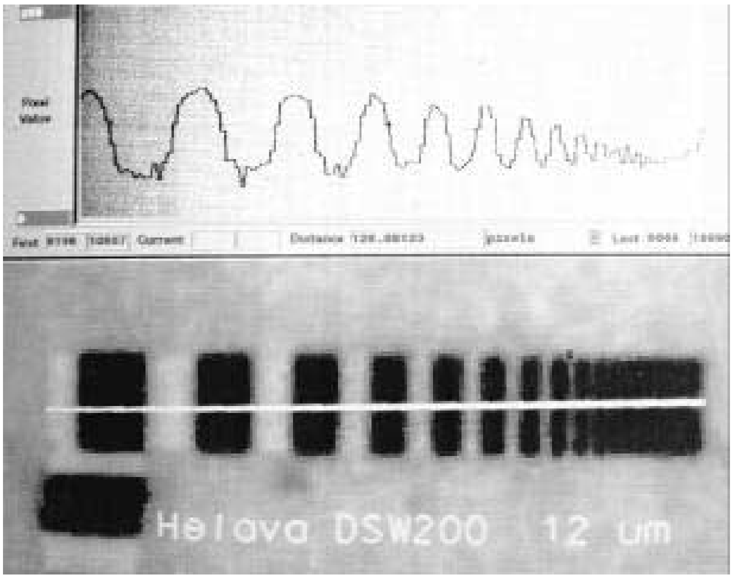
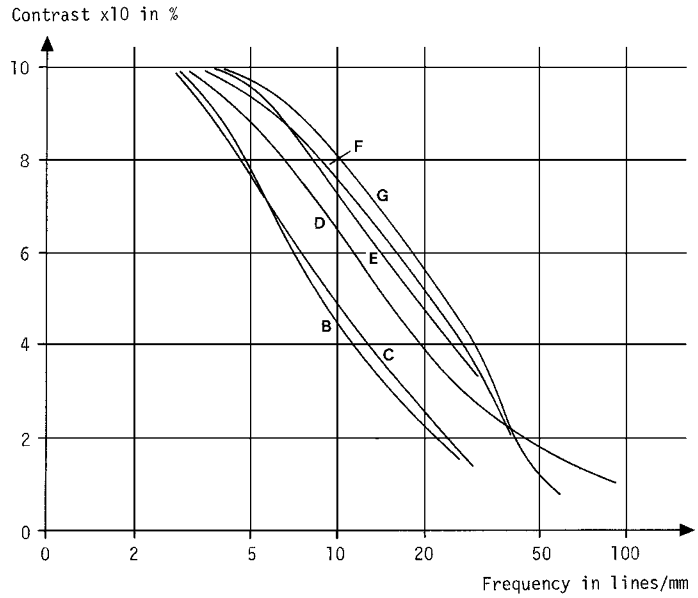


Fig. 7 – Resolution pattern (test 6) and density profile scanned on the DSW200.

Figure 8 gives an overview of the determined transfer functions for the different scanners tested and different image configurations. The best curve was obtained for the Scanner PS1, while the Helava scanner DSW gives a slightly less favourable result. However, it is obvious that the chosen pixel size of 15 µm for the PS1 and 12 µm for the Helava scanner is too large in order to properly exploit the aerial photographs. Consequently, tests were made with enlarged photographs simulating pixel size of 2.5 µm. These tests were limited to the Helava DSW200. In this case, the original photograph was enlarged 4 times on the Durst enlarger with a Rodenstock optic and then scanned with an effective pixel size of 10 µm. This image was then resampled to a pixel size of 40 µm, now corresponding to 10 µm with respect to the original. The effective transfer function for 12 µm is about 10%

lower. It is however astonishing that the transfer function obtained with the PS1 with a pixel size of 15 µm was very similar to that for the enlarged photographs. The results of the Wehrli Rastermaster RM1 (12 µm pixel size) and the Agfa Horizon Plus (20 µm pixel size) are very similar. The results do not show the importance of the pixel size as one would expect.



B	Rastermaster RM1 12 µm
C	Agfa Horizon Plus 20µm
D	Helava DSW 200 12 µm
E	Photoscan PS1 15 µm
F	Helava DSW200 photo 4 x enlarged resampled 40 µm corresponding to 10 µm on original
G	Helava DSW200 photo 4 x enlarged 10 µm

Fig. 8 – Relative modulation transfer function for different scanners

7 Conclusions

Although a lot of studies have already been made with scanners, it seems that many aspects still have to be analysed. We are aware that the discussion here is still limited to the scanning process and should also finally include the presentation of the image on a screen and the printing technique. It is hoped that the study will initiate wider discussion and that finally recommendations can be given for an overall scanner test.

The present study definitely does not allow one to give an answer as to which of the scanners discussed might be the best. Anyhow, such goals are very difficult to achieve. Really unsatisfying products disappear very quickly from the market and many other products have various merits and only a very detailed analysis allows one to decide case by case which of the tested instruments satisfies the specific requirements of a user.

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Archiving of Digital Image Data

L. Rosenthaler
Scientific Photography Lab University of Basel

Abstract

The rapid pace of development in the computer industry has led to extremely short product cycles. New versions of software products have a lifetime of at most a year, whereas computer hardware seems to become outdated in the time between ordering and receiving the hardware. Thus, longevity in the computer industry is measured in months.

However, in the domain of archiving, longevity means preserving the images of concern for decades or even centuries. Therefore computers seems to be extremely unsuitable for this kind of task. This is especially true for images with a digital origin as produced by modern digital cameras.

I will show in this paper that long term preservation of digital image data is possible and that in fact digital images are very suitable and even superior to analogue images for long term archival.

1 Introduction – a very short history of computing machinery

The computer industry is very young and in general its products are very short-lived. Whereas the concept of computing machinery is quite old and conceptually dates at least back to the 18th century (by Charles Babbage and Lady Ada Lovelace [1]), the first real working computing machines date back to the end of World War II where they were used in cryptology.

One of the first usable computing machine, the ENIAC (Electronic Numerical Integrator and Computer) was completed in 1945, contained 17'468 vacuum tubes, weighted 30 tons and measured 6 x 26 meters. This first computer was programmed by physically changing the wiring of the computer. The next generation of computers followed in 1949 which, applying the von Neumann principle where both the data and the operating instructions are stored in the same memory. Because the computer's program resided in its memory, users could change instructions by rewriting the program instead of rewiring the machine. This principle has proven to be so efficient that all modern computers follow the von Neuman architecture.

However, one problem had to be solved: switching off a computer where all the data and programs reside in memory erases definitely all its data and programs. Means of off-line storage had to be found where both data and programs could be permanently stored. Many early computers used teletypes as peripheral devices. Teletypes could read and write data directly from and to punched tape. So punched tape was used very early as off-line storage medium. However, soon magnetic media was found to be superior with respect to speed and data density. Whereas magnetic tapes were used as secondary storage and backup, magnetic drums and disks provided online storage of data and programs.

A quantum leap for the computer industry was achieved in 1981 with the creation of the Personal Computer. Up to this time, computers were big machines located in air-conditioned rooms with no access for the ordinary staff and cared of by highly paid specialists. Now with the PC everything changed. Computers now are designed to be on everybody's desk. The PC was a revolution that changed the computer industry totally. A direct consequence is an ever-increasing pace of development that still is prevailing today. Yesterday's supercomputer is standing tomorrow as PC on my desk.

2 Principles of digital storage

All digital data is recorded in form of binary numbers that can be represented by a certain number of simple on/off switches. However, the plain binary representation is very seldom used directly. There are two contradictionary principles used, even often in combination.

2.1 Error correction

The misinterpretation of an on/off switch (a bit) always leads to a significant error in the interpretation of data. However since digital media of every kind are far from perfect, one has to deal with a certain error rate. In order to cope with this inherent error, redundant information is added to the plain digital data. A simple form is the parity bit, where to each 8 bit (a byte) a ninth bit is added in such a way that the resulting 9 bits always have even (or odd) parity. While reading the binary data, the parity of each 9-bit "word" is checked in order to know if there has been an error by misinterpretation of one bit within the word. This method has been replaced by very elaborate error correction codes like the cyclic redundancy check (CRC) which not only allow to detect an error but also allow to correct it, if not too many bits within a group have been misinterpreted. Today's storage technology would be impossible without this kind of error correction. However, the principle of all error correction schemes is to add redundant information.

2.2 Data compression

Much information contains a certain degree of semantic or syntactical redundancy. In order to achieve an efficient storage as binary data, data compression algorithms have been developed which try automatically to detect redundancy and eliminate it. There are two fundamentally different approaches to data compression.

Lossless compression tries to remove redundant information by the detection of patterns in the data and then using optimal coding to represent these patterns. The compressed binary data can be restored to be identical with the original input data. Huffman encoding [2] and the LZW-compression [3] represent typical lossless data compression schemes.

In contrary to these compression schemes, *compression with loss* irreversibly removes information that the algorithm finds to be redundant in the semantic sense. That is, all information is removed where the algorithm determines it is not used for the correct interpretation of the data. As example the well-known JPEG-algorithm [4] which is used to compress digital image data throws away all information which is considered irrelevant with respect to a human viewer. Artefacts in the restored data are accepted as long as they do not impose restriction to the purpose of the data. In case of images, the purpose is defined to be viewed by a human.

It is obvious, that compression with loss can be much more efficient by achieving much higher compression rates as compared to lossless compression. However, the artefacts imposed by all compression schemes with loss can become very problematic if the data is used with a different purpose than the compression algorithm was designed to. For example, using JPEG-compressed images in pattern analysis tasks can give wrong results since the algorithms used may be sensitive to the artefacts produced by the data compression.

Error correction and data compression are very often used in combination. Very often on a hardware level digital storage devices use error correction in order to guarantee a certain level of data quality. This error correction is performed automatically without the user being aware of. However the internal error correction rates (and its development with time) may be an interesting estimate of the quality of a storage medium.

3 Development of digital storage media

3.1 Magnetic media

Magnetic media have been the dominant technology used for permanent storage of computer data. The physical principle used is the magnetisation of magnetisable material. The bits are recorded by either changing the strength and/or the direction of magnetisation.

Magnetic storage media represent a very known and proven technology. The capacity of magnetic media doubles about every two years and there is still room for much more improvement.

From the point of view of longevity magnetic media are quite well understood. Spontaneous demagnetisation does almost not occur. As long as magnetic media are not exposed to external magnetic fields or excess heat the magnetisation remains stable and is expected to be readable even after 50 years (For example the first magnetic sound recordings made on iron wire around 1940 are still in good shape).

However, since the magnetisable material is very often attached to a supporting substrate (as for example the metal oxide of magnetic tape is attached to a polyurethan binder on a polyester support), the stability of this carrier material determines the longevity of magnetic storage media. Experience has shown that most tape-like magnetic media have a lifetime of at least 20-30 years given proper storage conditions. Modern recording methods as the helical scan method developed for recording video data are more sensitive to the physical accuracy of the magnetic media and therefore do have a shorter lifetime.

3.2 Optical storage media

Optical storage media use lasers to record and read the information.

Magneto-optical storage is based on the principle of the Kerr-effect: polarised light reflected from a magnetised surface changes the direction of polarisation. Recording is made by heating the surface of the medium with a laser above the Curie point, which allows changing the direction of the magnetisation by applying a magnetic field during the cooling process. Magneto-optical devices are read-write devices. The longevity of magneto-optical storage media is better than 30 years.

WORM-media (Write Once, Read Many) use different techniques to permanently change the optical properties of a surface. Many are very stable and a lifespan of more than 100 years is expected.

CD-R (Recordable CD) is a type of WORM that had a tremendous success during the last years. CD-R's consist of a clear disk with a sensitive layer applied on the top. Information is burnt with a laser into this sensitive layer from the downside. So the laser light passes the clear disk support. The sensitive layer on the topside is not protected and thus susceptible to any physical damage. Even writing on it by a felt pen or attaching a label to it can damage it and make the disk unreadable after a short time. Thus CD-R's are quite problematic with respect to longevity even if some manufacturers claim durability beyond 200 years.

There is very little know about the long term archiving properties of new DVD-based media. Therefore this type of media cannot yet be recommended for archival purposes.

4 The compatibility crisis

4.1 Hardware compatibility

The longevity of digital recording media is only half of the story. While the coded information may be readable for a long time from the physical point of view, the machine to read it has to be existing and the code has to be known. For example, there are many etruscian texts that are written in roman letters and can deciphered without problem. However, since the language is unknown, the meaning of these texts remains hidden.

Because of the rapid development in storage technology, the device needed to read and write a certain type of digital storage medium is likely to be produced only during a short period. After this period, a new, enhanced device will be put to market with increased speed and/or increased capacity. For all know media types, about every 2 years a new generation can be expected. Generally a new generation is able to read and write to media of the previous generation, and read only the media of the generation before this. All earlier generations are incompatible and cannot be used any more! As a result media has a useful lifetime of about 5 years, after which there are no more device to read the media. Since often support for the older devices is no more available (no spare parts, no one to fix it if it breaks), there is a high risk that these media can no longer be read even if the recorded data is still in excellent condition.

4.2 Software compatibility

Another issue is the software compatibility. Even if the digital data can be transferred to the computer, there is still the problem that the data has to be interpreted to be useful. It is well known that new software releases often change the data format. A data format is in principle a convention on how the bits or the numbers have to be interpreted in order to give meaningful information. Often Metadata has to be stored in order to allow the interpretation of data. For example the digital representation of an image makes only sense if Metadata as the image size in pixel and the meaning of each number is known. By convenience, this metadata is often stored together with the actual image data. The knowledge on how this data is ordered and arranged on the media consists of the *data format*.

Thus, the longevity of digital data is also determined by the capability of software to read "old" software formats and how often these formats change. Experience shows that many formats that represent structured information such as text from word processors change with each new release. It has occurred to us many times that texts written 5 years ago couldn't be read anymore since there was no software available which could "open" such old formats. The old software – may be still available on a backup – does not run anymore on the latest release of the operating system of the computer, and putting back an old release of the operating software does not work because it does not support the new devices (such a system disks) attached to the computer. The only remaining option is to use the paper copy if available…

5 Cloning – the way out

Given the circumstances as described above, digital storage seems to be absolutely unsuitable for long term storage. However, digital data offers a unique advantage that makes digital long-term storage not only useful but also superior in many cases.

Copying information as e.g. images using analogous techniques always results in a certain loss of information: The copy is not identical to the original but degraded in quality to some degree. Digital data however can be copied – cloned – such that the copy is 100% identical to the original. Thus digital data can be copied for an infinite number of times without any degradation. Even the latest generation is indistinguishable from the original.

Thus we propose a novel approach to long term storage which requires periodically to copy the data to new media and to reformat it to the current standards. As long as this "*active storage*" is carried on, the information will be available with absolutely no degradation. Conceptually, this is the contrary to the traditional storage concepts where the information (or the media that holds the information) is stored under optimal environmental conditions and touched as little as possible. Active storage requires touching the data periodically. Using some redundancy such as multiple copies stored at different location, a degree of security can be achieved which is higher than with traditional long-term storage concepts.

6 What can be done?

6.1 The digital facsimile

If the original image is not already in digital form, the analogue image has to be digitised. Digitisation is an art that requires knowledge both in photography and computers. In general, digitisation for long term archival should record all *visual information* of the photograph. Thus both the spatial and optical density resolutions have to be carefully optimised for each photograph. On one hand only as little resolution as possible is desired in order to reduce the data size, on the other hand, all visual information of the original photograph has to be recorded. In practice, the quality of the photographic material and the quality of the optics used for the photograph limit the visual content of a photograph. Thus there exists an upper limit beyond it makes no sense to increase the resolution of the digitisation process.

6.2 Storage formats

For archival purposes, images should be stored without compression. Compression with loss such as JPEG are unsuitable because the introduce artefacts which may hinder future use of the image (e.g. zooming into the image for reading a small numberplate of a photograph of an old steam engine). Current lossless compression schemes are not efficient enough in order to reduce the amount of data significantly. We suggest using a standard format such as TIFF [5], which is thoroughly published, and several implementations (even in source code form) are available. This reduces the necessary reformatting of the data.

In addition to the uncompressed archive copy, several working copies of each image in different resolutions and with different compression schemes may be created.

6.3 Example of Active storage

The archive copies of the images are stored on magnetic tape media such as DLT (Digital Linear Tape). The DLT is chosen because it has a high reliability, it is compact with a tape casette holding up to 35GB of uncompressed data and it is a standard medium so quite a long term support from hardware manufacturers can be expected. Therefore, at present time the DLT sems to be the optimal and most cost effective medium for archival of image data. There are 3 copies, where copy a) is stored at a secure location such as an underground storage vault, copy b) is located at the archive and copy c) is directly accessible as near-line storage by a tape robot.

Each second year, all 3 version are proofread and the data compared to each other. At the same time the hardware error rate is determined. If it is necessary through the change of technology or indicated by the hardware error rate, the data is copied to new media. If necessary, the data is reformatted to a new standard (e.g. the – not yet existing – Universal Preservation Format UPF). Since this process is automated to a high degree, only little human interaction is required and the cost is basically determined by the cost of the machines and the media. Using current hardware costs, a price of about 10 ECU per Gigabyte seems to be appropriate.

7 Conclusion

I have shown that despite the obvious shortcomings of computer technology with respect to longevity it makes sense to envision digital long term archives. The shortcomings such as the high pace of change in the computer industry is over-compensated by the fact that digital data may be copied an unlimited number of times without any loss. The digital long-term archive requires a change of the paradigm from a *passive archive* with as little interaction with the information carrier as possible to an *active archive* where perpetual copying takes place. Given this active archive, the longevity is unlimited with time.

References

[1] See for example: W.J. Kaufmann III, L.L. Smarr, "Supercomputing and the transformation of science", Scientific American Library, New York, 1993.

[2] *D.A. Huffman:* "A method for the construction of minimum redundancy codes", Proc. IRE, vol 40, no 10, pp. 1098–1101, 1952

[3] United States patent #4,558302 by Sperry Corporation, Dec. 10, 1985

[4] JPEG = Joint Photographic Experts Group. Description can be found in: C.W. Brown, B.J. Shepherd, "Graphics File Formats: reference and guide", Manning Publ. Co., Greenwich, CT06830, 1995

[5] TIFF = Tagged Image File Format. Description can be found in: C.W. Brown, B.J. Shepherd, "Graphics File Formats: reference and guide", Manning Publ. Co., Greenwich, CT06830, 1995

Discussion

Archiving of Digital Image Data
L. Rosentaler, University of Basel, Switzerland

Baltsavias (ETHZ, Switzerland):
Just a question about the famous meta data. Very often it is not only the image itself which has to be stored, but there is much more information like orientation elements, flight conditions, etc. How to store, archive and manage this type of information?

Rosentaler (University Basel, Switzerland):
There are two basic ways: one is, if you have this meta data in a database let's suppose a relational database, then you have to take this meta data with you at every change of release of the software, so you *do not* make a backup and you cannot put it aside; this is a dangerous way. The other one is to use plain ASCII files for the meta data. Maybe you can structure these files and then document the structure. Thus you will always have the possibility to reinsert them into a relational data base. And this is the only safe way.

Nicoletti (Intergraph):
This is just for clarification but not a question. You spoke about compression and warned us against using it. I fully agree if images for a specific workflow have been acquired in an uncompressed format and if you wish to keep them alive to re-use them exactly the same way in 10 or 20 years. In this case you cannot degenerate the original information. But if you are already using them, for a specific workflow, then you should also keep them as they are even in compressed form.

Rosentaler (University Basel, Switzerland):
But if you are thinking of long-term archiving you will not know how you will use the image in 10, 20 years. Maybe the images will have a totally different use.

Nicoletti (Intergraph):
I agree with you, but it depends on the initial usage, so the main target is to keep the information alive across time.

Part 3

Automation in Photogrammetric DTM Elaboration

Chairman

A. Dupéret

Principles of matching techniques (feature based matching-area matching, least square matching), editing and filtering of automatic derived DTM data, experiences in practice and performance of automatic DTM derivation in comparison to laser measurements.

Principles of Digital Matching

P. Julien
Institut Géographique National, Laboratoire MATIS,
Saint-Mandé, France

Abstract

The objectives of digital image matching are recalled, and the principle of best correlation of areas is described. Geometrical constraints for oriented stereoscopic pairs are introduced, suitable to decrease the amount of computation. Finally we point out the higher significance of correlation for geometrically alike details, and the advantage of rectifying geometrical distortions while matching details.

1 Definition of digital matching

Image matching designates the action of associating point to point two images of a same object or scene. For example our natural binocular vision system permanently performs image matching, in order to merge the two images seen by the eyes into a unique perceived one. This natural image matching is also of permanent use in classical analogical photogrammetry, when processing stereoscopic pairs of photographs.

Digital image matching is a substitute for visual matching with an artificial vision system, where the images are digital and the point to point association is performed by a computer program. By "point to point" association we mean that for any point P in one image, the program can tell which point Q in the other image represents the same detail, or is *homologous* to P. Now digital matching can be defined as follows: *given two digital views of an object, find automatically all the pairs of homologous details.*

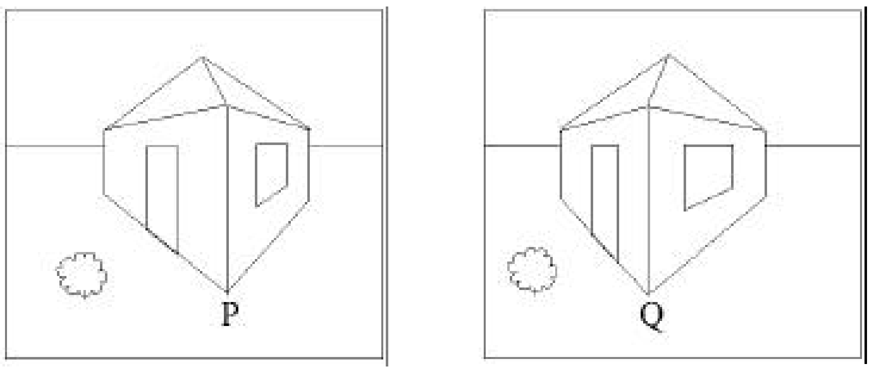


Fig. 1

This definition needs several complements.

1) It is better to speak of details rather than of points, because a detail is not necessarily punctual. For example, on the images of figure 1, a corner of the house can be

considered as punctual; an edge of a wall is linear, not punctual; a detail such as the bush is not punctual, and its description cannot be reduced to a single point.

2) By "all the pairs", one must understand a number of pairs, great enough to describe completely the correspondence between images. Furthermore note that some details may have no visible homologous, because of occluding objects.

3) The definition does not assume stereoscopic views, because digital matching can apply to non-stereoscopic views, for example for image registration, or measurement of fiducial marks. Neither is there any a priori assumption about the nature and geometry of the views; they can be photographs,terrestrial or aerial ones, satellite images, or also drawings.

4) Finally note that, although the definition mentions only two images, searchers now develop digital matching on three or more images.

2 Applications of digital matching in photogrammetry

Digital matching applies in photogrammetry whenever pairs of homologous points are needed, namely for acquisition of tie points and of dense digital terrain models in the case of aerial stereoscopic pairs; but also for image registration and measurement of fiducial marks.

3 Best correlation principle

Amongst the different possible approaches for digital matching, we only consider in this paper the one based on the *best correlation principle*, which can be stated as follows.

Let $r_1(c,l)$, $r_2(c,l)$ be the matrices representing the digital images. In theory, two homologous details, assimilated to pixels $P_1=(c_1,l_1)$, $P_2=(c_2,l_2)$, should appear identical in both images: $r_1(P_1) = r_2(P_2)$. One can easily guess that this condition cannot characterize homologous pixels, because there are lots of non-homologous pairs Q_1,Q_2 such that $r_1(Q_1)=r_2(Q_2)$.

On the other hand, one can notice then if two pixels $P_1=(c_1,l_1)$, $P_2=(c_2,l_2)$ are homologous, then their neighbourhoods must appear identical, which means:

$$v_{P1}(c,l) = v_{P2}(c,l) \quad \text{for } -h \le c \le h,\ -k \le l \le k,$$

where $v_{P1}(c,l)=r_1(c_1+c,\ l_1+l)$, $v_{P2}(c,l)=r_2(c_2+c,\ l_2+l)$, $-h\le c\le h$, $-k\le l\le k$, define two neighbourhoods of P_1,P_2. This condition appears rather more severe than the previous one, since there is a low probability to meet two neighbourhoods v_{Q1},v_{Q2} of non-homologous pixels Q_1,Q_2 such that $v_{Q1}=v_{Q2}$.

In brief, a necessary condition for two pixels P_1,P_2 to be homologous, should theoretically be:

$$v_{P1}=v_{P2}, \text{ and } v_{P1}\neq v_{Q2} \text{ for any pixel } Q_2\neq P_2, \text{ and } v_{Q1}\neq v_{P2} \text{ for any pixel } Q_1\neq P_1.$$

Now in the reality, two neighbourhoods v_{P1},v_{P2} are never rigorously identical; they only are alike, with differences in radiometry and in geometry; in particular the geometrical differences, or relative distortions, are caused by the local relief of the object (terrain). Furthermore even in the absence of geometrical distortions (locally flat terrain), the digital images of the detail are generally distinct, because of a sub-pixel shift of the sampling grid. Then it seems natural to introduce a measure of the likeness of the two neighbourhoods, which is a number $I(v_{P1}, v_{P2})$, defined either through a distance, for example $I(v_{P1},v_{P2}) = d_1(v_{P1},v_{P2}) = \Sigma_{c,l}|v_{P1}(c,l)–v_{P2}(c,l)|$, or through a correlation index such as $I(v_{P1},v_{P2}) = \Sigma_{c,l}v_{P1}(c,l)v_{P2}(c,l)$.

The more the images are alike, the closer is the value $I(v_{P1},v_{P2})$ to the optimum $I_{opt}=I(v_{P1},v_{P1})$, obtained with two identical neighbourhoods. For two homologous pixels P_1,P_2, the neighbourhoods are as much alike as possible, or in other words, the absolute deviation $|I(v_{P1},v_{P2}) – I_{opt}|$ must be minimum, which means explicitly:

$$| I(v_{P1},v_{P2}) – I_{opt} | < | I(v_{P1},v_{Q2}) – I_{opt} | \qquad \text{for any pixel } Q_2 \neq P_2,$$

and $$| I(v_{P1},v_{P2}) – I_{opt} | < | I(v_{Q1},v_{P2}) – I_{opt} | \qquad \text{for any pixel } Q_1 \neq P_1;$$

this necessary condition for homology of pixels P_1,P_2 is what the best correlation principle consists of.

4 Examples of likeness measures $I(V_{p1},V_{p2})$

The simplest measures are defined through d_1 or d_2 distances: $I=d_1$ or $I=d_2$, with

$$d_1(v_{P1},v_{P2})= \Sigma_{c,l} |v_{P1}(c,l)–v_{P2}(c,l)| \quad , \quad d_2(v_{P1},v_{P2})= (\Sigma_{c,l} (v_{P1}(c,l)–v_{P2}(c,l))^2)^{1/2}.$$

For these indexes, the optimum $I_{opt}=0$ is a minimum.

But the most frequently used measure is probably the correlation value, normalized and centered, also called linear correlation coefficient:

$$I(v_{P1},v_{P2}) = \mathrm{cov}(v_{P1},v_{P2}) / \sigma(v_{P1})\sigma(v_{P2})$$

$$=\Sigma_{c,l}(v_{P1}(c,l)–Ev_{P1})(v_{P2}(c,l)–Ev_{P2}) / (\Sigma_{c,l}(v_{P1}(c,l)–Ev_{P1})^2)^{1/2}(\Sigma_{c,l}(v_{P2}(c,l)–Ev_{P2})^2)^{1/2}$$

where v_{P1},v_{P2} are defined for $–h\leq c\leq h$, $–k\leq l\leq k$, $N=(2h+1)(2k+1)$, and

$$Ev_{P1} = 1/N\ \Sigma_{c,l}v_{P1}(c,l),\quad Ev_{P2} = 1/N\ \Sigma_{c,l}v_{P2}(c,l)$$

For this measure: $–1 \leq I(v_{P1},v_{P2}) \leq 1$ and $I_{opt}=1$ is a maximum.

Then the necessary condition for homology of P_1,P_2, given in paragraph 3, becomes:

$$I(v_{P1},v_{P2})>I(v_{P1},v_{Q2}) \text{ and } I(v_{P1},v_{P2})>I(v_{Q1},v_{P2}) \text{ for any pixels } Q_2\neq P_2 \text{ and } Q_1\neq P_1.$$

Furthermore $I(v_{P1},v_{P2})=I_{opt}=1$ if and only if v_{P1},v_{P2} are linked by a linear relation $v_{P2}=av_{P1}+b$, $a>0$; in other words, $I(v_{P1},v_{P2})$ is insensible to a linear change of dynamics between the two images; this property is often useful and justifies, together with experience, the wide use of this measure.

5 Implementing the best correlation principle

According to the best correlation principle, digital matching now comes down to evaluating the index $I(v_{Q1},v_{Q2})$ for a number of pairs Q_1,Q_2.

For example figure 2 shows a portion of an aerial photograph, from which a 33x33 pixels neighbourhood v_{P1} of pixel P_1 has been extracted. The linear correlation coefficient $I(v_{P1},v_{Q2(i,j)})$ has been evaluated for a set of 21x21 neighbourhoods $v_{Q2(i,j)}$ extracted from an other photograph, and corresponding to pixels $Q_2(i,j) = (c_2+i,l_2+j)$, $-10\leq i,j \leq 10$, around an estimated homologous (c_2,l_2) of P_1. The maximum 0.9478 of the "correlation surface" $\sigma(i,j)=I(v_{P1},v_{Q2(i,j)})$ occurs for i=-2, j=+3, giving the position of the true homologous $P_2=(c_2-2, l_2+3)$ of P_1.

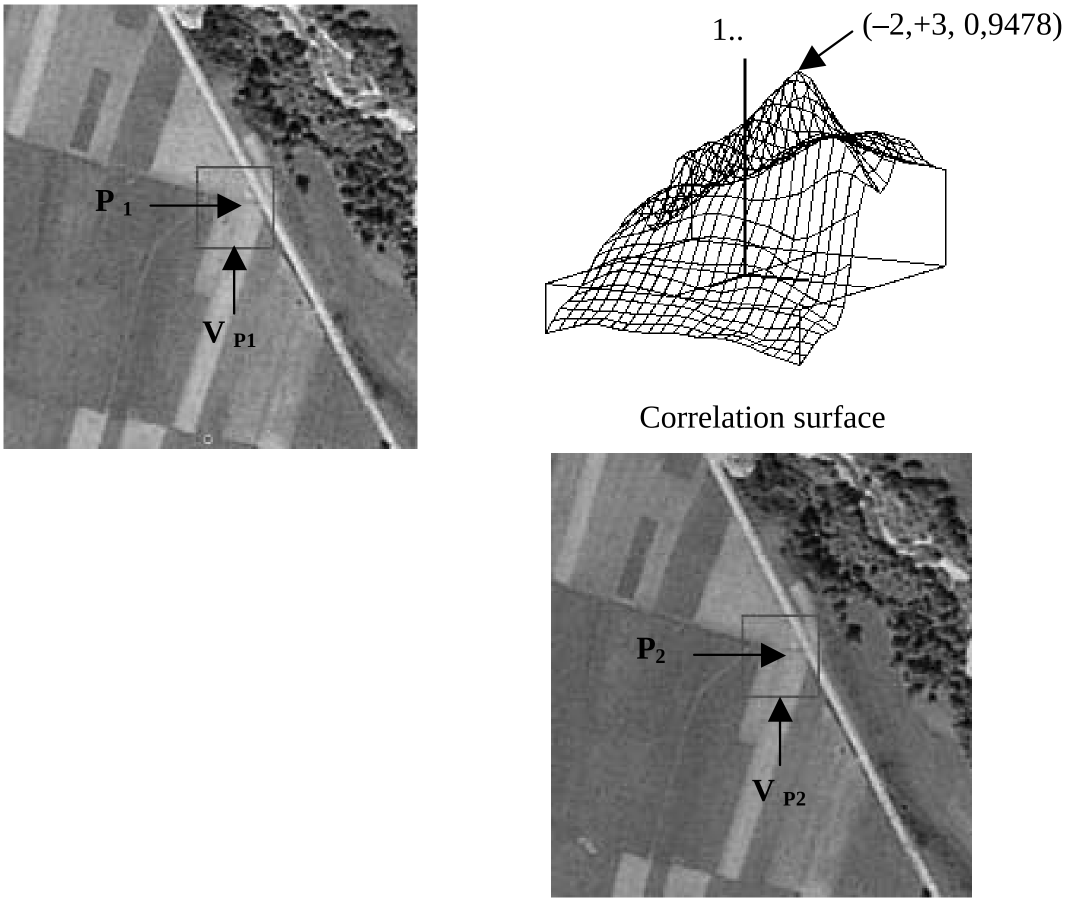


Fig. 2

As an information, let us evaluate the computation time necessary to obtain the above correlation surface.

The linear correlation coefficient of two N-arrays needs about 8N floating operations; here for N=33x33=1089 and 21x21=441 coefficients, about $3.84\mathrm{x}10^6$ floating operations are needed. On the basis of a 500 MHz processor and of 10 cycles per floating operation, $3.84\mathrm{x}10^6\mathrm{x}10/5\mathrm{x}10^8=0.077$ second is necessary to obtain an homologous P_2. This is cheap if one wants to obtain a small number of homologous pairs, for example for tie points.

Now in the above example, the photograph has 4600x4600 pixels (23cmx23cm photo digitized by 0.050mm). If one wants to obtain the homologous for each pixel P_1, in order to get a digital terrain model (DTM), the total time is about 4600x4600x0.077s = 452 hours = 19 days; this amount, several times as much as in a classical photogrammetric survey, is unrealistic.

These estimations show it is important to reduce the computation time, more especially as digital images are often much larger, and may count up to 15000x15000 pixels.

In order to reduce the computation time, one can act on three parameters: 1) the DTM density, by processing only one pixel on 2x2, or 3x3, etc...; 2) the neighbourhoods size; 3) the size of the correlation surface. For example processing only 1 pixel on 3x3, using 11x11-neighbourhoods instead of 33x33 ones, and computing 7x7-correlation surfaces instead of 21x21 ones, will reduce the computation time to 37 minutes for a 4600x4600 image, and 6.5 hours for a 15000x15000 image, which seems now realistic.

In the particular case of a stereoscopic pair, the correlation surface can be reduced to a "correlation curve" (1x21 instead of 21x21 in the above example) provided that the pair is oriented; this possibility follows from geometrical constraints, which we now describe.

6 Geometrical constraints for an oriented stereoscopic pair

The geometrical constraints are of two kinds (see figure 3): the epipolar constraint, for which the relative orientation of the pair is required, or the vertical constraint, for which the absolute orientation is required.

6.1 The epipolar constraint

Consider a pixel P_1 in the first image; P_1 is the image of some detail M; the position of M is unknown, but M is known to be located on the perspective ray S_1P_1; so the image P_2 of M in the second image is located on the line D_2 – known as an epipolar line –, image of S_1P_1; then P_2, the homologous of P_1, must be searched for only along D_2, i.e. in a one-dimensional area. In other words the "correlation surface" reduces to a "correlation curve" $\sigma(i)=I(v_{P1},v_{Q2(i)})$, corresponding to a set of points $Q_2(i)=P_2+iD_x+iD_y$, aligned on D_2.

Note that determination of the epipolar line D_2 assumes that the position of the second image with respect to the first one – i.e. the relative orientation of the pair – is known.

6.2 The vertical constraint

Let M be a detail of the terrain, whose planimetric position m is given, but whose altitude is unknown: M is located somewhere on the vertical line above m; so the "correlation surface" reduces to a "correlation curve" $\sigma(i) = I(v_{Q1(i)}, v_{Q2(i)})$, corresponding to a set of pairs $Q_1(i)=Q_1(0)+iD_{1x}+iD_{1y}$, $Q_2(i)=Q_2(0)+iD_{2x}+iD_{2y}$ images of points M_i on the vertical line.

Note that considering vertical lines assumes that the positions of the images with respect to the ground – i.e. the absolute orientation of the pair – is known.

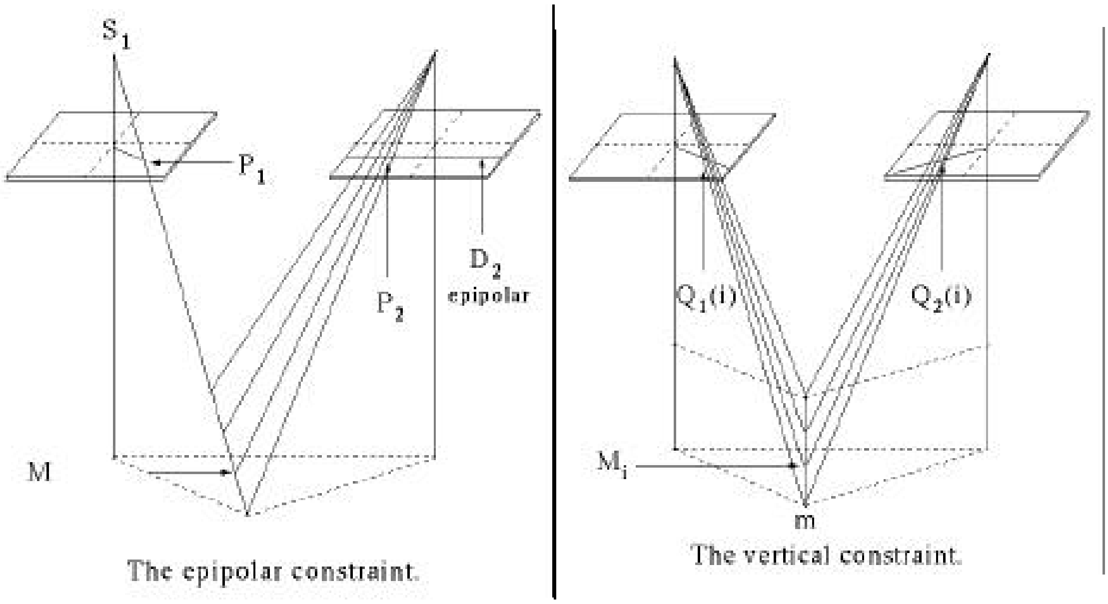


Fig. 3

7 Effect of the neighbourhood size on the correlation curve

Decreasing the size of neighbourhoods v_{Q1}, v_{Q2} seems an easy way to reduce the computation time. On the other hand, smaller neighbourhoods involve a higher probability to meet non-homologous pixels Q_1, Q_2 such that $v_{Q1} \approx v_{Q2}$, i.e. $I(v_{Q1}, v_{Q2}) \approx I_{opt.}$ The diagrams on figure 4 give examples of correlation curves for various neighbourhood sizes: for too small neighbourhoods, the multiple maxima of the correlation curves make the research of an homologous indeterminate. In this example, for the considered pixel, the neighbourhood size should be at least 30 meters (19x19 pixels). For smaller neighbourhoods, the best correlation principle is not a sufficient condition for homology, and additional conditions, such as coherence between adjacent pixels, are necessary.

8 Coping with geometrical distortion in digital matching

As mentioned above, too small neighbourhoods v_{Q1},v_{Q2} are proscribed. On the other hand, larger neighbourhoods may be affected by geometrical distortions, due to terrain relief. This "basic problem", according to Hobrough [1978], is illustrated in figure 5: the strong distortion between the two neighbourhoods v_{Q1},v_{Q2} makes it difficult to appreciate their best registration, either visually, since the sum $v_{Q1}+v_{Q2}$ appears fuzzy for any shift of v_{Q2} with respect to v_{Q1}, or digitally, since the correlation curve – not represented – is flat, involving an imprecise determination of the maximum, not to mention the low value 0.55 of this maximum.

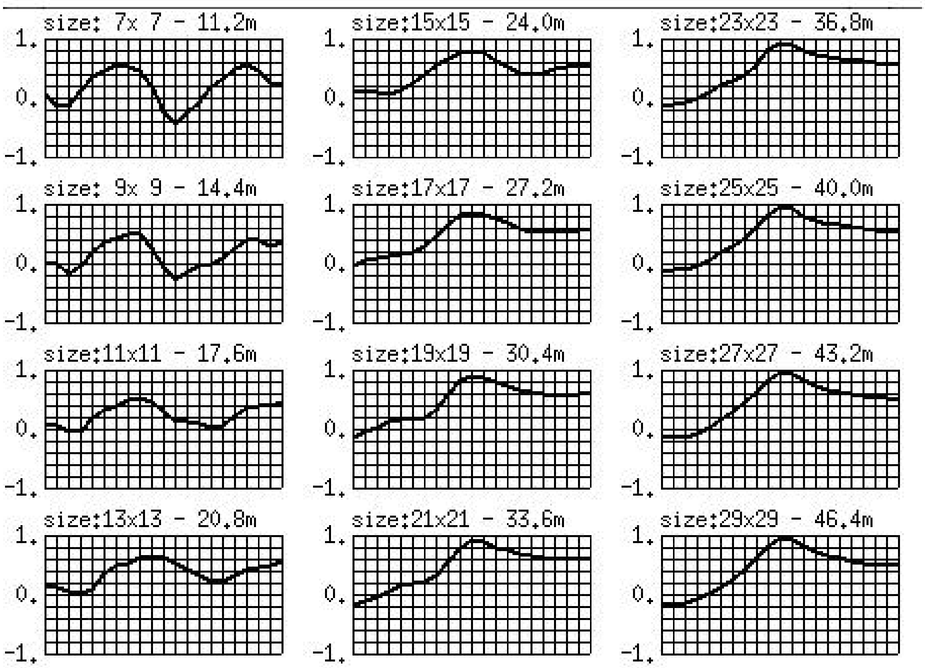


Figure 4. Correlation curves, with a 3m interval, for pixel P_1 of figure 2.

Size (m)				Z corners (m)					$I(v_{Q1},v_{Q2})$
5850,2	7456,4	167,5	167,5	0,0	1547,0	1547,0	1547,0	1547,0	0,5538

Fig. 5

Then the way to overcome the problem is to transform geometrically one (or both) neighbourhood(s) to get them superposable. Such a transform is a priori unknown, depending on the – unknown – shape of the terrain. So the transform has to be determined together with the shift between neighbourhoods; a simple transform – with a minimum number of parameters – is suitable, in order to preserve robustness.

A natural choice is a linear transform L, applied to v_{Q2}, defined by parameters $\alpha,\beta,\gamma,\delta$, with which the matching problem now states: find the values $\alpha,\beta,\gamma,\delta,i$ optimizing the function $\sigma(\alpha,\beta,\gamma,\delta,i) = I(v_{Q1},L(v_{Q2})+iD_x+iD_y)$.

For example, if $I=d_2$, the explicit value of $\sigma(\alpha,\beta,\gamma,\delta,i)^2$ is

$$\Sigma_{c,l}\,(r_1(c_1+c,\, l_1+l) - r_2(\,\alpha(c_2+c)+\beta(l_2+l)+iD_x,\ \gamma(c_2+c)+\delta(l_2+l)+iD_y\,)\,)^2;$$

this is the "least-squares correlation" method described by Ackermann [1984] or in Wrobel's state of the art [1988].

Another possible transform consists of a double projection of both neighbourhoods v_{Q1},v_{Q2}, first on a surface approximating the terrain, then on the horizontal plane (figure 6); in other words the transformed neighbourhoods u_{Q1},u_{Q2} are local orthophotos. The simplest choice for the approximating surface is a plane, defined by three parameters ζ,η,θ, with which the matching problem states: find the values ζ,η,θ optimizing the function $\sigma(\zeta,\eta,\theta) = I(\, uQ1(\zeta,\eta,\theta),\, uQ2(\zeta,\eta,\theta)\,)$.

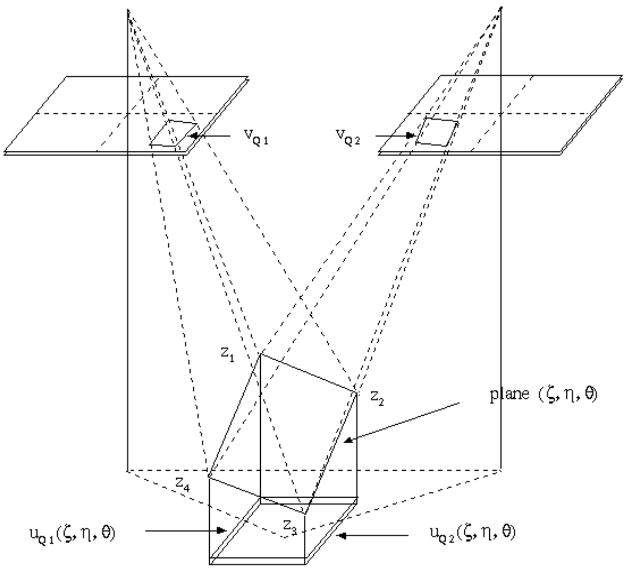
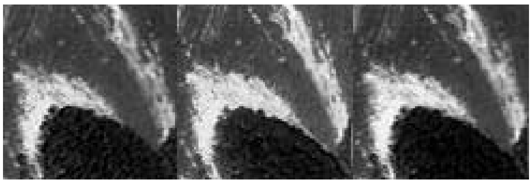


Fig. 6

Figure 7 shows the resulting transformed neighbourhoods u_{Q1},u_{Q2} after fitting the best parameters $\zeta=z_1$, $\eta=z_2$, $\theta=z_3$; note the plane condition $z_1-z_2+z_3-z_4=0$. The sum $u_{Q1}+u_{Q2}$ is now sharp and the correlation 0.90 significant, with 167m large neighbourhoods (121x121 pixels) ; as an information, the slope of the plane (or terrain since the plane fits the terrain well) is 0.65.

u_{Q1} u_{Q2} u_{Q1} +



		Size (m)			Z_1	Z_2	Z_3	Z_4	$I(u_{Q1},u_{Q2})$
5850,2	7456,4	167,5	167,5	0,0	1542,0	1621,0	1546,0	1467,0	0,9052

Fig.7

In this example, the function $\sigma(z_1,z_2,z_3)$ was optimized by relaxation, described precisely as follows. Let (z_{1k},z_{2k},z_{3k}) be the kth-approximation; if $\sigma(z_{1k}, z_{2k}, z_{3k})$ is not locally maximum with respect to z_{1k}, then z_{1k} is successively decreased: $z_{1k}-\Delta z$, $z_{1k}-2\Delta z$, ..., $z_{1k}-j\Delta z$, or increased $z_{1k}+\Delta z$, $z_{1k}+2\Delta z$, ..., $z_{1k}+j\Delta z$, until $\sigma(z_{1k}-j\Delta z, z_{2k}, z_{3k})$ or $\sigma(z_{1k}+j\Delta z, z_{2k}, z_{3k})$ is a local maximum; then $z_{1,k+1}$ is set to $z_{1k}-j\Delta z$ or $z_{1k}+j\Delta z$; $z_{2,k+1}$ and $z_{3,k+1}$ are obtained in the same manner.The initial approximation (z_{10},z_{20},z_{30}) is the one minimizing a small set of values $\sigma(z_j,z_k,z_l)$, $z_{min}\leq z_j,z_k,z_l\leq z_{max}$, for example $z_j = z_{min}+j(z_{max}-z_{min})/10$.

9 Conclusion

This paper discussed some basic facts in digital matching based on correlation between neighbourhoods, or "area based" matching, but other basic facts have been omitted. For example, approaches based on other features, such as extracted contours, are also of frequent use. Also, only the geometrical aspect of digital matching has been considered; but radiometric image quality also influences digital matching. As a final remark, we wish to point out that correlation is a powerful -robust and precise- tool for digital matching, under the condition that images are made geometrically alike.

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Ackermann,F. 1984: Digital image correlation: performance and potential application in photogrammetry. Photogrammetric record, 11(64): 429–439 (October 1984).

Wrobel,B. 1988: Least square methods for surface reconstruction from images. Invited paper, ISPRS Commission III, Kyoto: 806–821 (1988).

Discussion

Principles of Digital Matching
P. Julien, IGN France

Boulianne (Laval University, Canada):
You assume that when you found the two parallelograms you can make the transformations to transform them into rectangular forms. But you have to find the homologous points of these parallelograms for that purpose. How do you choose the points of the parallelograms?

Julien (IGN, France):
In fact the two parallelograms are images of a quadrilateral inverse object space.

Boulianne (Laval University, Canada):
Which means that the summit of the two parallelograms are homologous points?

Julien (IGN, France):
Yes, they are almost homologous points.

Boulianne (Laval University, Canada):
Do you have to make the first correlation to find them?

Julien (IGN, France):
No, that is another problem. I did not say *how* to get the parallel facet on the ground which would maximise the correlation function.

Kölbl (EPFL, Switzerland):
Here a question concerning the quality of correlation has cropped up and it is of some importance as we all know we need the figures of merit. The question you suggest is on parallelograms; if you look at least square matching, it is done like solving the correlation. You determine the parameters of transformation too do you not?

Julien (IGN, France):
Exactly, when I was doing that I actually thought of least square matching.

Kölbl (EPFL, Switzerland):
Yes, it would be interesting to hear from the manufacturers which quality criteria they use in order to inform on the reliability of the matching process, and whether least square matching is actually used.

Miller (LH Systems):
In the case of LH Systems software, the matching does not typically use least square matching, it is an iterative process which rectifies images to each other, based on previous iterations of correlation and it may or may not do a good job of shaping images in these types of conditions. Generally, as it learns about the terrain shape, it uses that information to shape itself for the matching process.

Heuchel (Inpho):
In the Match-T software we use a combination of different matching methods. We do apply least square matching to refine matching but it is very sensitive to initial values, so we have to apply strategies to get very close to the homologous image patches. So if we

find the latter with an accuracy of 2–4 pixel values, then we can apply least square matching and can get up to a 10th of a pixel accuracy.

Julien (IGN, France):
Yes, this depends on the way you optimise the correlation index. In least square matching you must use very good approximations to start with, because it supposes that the density is a differentiable function of the terrain. It is possible that you get an optimising process without the assumption that the images are differentiable function of the ground. It is possible to optimise by trying a great number of possible solutions, so you do not need to start from a very good approximation.

Kölbl (EPFL, Switzerland):
There is also something called figure of merit; it is a characterisation of the quality of the matching process for every point. Can you elaborate on that?

Heuchel (Inpho):
MATCH-T also determines quality parameters over an adjustment process. You have geometric and radiometric parameters, statistics and residuals. These values can be analysed like in an adjustment. This delivers a quality measure for the patches showing how accurate the matching was.

DTM Edition in IGN France
An Operational Process to Generate Contour Lines

A. Dupéret,
Institut Géographique National
Ecole Nationale des Sciences Géographiques
Marne la Valée, France

Abstract

IGN introduced a new semi automated tool for cartographic contour line generation at the beginning of year 1999. After six months experience in the three digital units involved in this evolution, new requirements appear concerning large data flow management, increased reliability for the existing functionalities and new interactive tools to improve manual editing.

1 Introduction

IGN France is a government agency commissioned to capture and manage the French national geographical databases. The Ecole Nationale des Sciences Géographiques, and four research laboratories improve and support these products, with fields of proficiency such as digital cameras, image processing, GIS and geodesy. IGN carries out research of common interest corresponding to its activity with the goal of mid and long term improvement of its own production tools. Considering digital photogrammetry, 3 work units equipped with four fully digital plotters each complete the 6 other analytical units designed for BD TOPO® data capture (under completion, with sub-metric positioning).

Although many subjects such as roads and building recognition are under development, the first new semi-automated tool, for contour lines generation, was put in the 3 digital units at the beginning of year 1999 and will now be presented. This needs to compute the DTM at first and requires automated post-processing. After manual editing, a raster to vector transformation is performed to achieve the cartographic purpose. Two kinds of software components are used:

- Socet Set (LH Systems) with several specialised modules such as Automatic Terrain Extraction (ATE), Interactive Terrain Edit (ITE), FGIS (Feature GIS) and the Developer Kit (DEVK).
- Home made softwares written in C, Cshell.

Contour lines produced are imported the GIS GeoCity used for data capture. The images used are black and white, at 1 : 30 000, scanned at 14 μm on the film. The data capture is made in a model at 1 :10 000. In addition to the database constitution itself, the basic product is cartography at 1:25 000. A possible use at a larger scale requires special attention. The steps of this new process will be illustrated from DTMs computed from the following pair of images.

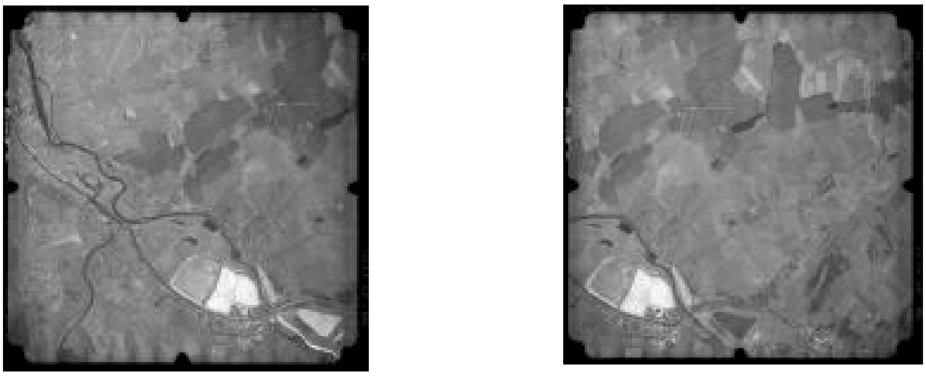

Fig. 1 – Nancy area (East France): scale 1 :30 000, 14/04/96, images 77–79

2 Description of the new process

2.1 Automatic DTM computation

Image correlation is now a standard technique to identify automatically homologue points within a large set of images. The Adaptive ATE (AATE) combines intensity-based and edge-based methods, the algorithm has a recursive approach to determine the parallax between two images. It works firstly on small scale images, under-sampled. At every step, the post density is doubled along both X and Y axis until the full resolution is reached. At the beginning, a sparse post spacing is used for the DTM completion; afterwards, it is progressively densified. A few years ago, the user had to use pre-defined strategy files containing a complete set of parameters for every step of the correlation algorithm; one could also edit it to tune some of these default values more precisely. Now, the software sets the parameters automatically according to several characteristics including terrain type, signal power, flying height, X and Y parallax and image noise level.

Even if the algorithm behaves properly on black and white images, one can never assume how ground surface and above ground objects will be measured according to the date and the hour of flight, the vegetation development, the digitised conditions, local reflectance… A visual control is still required to make an appropriate diagnostic of the result accuracy. This helps tuning the automated post processing strategy to make this data fit the user's requirement.

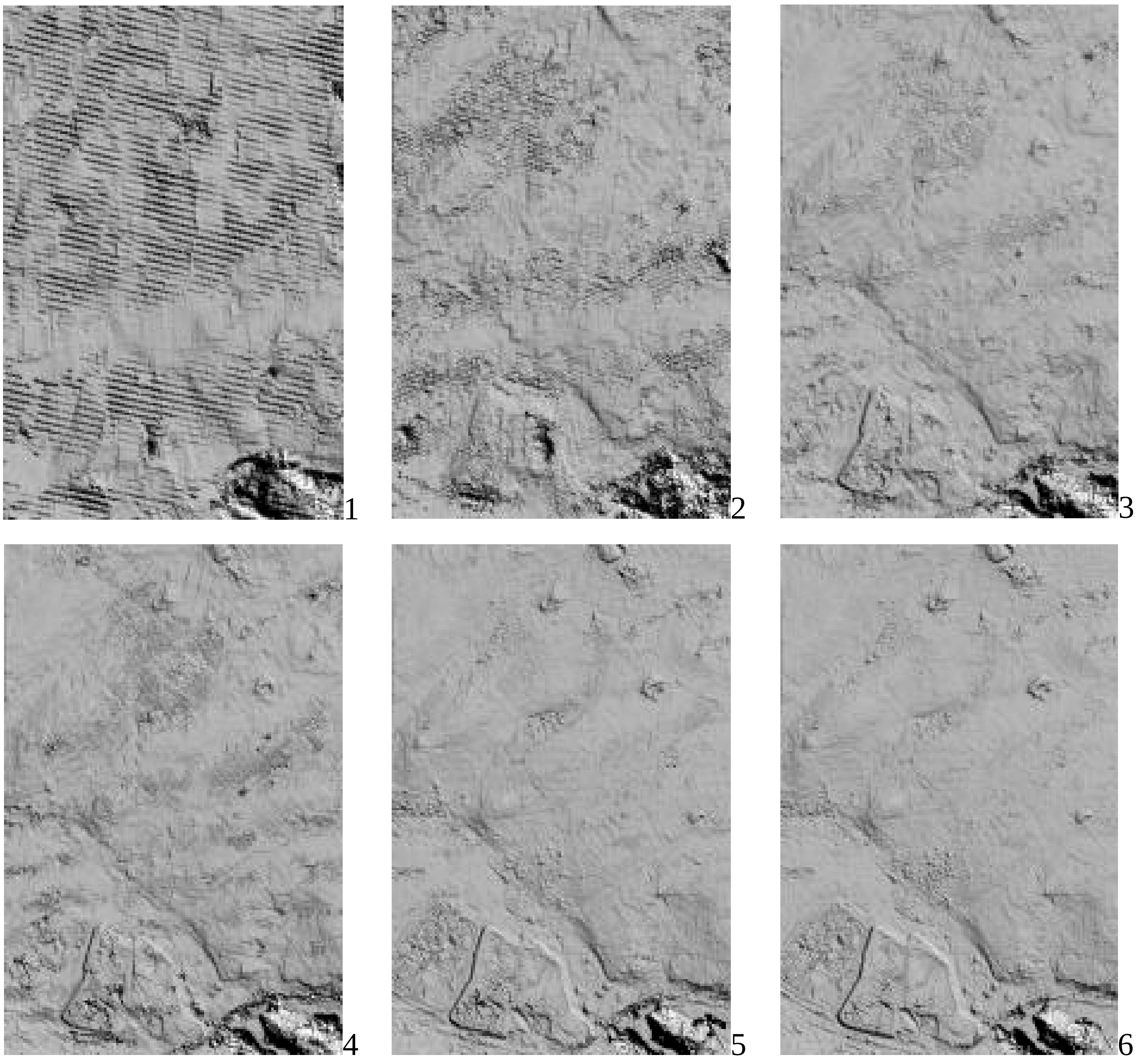

Fig. 2 – Nancy area: terrain shading provides powerful control to visualize surface evolution after each step; here, the first one is on the upper left and the last on the lower right. No additional filtering should be performed before the end of the correlation to allow a quick visual control of the rough DTM.

2.2 Automated post-processing

2.2.1 Standard filtering

The visual control gives a good idea of height and width of objects above ground such as buildings. For trees, it depends on the date of the flight; in early spring, the ground can be seen in woods, with shadows that help correlation to lay on the ground and obstructions are smaller, except for tree with persistent leaves. To tune these two parameters properly should preserve characteristic terrain elements (talwegs, crests, summits, depressions…). After this step, obstructions are removed and the DTM is also slightly smoothed.

For the purpose of the mean scale cartography considered here, a post spacing of 5 meters is chosen for lack of a smaller one. A larger value would produce smaller files but with a worse description of the ground surface. This generates approximately a DTM of 1000 lines x 600 columns for one single pair of images. Larger DTMs are often processed on strips of 4 to 12 images, assuming that this is a homogenous correction, whatever the images are.

2.2.2 External data merge

If available, a database can bring external information to optimise the result given by the post processing exposed above. Elevations in DTM can be changed within an area delineated by the polygon surrounding the features. The most common uses are:

- inside polygons such as lakes or large rivers, all the elevations are valued with a constant that can be the average, the minimum or the maximum of all the posts inside the delineation;
- the possible addition of a constant to all the elevations inside a given polygon to remove over-ground obstructions such as canopies or buildings.

Elevations from networks of different classes of objects can also be used. According to the nature of these objects, a ground profile can be imposed. The available tools reset the elevations closer than an interpolation distance D from the axis of objects. If the elevations further than the interpolation distance are not affected, the others are interpolated from the axis to the frontier of the area given by the interpolation distance, according to a kind of profile given by the operator. The most common options are to interpolate with Uniform, U shape, V shape or Bulldozer option. This can be used for rivers, roads, hedges…

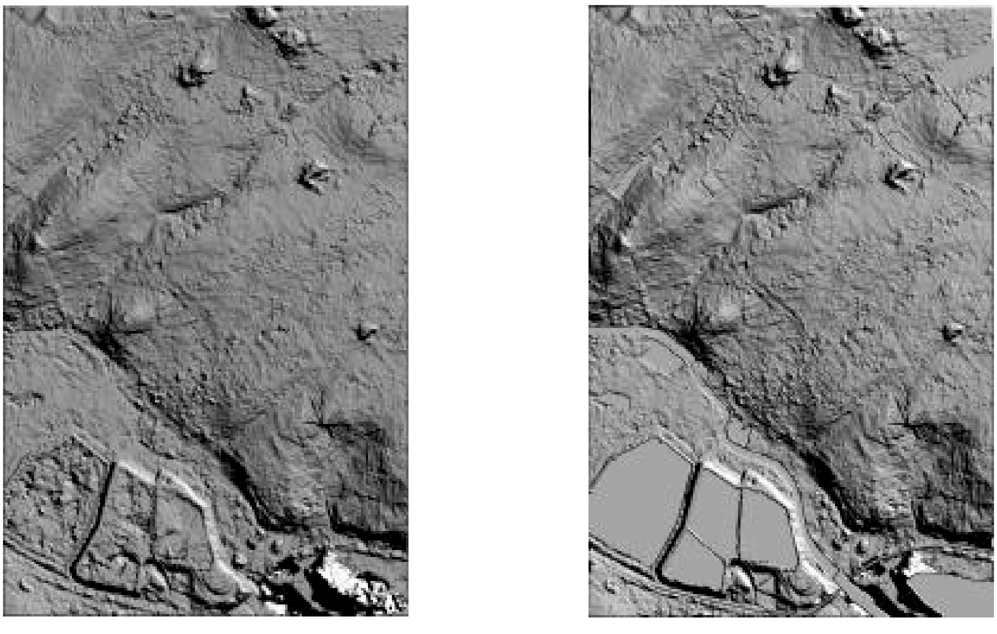

Fig. 3 – Nancy area: on the left, terrain shading after filtering trees and houses; woods and large buildings remain but the small characteristic lines are also preserved; on the right, elevations corresponding to lakes, rivers are set to a constant, and a bias has been removed for those corresponding to woods and houses

2.2.3 Cartographic smoothing

Assuming that the cartographic constrains for the contour lines are to look smooth but also to give a good caricature of the terrain, IGN developed an algorithm called cartographic smoothing independently from Socet Set. The first step consists in computing a DCM (Digital horizontal Curvature Model). From this information, and by identifying appropriate thresholds, the topography is structured as connected areas labelled from the bottom line of valleys to ridges. That classification of the topography, usually in 4-6 classes, is enough to perform the second step that consists in an adaptive smoothing, with customised parameters for each one of the areas identified from the DCM. This DCM needs to be performed on a very smoothed DTM, temporary data issued from the rough data by using very large average smoothing windows (this prevents a complex set of small characteristic lines).

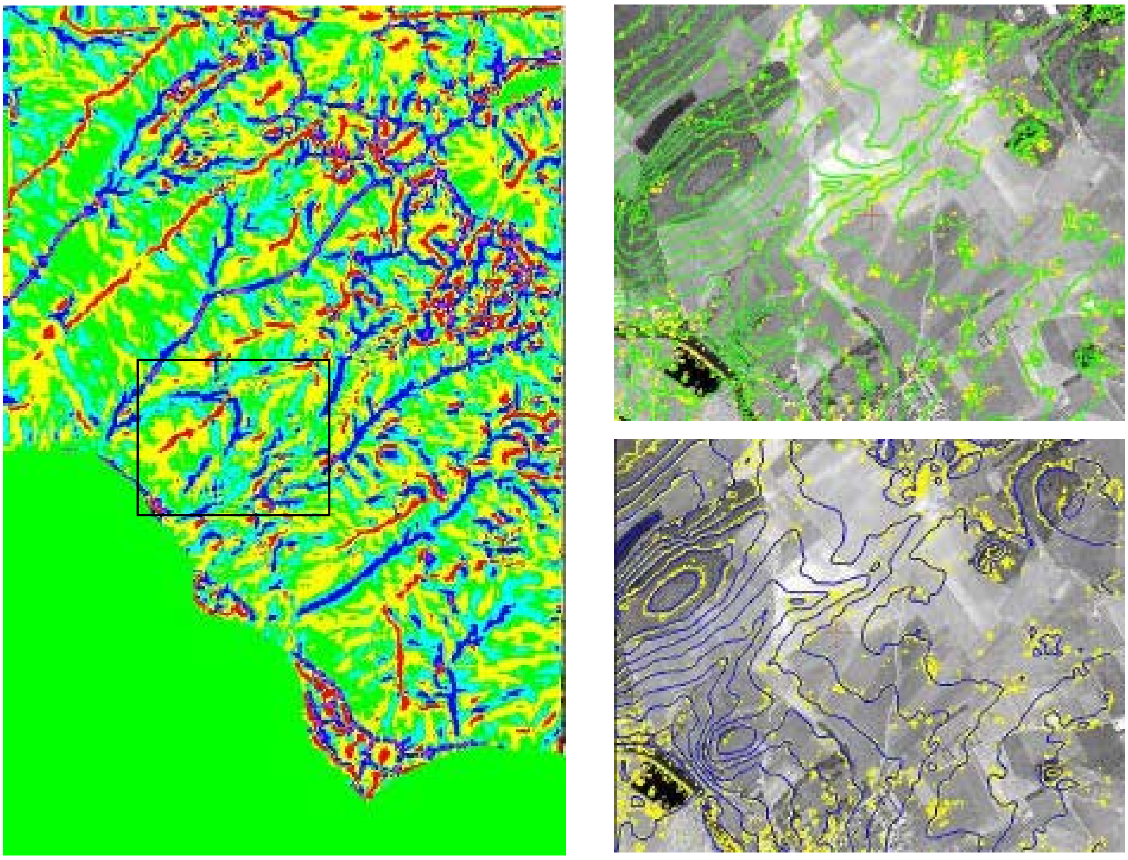

Fig. 4 – Nancy area: on the left, landform categories from the DCM; crest (in red), low convex areas in yellow, low concave area in green, and talwegs in blue and violet; on the upper right, comparison of contour lines (interval 5 meters) directly from correlation in yellow and after standard smoothing in green; on lower right, same in yellow, and cartographic smoothing in blue (this last result could probably be accurate enough for smaller scales)

In the near future, the choice of the parameters and thresholds has to be reduced according to the operator's recommendation. This will allow more automation at this stage.

2.2.4 Manual editing

Manual editing is the last step. After all the previous processes, the DTM obtained has still to be manually corrected. The module ITE offers three DTM editors for interactive manual editing:

- post editor: adjust the point height by manual measurement with the moving floating mark. The only use found valuable is to create spikes or small summits but is almost never used.
- linear editor: recalculate the elevation in a given bandwidth when characteristic lines do not caricature the terrain enough (because of trees or other "annoying objects"). For sub-urban areas, its use is also appreciated to figure small relief due to human activity which usually presents sharp slope changes: bridges, motorway, talus, which are always smoothed too much.
- area editor: change all elevations within an area delineated by a polygon given interactively, either to remove artefacts, or to modify the surface texture. The most useful tools are smoothing convolution (unfortunately pre-defined), interpolation in a 2D or 3D polygon, interpolation under constrains, plane fill, constant fill bias and filtering obstructions by giving the height and the width of objects to be removed.

The algorithms for the last two editors are available for an interactive use and for the automatic merge with features coming from a database. The time spent for editing seems to vary from 5 to 15 hours for a pair of images sized DTM (this range depends on the operator's experience and/or the difficulty of the area). On a project such as Ile de la Réunion, 40–50 hours were planned to do the job with the standard process. For huge relief such as mountains, a single correction applied by the operator with the tools mentioned above modifies large areas very quickly even if large shadows and trees slow down the work.

This remains true that for a flat landscape, the manual process would go faster and it is up to the work unit to choose the correct way of plotting contour lines: manual or semi-automated. The technique of DTM edition and tuning the parameters for the cartographic smoothing requires motivated operator, with an accurate 3D vision and a good aptitude to analyse the relief with its characteristics elements.

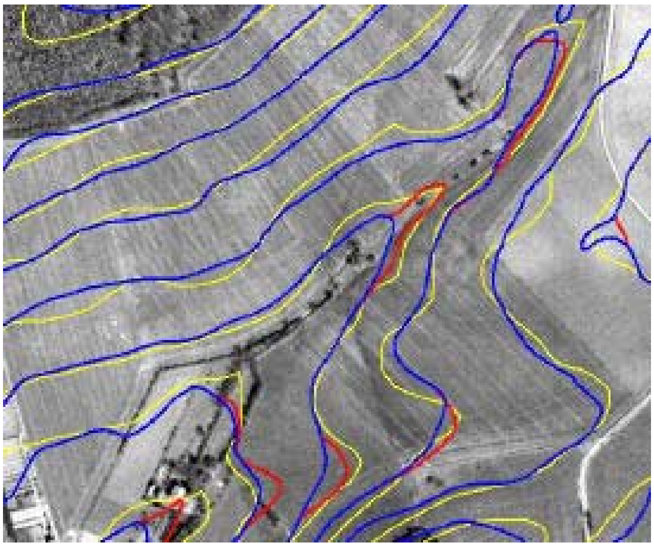

Fig. 5 – Nancy area: contour line comparison; in yellow, the manual plotting, in blue, after cartographic smoothing and in red, example of local edition on the cartographic smoothing.

2.2.5 Data project management

After the previous step, the DTM is converted into contour lines with an export format that can be imported into GeoCity.

Two kinds of operators use the process: the data manager prepares the data, by using ATE on the strip block. Afterwards, he performs post processings and cartographic smoothing.

Then, the edition operator can use ITE (DTM interactive tools). Prior to that, he extracts from the block a DTM corresponding to a pair of images, by taking also into account elevations which comes from overlapping strips already edited. Afterwards, he merges the edited data back with the strip from which they were extracted and with all the overlapping strips. All these steps have to be done very carefully to ensure that all the data used are correct and updated. An additional functionality was added to capture spot heights.

The global process guiding the operator is written in shell programs with menus that inform on the available data, activate home made softwares or open the required SOCET SET window to accomplish a task.

3 Technical requirements for the near future

3.1 Unlimited sized DTM

With the IGN France way of working, a BD TOPO® project is a block of 4 strips of 12 images each. Non interactive tools can be performed with difficulty for batch processing but their use becomes impossible when manual editing is required, performance being slowed down. This needs to extract from the DTM block, smaller areas to work on and to replace them after manual editing. This requires a heavy and day-to-day management of the overlap areas.

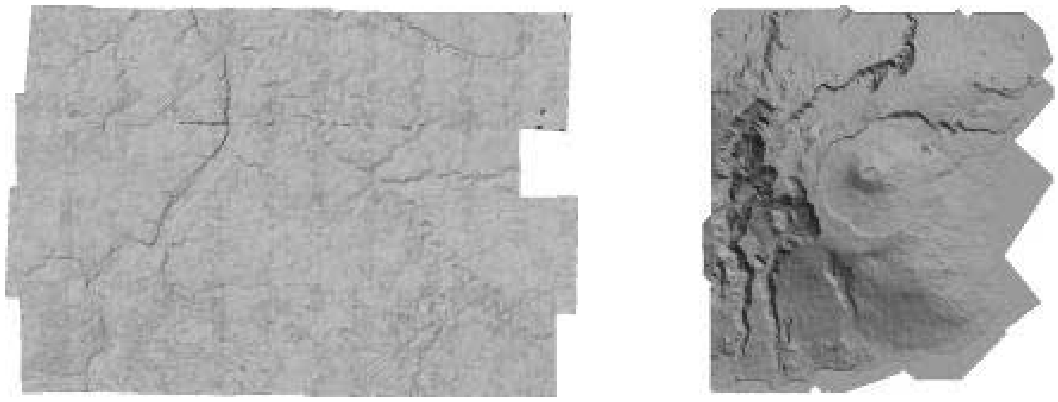

Fig. 6 – Large data sets: on the left, Chartres project composed of 4 strips of 12 images corresponding the a DTM of 4300 lines x 6300 columns and on the right, extract of Ile de la Réunion block: 23 strips for a total of 70 DTM, corresponding to a pair of images each; this leads approximately to a DTM of 7000 x 6500 posts.

Bigger the data are, slower the softwares go. Here, the new process deals with large blocks and the software does not enable the operator to work interactively on them. As was done with the images, a tiled DTM format could be helpful. This is a major requirement because without it, processes have to cut frequently into the large data set, to allow edition on small areas, and then merge back the result with the first data set. This needs some temporary data, complicates the storage problem, slows down the process… More than half of the time spent on non edition tasks is lost in data management in the overlap areas.

3.2 Higher reliability; "What you see is what you get"

When editing a DTM, the operator usually uses images with a pixel twice bigger in both dimensions than the full image resolution. At that scale and after edition, the result appears correct and is exported nearly directly as contour lines. Unfortunately, the integration in a GIS shows unacceptable jagged segments when a display is asked to a much larger scale, as often done.

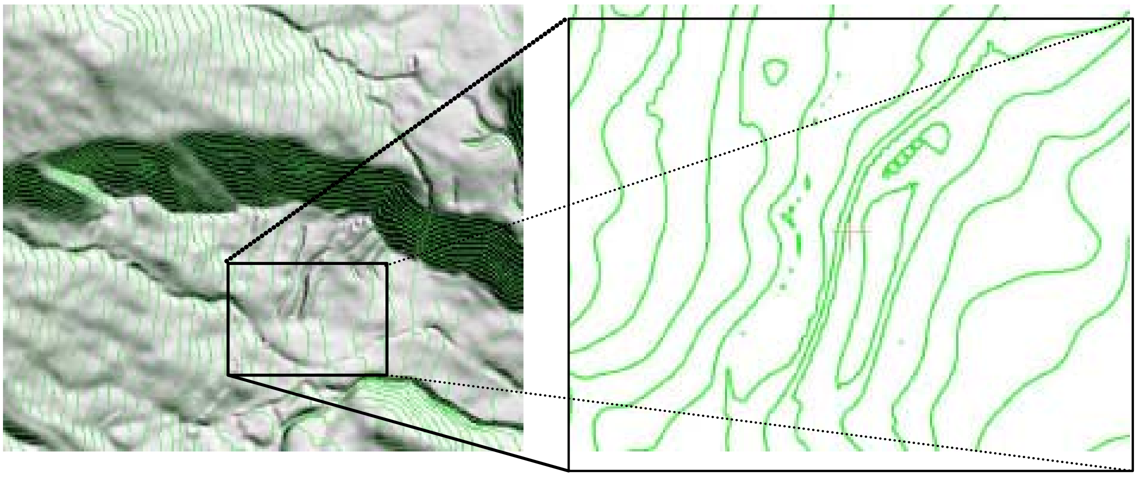

Fig. 7 – Jagged contour line: the size of these little breaks is in the same order as the DTM post spacing. These artefacts are localised along narrow characteristic lines edited by the linear editor; their size is close to the post spacing value.

This probably happens during the resampling from raster to vector. The smoothness of contour lines should be preserved for all the scale bigger than the one used with primary data. Even if an additional filtering can be performed on the raster data, the only satisfactory solution is a reliable algorithm to convert the DTM to contour lines.

3.3 More functionnalities

3.3.1 Powerful batch-processing

To merge external data to improve elevation reliability means to be able to choose the order of use the different classes and the different smoothing used. The same features are often used several time, at different steps. As it is not possible to be done with Socet Set, all the main batch functionalities are at present done by home made procedures very basic tools from the Socet Set developer’s kit.

3.3.2 An hybrid linear/area editor

The use of an area tool often generates bord effects, comparable to stair steps along the polygon perimeter. These undesirable effects could vanish if a reliable resampling method was used. Another approach would involve a linear algortihm such as making a uniform slope resampling in a bandwidth following the polygon contour given by the operator.

3.3.3 Integration of cartographic smoothing in interactive tools

At the moment, our experience in production is only 6 months long. The relative complex tuning of the algorithm presses a more automated procedure to be used in the near future. With no more than two or three parameters accessible, this should give the opportunity of allowing its use, not only globally on an entire DTM, but also as a new area tool, inside a polygon given by the operator. To make this possible, a bigger experience is necessary. The operator’s feedback will enact what can be done in terms of development.

3.3.4 More functionalities

All IGN home-made tools are interesting, in reference to the cartographic mean scale purpose given in the introduction. Time spent on their development should not be lost again for similar application. In addition to the topics listed above, the other programs perform:

- large window smoothing: to prepare the terrain caricature,
- a slope calculator,
- a viewer of DTM, DCM or similar raster files to display their content on a grey level,
- a procedure to adapt the operator’s personal bias by averaging measures of the image pair on the check/control points available.

3.3.5 Higher ergonomy

Many of the programs involved in the new process are young tools. Their ergonomy was made at first from the developer’s point of view, even for some Socet Set modules. The most important items are to:

- share properly the cursor between the different Socet Set modules such as ITE, SKECTH or FGIS,
- give standard references for naming,
- set the different default parameters to useful values,
- reduce the number of mouse clicks.

4 Conclusion

Introducing this new tool in production at IGN unit is now achieved but a lot has to be done to improve its performance. The present state of the art is a process that gives good results on area with high relief but a larger use is still a goal. The use on sub-urban area is more problematic because of the numerous and various obstructions, with human-built shapes (non natural) such as bridges, talus along the roads… This will be possible with more automated programs and more reliable tools. The result given is enough for mean scale cartographic purpose but will improve with higher quality images, such as those given by IGN’s digital camera; tests have already been performed and prove that the result is better, especially for flat and poor textured images.

The major change for operators is to work on raster data; the contour lines displayed must be recognised just as a very sparse representation of ground surface. This justifies the visual controls given by terrain shading, always proposed during the editing process. The boring part of the operator’s work is here reduced, replaced by redundant information (as shown by the low value post spacing of 5 meters presented here). The manual part focuses now on a more specialised task that is to enhance the characteristic lines in the DTM, correlation algorithm still giving a surface which is not caricatured enough. The near future is now fully open to semi-automatic tools. This period will require a lot of effort on the interactivity between Man and Machine.

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Discussion

IGN's New Semi-automatic Process to Generate Contour Lines
Alain Duperet, ENSG/IGN France

Sassor (LH Systems):
If I understood you right, you match the DTM afterwards, so you have to compute them to have an overlap of the individual models. Have you used this technique of matching for more than two images at a time? This should also allow one to join them together to a block which should save time. Why don't you do that?

Duperet (IGN, France):
Yes, I guess you can work it that way. Then, this generates a single DTM, a small one. Then, I match these small DTMs to get a DTM strip and then transform the strips into a block. This is the process we are using now. But I do not care how many images were taken into account to get the DTM and hope the best choice is made each time by the system.

Sassor (LH Systems):
Yes, but in the process you can interchange and match many images so that you do not have to do the matching of the DTM in a later stage, which saves a lot of work.

Heno (IGN, France):
Actually we compute the DTM for one model, then for one full strip, two strips and afterwards we might get a very large DTM, which might be too big for the software so we have to cut it for interactive editing; this is a problem and since the DTM has been cut, the problem of edge matching emerges again. It is not a question of computing, it is one of handling large DTM-data sets in the software.

Boberg (Royal Institute of Technology, Sweden):
You mentioned doing cartographic smoothing of the curves. Do you use any geomorphological criteria when you perform the smoothing in an interactive manner? It seemed that it was an ad hoc decision in trying to get something that looked reasonable, but it could be improved if you had some geomorphological criteria.

Duperet (IGN, France):
Delimiting these areas means, in a sense, finding geomorphologic criteria. For me it is more important to find a homogeneous area than to have breaklines. The whole process should be as automated as possible and we find that the process of calculating the curvature can work unsupervised. Then the results are given to the operator for a thorough control and for editing. If he is not happy with the curves obtained, he starts the process again after modifying a few parameters. Once he considers the breaklines to be connected well enough, then the geomorphology of the area is adequate. In fact there are two steps, the first is to find the curvature of the terrain, and then we go on to the smoothing with different parameters according to the specific area. Considering specific areas, you will know that the DTM has to be pushed above the ground and you have to make a bias. It is also important to use a window size that is not too large. If you are not on a mountain ridge or on a valley apth then you can use a larger window size, but be careful not to put a bias on terrain with the smoothing process. So these are the two steps involved. I insist on the fact that to obtain the digital curvature model we must know the

DTM given by correlation beforehand. Otherwise there will be plenty of little breaklines that will annoy you later. But of course you can use a 21 by 21 window if necessary and only the breaklines you need will remain. This is cartography; you are interested in the curvature of the terrain.

Madani (Intergraph):
As far as I know, when this data set was provided, we ran it through and when we look at the internal precision that was discussed here, that of the DTM, it was around 3/10 of a metre. This was a surprising number, but we have to take into account your control points and how you have derived them. I cannot, at this point say whether they are good or bad, or if the DTM generators were good or bad. So further investigation has to be done to see where the differences come from.

Duperet (IGN, France):
I think the correlation is working fine on top of the trees and there are not many shadows and plenty of details. Shadows probably also contribute a great deal to disturbing the statistics.

Nicoletti (Intergraph):
It would be interesting to see how the contribution of shadows is weighing on the results, so I would like to see this for the analysis to have an actual visualisation of the residuals in the DTM in terms of the distribution, comparing the two images that are behind.

Duperet (IGN, France):
It is possible; I can do that before the end of the congress if you like.

Miller (LH Systems):
These results are very much what we would have expected as these areas are densely tree covered and contain many cliffs. You often find the root mean square going way up in the steep areas because the very small xy position displacement would cause a large z discrepancy resulting in high root mean squares.

Proposal for the Demonstration of the DTM Software at the OEEPE Workshop

A. Dupéret

The present data set is for the DTM session, scheduled on the 22th june 1999, in Marne la Vallee. It consists in:

1. Two images: 343oeepe.tif and 345oeepe.tif
2. Ground/check point in the file "ground". In this file, the data structure is
   Point number Y X Z
   Points 34* are PUG points.
   The approximate location can be found in the overview images 343overv.tif and 345overv.tif.
3. The camera is rmk_144112, calibration done in march 96.

Calibration elements are given in the "camoeepe"

You are invited to compute various correlated DTM on this area, to illustrate the way you recommend to work for this kind of landscape. At least, we expect at minimum the presentation of the following DTMs or functionalities:

- DTM with post-spacing 5m, without filtering, for the entire overlap region between the two images.
- DTM with post-spacing 5m, with a filtering you recommend to have the elevations as close as possible of the ground.
- Presentation of the interactive tools that the operator can use to improve DTM's quality

It is also asked to generate an ASCII export of these DTMs, with the following format: one line per post, X Y Z and send them back to Alain Dupéret IGN/ENSG at least two weeks before the workshop on a CDROM. A set of control points will be used to make a quality control, if possible during the DTM session.

Of course, you are invited to generate others DTM, with various post spacing and different kind of filtering, to improve the surface obtained. This can be done during your presentation in the auditorium, after the presentation of the results on the DTM required.

Editors Note
For technical purposes, the vendor's presentations, are reproduced at the end of the proceedings, in part 7.

Discussion after the Demonstration

Vendors' Demos with standardised images in terms of preparation of correlation, data checking and editing (Intergraph, LH Systems, Zeiss)

Kölbl (EPFL, Switzerland):
You mentioned that the SocetSet software can use more than two images. What is the algorithm? Do you match between two images especially selected or do you really treat several images simultaneously?

Miller (LH Systems):
The process we use starts to run on a pair of images and determines the terrain shape; then it analyses from which pair of images it will have the best view. It is a sort of pairwise type approach but very fast. Within certain constraints concerning the amount of convergence and the amount of the terrain slope, it chooses the images by which to get the highest quality. But, in the end, the matching process is done on one pair of photos at a time although that pair may be switching for each point.

Duperet (IGN, France):
In the case you have shown you could have chosen the pairs of strips where the slopes were without shadows.

Miller (LH Systems):
In the case discussed we had only one pair so there were only a few parameters, but often we had very steep slopes, etc.

DTM Derivation at Ordnance Survey Ireland

M. J. Cory, A. McGill
Ordnance Survey, Ireland

Abstract

There is still debate in some circles as to the effectiveness of digital over conventional photogrammetry. This debate rarely considers the overall map making process, neither does it consider the requirements for an efficient, effective flowline for the creation of digital mapping in the era of the Information Society.

Ordnance Survey Ireland (OSi) have been at the forefront in applying digital photogrammetry in map production since 1992. This paper describes the development of photogrammetry at OSi and its implementation of digital systems in response to requirements for systems to efficiently complete the contouring of the 1:50,000 scale Discovery Series of tourist and leisure mapping. The manner in which the potential of digital systems has been realised for the semi-automatic collection and creation of Digital Terrain Models (DTM's) is described. Some practical considerations on the employment of digital systems in the collection of DTM's are discussed, and examples are given where specific benefits have accrued to the overall map making process.

The impact of digital systems in general and digital photogrammetry in particular has been significant. Productivity gains due to the use of such innovative technology, allied with managerial and organisational improvements facilitated by new technology, have substantially improved the output of mapping compared to previously employed systems and methods, whilst maintaining quality. Despite the debate elsewhere, the use of digital photogrammetry at OSi has been an unqualified success.

1 Introduction

1.1 Ordnance Survey Ireland

Ordnance Survey Ireland (OSi) is the national mapping agency of the Republic of Ireland. It is a Government Organisation with some 300 people, with offices in Phoenix Park, Dublin, and six other offices in Cork, Ennis, Kilkenny, Longford, Sligo and Tuam.

In its Statement of Strategy (*OSi* i, 1996) the overall purpose and mission of OSi is described as

"To provide the maps and data essential to users of Geographic Information"

and four main objectives

Production: to provide a national, up-to-date database for users of mapping and GIS in support of national, economic and social development;

Customers: to develop services to exploit the potential of existing and new public and commercial markets;

Financial: develop appropriate financial management systems, improve value for money and continue to reduce the reliance on the exchequer;

Staff: put in place policies to ensure OSi has an adequate supply of skilled and highly motivated staff in a satisfying working environment.

OSi is responsible for all national mapping in the State. It also has a commercial mandate for activities that are compatible with its national mapping program. The national mapping program itself has two major components for which there are individual databases:

- Large scale mapping which incorporates scales from 1:500 to 1:10,000. This includes urban mapping that is currently updated on an annual basis. It also includes rural mapping where a total resurvey of the country is underway, using Photogrammetric methods. Negotiations are currently underway with the Department of Finance to resource this program more fully in order to complete it in a limited time frame.
- Small scale mapping incorporates scales from 1:10,000 to 1:1,000,000. A new database has been completely resurveyed using Photogrammetric methods and was completed at the end of 1998. The highly acclaimed *Discovery Series* at 1:50,000 scale is the major product of this database.

All OSi mapping is in digital form. The urban mapping, the resurveyed rural mapping and the small scale mapping are held in fully structured databases that provide additional benefits to the users. The older part of the rural database is in raster form; it was not considered economic to convert it to vector.

1.2 The development of Photogrammetry at OSi

Photogrammetry was adopted at OSi in the 1960’s, with a Wild A8 installed in 1965, and the Irish Air Corps supplied photography from a Wild RC8 aerial camera, and full ground control was provided for each model by field survey.

Aerial triangulation was introduced in the 1970’s with PAT-M4 running on a PDP 11/34. In 1974 a Wild A10 was added, in 1979 a Kern PG2 analogue stereoplotter and not much later, a Wild AMH. Analogue stereoplotters were equipped with PDP11 computers and Kern MAPS200 software and in 1980 the SysScan digital mapping system was installed. Photogrammetric data were successfully transferred from the PDP11 computers of the analogue instruments to the VAX machines of the SysScan system.

In the late 1970s, OSi had contracted out some aerial photography to commercial companies since the Air Corps’ schedule often did not meet mapping requirements, for example Institute Gèographique National (IGN) of France flew the country at 1:30,000 scale. In 1980 OSi decided to fly its own photography with hired aircraft. The RC8 continued to be used and was replace in the mid-1980s with Carl Zeiss Jena LMK camera systems. The recently installed RMK TOP camera systems with integrated GPS navigation and control has, this year, further enhanced OSi capabilities and improved efficiency.

In a series of procurements beginning in 1982, 11 Kern DSR analytical plotters and a GP1 flatbed plotting table were purchased and deployed not only in Dublin but also in Kilkenny. At the beginning of the 1990s, 4 Carl Zeiss P3s and a Leica SD2000 were added. From the software point of view, the analogue instruments and DSRs were at first equipped with the Kern MAPS200 package for feature collection, which had no interactive graphics but relied on drum plotting for quality check plots. The P3s were delivered with PHOCUS and the SD2000 with PC-PRO600/MicroStation. Around 1993, the analogue instruments, the DSRs and most of the P3s were upgraded with ATLAS, from the Boston software house KLT. The analogue and analytical plotters were heavily used for 1:1000 urban resurvey, establishment of the new 1:50,000 series and various commercial contracts, most of them at large scales.

The need for a rapid expansion of the survey programmes, in particular in rural areas and plans for completing a 1:50,000 tourist map of Ireland, and reduction in staff numbers led to a review of operations in 1992. The potential for the automated generation of contours and DTM's was investigated first because this was a time consuming task. Digital photogrammetry offered:

- Double the productivity for height generation compared to analytical plotters
- Stereo superimposition, orthophoto generation, easier training, greater flexibility in planning workflows
- Future benefits from R&D.

From loading images and orientation through to edition, compilation and final output of hardcopy and digital contours and DTMs, digital methods gave benefits of the order of 4:1 over conventional methods.

Further trials were run to assess the potential of digital photogrammetry for feature collection for the large scale database. Traditional methods appeared to offer a slight advantage, but OSi elected to go the digital route because:

- The cost differential was small, given the need for superimposition
- Orthophotos were an added benefit
- Digital photogrammetry had unarguable advantages for spot heights, contours and DTMs.
- The potential for further development in digital photogrammetry was greater
- Investment in an old technology was inappropriate since a new one had come on to the market.

The subsequent development of digital superimposition of the old raster data during data capture now greatly assists feature collection. 'On the fly' transformations ensure mapping features with different survey histories are possible, maximising office capture, and minimising field completion. The introduction of automatic aerial triangulation has permitted a 3:1 saving in time in photo-control collection, finally heralding the demise of the OSi analytical instruments.

1.3 OSi Photogrammetric Systems

Table 1 depicts the current installations at OSi. Figure 1 depicts the configurations diagrammatically.

Table 1 – OSi Photogrammetric Systems

Systems	**Dublin**	**Cork**	**Kilkenny**	**Sligo**	**Ennis**	**Total**
Scanner	2	–	–	–	–	2
Disk Storage	260 gb	56 gb	48 gb	32 gb	–	396 gb
DPW (NT)	5	7	6	4	–	21
DPW (Unix)	14	–	–	–	–	14
RMK Top (camera)	–	–	–	–	2	2
Analytical	4 Zeiss P3's	–	–	–	–	4
Analog	3 Wild (A8,A10, AMH)	–	–	–	–	3
Other	3 PC's 5 GPS Receivers	–	–	1PC	2PC's	6 PC's 5 GPS

Local area networks are available in each office. Currently work is under way to establish a Wide Area Network to enable the transfer of data between Dublin and the Regional Offices.

2 DTM's at OSi

2.1 Overview

A Digital Terrain Model (DTM) is usually an array of three dimensional co-ordinated points; each co-ordinated point has a planimetric position in terms of a co-ordinate system, and height relative to some datum – usually mean sea level at a designated point. This data can be arranged as a regular grid of points at a set interval apart, usually known as a grid DTM. Alternatively the points may be arranged as an irregular series, each point forming the apex of a triangle, with triangles arranged to model the ground surface, known as a Triangulated Irregular Network, or TIN.

At OSi DTM’s are collected and stored as grid DTM’s. The co-ordinate system is currently the Irish Grid (*OSi*, 1996 ii), with height referred to mean sea level at Malin Head. Heights are collected at Ground level. The grid array is always aligned with the co-ordinate grid system north-south and east-west.

Digital Terrain Models are produced at OSi for two main purposes:

1. For the production of contours on the 1:50000 Scale Discovery Series of mapping.
2. As part of large scale Local Authority contracts, usually for road surveys or other engineering works.

2.2 Small Scale Grid DTM

This data has been collected from 1:30,000 scale black and white aerial photography captured in the 1970’s by IGN France for OS*i* under contract. It was collected to facilitate the derivation of 10m contours for the 1:50,000 scale Discovery Series of mapping, the recently completed all Ireland series of general purpose topographic mapping. The first map sheets completed in this series were directly contoured using analytical Photogrammetric plotters, but the introduction of digital Photogrammetric workstations (DPW’s), and the subsequent productive benefits in utilising auto correlation techniques for the automatic generation of DTM’s, resulted in a change of tactics, whereby DTM’s were collected instead, and contours generated from these base DTM’s, using inter-polation algorithms..

Data was collected on a sheet by sheet format, edgematched, and stored as 20km x 20km tiles in OSi databases, both as contours and DTM’s, for subsequent supply to customers as data, or to the Cartographic production area for preparation of contour layers for printing and publication.

Due to the increasing demand for digital data OSi are currently re-evaluating this data, its specification, format, content and accuracy in order to facilitate the development of the market for such data, in particular for telecommunications and environmental analysis. Early contoured sheets are being evaluated for conversion to full DTM’s either by reformatting as DTM, or re-observation from source imagery.

2.3 Large Scale Grid DTM’s

DTM data associated with 1:2500 scale mapping is collected from photography captured at 1:10,000 scale. This photography is usually flown on a contractual basis for the production of 1:2500 detail as well as DTM’s. Only selected map sheets have an associated DTM, depending upon customer demand. As with the small scale grid DTM the grid interval is usually specified as 10m.

Large scale grid DTM’s are produced, using digital photogrammetric systems at an initial sampling distance of 3m. This grid is then used to produce digital contours at a 1m interval, or an ASCII listing of grid points at the required 10m interval.

3 DTM Collection Process

3.1 Overview

The current DTM collection process uses SOCET Set software tools on DPW's supplied by LH Systems LLC, of San Diego, California. As part of the normal work flow process to supply digital mapping at various scales all photography have ground control supplied by field crews. Aerial photography is scanned, using the DSW 200 or DSW 300 roll feed scanner, and control is supplemented by aerial triangulation using LH Systems HATS Software.

Imagery and control files are then made available to all work stations from a central data store in Dublin, or are sent to one of the field offices with DPW's installed. Currently this data transfer is by tape, although a current project to enhance the communications infrastructure at OSi will result in the development of a Wide Area Network (WAN) to permit 'on-line' data supply to the regional offices also.

Following the automatic generation of DTM's, a terrain editing process follows, and after necessary edge matching data is output for translation into the OSi database.

Figure 2 depicts the overview of this process as a flowchart.

3.2 Control

Field crews utilising GPS geodetic receivers at the IRENET ETRS89 GPS control framework provide ground control. Positions are computed in terms of the Irish Grid, although this will be replaced in the near future to full GPS compatibility. 3 Dimensional control points are collected every 3–6 models around the block of photographs covering the area to be mapped. This is supplemented by height control within the block extracted from levelling lines or existing mapped spot heights from large scale data. IRENET control has been established to a precision of ± 2cm in plan and ± 3 cm in height.

OS*i* have recently installed Zeiss RMK Top Camera systems with integrated GPS receivers. These are currently used as a navigation aid. However, the full integration of GPS into the work flow will follow in the near future in order to minimise the amount of ground control required.

3.3 Aerial Triangulation

Ground control is supplemented by full photogrammetric control obtained through Aerial Triangulation using LH Systems HATS.

All imagery used for large scale DTM derivation is scanned at 12.5µm. The small scale grid DTM has been derived from imagery scanned at 25µm, although with the increased power of current CPU's and increased cost effective disk storage this can now easily be reduced to 12.5µm, with the consequent benefits of clarity and resolution.

OSi uses the Helava Automated Triangulation System (HATS) to complete the fulfilment of Photogrammetric control requirements. HATs permits the block of images to be registered with the ground and to each other. The process allows the automatic point measurement (APM) of pass and tie points in the block of imagery. Following the APM process the RMSE parallax value is calculated and displayed for the operator to accept or reject the block measurement. For large-scale grid DTM's from 1:10,000 scale photo scale the guideline for acceptance varies from 0.4 pixels for blocks of four or more strips, down to 0.25 pixels for a one strip. If the parallax RMSE guideline is not met, additional point measurement is carried out interactively at tie and pass points that have been flagged by the software as possible blunders. At this point the images are oriented with respect to each other in the photo co-ordinate system.

Ground control points are measured interactively by the operator and a simultaneous least-squares solution performed. The software reports the ground control RMSE, with guidelines for acceptance set at 0.1m in plan and height. If these guidelines are not met then possibly erroneous points are flagged and re-observed, and the simultaneous least squares solution re-performed.

All images at this stage have absolute orientation and are ready for data extraction.

3.4 DTM Extraction

To begin the automated DTM extraction process, some manual operator manipulation must take place. From the software suite Socet Set the project is opened and the extraction images are displayed for viewing purposes. Automatic Terrain Extraction is executed and a new DTM name is created. Additional information required is supplied following a series of window interfaces. The DTM boundary is defined by drawing a polygon, drawing a minimum bounding rectangle, selecting the entire images or typing lower left and upper right co-ordinates of a bounding rectangle. The image numbers are identified for extraction purposes and the post spacing set.

In order to assist the correlation process some indication of the terrain type is given to the system. There are two main strategies:

- Adaptive Automatic Terrain Extraction.

  The selection of this strategy uses a combination of sub strategies, flat terrain, hilly terrain, steep terrain or a custom strategy that permits the system to decide the appropriate strategy.

  The adaptive automatic terrain extraction allows for a smoothing process of high precision, medium precision and low precision. An additional filtration process is available for the elimination of buildings and trees, which is based on a nearest neighbour process.

- Non Adaptive Automatic Terrain Extraction.

  This strategy allows one of the sub strategies: flat terrain, hilly terrain, steep terrain or a user defined custom strategy, to be selected.

  The non-adaptive automatic terrain extraction does not permit filtration options, but employs pre-determined filtration processes included as part of the pre-selected sub strategy. All these parameters together with the new DTM name are saved and the automated correlation process is executed either as a background or as a batch process overnight.

Strategies such as terrain types indicate to the correlation process that the terrain should not exceed predefined degrees of slope. The output model, either a grid or triangle TIN DTM is also selected.

Figure 3 depicts this process as a flow chart.

3.5 Terrain Editing

The primary output of automatic terrain extraction is a DTM file containing posts extracted from correlating a stereo pair of images. In order to review and edit where necessary the output from the autocorrelation process, a suite of tools called Terrain Graphics is provided within Socet Set.

Three main processes within terrain graphics are

- Interactive Terrain Edit
- Terrain Analysis
- DTM Registration

For the purpose of DTM derivation Interactive Terrain Edit is the process used.

To start this process the DTM file is identified. A choice of DTM depiction, posts or contour graphics is selected solely as a means of viewing the correlation output on-screen – the operator may view the underlying DTM as a DTM or as contours generated from the underlying DTM. Further parameters such as contour interval, linetype, colour, and linewidth are set. A figure of merit allows for posts to be coloured according to the terrain extraction process or edit process from which they have been derived.

With the zoom set to view the entire DTM area the graphic display is drawn based on the selected parameters.

This initial depiction of the raw correlated data usually appears rather coarse. A smoothing routine is run on the data to allow for a detailed editing process to take place. This smoothing process is based on the comparison of the altitude of each post with the altitude of adjacent posts and adjusting their altitude accordingly. This process is repeated until the superimposed 3d graphic representation of the DTM reflects the terrain on which it is superimposed.

A detailed editing of the DTM is now performed. The procedure followed is an articulate examination of the entire area section by section using maximum graphic zoom factor. For detailed editing the following three main editing tools are available, area editor, geomorphic editor and post editor.

- The area editor changes all posts within an area defined by a polygon.
- The geomorphic editor supplies additional height information to the DTM and the existing post altitudes are adjusted accordingly.
- The post editor allows for each post to be individually changed.

On completion of the detailed examination and editing the edited data is saved and output to a feature or ASCII file. This feature file is then output for translation to OSi databases.

Figure 4 depicts this process as a flow chart.

4 Practical Considerations

4.1 Quality

There are no internationally accepted or adopted quality specifications for DTM's. A common definition for "Quality" is that it is "fit for purpose". There are, however, developing criteria for what makes a "quality" item in terms of digital spatial data, and these include:

- Completeness
- Reliability
- Consistency
- Uniformity
- Content
- Accuracy

Requirements vary considerably according to the intended application and the conditions in which they are used (for example the software environment).

Factors which may affect the quality of a DTM include

- Quality of imagery, or other source data (such as cartographic contours)
- Quality of control and aerial triangulation
- Software algorithums and auto correlation methods
- Type of surface, its slope variation and type of ground cover
- Grid spacing chosen to depict the terrain
- Operator effectiveness and consistency

At OSi the original requirement was to generate contours for depiction on 1:50,000 scale mapping. In this instance there are conventionally accepted quality criteria in terms of accuracy of collected contour data – namely that in areas of medium relief accuracy should not exceed more than one quarter of the contour interval, which for the 1:50,000 scale mapping with 10m contour is ± 2.5m.

The finer the grid interval on a grid DTM the better the implied accuracy. It is suggested (*Ackermann*, 1996) that as a general rule the DTM grid should be such that the vertical accuracy would correspond to about 1/20th (smooth terrain) to 1/10th (rougher terrain) of the linear grid size. This implies an accuracy of between ± 0.5m and ± 1.0m for a 10m grid interval.

The adequacy of the terrain model, or fidelity, with which a given grid interval represents the terrain surface is also an important consideration. Conventionally this would have been considered in terms of the scale at which such terrain was to be depicted. In digital terms this guide is less useful. However, it allows a basis for determining the grid interval to be chosen. The OS*i* small scales database (from which the 1:50,000 map has been derived) has been captured using 1:10,000 scale criteria as a guide for survey specifications. Given that a 10m interval is 1mm at this scale it is clear that the resolution is more than adequate for the scale of survey. A course resolution DTM may well achieve the desired accuracy of representation, particularly if additional information is collected, such as break lines. In practice, however, due to the speed of data collection and quantity of points collectable using digital systems it is more productive to define a higher resolution grid as this is less manually or operator intensive.

It is beyond the scope of this paper (or space available) to consider factors such as quality of control, operator effectiveness and even quality of imagery. Although all have varying degrees of impact on the quality of the resultant DTM, it will be sufficient to summarise OSi criteria with respect to these (see table 2), before considering the manner in which the software performs and its influence on the quality characteristics of the resultant DTM.

Digital systems can measure many more points than can be observed manually. Therefore the accuracy and reliability of a DTM, as measured statistically, is improved considerably. In particular if points are over-determined (i.e. more points are observed digitally than are required for the final DTM) then there is less reliance on interpolation algorithms and a better fidelity of the final DTM to the ground being mapped. This over-determination permits better error detection, whether caused by the software auto correlation, or some other factor (such as scanner problems).

It is still necessary, however, to assist the software in the process by indicating a correlation strategy best suited to the type of terrain in the imagery. Clearly if these strategies fall over, or there is some other factor impacting on the situation, then problems may occur.

Again, because of the quantity of data then these problems can be identified statistically and appropriate action taken. Digital systems can provide powerful tools to assist operators in quality assurance.

Table 2 – OS*i* Quality criteria in DTM production

	Small scale grid DTM	Large Scale grid DTM
Photography Scale Type	 1:30,000 – 1:40,000 B + W Panchromatic	 1:5000 – 1:1000 B+W or Colour
Imagery Scan Resolution Scan Accuracy	 25µm ± 2–4µm[1]	 12.5 or 25µm ± 2–4µm
Ground Control Accuracy of Network Height control Plan Control	± 2cm in plan and height ± 0.25m absolute, ± 0.03m relative ± 0.25m (relative to Irish Grid)	
Aerial Triangulation Reported RMSE of Least Squares Adjustment (Guidelines): Plan Height	 ± 0.5 m ± 0.5 – 1.0 m	 ± 0.1 m ± 0.25 m

At OS*i* the final quality arbitrator (before the customer!) is the operator. A manual editing process is necessary in any case, in order to reduce post heights on buildings or trees, for example, and in the large scale DTM in the vicinity of hedges. There is not an over-reliance on either the software or the statistics reported, and the normal process includes a visual examination of the resultant DTM, to ensure it 'looks right' in stereo.

4.2 Measures of Quality

In order to assess the quality of a DTM (or any spatial model of the earth) one must establish what is "truth". This can be done either by comparing the DTM with one of a higher quality in some structured way, or by carrying out extensive, statistically significant, sampling of the terrain by independent direct measurement using more "accurate" systems and methods than used to create the DTM to be assessed.

In Ireland, the absence of any DTM previously prevented comparison with a higher quality model. As no truly independent measurement was possible (because the existing height network was used to control the models in the first place) it is arguable whether statistical sampling would be effective, or scientifically sound. However, some comparisons were undertaken in various areas using pre-existing levelled heights or newly levelled lines. These indicated that DTM's were acceptable for the purpose they

[1] Manufacturer quoted precision is 2µm. In general OS*i* have achieved 2–4µm on a wide range of imagery in a production environment.

were collected for, in terms of accuracy, and in the absence of any existing comprehensive model of the land, they were certainly acceptable in terms of completeness, and other quality criteria. With the availability of the high precision GPS network, and the proposed development of a geoid model, there will be the basis for truly independent accuracy tests of DTM's to be carried out in Ireland in the future.

The adequacy of the modelling of the terrain is dependent on the grid interval and the nature of the terrain. In this instance, oversampling is a safe option, and visual inspection ensures that the terrain model is an adequate representation of ground.

Finally, it is notoriously difficult to establish a measure of quality that is widely understood by users of spatial data. It is possible that as a result, surveyors and photogrammetrists over-specify quality requirements, thus "blinding" the user with science. The bottom line remains fitness for purpose, and if this is borne in mind then few problems should arise.

4.3 Productivity

The impact of digital systems on Photogrammetric productivity has been widely discussed and reported elsewhere (*Cory et al*, 1998). This impact has been noted particularly in the area of height collection and DTM deviation. Productivity improvement have also been expressed in terms of increased number of points observed per second, which allied to the increased number of points covering the area realise significant gains in productivity and quality. An increase from 1 point over 2 or 3 seconds to 12 points per second are possible (*Ackermann*, 1996), depending on the precise set of circumstances.

At OSi the impact on productivity has been marked throughout the data collection flow line, not just in the number of points collected per second. The introduction of digital phogogrammetry has enabled other digital processes to be introduced with significant benefits in terms of numbers of map units produced, the time a map is "in the system", and the quality of map produced.

A number of examples will be given, and a summary of the benefits in the overall productivity of OSi since the introduction of digital photogrammetry provided to enable both the macro improvements to be assessed, alongside the detailed process improvements.

4.3.1 Example 1: Automated Air Trig

Each 1:50,000 map sheet consists of approximately 50 stereo models. The observation of pass points, tie points and ground control, digital processing and adjustment, and the preparation of control files to enable operators to set up stereo models took up to 3 weeks using the Kern DSR Analytical plotter and PAT-M Software. This has now been reduced to less than 5 days, including scanning of imagery.

4.3.2 Example 2: Contour Generation

Prior to the introduction of digital systems in the map making process a typical 1:50,000 map sheet covering a ground area of 30km x 40km would take up to 5 years to produce. The contour generation alone, excluding acquisition of photography, control, aerial triangulation and cartographic work, could take many weeks for one sheet. A similar sheet today utilising DTM processes and contour generation software takes a few days.

4.3.3 Example 3: Digital "Trace-off"

The re-survey of large scale mapping by photogrammetry was greatly enhanced by the tracing of detail hidden on the photography (due to trees or shadow) off older mapping. This was carried out manually, and reduced the amount of field completion time considerably. With the introduction of digital photogrammetry the old map could be introduced at Photogrammetric plotting stage, minor transformations carried out to ensure a good local fit, and the detail traced off by the operator with the old map, photograph and new detail all visible on one screen. Although this gives only minor productivity gains, enhancements to the quality of the finished map (less re-drawing, better fit of detail etc) were achieved.

4.3.4 Example 4: Flexible, parallel working

In the 'traditional' Photogrammetric operation model set up time was a significant overhead in the planning and execution of mapping projects. The amount of work, the flow of work to plotters and the time spent on a plotter all contributed to the overall time a task takes. Furthermore, only one operator could work on a given area at one time on a specific machine. In the digital environment, set-up time is reduced from 15 minutes to less than 2 minutes. An operator may now occupy any workstation (if licenses are available), and imagery may be shared, facilitating edge working, or even DTM collection occurring at the same time as feature collection. The overall impact on through time is significant.

Because of the increased integration of systems the productivity gains may best be demonstrated by Table 3 which summarises the overall improvements experienced over the last 4 years during the introduction of digital photogrammetry. It should be stressed however, not all these improvements can be, or should be, solely attributed to the new technology, as new organisational and managerial initiatives have also had a significant impact.

Table 3 – Productivity gains during introduction of Digital Photogrammetry

	1994	**1997/98**
Air Trig. (Large Blocks)	1 DSR 1200 Models/Year 2 Staff required	1 HATS DPW 3600 Models/Year < 1 Staff required
DTM / Contouring	3–5 Days/Model contouring 19 Staff required on DSR 9 Staff required on DPW	1–1½ day/model DTM
Overall Output **1:1000 Revision** **1:2500** **NPS+DTM** **1:50000**	 600 plans 210 plans 7 maps 171 Staff on Data Collection	 1800 plans 640 plans 13 maps 150 staff on Data Collection

4.4 People Issues

The adoption of digital photogrammetry necessitates a shift in attitudes. These shifts are required both by managers and staff.

Despite initial reluctance to embrace the new technology (which is common with change of any form) staff have adapted well and, in general, prefer DPW's to analytical and analogue equipment. The drudgery of point DTM collection is now removed! It is interesting to note that new operators trained on DPW's are keener on this technology than those who have converted from 'traditional' photogrammetric plotters, although all accept it. The new skills required, such as systems management, networking, data management and system administration, are common throughout a modern technological operation.

With DTM's in particular, a tendency to over edit was noted, along with an initial mistrust of the output from automatic elements in the software. This has receded as experience and familiarity with the software increased. Good training has been crucial to the successful implementation of the systems, as has good, effective and timely support and development from the suppliers, LH systems LLC and their Irish Agent, Survey Instrument Services Ltd.,

The whole management environment required to be built on trust and value in the adoption of new technology. Without a relationship more akin to a partnership at times, it would have been difficult to have overcome the initial difficulties in installing such cutting edge technology. This attitude is required from the top down in both organisations.

After almost 20 years of reducing staff numbers OSi has begun recruiting staff again. In the last 2 years up to 8 new staff, mostly graduates with some experience in spatial data capture, have all been employed on the DPW's with a high degree of success. Experience so far is that they adapt very quickly to the new technology and become productive in almost 6 months. However, OSi are experiencing difficulty in recruiting (due to the buoyant economy and bureaucracy involved in employing in the Civil Service), and have shortages in DPW operators which are now affecting production. This has necessitated a rethink on the recruitment strategy, and in future OSi will probably employ school leavers for training as operators. It will be interesting to see how quickly they adapt to digital photogrammetry.

5 Conclusions

Ordnance Survey Ireland aims to provide the maps and data essential to users of geographic information. In order to provide a national, up-to-date database, new and innovative technology has been employed throughout the operation.

Photogrammmetry at OSi dates from the 1960's. With the expansion of its programmes and pressures on staff numbers, digital photogrammetric systems were introduced in 1992. OSi now have one of the largest installations of such systems among civilian mapping organisations in the world.

A key driver for introducing this technology has been to enable the completion of the 1:50000 scale Discovery Series by the end of 1998 and in particular the collection of height data for contours in this map series. The most efficient method for doing this has been by collecting DTM's and subsequent conversion to contours by software interpolation. The DTM collection process is largely automated, with operator intervention in the beginning – to ensure appropriate auto correlation techniques are employed for the terrain concerned – and at the end in quality assurance and editing.

Although no formal international quality specifications exist for DTM's, OSi data conforms to accepted practises, both in terms of conventional mapping criteria, and developing standards for such data. Productivity improvements have been significant both within individual photogrammetric processes such as Air Trig and contour collection and also in the overall map making flow line, although organisational and managerial initiatives also played a role in these. Staff has adapted well but thought is required regarding recruitment, training and the level of skills required for the continued efficient operation of such systems.

The use of digital photogrammetry at OSi is an unqualified success.

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1998, *Cory, M. J.; Kirwan, R. A.; Walker, A. S.:* "Ordnance Survey Ireland and the transition to digital photogrammetry". Information paper published by OS*i*, Dublin.

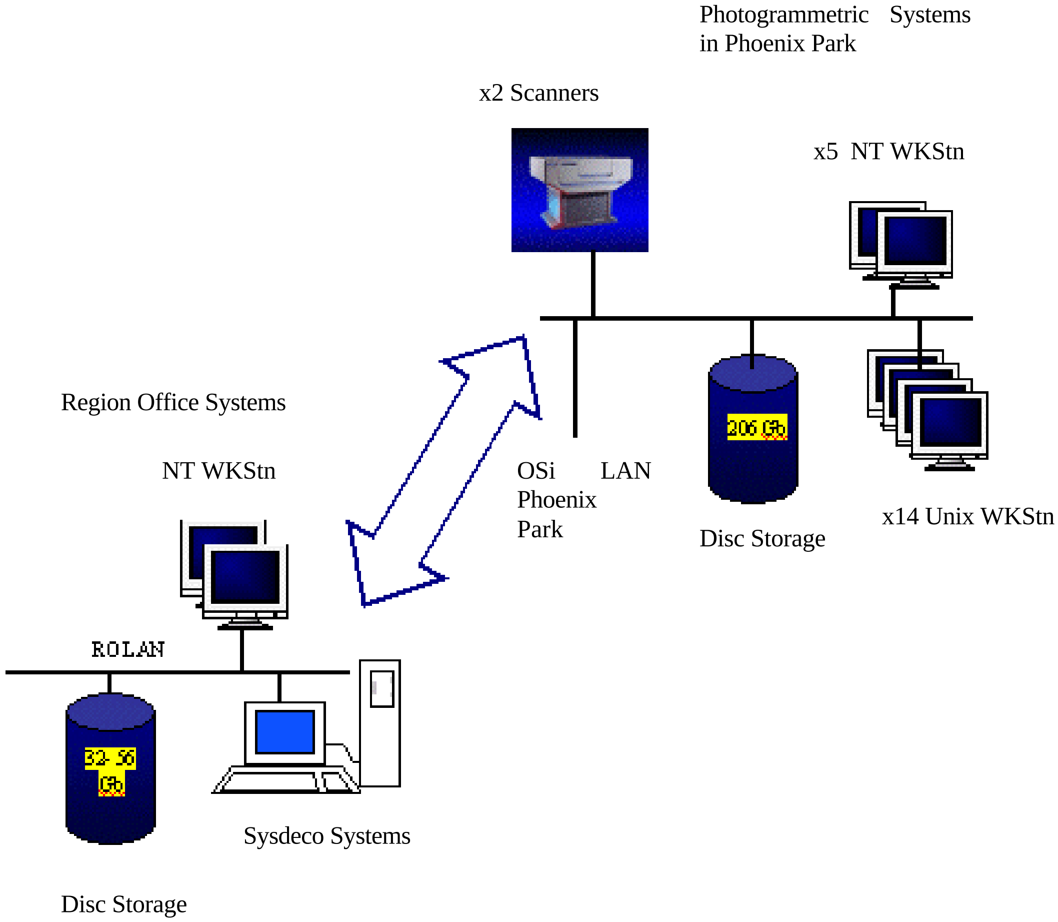

Figure 1 – Photogrammetric Systems

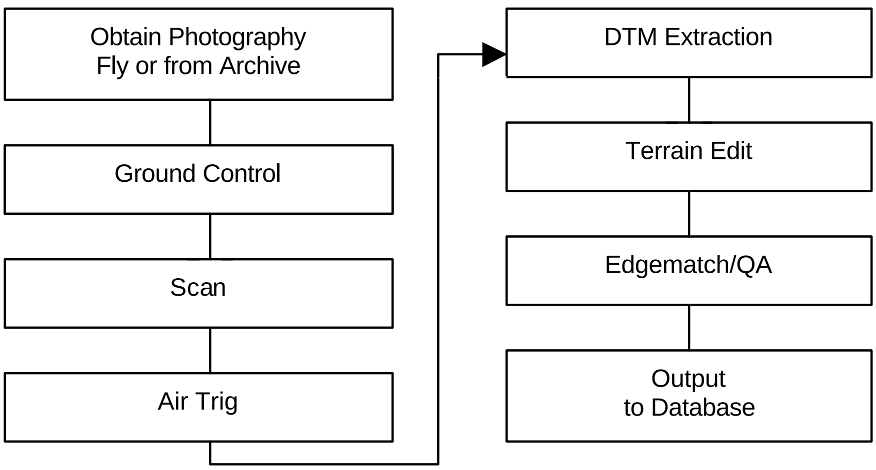

Figure 2 – Overview of DTM Collection Process

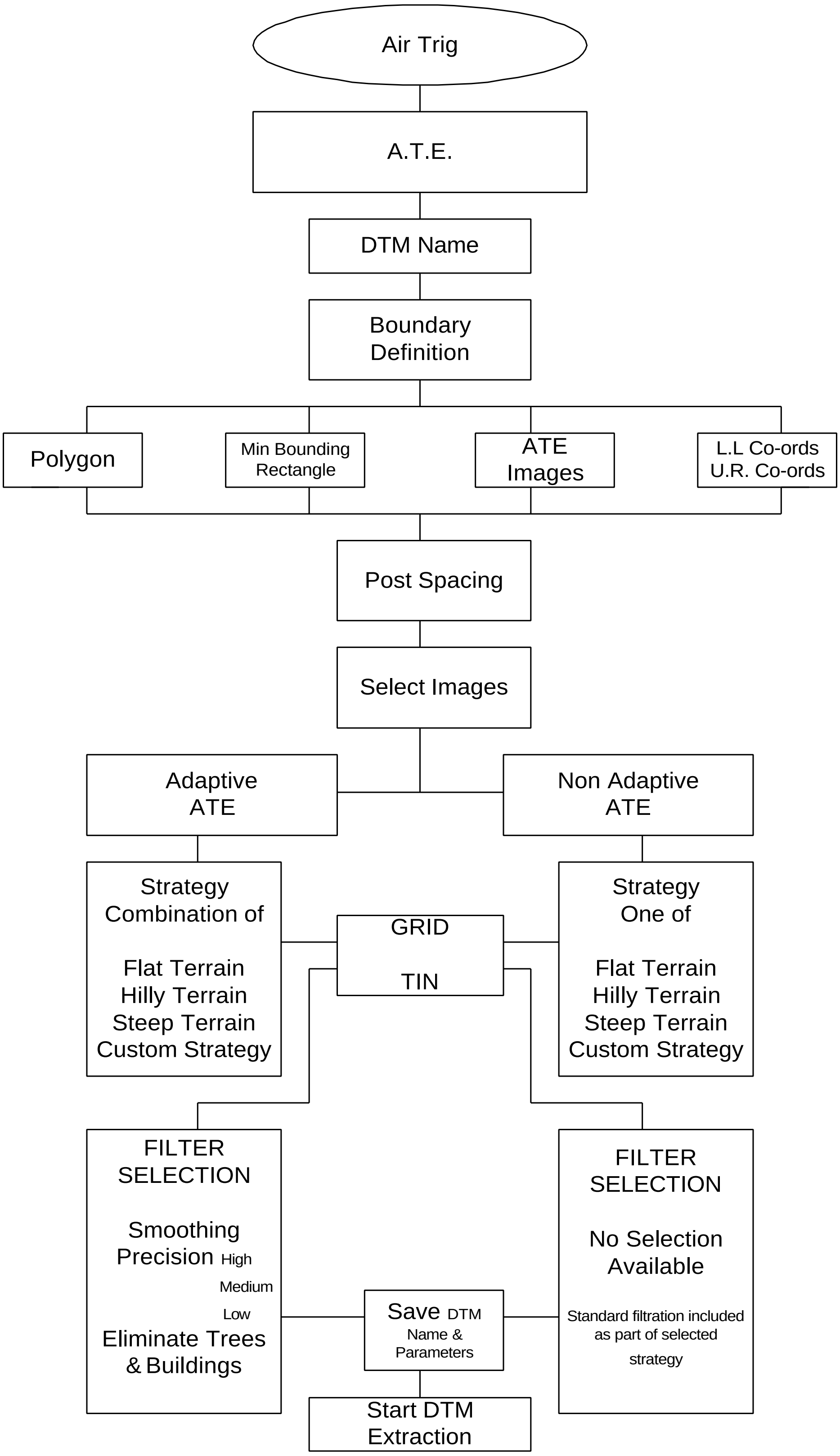

Figure 3 – DTM Extraction Process

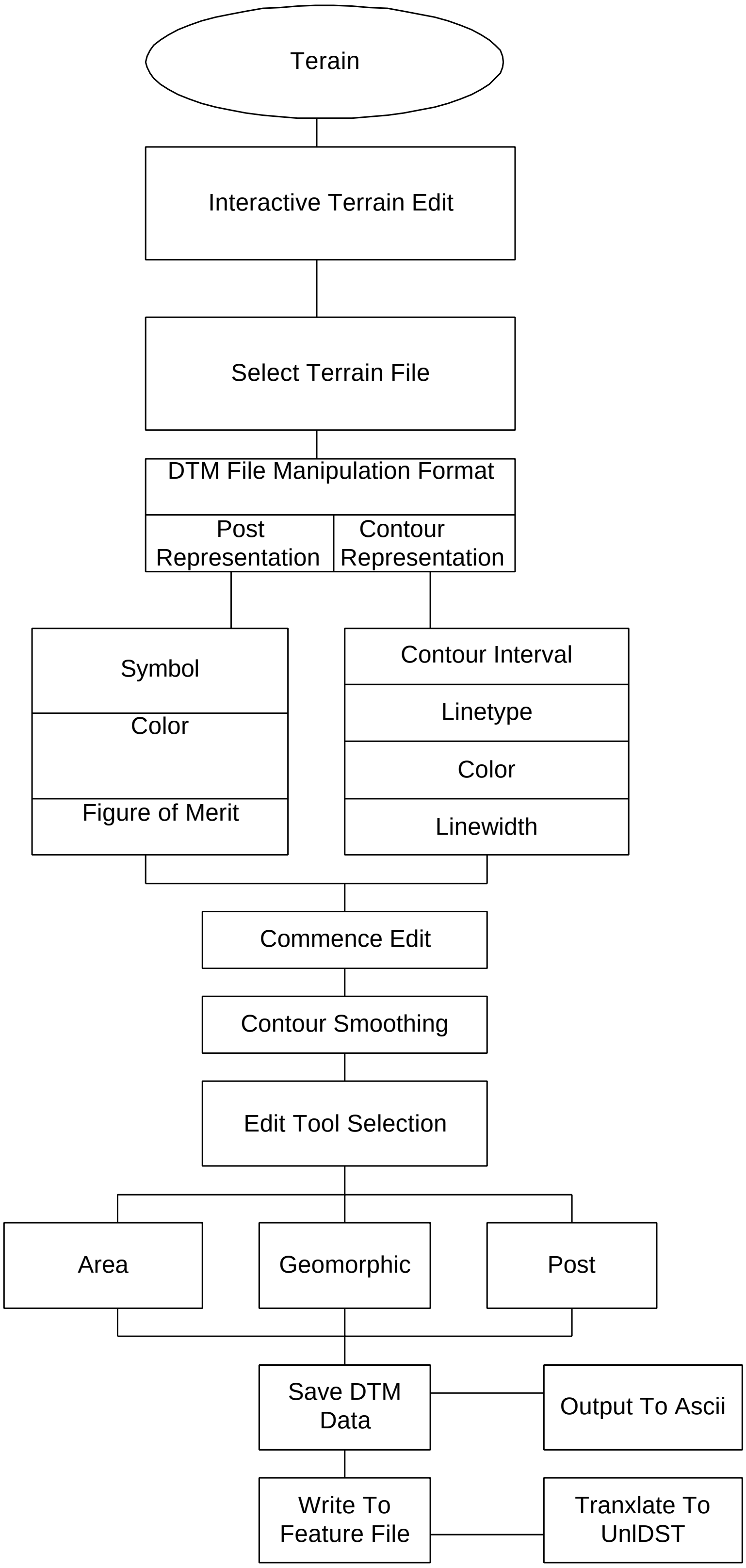

Figure 4 – Terrain Editing Process

Discussion

DTM Derivation at Ordnance Survey Ireland
M. Cory, Ordnance Survey, Ireland

Kölbl (EPFL, Switzerland):
It was an interesting paper and it is reassuring to hear that you can use the technique of matching in production. I was very much impressed by your method of quality assessment. If we analyse the precision of a DTM we will get a mean square error, but the mean square error hardly tells us anything because all the difficult areas are not especially taken into consideration. But if you use a profile, as you showed, you can interpret all the details and identify where the problems are. Is this a standard procedure in your service to use profiling for quality assessment?

Cory (Ordnance Survey, Ireland):
The bottom line for us is what the customer wants. We often find that the expression of the root mean square can confuse a lot of customers because they do not really understand how it has been derived as there are a lot of factors throughout the line of production that can contribute to the ultimate accuracy. To answer your question, profiling is not the standard way, for us it is a tool and the quality assessment carried out by the operators use the tools provided by the supplier. We have done a limited amount of quality assessment. I would like to do a lot more but it is an expensive business and we have to consider costs. Ultimate truth would require levelling on the ground. But the operators use their tools to assess their output and of course, there is an independent quality assessment too.

Hoschtitzky (ITC, Netherlands):
There are features typical to Ireland: one is the continuous rain, the second is the cliffs in the coastal areas and this has already caused problems in depicting them on classical, conventional maps. How do you a) describe the cliff areas by means of DTM and b) what problems do you encounter in those areas with the new systems, when you establish the DTM?

Cory (Ordnance Survey, Ireland):
Manual editing is the answer. There are problems you get from the automatic correlation in those areas and we have to do it manually. Because we have used these automated methods to produce the contours, there is still a cartographic element at the end of the line. These data sets are transferred to a cartographic map publishing system supplied by Barco and they are corrected to make it look appropriate on the map. But we have used very densely concentrated contour lines and that adequately depicts the problems in cliff areas.

Grabmaier (ITC, Netherlands):
You have made a comparison of different checking tools, showed the use of existing contour lines and you used the interpolation between the contour lines as a comparison with other DTMs. But to my mind this should not be done; you should take the contour line only as it is and not in between; there is very little information about the terrain in between them. Whatever height you interpolate there, it does not have much significance. Another remark is related to what professor Kölbl (EPFL, Switzerland) said about

standard deviation. I think that especially on large data sets like a big DTM, the standard deviation does not tell us very much. For example if I take the laser scanning of half of the Netherlands, the standard deviation is ±3m, so this does not say much about the real quality of the DTM in the important areas.

Boberg (Royal Institute of Technology, Sweden) (Stockholm):
In the investigation of DTM that we have done, we found that the nature of the terrain had a clear influence on the standard deviation of the checkpoints as well as on systematic error, i.e. rough terrain gave a clearly higher systematic error than smooth terrain, Moreover, this has implications on vegetation and other aspects of terrain. So in discussing the quality aspects of DTM, there are many parameters to take into account. Did you think about these types of influencing factors?

Cory (Ordnance Survey, Ireland):
Indeed, this is a challenge for us to come up with a quality assessment that people can understand. Users of DTMs would like some factor which would tell them what is the quality of this DTM. How do you express it so that people who are non technical can understand it? We talk about things like fidelity, we can express our mean square errors and different types of terrain and it is important for us to know all this as experts. But, as suppliers of data to users, the bottom line is to tell them in a comprehensive way what they can expect to get and how they might be able to use it.

Utilisation of Match-T Intergraph Software in the Automatic Production of Digital Terrain Model

T. Blaudet,
Alpes Pyrénées Images, France

Presentation

The speaker is the responsible of the digital photogrammetric department in the firm Alpes Pyrénées Images.

This firm was set up in 1998 from a joint venture of the Degaud Group (Grenoble – France) and a photogrammetric firm known as Pyrénées Image Environnement (Tarbes – France)

Since the creation of this company, we have used an Intergraph Z II station, equipped with the "Crystal Eyes stereovision system". We made the decision to produce Digital Orthorectified Images. This decision generated for us a demand for Digital Terrain Model (DTM) and, as a consequence, we bought the Match-T software

This presentation is about the use of the Match-T software from the point of view of users who have to product.

Maybe this speech will be heard by the vendors as a bit critically, but I want it to be constructive.

1 Programming in Match-T

In order to obtain the Digital Orthorectified Images, we use the Intergraph treatment chain "PHOTOGRAMMETRY". Among these products, the Match-T software opens the possibility of automatic generation of DTM by automated correlation.

To make it work properly, we have to carry on a number of initial preparations and to setup the appropriates parameters in the software. I will talk to you about these points now and I'm going to try to highlight the positive and negative points (pros' and cons') we found when using this software.

1.1 Generation of epipolar images

To use Match-T, we have at first to create epipolar images in order to allow the software to generate homologous points through automatic correlation. These types of images must be prepared separately during the creation of the project. It's a long process of calculation (about 1/2 hour per image) however this process can be made to work in batch during the night, for instance.

1.2 Setting up the parameters in Match-T

We have to setup many parameters in differents Match-T dialog boxes, these boxes offers a lot of choices.

1.3 DTM extraction parameters

We have to define, for each model one or more collection boundary according to the terrain type.

POSITIVE:

1. It allows us to withdraw the peripheral areas of the images where the DTM is often wrong
2. It allows us to adapt the calculations to the area

NEGATIVE:

1. The parameters of various areas can be very different

1.4 Geomorphic Information

This function allows us to take in account the digitized elements drawn in stereovision through ISDC which is another part of the ISSD sofware.

POSITIVE:

1. It offers multiple possibilities, we can digitize obscure areas, ridges, drains, vertical faults and so on...
2. It offers the possibility to use elevation points coming from previous jobs

NEGATIVE:

1. We found that without breaklines, the DTM gave erroneous results at the places where the slope varied suddenly. This happens despite the different possibilities that the software offers to set up the “smoothing filter”.
   As a result, because we need a good DTM, it's essential for us to digitize breaklines before proceeding Match-T. It can take a long time to do this.

2. Some options such as "breaklines densification" which allow you theoretically to create a densification of elevation points along a digitized element and, incidentally, to improve the quality of the resulting DTM, do not work properly.

1.5 Surface reconstruction

This parameters area allows us to set up the grid width and the “smoothing filter” to use during the process.

POSITIVE:

1. There is an interesting option named "adaptive grid" which enables the software to generate a denser grid at the places where the terrain has got more important elevation variations.

NEGATIVE:

1. It is too complex and maybe too hazardous to try to change the default values of the different parameters. For instance, when the threshold of tolerance (sigma) is changed, it gives, after processing, big variations of precision in the DTM
2. The “smoothing filter” creates accuracy problems in intermediate areas where elevation varies a lot.

1.6 Terrain type and Matching

We can use 4 methods to set the parameters of the terrain type: flat, hilly, mountainous and user-defined, this allows the software to adapt to the possible changes in the elevation of the terrain.

NEGATIVE:

We found that this parameter did not seem to have a big influence on the results except, we just learned it yesterday evening from Inpho people, if we change the value of epipolar line distance in the appropriate dialog box

1.7 More DTM Extraction Parameters

This option dialog box is supposed to allow us to change some calculation parameters such as "threshold of tolerance for correlation", "reduction of interest points", "precision limit for calculation",...

NEGATIVE:

We found this too complex to use, the cautionary changes that we made, even for a limited number of parameters, gave very erroneous DTM results.

1.8 External Data to ISDC (ImageStation Data Collection)

This part of the program allows us to send the datas in a graphical file, this part of the program works well, no particularly comments.

2 DTM extraction

This process can work in batch mode, it consists in a three steps operation, and each process can be done at different time. The process sequence is as follow:

1. Generation of the «feature pyramids» on 5 levels in order that the homologous points can be correlated using an epipolar geometry approach. This part of the process is quiet fast and reliable.
2. Extraction of the DTM points from the features pyramids using a method known as "coarse to fine". This process is quite a long process and can become much longer depending on the parameters chosen during the “parameters setup in Match-T”.
3. Transfer of the DTM data in ISDC, no comment.

POSITIVE:

It is possible to generate many DTMs with different parameters using the same “features pyramids”.

3 Analysis of the results

I will remain on a cautious position for this analysis. Till today, very few explanations have been given to us by Intergraph about the non-functionality we have in the DTM results. Now I’ll tell you about the main problems we encountered sometimes.

- Doing a completely standard Match-T workflow, it occasionally happen that the DTM points, in a large area, are completely wrong, for example as much as 2 to 10 meters in elevation. The only solution that we found after a long investigation was to restart the model at the very beginning, that means that we had to regenerate the epipolar images, the features pyramids and to reprocess the DTM extraction.
- We can say that, the “smoothing filter” is not capable of making accurate very often the transcription of the sudden variations of the terrain slope. That creates a problem when we have to generate contour lines from the DTM. As a result, we have to digitize manually the breaklines.
- At the moment, it is not yet possible to program the next step of the treatment, which is orthorectification from the autogenerated DTM, without proceeding a stereovision verification of the elevation points that we obtained. Too many point considered by the software as "good" or "next to the threshold of tolerance" are really out of the fixed tolerance.

We still obtain no explanations today from Intergraph about these experiments.

4 Conclusions and recommendations

As a conclusion, I will say at first that we wait from Intergraph a more efficient technical support. Too many of our questions on the "Photogrammetry" applications remain unresolved.

We hope that the Match-T product will advance (next version) to more reliability especially regarding the advertised accuracy when setting up the parameters. We also wait for more possibilities for the “smoothing filter”; in order to obtain a more improved version of DTM.

Our experience at this time shows that this product is efficient for large-scale images and that it is more efficient with black and white images than with color images.

For the small scale images, the precision of a manual DTM it so accurate that an automatic DTM extraction still can not compete. However it is certainly possible to orthorectify very regular areas with an automatic DTM extraction if a large number of breaklines have been digitized.

We are generally satisfied with this product which allowed us to save a lot of digitizing time, but failed to deliver all the possibilities we were expecting. Maybe these are "youth mistakes" and the next coming up version will improve the capacity and reliability of the product.

We have now a year of practice with Match-T, this experience is with black and white and color images. We allready generated for different purposes more than 100 square kilometers. The results obtained are considered to be 75% of that which we were expecting. More automatization is required in order to decrease the digitizing time that we have to spend and would be a great step forward.

Discussion

DTM derivation with Match-T
T. Blaudet, France

Kaczynski (Institute of Geodesy and Cartography, Poland):
About the Match-T: as we have seen, you had mostly used default parameters which are apparently very sensitive. Moreover, why did you use the green band for DTM generation of colour images? Secondly, to my mind the grid space of 11m for 26 000 is unnecessary.

Blaudet (Alpes Pyrénées Images, France):
The use of the green band first is a default value. We made a test with the blue and red one and it did not make a big difference, but as we live in a mountainous area, the results were better with the green band. This choice was made by those who did the programming and my test seemed to show that it was the right one for mountain areas. Secondly, the grid spacing here was an example; 11m is a default value. For practical work we use a smaller grid spacing, in this example a 3m grid width.

Kaczynski (Institute of Geodesy and Cartography, Poland):
Another comment concerning the green band; if you scan an aerial photograph in colour, you can make it black and white. This scan can be used for DTM generation with better accuracy than with the green band.

Blaudet (Alpes Pyrénées Images, France):
I agree with you, but this would require a special scan for DTM-generation.

DTM Determination by Laserscanning
An Efficient Alternative

B. Petzold

Landesvermessungsamt Nordrhein-Westfalen,
Bonn, Germany

Abstract

Laserscanning was proposed as a new technology for the derivation of Digital Surface Models and Digital Terrain Models. From the beginning it was tested in Germany by a user group of the National Mapping Agencies (NMA). Since the results came up to the requirements, a proposal for using laserscanning as a standard method for the derivation of DTM was set up.

1 Introduction

In the beginning of the nineties first articles could be read about laser scanning technology, used for the determination of Digital Surface Models (DSM) or even of Digital Terrain Models (DTM). In the following, DSM stands for an elevation model describing the ground surface *including* objects on them, e.g. buildings, and DTM stands for an elevation model describing the ground surface *without* objects on them. A DTM is often equivalent to a Digital Elevation Model (DEM).

Laser scanning technology promises to be an alternative to traditional photogrammetric methods used for different survey tasks since it offers a really high point density. The advantages are achieved among others by taking profit of the availability of high frequency lasers, high precision airborne Inertial Navigation Systems (INS) and high precision scanners. These are combined with multi-channel GPS receivers to result in a complete topographic system (GPS = Global Positioning System). The technology was said to have advantages over photogrammetric methods in forest areas or in coastal zones where photogrammetric point measurements are problematic.

Some preliminary tests of that new technology were already obtained in different Federal States of Germany when these experiences were bundled in a user group of the Federal Republic of Germany State Survey Working Committee (Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland (AdV)). The task of this group was a general exchange of experiences and, more important, the drawing up of a general description of all the details that have to be considered for planning and ordering laser scanning flights and controlling the results. This article gives a summary of the experiences of that working group and the intermediate report given to the AdV.

2 Description of Laser Scanning Technology

Laser scanning flights are offered meanwhile by different companies. The basic technology as described in the previous paragraph is the same. The differences are in general the different lasers used, the different scanning technology leading to different point distributions and the filtering technology, the latter being very important for the applications deriving a DTM. First a general description is given, followed by the different scanning technologies and the main ideas of filtering the given laser points.

2.1 The Basic Technology

As already described, three important components determine the technology: the laser, INS and Differential GPS (DGPS). The basic idea is to calculate polar coordinates for the laser point. The laser rangefinder itself is installed in a commercial camera mount of a single or twin engine aircraft and measures the distance between the aircraft and the laser point. The direction of the beam is calculated by combining the angle of the scanning system with the aircraft's angles, given by the INS. The position of the aircraft and thereby of the origin of the laser beam is known by using DGPS, and finally the coordinates of the laser points can be calculated in the European Terrestrial Reference System 1989 (ETRS89). For the transformation from ETRS89 to the local reference coordinate system, the transformation parameters and the geoid undulations are needed, the latter to define the height above sea-level of the laser points. In short the determination of laser point coordinates is for the most part transformations and interpolations.

As the laser beam can be extremely focussed, the diameter of the laser spot on the ground is only of some decimetres and varies from 3 dm to 14 dm for the different systems. The reflection coefficient of the ground determines which portion of the emitted signal returns to the laser. It depends on the wavelength of the laser and differs especially for white and black surfaces.

Most systems are using a pulsed laser. In this instance the distance is given by measuring the time the laser emission, modulated by a distinct pulse of some nanoseconds, needs to run the (double) distance from the aircraft to the laser point. Even though the diameter of the laser beam is very small (see above), it is not infinite. So, often the beam meets two or more obstacles partially, especially in forest areas where for example one or more branches before reaching the ground. This results in two or more reflections of the pulsed beam returning to the laser rangefinder. Most of the systems are capable meanwhile to register all pulses returning to the laser rangefinder, at least the first and the last pulse (first pulse mode / last pulse mode). Based on these measurements, different applications are possible. The derivation of a DTM is of course based on the last pulse measurements: if there are several pulses returning, only the last one can belong to a point laying on the ground. For other applications, for example the derivation of 3D-city models, the first pulses are more important, and for the derivation of the biomass the first and the last reflections are needed.

One system is using a multi-frequency sidetone concept for the distance measurement. The laser beam is intensity modulated by a sinusoidal signal. The received sidetone phase is compared to the phase of the emitted sidetone. The distance is finally calculated from the phase shift which is proportional to the time the beam needs to run the distance between the aircraft and the ground. Two or more modulation frequencies are necessary to solve the ambiguity that occurs since the wavelength is normally smaller than twice the distance between the aircraft and the laser point. The system is described more in detail in *Lohmann*.

Meanwhile nearly all systems offer the possibility to register the reflectance value of the returned signal. As already mentioned above, the reflectance depends on the surface material so that the differentiation of the reflecting surface material is possible. “Natural surfaces” (vegetation) have a higher reflectance value than man made materials like asphalt or concrete so that in general the differentiation of vegetation and buildings should be possible. Up to now there are not yet many experiences with the interpretation of this value, but it can be expected that the filtering algorithms for a DTM and for 3D-city models are strengthened.

2.2 Different Scanning Techniques

While the laser rangefinders used for the distance measurements are more or less similar, the differences in the scanning technique are more important. In order to send the laser down to the ground left and right of the flight path, scanners are used to reach at a more or less wider strip of laser points. To achieve that, mirrors or, for one system, fibre optics are used.

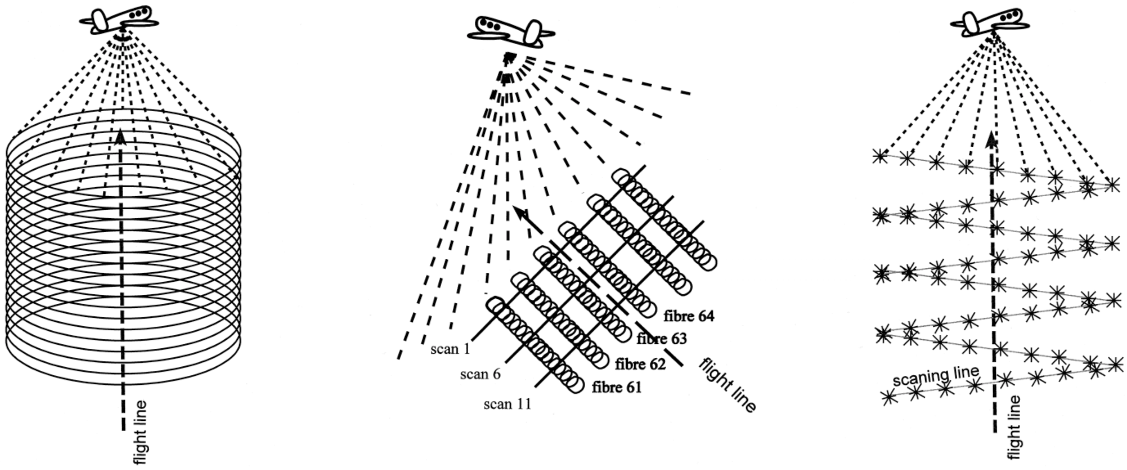

Fig. 1 – Sketch of the basic principle of the different laser scanning systems

In a first mirror system, a swinging mirror is mounted in the front of the pulsed laser deflecting the laser beam to the ground. The scanning angle of the mirror is registered or interpolated for each laser pulse. The technique results in a z-line pattern of the laser points on the ground. It makes the system very flexible while the laser frequency, the scanning frequency, the scanning angle and, to a minor extent, the flight height can be changed, resulting in different point distributions or densities.

The second mirror system uses a rotating mirror. The rotation axis of the mirror has a little inclination to the mirror, resulting in an almost elliptical line pattern of the laser points on the ground. Due to this kind of deflection no points beneath the aircraft are measured, but all points have, under the presumption of a horizontal ground, nearly the same distance to the aircraft.

The third system is using a fibre optics to build up a pushbroom of laser measurements. The laser beam is deflected in the different fibres of the fibre optic which is opened to a pushbroom. This results in parallel profiles of laser points on the ground and a very high point density in the flight direction. As the system is fixed, the only possibility to change the point density is to change the flight height, and that is limited by the maximum range of the laser.

The basic principle of the three different systems are shown in figure 1.

3 Filtering Algorithms

The NMAs are responsible to build up state wide DTMs. So the used filtering algorithms are of great importance because they are determining automatically which laser points are laying on the ground and which on the vegetation or on buildings. Thus they are leading to a high precision DTM. All agencies gathered in the above mentioned user group have experiences with the company TopScan from Germany who realized the first laser flights, so the basic idea found in the algorithms of that company are described in short.

First the lowest points in the laser point database are searched in a fairly large moving window and used to calculate a rough DTM. All points having a higher distance to the DTM than a given threshold are filtered out. Based on the remaining points a new and more precise DTM is calculated. The process is repeated several times with a reduced window size until the final DTM is found. The final window size depends on the given mean point distance and influences considerably the result. If the window is chosen too large, the terrain is smoothened and especially in rough terrain small terrain forms are cut out. If the window is chosen to small, points on large buildings are remaining in the final file of ground points. In addition, the final threshold used to determine definitively the ground points has a great influence on the result and depends on the morphology of the terrain. A lot of experience is necessary to set the correct parameters. For details look at Lindenberger, 1991 and 1993, and TopScan, 1998.

4 First Experiences in User Group

The tests already conducted by the user group members, covered the different types of landscape as they can be found in Germany. That includes very different morphologies such as flat and open terrain, forest areas with natural, small terrain forms, hilly areas with and without forest and even special morphology like vineyards.

One of the first and most surprising results was the fact that even in coniferous forests ground points were measured. Of course a lot of vegetation points were filtered out, resulting in a mean ground point distance of about 15 m or 20 m. But within photogrammetric measurements, the method used up to now by the NMAs, forest areas are handled as cut-out areas because the ground can not be seen, especially in coniferous forests. Subsequently the mentioned mean point distance is a very good result, even compared to the mean point distance of 30 m laid down for the photogrammetric restitution in open terrain. The vegetation penetration is one of the great advantages of laser scanning methods as it reduces a lot the time necessary for the field checks.

But besides this obvious advantage of the technology, the height accuracy of the laser points was still unknown. The only conceivable method appeared to compare the ground points to a known DTM. The first results were not that bad for open and flat areas and, as expected, worse for hilly, especially steep forest areas, as consequence of the higher point distance and the rough terrain. For 35 % of the ground points the difference to a DTM derived from digitized contour lines were bigger than half a meter. But this test already demonstrated how difficult it was to find a good reference, i.e. a DTM measured with a higher accuracy **and** about the same point density. A statement concerning the accuracy and the reliability of the laser DTM was nearly impossible. As the existing photogrammetric measurements did not fulfil these requirements, field measurements were necessary. So the NMAs carried out tacheometric and GPS field surveys and levellings for different and complicated terrain forms. One of the main results was an absolute height difference less than three decimetres for about 90 % of the ground points for flat and not too rough terrain.

After the tests had shown that laser scanner flights do result in a DTM with a sufficient accuracy a cost-benefit analysis had to follow. The former method used by the NMAs for the derivation of high precision DTMs was the photogrammetry, so the analysis lead to a comparison of the two methods. The advantages of the laser scanner flights are in the considerably reduced time for the field check, necessary for the cut-out areas of a photogrammetric restitution. This is a result of the vegetation penetration. In addition there are less restrictions concerning the weather and the daytime for laser scanner flights than for a photo flight. Since it is an active illumination system, laser scanning can be used during night time and at low sun angles when aerial photogrammetry is failing. It can be carried out below clouds and even with a slight snow coverage whereas the number of days with good photo flight conditions are more and more reduced by smog. And finally data processing time is really shorter.

The investigation revealed that only a quarter to a third of the former budget was needed. Finally some NMAs decided to use laser scanning as the only method for the derivation of a high precision DTM. The user group started with the already mentioned general description of the complete procedure.

5 The proposals of the User Group

The experiences of the user group members lead to a general description of the whole procedure of laser flights, including all the requirements, the preparations and the negotiations with the companies to the final confirmation that the result comes up to the requirements. The most important proposals are listed as follows:

5.1 Planning and Preparation of the Laser Scanner Flight

As mentioned above, the flight should be carried out during winter time to achieve a better vegetation penetration in deciduous forests. For the exact planning of the laser flight large or medium scale topographic maps are the basic documents for all discussions between the NMA and the providing company. The morphology of the terrain has big influence in the parameters chosen for the flight.

The user group proposes the determination of so-called check areas. They are necessary for testing the final results of the laser scanner flights and are used to discover possible height differences between the laser points and terrestrial measured points. Only one check area is given to the company and used for internal tests. The check areas should extend to about 1000 m² each and be without or with only low vegetation. For these areas the absolute height should be determined with a high accuracy, measuring a dense grid (e. g. 10 m) of ground points. The approximation of the terrain by the check areas should be possible with an accuracy of ± 0,15 m. Sport fields are very suitable, and mostly GPS methods are used. The position of the check area given to the company should be determined before the flight. Thereby it is possible to fly over it again if the flight had to be interrupted and to discover possible height differences between the different flights. The other check areas are used exclusively by the NMAs for the final tests before paying the bill.

The scanning parameters are very important for the final accuracy of the DTM. As mentioned above the different systems and techniques used by the different companies have advantages and disadvantages. The flight should result in a dense and homogeneous point distribution, therefore all parameters have to be discussed in detail before the decision on the final order can be taken. In addition, it is considered to be essential that the strips should have a sidelap of 100 m for the precision of the flight is of about 50 m and gaps between the strips, resulting of irregular movements, should be avoided in any case.

5.2 Requirements to Geodetic Basis Data and GPS Measurements

For the measurements and the final calculations DGPS measurements are necessary, so GPS data have to be registered at reference stations. Some companies take advantage of the registration at two or more reference stations to improve the resulting accuracy. The coordinates of the reference stations have to be known in ETRS89 and in the local coordinate reference system, and the distance to the aeroplane should be inferior to 50 km. If possible, permanent stations can be used. And it is in the interest of both, company and NMA, that the registration is conducted on an additional reference station to achieve reliable results even if the registration at one station fails. Today the standard for the registration rate is 1 Hz or even less.

To calculate the coordinates of the laser points in the local reference coordinate system, first a datum transformation to the Bessel ellipsoid is necessary, followed by the calculation of the x/y-coordinates in the Gauss-Krüger-coordinates (in Germany). For the datum transformation at least four points known in both systems are needed, distributed regularly outside of the whole working area. It should be discussed if transformation parameters valid for the whole country should be preferred, or if parameter sets for each working area are used. For the latter, the differences at the borders of neighbouring working areas

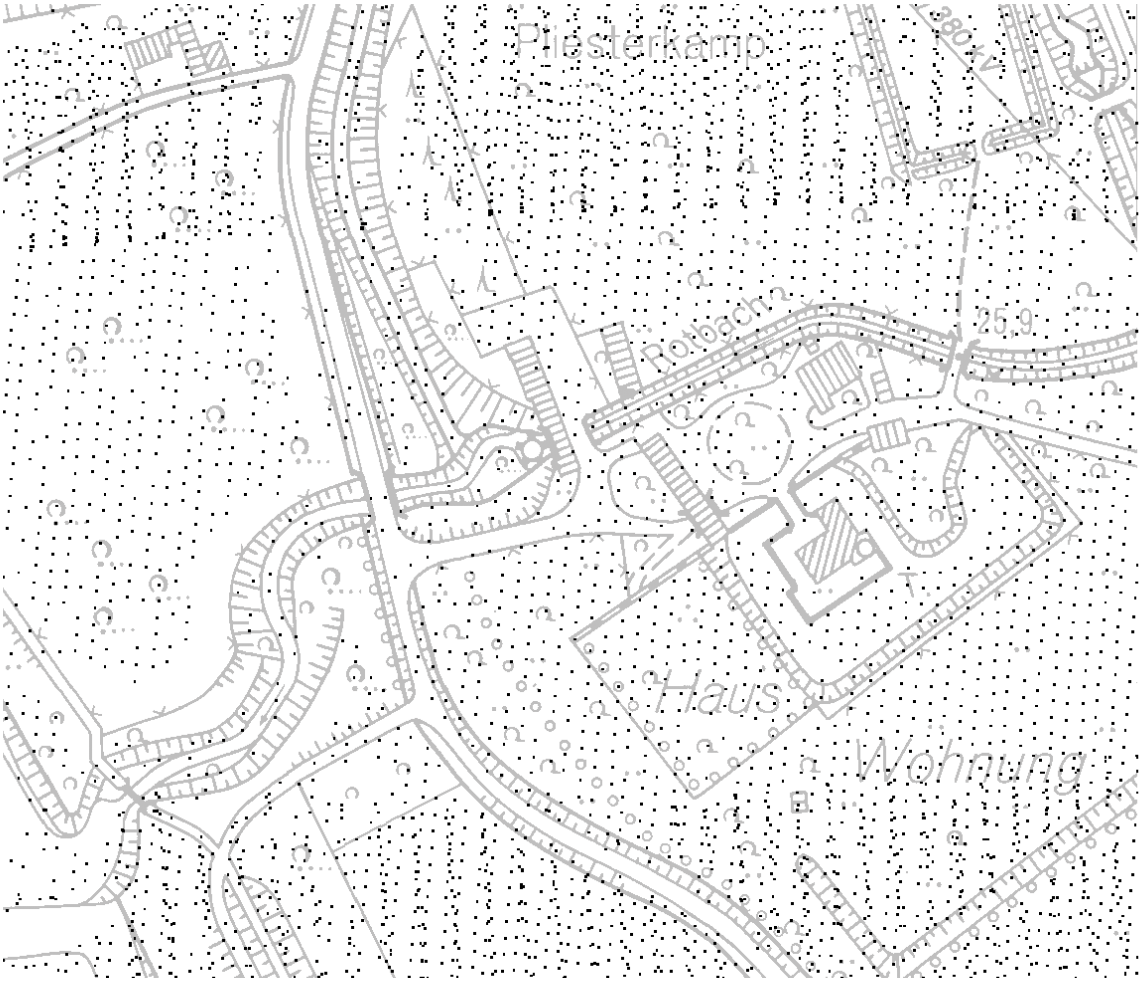

Fig. 2 – Ground points plotted on the German Base Map 1:5000

should be estimated. Finally the geoid undulations are needed to calculate the height above see-level of the laser points, their values preferably stored in a grid.

All these facts should be discussed in detail before starting the campaign.

5.3 Delivery and Tests

The user group thoroughly discussed the data delivery and the final tests to be carried out before the contract can be paid. Finally it stated that the following can be considered as a standard.

The providing company should deliver two data sets, one for the ground points and one for the filtered points, laying on buildings and on the vegetation. In addition the coordinates of the flight path should be part of the delivery, and finally a project report. In the latter the company should confirm that

- the flight and the data treatment has been without any disturbance,
- the working area is covered by laser points without any gaps,

- the height differences between the laser points and those of the checking area are within 0,15 m,
- the laser points do not have any systematic errors like offsets or tilted strips, and finally that
- the height of the laser points is not adapted to the height of the checking area.

The differences inside the checking area are to be revealed. As the main criteria before accepting the results, the user group proposes that the height differences inside the checking areas should be less than |0,3 m| for 95 % of the laser points.

Some careful inspections on the data have to be carried out. Such as using plots of the ground points and filtered points, overlaid to the base map or the orthophoto map, or by the superimposition of the ground and filtered points to the photogrammetric stereo model. By this the overlapping of the strips and the successful filtering can be seen. In addition possible errors can easily be detected in products derived from the DTM, for example contour lines or shaded relieves.

In figure 2 the ground points are plotted together with the German Base Map 1:5000. The overlapping of the strips can be seen in the north and the south as well as the filtering, that seems to be correct. There are no ground points on the houses, and also vegetation points are filtered out, visible especially along the roads and the river and in a small forest (south-west). The figure is given in the scale of 1:2500.

The experiences in the user group are showing that, so far, there are still some few misclassifications. These can occur in complicated situations where the real ground points are difficult to be determined automatically. For example, on big houses ground points are remaining, and laser points are eliminated when situated on steep fills along roads and railways or on steep slopes along ridges. But the user group is very optimistic that the filtering software will still be improved.

The above mentioned products like the contour lines and the shaded relief are used for the interactive classification and, if necessary, for the determination of cut-out areas. In the different States different methods and different kinds of hardware are used. Some editing tools were developed for changing the classification, other States are using photogrammetric stereo stations to superimpose the laser points to the stereo model. In addition some field checks might be necessary, especially in young and dense coniferous forests. More details of these different procedures can be found in *Hoss*, *Petzold et al.* and *Reiche et al.*

6 Conclusion

Meanwhile laser scanning is used in some States of Germany as a standard method for the derivation of a high-quality DTM. The requirements for using this new technology successfully are shown. Some practicable procedures necessary for testing the final data set are presented. The user group is optimistic that the potential of the high point density is used to develop some more sophisticated software, for example for the derivation of the break lines. First steps in that direction are already taken.

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Discussion

DTM Determination by Laser Scanning: an Efficient Alternative
B. Petzold, LVA Nordrhein-Westfalen, Germany

Miller (LH Systems):
Do you have a comment on the following: often in photogrammetry when the DTM is derived, the xy accuracy is very similar to the z accuracy; it is in the same order of magnitude. In laser scanning I often noticed that the xy accuracy may be a factor of 10 worse than the z precision. How does that affect the products we make from that and how should we deal with that?

Petzold (LVA Nordrhein-Westfalen, Germany):
We did not do a special test on the xy accuracy, all the check areas we used give us an idea on the z accuracy but we are sure that the precision in xy is less than 1/2 m and that is enough for the DTMs we want to build up. But we have never made an exact analysis on this.

Heipke (Hannover Univ., Germany):
A comment on that. We have made a short study on laser scanning recently, and compared data from two different companies. We found differences in position in the order of 3-4 m. We are still working on where these differences come from. It seems that Scott's point might give us a clue to this question.

Kölbl (EPFL, Switzerland):
This conference has been put into the context of digital photogrammetry to show the alternatives to photogrammetric techniques. Thus, it is no longer image correlation and matching which is the only technique, beside classical DTM collection, but new techniques are coming up. My question is, where does photogrammetry stand right now? We consider that if you need breaklines in delicate areas for example to analyse flood areas, you cannot fully rely on what can be obtained from laser scanning. So for high precision models, I hypothesise, we still need correlation and photogrammetric techniques, whereas for topographic mapping, as you showed us, laser scanning is definitely superior.

Petzold (LVA Nordrhein-Westfalen, Germany):
That is right. I think that you have to look for the precision that you want to have in your DTM and one manages to get the same precision with laser scanning as one had with photogrammetric methods before. If you want to be more precise, you need breaklines. There are some developments to get breaklines out of the laser data and perhaps this will be the method of the future i.e. to get breaklines from the ground points of the laser data.

Reiss (Bayer. Landesvermessungsamt, Germany):
We switched from photogrammetric compilation of contours in combinations with field measurements to laser scanning combined with digital photogrammetry and field checks. We use digital photogrammetry to edit the data and check it on a digital workstation by using an overlay over the photogrammetric stereo model. Before we do the computation of the DTM and the checking, we plot by photogrammetric means the breaklines and, if necessary, ridgelines. Point density is so good that we do not usually need ridgelines, just the water surfaces and the valleys but no seldom ridgelines. As for laser point density, it is not good enough to get breaklines for dams. So, as I said, we have a combination of

laser scanning, photogrammetry and field completion with the same or smaller number of people to get the same results with about four times the output compared to photogrammetric compilation and field checking. Approximately the same amount of money is used too.

Vögtle (Univ. of Karlsruhe, Germany):
I do not agree with Otto Kölbl (EPFL, Switzerland), I think that high precision laser scanning is also better for building extraction, but the interpretation of these objects ought to be done photogrammetrically. Texture information is needed to interpret what you have in the laser scanning DTM. Another remark is, I do not agree with the statement that the first echo is better for building extraction. We have the experience that the last echo is better because there is less disturbance. The difference between the first path and last path is only a few cm for buildings.

Hoschtitzky (ITC, Netherlands):
In reference to the previous speakers, I think that you should exploit the full potential of both technologies simultaneously, take advantage of the precision aspects and enhance the other in weak points.

Dowman (Univ. College London):
You made a brief mention of filtering techniques and this is the subject of discussion in the literature. I am not aware of what the position on these is; for example, is software available to differentiate vegetation from buildings, and if there is, who has been developing this software and is it generally available?

Petzold (LVA Nordrhein-Westfalen, Germany):
The software that has been used so far in our company did not use the reflection coefficient for filtering but the development of lasers went on and now it is possible to register that coefficient. Some universities and institutes are doing research on what you can get out of the interpretation of this value, but I do not think it is already a usable software, it is more in a test phase.

Dowman (Univ. College London):
I was actually thinking more of the analysis of single distribution of points.

Petzold (LVA Nordrhein-Westfalen, Germany):
It is true that research is also done in this field, but we look for the DTM and not for any other applications.

General Discussion on Automation in Photogrammetric DTM Elaboration

Colomer (ICC, Spain):
I have noticed that to derive DTMs there is a lot of data involved even before, by connecting breaklines and morphological lines and after, so I wonder if anyone has computed whether some of the benefits from automation are eaten up by pre or post editing.

Duperet (IGN, France):
You want to know the benefits of using this DTM process. I can give you an example that corresponds to this area and this kind of work, which is of a cartographic nature, with plenty of features; this is a reduced context. We estimate that 30 hours would be needed to do the contour lines and all the point collection compared to 10 hours for automated DTM derivation. It depends on the operator too, some are faster than others, let us say from 5-15 hours of work. But if lots of trees are present it is more difficult and consequently the job is slower.

Colomer (ICC, Spain):
Our experience shows that it is preferable to do pre-processing because when you digitize breaklines and choose most points before extracting the DTM, it really improves the DTM quality. If you fail to do so and do post-processing you first have to find the places where the DTM is wrong. This takes a lot of time as it is a visual check.

Maalen-Johansen (Norway):
What was the flight path of the imagery you used? Moreover, were the 200 ground checkpoints that were allocated in the shadow areas, flat areas or on steep hillsides? Can you comment on that please?

Duperet (IGN, France):
The flight height was 4600m, very few of the checkpoints were in the shadow areas, and since there were no flat areas in this mountainous terrain, most of them were on crossroads.

Dowman (University College, London):
Just a comment on the issue of checking and quality. Otto Kölbl (EPFL, Switzerland) said that the root mean square error is not a good indicator, but I think that, as the figures show there, if you give the bias the root mean square standard deviation, together with the maximum and minimum error, then it is a good indication. But that itself is not enough, because the accuracy of the DM is dependant on so many different factors, so it would be different in various parts of the model or of a considered area; so a single root mean square error does not suffice for the whole area. One thing that seems useful and that manufacturers could take up, is to include in the software some method of telling the user what to expect in a particular area i.e. to have a spreadsheet with the slope of the ground, the flying height and other parameters like the land cover. This could help give an idea of what accuracy to expect in a particular area, thus pointing the way towards resolving the problem of checking and DTM quality control.

Madani (Intergraph):
I do not mean to question your analysis or the quality of your control points or their distribution. What I want to say is that the product is not perfect; it is just at its beginning stage, so in time it will mature while being given more statistical indicators. This is raw data generated by an automated DTM program, so to obtain good quality DTM, one must do some editing afterwards and pass this information to you, to check the results with the control points.

Part 4

Automatic Aerial Triangulation

Chairmen

T. Kersten **Ch. Heipke**

Show the efficiency and difficulties of automatic aerial triangulation (problems on point transfer due to scale changes, height differences, texture), demonstrate the possibilities for quality control and discuss the optimal work flow.

Performance of Tie Point Extraction in Automatic Aerial Triangulation

C. Heipke*, K. Eder**
* Institut für Photogrammetrie und Ingenieurvermessungen, Universität Hannover
** Lehrstuhl für Photogrammetrie und Fernerkundung, Technische Universität München

Executive summary[1]

The European Organisation for Experimental Photogrammetric Research (OEEPE) and the International Society for Photogrammetry and Remote Sensing (ISPRS) have carried out a test on the performance of tie point extraction in automatic aerial triangulation (AAT). The aims of the test were to investigate the geometrical block stability, the accuracy of the tie points and the derived orientation parameters, and the limitations of existing commercial and experimental software systems. In order to separate the essentially new aspect of digital processing, namely automation, from conventional issues of aerial triangulation, control information was not assessed, and the test blocks to be processed had an arbitrary block datum.

The Chair for Photogrammetry and Remote Sensing, Technische Universität München acted as pilot centre for the test. In early 1997 various small blocks of different scene content were distributed to interested participants. Guidelines for the selection of the test data were the need for a representative test data set covering different standard applications in photogrammetry, for small blocks/strips resulting in manageable data volumes, and the use of photogrammetric images and scanners only. The first point inspired the use of different scene contents, topography, cameras, scales, film material, and overlap configurations. As far as image scales were concerned, preference was given to larger scales, because in these cases, potential matching problems due to occlusions and relief displacement are more pronounced. The second point led to the selection of blocks with 3x2 and 3x3 images, strips with 3 images and pixel sizes of 20–30 µm. While operational problems cannot be detected with such small blocks, the geometrical block stability and the accuracy of the tie points can be assessed. As for the third point, only first generation film products were scanned and all employed scanners are especially designed for photogrammetric applications.

The task of the participants was to automatically generate tie points without human intervention using an AAT software available to them, given the digital imagery together with auxiliary information. 21 participants (4 major commercial AAT software providers, 5 national/regional mapping organisations, 4 private companies, 3 research institutes employing commercial products, and 5 research institutes who had developed their own AAT software) returned results.

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[1] A complete description of the results is available as a separate OEEPE publication and can be obtained from OEEPE.

The results were analysed at the pilot centre using robust bundle adjustment and independent reference measurements. The following conclusions can be drawn from the obtained results:

– A good **geometric block stability** can be guaranteed, if and only if a sufficiently large number of tie points (say 100 to 300 per image) is extracted. The reason is that local matching procedures, as they are employed in the tested systems in order to achieve an acceptable level of accuracy, are subject to blunders, and these blunders can only be reliably eliminated if their percentage is relatively small. If too few points are extracted the resulting block can be heavily deformed.

– Especially in larger blocks the geometric stability also depends on the number and distribution of the available GCP and/or the quality of the direct measurements for the orientation parameters from GPS and/or INS. Such information can lead to a somewhat reduced number of necessary tie points per image. As mentioned before, however, no such effects were investigated within the test.

– The high redundancy in the adjustment leads to a smaller theoretical standard deviation and an improved reliability for the exterior orientation parameters as compared to analytical photogrammetry. These parameters, of course, must be regarded as the prime result of AAT.

– While the significance of a large number of multi ray points is not as high as in analytical photogrammetry neglecting this aspect too much can also lead to severe block deformations. In the test all commercial systems generated enough multi ray points, but it seems safe to predict that more emphasis should be concentrated on this point.

– Under favourable conditions (open and flat terrain, good texture) the **accuracy of the tie point coordinates** as expressed by σ_o can reach 0.15–0.2 pixels or 3–4 μm using only natural tie points if least squares matching is employed for coordinate refinement. In one of the projects one participant even achieved 0.11 pixel or 2.2 µm. In analytical photogrammetry a comparable accuracy has only been achieved using signalised points.

– Taking all test results into account a realistic value for σ_o lies in the range of 0.2–0.3 pixels or 4–9 μm (again with only natural tie points and least squares matching), at least when the images were scanned with a pixel size of 20–30 μm. The values are rather similar across the different systems. Since most systems use least squares matching in the final coordinate measurement this result seems plausible. In this test the effect of pixel size was not separately investigated. Experience and the literature suggest that pixel sizes smaller than about 20 µm will not increase the accuracy of the tie points accordingly.

– **Limitations of existing systems** showed up in the test data set which contains mountainous and forested terrain. Most participants failed to produce correct and accurate results. The strip connection was shown to be the weak point.

– Failure to produce an acceptable result was not adequately indicated by most systems, because internal self control is not sufficiently accounted for. Elements of self control are the individual matching results, the distribution of the tie points and the number of multi ray points within the block, the measurement accuracy, and the covariance matrix of the unknowns. As was shown in a number of cases the σ_o of the block adjustment is by itself not a valid indicator of errors or deformations within the block. The adjustment theory developed for analytical photogrammetry including measures for reliability and blunder detection and elimination seems to be the proper starting point for the necessary improvements.

– Due to the large amount of required observations the self control mechanism should be automatic.

– A minimum requirement for assessing the quality of the results is a graphical output showing the distribution of the tie points in image and/or in object space, preferably with the images as back drops.

– It is interesting that both success and failure occurred partly within one and the same system. This suggests that an extensive amount of experience in handling the software is necessary in order to appropriately tune any available free parameters. If the number of free parameters cannot be significantly reduced additional effort should be focused on

Not all issues related to a complete AAT system analysis could be investigated in this test. For instance, issues related to an economical use (e.g. the time and cost needed for preparation, computation, and post processing) have not been considered. Furthermore, the behaviour of AAT systems for larger and non-regular blocks, and the influence of control information were not investigated. From the results obtained, it can be concluded that the current AAT systems after only a few years of market presence, show a remarkable level of performance. A number of details, however, need further refinement. In summary, it can be predicted, that in a production environment fully autonomous tie point extraction while feasible in many cases, will be followed by a verification and editing stage carried out by a human operator. Software development should be concentrated on creating more reliable self control mechanisms and on designing user friendly interfaces for an efficient verification and editing of the AAT results including a stereo measurement capability for high accuracy requirements. Further work is needed to create proper quality specifications for the results of automatic aerial triangulation, especially for the parameters of exterior orientation.

Acknowledgements

We wish to express our gratitude to OEEPE and ISPRS for supporting the described test, and in particular to Prof. Ackermann and Prof. Förstner for initiating the test. We are also grateful to the organisations and individuals having provided the test data. Special thanks go to Prof. Kölbl. At his institute the first author was able to spend a sabbatical in which much of the test analysis could be carried out. The authors are also thankful to Roland Winkler, who developed the analysis procedure very efficiently during his diploma thesis, and to Rüdiger Brand who significantly contributed to the analysis software. Finally, this test would not have been possible without the enthusiasm of the test participants. We were very surprised and excited by the large interest in the test and by the number of groups participating. They all put a considerable effort into processing the data sets while keeping up with a rather tight time schedule. More often than not processing had to be done in addition to the every day work load. We hope that we have fulfilled their expectations.

Discussion

Summary of Results of the OEEPE/ISPRS Test
Ch. Heipke, Univ. Hannover and K. Eder, TU Munich

Simmons (Simmons Mapping, UK):
Did you only test with black and white images or with colour ones too, and is there any difference in results between the two?

Heipke (University Hannover, Germany):
I cannot comment on the basis of this test. We used colour images but we only scanned one of the colour channels of the images. We do have a green, red and infrared channel but we did not scan all of them. From my experience, however, I do not expect major differences while using colour images.

Baltsavias (ETHZ, Switzerland):
I wanted to know how intelligent the system is in selecting the points at appropriate locations depending also on the texture of the images. For example if you have a water surface or difficult regions, then some systems try to shift the tiepoint location. Did you notice any differences between the systems with respect to these characteristics?

Heipke (University Hannover, Germany):
No, I did not. Obviously, there are points that have been matched according to local point operators. They have limited intelligence as mentioned. In 1997, none of the systems investigated had a pre-selection of tiepoints as you have suggested.

Proposal for the Demonstration of the Automatic Aerotriangulation Software at the OEEPE Workshop

C. Heipke

General Aspects

- Sensitivity towards approximate orientation parameters:
  How accurate do these values need to be, what does it depend on?
  How is the quality of an AAT run measured and checked?

Algorithmic Aspects

- Handling of gross errors:
  How are these errors detected and eliminated?
- Set up of point tuples:
  Does the algorithm rely on pairwise or simultaneous multi-image matching? If pairwise matching is carried out: how are point tuples generated?
- Which algorithms are implemented for measurments and adjustment?
- How is the reliability of matching defined/realised?
  Is there a feedback between matching and bundle adjustment? if yes, how is it realised?
- Problems for automatic point transfer (scale differences,
  height differences, texture, etc.)?

Operational Aspects

- Number of successful installations
- Number/percentage of successful AAT projects vs. image scale
- Typical examples for unsuccessful automation:
  What was the reason for lack of success?
- Did you observe any effects of image compression?
- What is the pixel size you advise your customers to use?
- How does the automated workflow look like (Import, AIO, preparation of parameters, measurements, quality control, etc.)
- What is the role of the human operator in your AAT solution, what information is given to him, what actions are required from him?
- How is the quality control realised?
  a) During measurements (sequential adjustment, spatial resection, etc.)
  b) After the measurements (image and strip connections, etc.)

Editors Note
For technical purposes, the vendor's presentations, are reproduced at the end of the proceedings, in part 7.

Discussion after the Demonstration

Vendors Demonstration with standardized images in terms of the preparation of aerotriangulation and the quality check

Grabmaier (ITC, Netherlands):
We said that Match-T had a problem with moving shadows. This is probably a phenomena that requires human intelligence to avoid; especially if you use interest operators, the system will always try to use the dominant interests like the corner of a shadow of a house which is going to move etc. Also, we have learnt from LH Systems that they have a problem in forest areas. It seems that there, the selection by the interest operator is doing the harm, because he will always jump to some place in the forest which gives him a very good texture on one of the images, whereas the same forest on the neighbouring image will have no contrast at all. This is where the typical problem comes from. But in the first image the interest operator will say this is the best spot and the other image is lousy. In the LH Systems, I noticed a change in the surf drop because before, when I specified 3 areas, in the Gruber positions just through the centre of the image, it gave me 6 points in the stereo overlap and in the new version it gives me only 3 points. So, it does not seem to look back to the previous image, which is why I would like a comment from LH Systems. Is it a change or is it a wrong interpretation on my part?

Heuchel (Inpho, Germany):
Can I comment on the first question about the interest operator and interest points? This is an important issue; we know this and it is one of the reasons why we introduced bundle block adjustment. If you have a point in the shadow on 3 or 4 photos and you test the intersection, if it is a shadow point and the intersection is fine, then the point is a good one. It does not mean that Match-AT takes all the points, though internally it produces 5 to 6 times more points than used in the adjustment and each one is tested as to wether it fits to a section. But you are right, it is extremely dangerous to use two fold points because they are parallax points and we all know the problem. I do not have a solution and perhaps we have to wait for one.

Miller (LH Systems):
The comment on the interest operator issue is very similar to what Tobias Heuchel (Inpho) is saying. We use what we call a modified interest operator: we first search for an interesting area and by doing so we avoid the trees and the shadows to some degree and then we try to place a cluster of points, generally away from the buildings and the trees with this modified interest operator. As for the trouble with trees: if the entire model is forested, then we have a much more reduced automation and editing is needed. As we try to avoid trees, we nearly always succeed. When the cluster of points is analysed, hopefully if it is a shadow or a tree point, it *is* rejected. As for what you said about an older version producing fewer points, it might be true that the newer versions are more stringent for checking. Now you need to give them a goal of more points to achieve a certain number of points; because it is stricter, it produces fewer blunders and more high quality points, therefore it will not produce as many points under the same goal because it rejects more in the newer version. So you have to increase the goal in the updated software.

Torre (ICC, Spain):
Firstly, I would like to apologise because our experience with Match-AT has been very short, about 3 months, but as time goes on we feel more comfortable and satisfied with it. So there are some questions I would like to ask about it. Sometimes we find a parallax between models though the adjustment has been perfect and this happens only when we go directly to the "stereo data capture" or to stereo revision of the automatic DTM for example. Even though we use the bulk tool delivered by the ISDM, nobody detects that there are parallaxes before the end of the working chain and this is time-consuming, as you have to go back many steps. Another problem is, I fully agree with Mr. Grabmaier (ITC, Netherlands), that Match-AT has a special affinity for shadow areas, small bushes and trees. But because of the projection of different photos, the derivation of certain areas might not be appropriate to the relative orientation of the photographs. Another worry is that points delivered by Match-AT always have some signal receiver so that in the further projects, those points are no longer taken into account. In order to give them more importance the signal should be changed when they have been perfectly calculated, although they had an unfavourable estimation. Actually these points are not taken into account for the formation of the model, for example in stereo resampling. From our experience, the next problem is that the preliminary matching does not help at all. This means that sometimes the preliminary matching gives worse results than working without it. This is time-consuming too.

Heuchel (Inpho, Germany):
I will begin with the last one: we find that the preliminary matching does not help a lot, but the idea behind it was that in certain areas we tried to determine the DTM in the beginning so as to use this DTM in the further processing steps. But we think that DTM generation takes too long for those patches. So in the current version, for the preliminary matching, we just apply the whole sequence of operations and we do the adjustment. Then the full matching is done and then we go back to the beginning and start the full matching again. I do not know if you want to clear the other problems after this session so that we can go into detail because I think these are specific implementation problems concerning your experience with Match-AT.

Madani (Intergraph):
We noticed that when you do aerial triangulation, rather like in the conventional process, and when you do bundle block adjustments with digital photogrammetry, if you accept the result and then set up a model, obviously you will not get the initial parallax model. So we have implemented something called bulk adjustment, in which you re-use the matched points, the adjusted control points and create a new absolute orientation tuned to the final result. This can replace the results of bundle block adjustment which has the nature of a least square adjustment.

Torre (ICC, Spain):
It would be very useful for production line purposes if all these problems were detected in advance, because to go back and forth is very time-consuming and expensive. For example, to give a clue as to where it is suitable to place some points that can help in the Match-AT to drive to the correct areas, as the process seems prone to failure due to a repetitive pattern etc. It seems the model obtained is not good enough in certain specific areas. To sort this out could help a lot.

Madani (Intergraph):
We had similar problems in the beginning. In the past when Match-AT generated tiepoint centres, they could fall on a lake or anywhere. So we offered the choice to move it somewhere else and the software thinks that it moved it but Match-AT ignored whatever the operator did and used a fictitious point. Fortunately, we have sorted this out and now, when the operator moves any point anywhere then it can become the centre of the cluster point evaluation. The second problem we found, as you did, was that sometimes from the bundle block point of view everything is satisfying, but then you see that some of the models cannot be orientated because when you look at the points distribution you may have only one or two useful ones.

Heuchel (Inpho):
As Mostafa Madani mentioned, we have now changed the procedure so that every manual measurement, whether it is a control point or any other manual measurement in a Match-AT environment, will be used as a potential tiepoint centre and will be one at each parameter level, so hopefully this will help in difficult mountain and forest areas. I must add that Match-AT also has problems with the model of photos covered let us say by 80-90% of forest and water areas where we also have difficulties in finding good points. So maybe these interactive measurements could help the user a lot here. Most of the times the user knows where to set a point which could be re-used later in adjustment.

Talts (National Land Survey, Sweden):
I want to talk about the practical problem of transferring orientation data from the automatic block triangulations to other places in map production because you cannot use exterior orientation data. They are not the same in other equipment: even the producers do not know what angular rotation is used in their instruments. Is this problem solved in the more recently manufactured systems?

Miller (LH Systems):
I think this continues to be a problem, as there is such a diversity of systems and the mathematical models through which they are implemented are different; if they are not exactly the same in the bundle block adjustment, then of course there will be slight differences. So, depending on where you are going from and where, there can be problems in strictly transferring the exterior orientation data. Some customers get around this problem by transferring the points and resolving the model orientation on the instrument of their choice. In some cases there is software with a reliable transfer in others there is not. So if you tell us which software you are using, we have an idea wether it has a reliable transfer or an exterior orientation only. In many cases it will not be reliable.

Heipke (University Hannover, Germany):
In the meantime, just a word to tell you that the triangulation is now finished with a sigma of 2.9 microns, so it is the same result as we got from Inpho two years ago. Just a comment on the 2.9 microns. I want to say that, as opposed to analytical photogrammetry where you are sure that the measurements are correct, since you have made them yourself, in automatic aerial triangulation a robust adjustment is being done. Cynically speaking, you can select the sigma you want to see beforehand. This does not mean that the results are correct, however. So we want to add, as a warning, that we have heard that an independent check has to be done afterwards.

Heuchel (Inpho):
If you can show that the points distribution corresponds to your expectations, if you have let's say 644 points per image, then I think that a sigma of 2.9 microns is a good indicator. This is similar to classical triangulation. It is clear that if you just measure 5 or 6 points per photo then you could also get a very nice sigma value; of course for manual measurements you have a good control of the geometry. The graphical output is very nice in LH Systems, if I can get information about exterior reliability, then that is exactly what you need.

Heipke (University Hannover, Germany):
I go back to Mrs. Torre's (ICC, Spain) remark that in those dark areas you may not have tiepoints. Now it is easy to analyse this problem, but it has to be done.

Madani (Intergraph):
It is obvious that sigma naught from a mathematical point of view is only a precision indicator. We have a least square solution: the sigma naught can be the same as the accuracy, provided systematic errors and blunders are removed and observations are weighted correctly (stochastical model is correct!). If you have some check points, then you can compute their root mean square values and check the accuracy of the solution.

Eder (Technical University München, Germany):
Earlier, you have pointed out that one goal is full automatic aerial triangulation and on the other hand we are discussing sigma naught, distribution of points and so on. So, I feel that the operator still has to have the complete background of aerial triangulation. This is important and you, as vendors, should point this out to the customer in order to avoid surprises. How can you comment this point?

Madani (Intergraph):
Aerial triangulation is the highest level of mathematics in photogrammetry but not every operator has the chance to possess all the necessary experience or knowledge. We give them some training, some numbers to look for; for example we always tell them to make sure that they have some check points and from those they can evaluate the results. Then, there is the graphical representation; we have had it for a long time in the UNIX environment but unfortunately not everyone in production is interested in this as they do not have the time to look at the patterns and analyse them; they want to get the result and get on with it, but then they complain. In this situation we try to inform and educate them as much as we can, in order to make them happy with the result they get.

Dörstel (ZI Imaging):
From our point of view, automatic aerial triangulation does not save you from thinking, it only takes away some work. If you have a look at our implementation, it is strictly divided in two parts: one part is automatic measurements, which is robust, and the other is bundle block adjustment where you need a lot of experience, and the latter stays with you forever; automatic aerial triangulation does not take it away.

Heuchel (Inpho):
I think that automatic aerial triangulation is a real challenge in that the operator can handle it easily and that he does not have to know what lies behind bundle block adjustment in the same way as we trust relative orientation systems today. They are not really interested in the mathematics so it is a challenge to reduce the workflow to a stage

where it is very easy to understand, while maintaining the quality control measures for the operator in order to see if he has done a good job. In this way it is interesting to combine automatic aerial triangulation with bundle block adjustment. There is no need for the 2 processes to be separated in aerial triangulation; so something remains to be done there.

Miller (LH Systems):
I would agree with Konrad Eder (Technical University München, Germany) and what is being said: we have not eliminated the experienced operator yet. You still need too much experience to get a high quality result.

Results of Digital Aerial Triangulation using Different Software Packages

Thomas Kersten
Swissphoto Vermessung AG
Regensdorf-Watt, Switzerland

Abstract

Commercial software packages for digital aerial triangulation are on the market since the middle nineties. The point transfer capability of the current major triangulation software packages was investigated in the OEEPE/ISPRS test on the performance of automatic point transfer in digital aerial triangulation. In this paper, results of digital aerial triangulation using the three major triangulation software packages Helava Automated Triangulation System (HATS), Match-AT and Phodis-AT are presented. For the comparison of the results of the adjustment and the elapsed time for triangulation, the Swiss triangulation block Wittenbach was used. The results of the triangulation, which were obtained from the three digital systems and an analytical plotter, were similar. But, the elapsed time for triangulation using the different systems varied. Finally, differences of the two software packages HATS and Match-AT are discussed with respect to their functionality and performance.

1 Introduction

Digital aerial triangulation is increasingly being carried out in photogrammetric production environments as greater efficiency is being aimed for through increased automation. Currently, the major digital aerial triangulation (AT) software packages on the market are the Helava Automated Triangulation System (HATS) from LH Systems, Match-AT from Inpho and Intergraph, and Phodis-AT from Zeiss. Furthermore, other vendors as Autometric, Vexcel (IDAS), and KLT provide software for digital AT since some years. Recently, new software for digital AT has become available from Erdas (IMAGINE OrthoBASE), VirtuoZo and DVP. The AT software from Erdas is based on algorithmic developments of the University at Hannover, Germany (Jacobsen and Wegmann, 1998; Wang, 1998).

Up to now only two comparison tests have been published to evaluate the functionality and performance of the major triangulation software packages. In the OEEPE/ISPRS test, the performance of tie-point extraction in automatic aerial triangulation of the major available triangulation software packages was tested using the same test material of various small blocks. The results of 21 participants (four major commercial photogrammetric software providers, five national or regional mapping organisations, four private companies, and three research institutes) using experimental software from Universities, HATS, Match-AT (Inpho and Intergraph) and Phodis-AT are summarised in Heipke and Eder (1999). Within an evaluation of digital photogrammetric systems at the Swiss Federal Office of Topography, the triangulation software of all participating vendors was tested. The results of this evaluation were published in Kaeser et al. (1998).

In order to test an alternative triangulation software to HATS in production, Swissphoto Vermessung AG rented Match-AT from Inpho (Stuttgart, Germany) for three months. The software was mainly tested in the digital aerial triangulation of Block Switzerland (Kersten, 1999). For a direct comparison, digital aerial triangulation of block Wittenbach, a small block in the north-eastern part of Switzerland, was performed using HATS and Match-AT. The same data set was also delivered to Zeiss (Oberkochen, Germany) for investigations with Phodis-AT. Furthermore, block Wittenbach was also triangulated at an analytical plotter DSR14 at Swissphoto Vermessung AG.

In section 2 the major automatic triangulation software packages are briefly compared. The test block Wittenbach and the triangulation software used are introduced in section 3. The results of digital triangulation using three digital systems and one analytical plotter are presented in section 4, while in section 6 HATS and Match-AT are compared in more detail with respect to the Swissphoto production environment.

2 Major systems for digital aerial triangulation

The following major digital triangulation software packages are briefly compared in this section:

1) LH Systems DPW670/770 with HATS on UNIX/NT
2) ImageStation Z (Intergraph) with MATCH-AT (Inpho) on NT
3) Phodis (Zeiss) with PHODIS-AT on Silicon Graphics
4) MATCH-AT (Inpho) on Silicon Graphics

The major triangulation software packages are described by vendors and some users as summarised in table 1.

Table 1 – Technical papers of vendors and users about aerial triangulation software.

AT software	Paper from vendors	Paper from users
HATS (LH Systems)	DeVenecia et al., 1996	Kersten and O'Sullivan 1996, Kersten and Haering 1997b, Kersten et al. 1998, Kersten 1999
Match-AT (Inpho)	Krzystek et al. 1996, Krzystek 1998	Kaeser et al. 1999
Match-AT (Intergraph)		Urset and Maalen-Johansen 1999
Phodis-AT (Zeiss)	Braun et al. 1996	Hartfiel 1997, Masala 1999

Table 2 – Important features of automatic triangulation software.

Important features	HATS	Match-AT (Intergraph)	Match-AT (Inpho)	Phodis-AT
Interior orientation	automatic	semi-automatic	semi-automatic	automatic
DTM integration	yes	yes	yes	no
GPS integration	initial values	yes	yes	initial values
APM	yes	yes	yes	yes
Algorithm	cross correlat.	FBM/ABM	FBM/ABM	FBM/ABM
IPM	stereo	stereo	mono	mono
Bundle block adjust.	module	Integrated	integrated	external

APM Automatic Point Measurement
FBM/ABM Combination of feature and area based least squares matching
IPM Interactive Point Measurement

In order to achieve a high level of automation in digital triangulation, the following features are important for the triangulation software (see table 2):

(1) Interior orientation is a simple task, which should be performed fully automatically today.

(2) The integration of an available digital terrain model (DTM) supports the performance of the automatic point transfer significantly, especially in difficult terrain with large height differences.

(3) The integration of GPS data (XYZ co-ordinates of the camera stations) or the use of initial values of the camera stations supports the performance of the automatic point transfer significantly due the sensitivity of the measurement algorithm to initial values.

(4) Automatic point measurement (APM) is the key module of automatic digital aerial triangulation.

(5) The measurement algorithm influences the quality of the measured points. The combination of feature (rough measurement) and area (precise measurement) based least squares matching achieves better precision than cross correlation.

(6) The interactive point measurement (IPM) provides the capability for the operator to measure semi-automatically control points and additional tie points in mono or stereo (3-D) mode.

(7) The integration of the bundle block adjustment increases the automation of the triangulation significantly (e.g. automatic blunder detection and elimination), if easy-to-use and automatic functionality for analysis of the results and quality control is available.

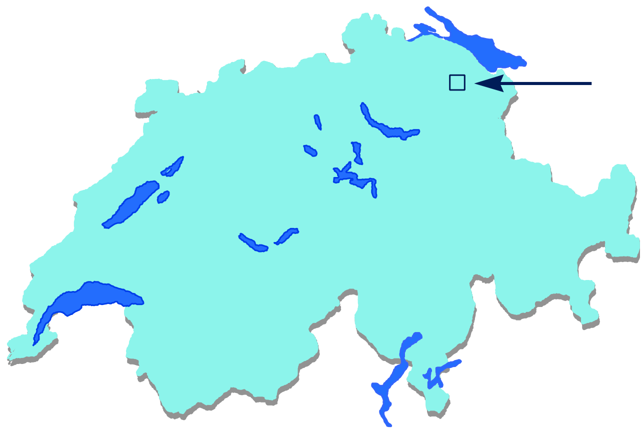

Fig. 1 – Location of triangulation test block Wittenbach (Switzerland)

3 Test block and systems used

For the triangulation tests, the Swiss block Wittenbach, which is located in Canton St. Gallen in the north-eastern part of Switzerland (see Fig. 1), was prepared. Four flight lines were flown in April 1998 in north-south resp. in south-north direction with an overlap of 80% in strip direction and 30% in across strip direction. The block represents an agricultural and urban (small villages) area with some forests, while the terrain is hilly with height differences of up to 340m in the block. 16 ground control points were signalised. The distribution of these signalised ground control point in the block is illustrated in Figure 2 (see points with error vectors). For triangulation, all images with an overlap of 60% in strip direction were used, but in some areas of lines 2 and 3 additional images with an overlap of 80% were integrated in the line (see in Fig. 2), to test the software for changes of overlap within the strips. The flight and block data of block Wittenbach is summarised in table 3.

Table 3 – Flight and block data of the triangulation test block Wittenbach.

	Block specifications
Flight date	April 20th, 1998
Camera/Lens	Leica RC30, 15 cm
Photo scale	~ 1: 8000
Overlap (F/S)	80%/30%
Strips/images	4/48
Height range	480 – 820 m
Terrain characteristics	agriculture, forests, urban
Scanner	LH Systems DSW300
Scan pixel size	12.5 µm

In total, 34 colour images of the block Wittenbach were scanned at a Digital Scanning Workstation DSW300 of LH Systems in RGB mode TIFF format. The turnaround time for scanning each photo was about 15 minutes using a SUN Ultra 1. The scan pixel size of the images was 12.5 µm. For triangulation, the digitised colour images were converted into greyscale images in order to reduce disk space usage. The file size of each greyscale image was about 330 Mbyte. For Match-AT and Phodis-AT, all images were available in TIFF, while for HATS the images were converted into VITEC format.

The aerial triangulation test was performed on both a digital photogrammetric workstation DPW670 (SUN Ultra 2) of LH Systems using HATS and a Silicon Graphics (SGI O2, R5000) using Match-AT. For HATS, software release 4.0.10.2 of SOCET SET (Softcopy Exploitation Tools) was used, while for Match-AT release 2.0. The analytical triangulation of 35 images was performed at the analytical plotter Kern DSR14 using the software ORIMA-T. The triangulation with each of the aforementioned systems was performed at Swissphoto Vermessung AG in Regensdorf-Watt. Additionally, block Wittenbach was triangulated at Zeiss in Oberkochen using Phodis-AT (Release 2.0.1).

4 Digital aerial triangulation and results

In the following, the triangulation of block Wittenbach is briefly described for each system. For all systems used at Swissphoto, the following information resp. data were available before the start of the triangulation: (a) colour contact copies of the photos, (b) analogue images, (c) digital images , (d) overview of the flight lines, (e) overview of the ground control point locations in a 1: 25?000 map, (f) sketches of each ground control point, and (g) initial values of each camera station determined from the 1: 25?000 map. For triangulation with Phodis-AT, the information/data c, d, e, and g were send to Zeiss. For all digital systems, the triangulation was performed without a digital terrain model as terrain approximation and without compression of the images.

4.1 Analytical triangulation with the Kern DSR14 using ORIMA-T

The workflow of analytical triangulation with the Kern DSR14 using ORIMA-T is summarised in the following:

(1) Preparation

- Marking of control points on the contact copies
- Input of camera and ground control point data

(2) Measurements with ORIMA

- Input of stereo model (colour diapositives) on the stage of the analytical plotter
- Interior orientation
- Measurement of ground control points
- Measurement of tie points in the „von Gruber“ locations including marking of their measured positions on the contact copies
- On-line adjustment of each measured model for quality control in strip direction

(3) Adjustment and quality control

- Data transfer (image and ground control co-ordinates) to the external adjustment software
- Bundle block adjustment using BLUH (University of Hannover) including blunder elimination and quality control
- Update of the orientation elements at the analytical plotter

The analytical plotter DSR14 has an estimated precision of 5–8 microns. A complete quasi on-line adjustment of the whole block is also possible using the full version ORIMA-T, which was not available at Swissphoto. In total, three gross errors were eliminated in the bundle block adjustment. Furthermore, one full control point was reduced to a vertical control point due to false measurements for this point.

4.2 Digital triangulation with HATS

The customised and modified workflow of digital triangulation using HATS is described in Kersten and Haering (1997b) in detail. To facilitate the use of the highly automated AT processing modules by the operator, some additional software for batch processing and easy-to-use graphical user interfaces (GUIs) were developed by Swissphoto Vermessung AG. The AT workflow was performed as follows:

(1) Preparation

- File preparation (camera, orientation parameter of camera stations, control points)
- Image data import including initial values of the orientation elements and image pyramid generation
- Automatic interior orientation including quality control (Kersten and Haering, 1997a)
- Definition of AT parameters including definition of a dense tie point pattern (98 points per image)
- Visual check of image/strip overlap (quality control of initial values of exterior orientations)

(2) AT measurements

- Semi-automatic or interactive point measurement (IPM) of ground control points
- Automatic point measurement (APM) of tie points
- Pre-adjustment using the module „simultaneous solve“ including blunder detection and re-measurements
- Semi-automatic or interactive point measurement (IPM) of additional tie points

(3) Adjustment and quality control

- Data transfer (image and ground control co-ordinates) to the external adjustment software
- Bundle block adjustment using BLUH (University of Hannover) including automatic blunder elimination and quality control
- Update of the orientation elements at the digital photogrammetric workstation

After APM, 65% of all measurements were successful, while, in total, 2192 points were automatically measured and 578 points were left unmeasured. These unmeasured points, which required editing, were neglected, in order to reduce editing to a minimum. In total, 10 points, which were detected as blunders, were re-measured using the module „simultaneous solve“ of HATS. In the bundle block adjustment, 146 observations with residuals over 20 microns were automatically eliminated. After the quality control (see also Kersten, 1999 for detailed description), which included the checking of the photo connections within and across strip direction, some points were additionally measured to connect lines 3 and 4 more strongly.

4.3 Digital triangulation with Match-AT

In order to use some automatic modules from HATS, an interface between HATS and Match-AT for data transfer before and after triangulation was developed by Swissphoto. Thus, all available triangulation parameters (camera data, interior orientation, initial values of orientation parameters, control point co-ordinates, etc.), which were already defined and imported in HATS, could be automatically transferred into the project file of Match-AT. The AT workflow using Match-AT is described in Krzystek (1998) in detail. The following workflow was used at Swissphoto:

(1) Preparation

- Automatic data transfer of triangulation parameters from HATS to project file of Match-AT
- Generation of image pyramids
- Definition and editing of the following parameters: project, photos, strips, block, points, matching, adjustment
- Semi-automatic measurement of four well distributed control points
- Initialisation of tie point areas in von Gruber positions including visual checks and editing

(2) AT measurements and integrated block adjustment

- Automatic point measurement (APM) of tie points through FBM/ABM least squares matching
- Integrated robust bundle block adjustment during all measurement processes
- Semi-automatic measurement of the control points

(3) Adjustment and quality control

- Data transfer (image and ground control co-ordinates) to the external adjustment software
- Bundle block adjustment using BLUH (University of Hannover) including automatic blunder elimination and quality control

The generation of the image pyramids was about 10 minutes per image and it took much longer than the automatic point measurements per image. All blunders were already eliminated within the bundle block adjustment of Match-AT, so that the results of the adjustment from BLUH were only used to analyse the block geometry.

4.4 Digital triangulation with Phodis-AT

The digital triangulation of block Wittenbach using Phodis-AT was performed at Zeiss in Oberkochen, Germany. The software and the workflow of the triangulation with Phodis-AT are described in Braun et al. (1996) in detail. To the author’s knowledge, the AT workflow of Phodis-AT is defined as follows:

(1) Preparation

- File preparation (camera, orientation parameter of camera stations, control points)
- Image data import including initial values of the orientation elements and image pyramid generation

- Automatic interior orientation
- Definition of AT parameters
- Visual check of image/strip overlap (quality control of initial values of exterior orientations)

(2) AT measurements

- Semi-automatic or interactive point measurement (IPM) of ground control points
- Automatic point measurement (APM) of tie points
- Semi-automatic or interactive point measurement (IPM) of additional tie points

(3) Adjustment and quality control

- Data transfer (image and ground control co-ordinates) to the external adjustment software
- Bundle block adjustment using BLUH (University of Hannover) including automatic blunder elimination and quality control

One signalised control point could not be measured due to bad visibility. Some tie points were additionally measured in the semi-automatic mode to connect lines 2, 3, and 4 more strongly. The final image co-ordinates of the digital aerial triangulation with Phodis-AT were delivered to Swissphoto. All blunders were already eliminated by analysing the results of the bundle block adjustment using PAT-B before data delivery.

4.5 Results from bundle block adjustment

Before the final bundle block adjustment, the image co-ordinates from all different systems were corrected for earth curvature and refraction. All observations (image co-ordinates, original ground control point co-ordinates) were adjusted in a bundle block adjustment with self-calibration using the bundle block adjustment program BLUH. As a priori value, the standard deviation of the ground control points were defined as s_{xyz} = 5.0 cm and the sigma naught was set to 5.0 microns, i.e. 0.4 pixel, to guarantee the same conditions for all adjustments.

The residuals (root mean square RMS) of the control points are summarised in table 4. The results were similar for all systems, but with slight differences especially in the planimetry. The best results with respect to the RMS of the control points were achieved with HATS. The sigma naught aposterori σ_0 was in the same range (5.5 micron) for the DSR14, Match-AT and Phodis-AT, which corresponds to a precision of better than half of the pixel size for the digital systems, while the result for HATS was slightly worse (6.6 micron). It was expected that the analytical triangulation would yield the best results, so that it could be used as reference, but unfortunately the results were not better than the results of the digital systems.

Table 4 – Results of the bundle block adjustments of block Wittenbach using BLUH.

System	I	S	C H/V	σ_0 [µm]	O	R	RMS X [cm]	RMS Y [cm]	RMS Z [cm]
AP DSR14	35	4	15/16	5.5	1256	521	3.3	3.2	6.2
Match-AT	34	4	16/16	5.3	7042	3314	4.1	3.7	6.1
Phodis-AT	34	4	15/15	5.6	15165	5292	5.3	4.5	6.7
HATS	34	4	16/16	6.6	4262	1775	2.2	3.8	5.0

I	Number of images		
S	Number of strips	O	Observations
C	Ground control points	R	Redundancy

In table 5 the number of n-fold measured points are summarised to analyse the performance of each system for providing stable block geometry through sufficient point connections within the block. The number of n-fold points from the analytical triangulation is a typical result of manual measurements resp. manual connection of the block, although the number of 4–7 fold points could be much higher. The best performance for the connection of the photos in the triangulation block has been achieved by Match-AT due to the point clusters in the von Gruber positions. A slightly worse result was obtained by HATS with respect to the 3–5 fold points. Phodis-AT is very strong in the connection of the photos by 2 and 3 fold points, but the system has problems to achieve points with more than 3 rays. It was told to the author, that this was a weak performance of the version 2.0.1 of Phodis-AT, but the new versions (2.1.0. and the new 4.0) will search for points with more rays.

Table 5 – Number of rays (percentage) in test block Wittenbach.

System	Number of photos/object point (percentage)											
	2	**(%)**	**3**	**(%)**	**4**	**(%)**	**5**	**(%)**	**6**	**(%)**	**7**	**(%)**
AP DSR14	38	(22.1)	83	(45.2)	15	(20.8)	10	(5.8)	14	(8.1)	12	(7.0)
Match-AT	410	(35.0)	537	(45.9)	94	(8.0)	90	(7.7)	40	(3.4)	–	
Phodis-AT	2231	(69.3)	889	(27.6)	74	(2.3)	21	(0.7)	5	(0.1)	–	
HATS	410	(54.1)	228	(30.1)	39	(5.1)	42	(5.5)	36	(4.8)	3	(0.4)

The empirical accuracy of each system was checked by using some control points as check points. Therefore, a minimum ground control point distribution of five points (one point at each corner of the block and one point in the centre) was used for block adjustment. The remaining eleven points were used as check points. The results of the empirical accuracy are summarised in table 6. Surprisingly, the results from the analytical triangulation were very bad, which could be addressed to insufficient connections of the photos in the block. For the digital systems, the results were very similar and compared to the RMS values by a factor of up to four worse. It must be stated, that the minimum ground control distribution was not very optimal for block triangulation.

Table 6 – Empirical accuracy of block Wittenbach.

System	Control H/V	Check H/V	σ_0 [µm]	µ X [cm]	µ Y [cm]	µ Z [cm]
AP DSR14	5/5	11/11	5.5	17.2	22.8	41.0
Match-AT	5/5	11/11	5.4	8.6	11.2	18.0
Phodis-AT	5/5	10/10	5.6	10.8	11.6	20.3
HATS	5/5	11/11	6.7	9.7	10.1	16.1

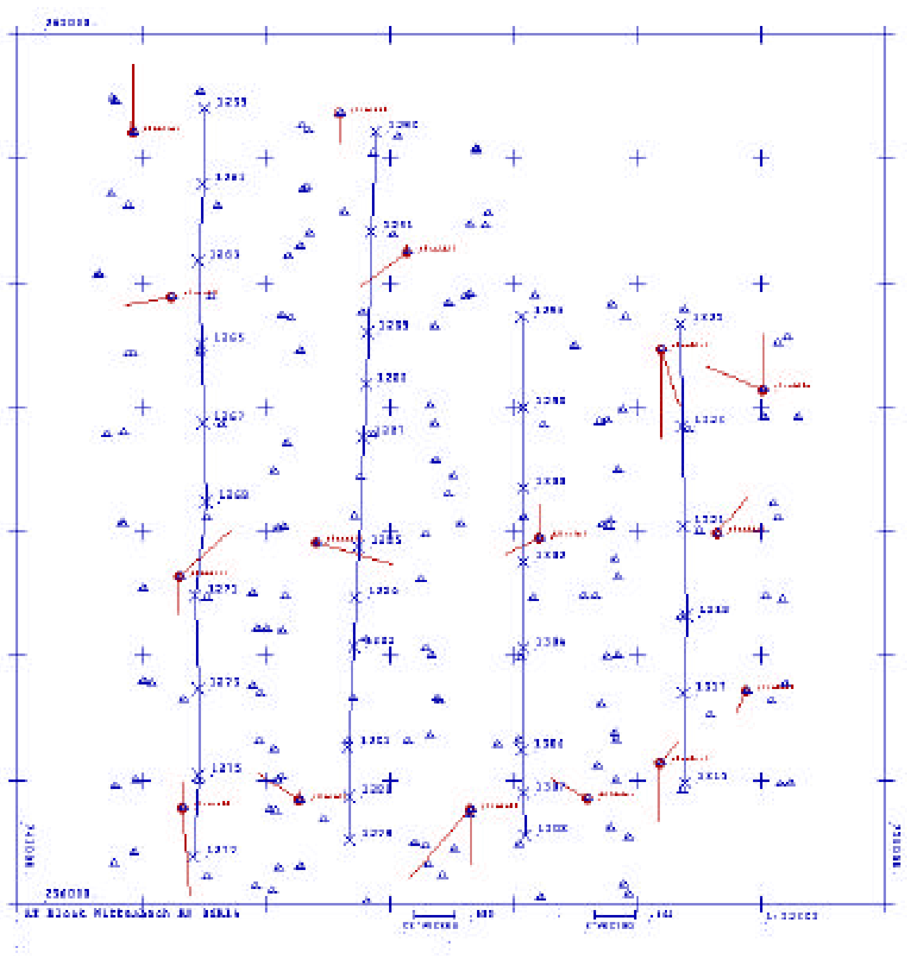

Fig. 2 – Analytical AT with Kern DSR14

In the Figures 2–5 the following information is summarised:

- location of measured tie points (marked as Δ) and their typical distribution for each system (for Match-AT, they appear to be less, because many points almost coincide in the plot, i.e. point clusters)
- locations of camera stations or photo nadirs (marked as crosses in the lines) with the photo number and the flight lines (marked as lines from south to north)
- location of control points (marked as Δ) and their XYZ residuals (marked as vectors)

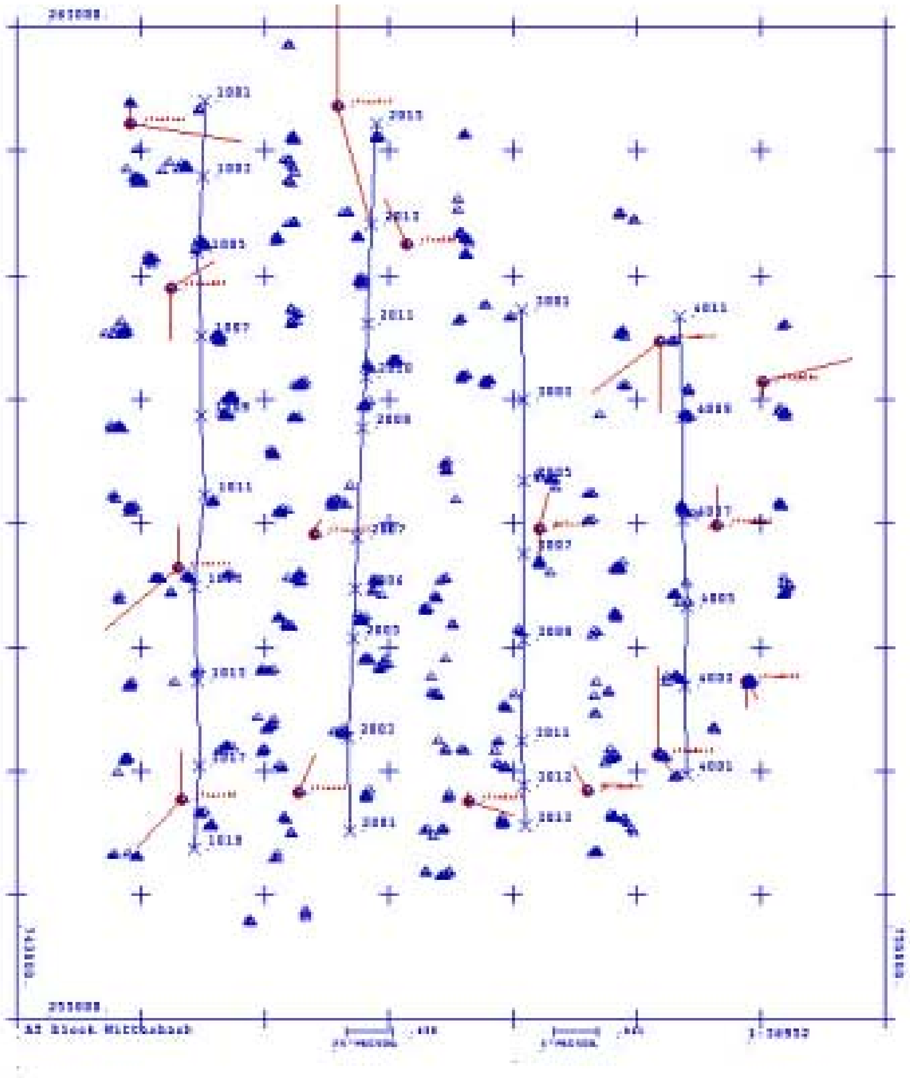

Fig. 3 – Digital AT with Match-AT

These figures demonstrate clearly that much more tie points are measured through automated digital aerial triangulation, which yields a higher reliability in the exterior orientation, if a good blunder elimination is performed.

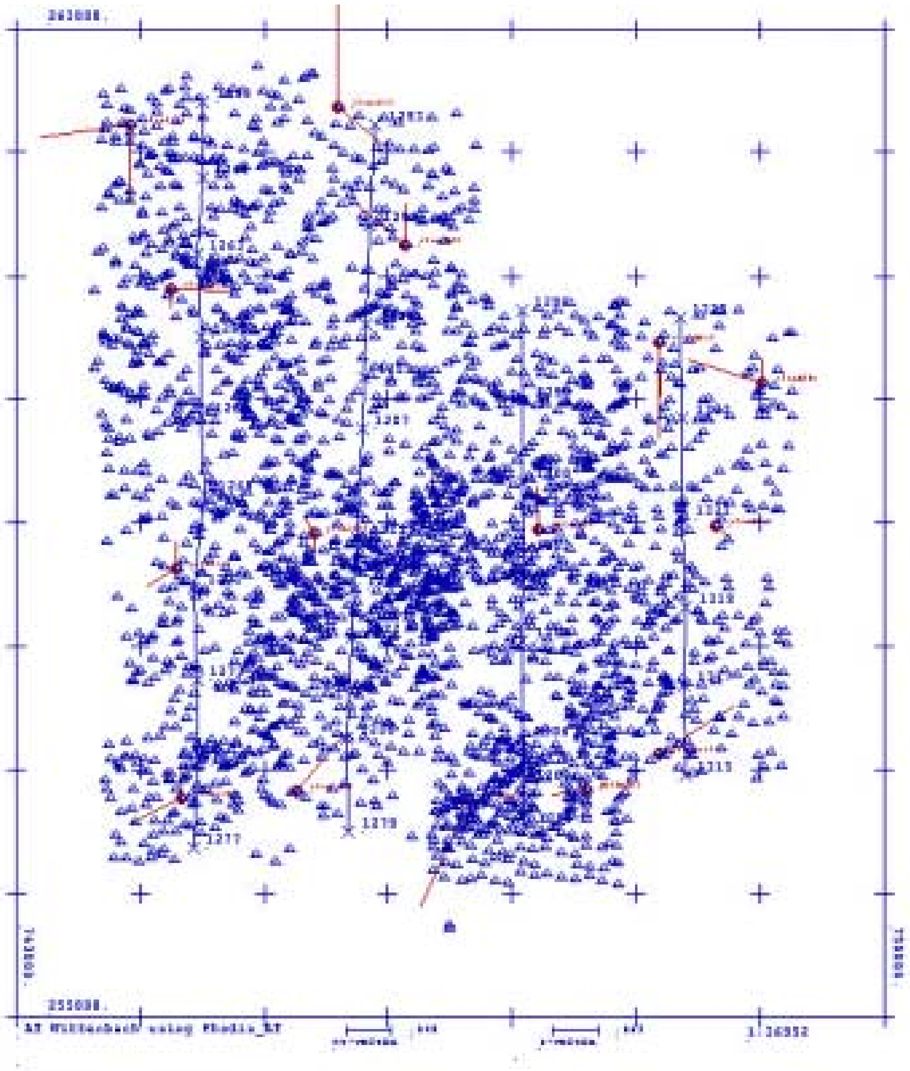

Fig. 4 – Digital AT with Phodis-AT

5 Time required

The time required for analytical and digital aerial triangulation of block Wittenbach is summarised in table 7. In this table, only the operator's time is counted, while the computation time of the computer for running batch processes, which is mostly done over night, is neglected. The triangulation of block Wittenbach was performed with a different operator for each system. The times for the triangulation with Phodis-AT were given by Zeiss, while for all other systems the elapsed time was estimated by the author.

In our investigations, it could be demonstrated that digital aerial triangulation of block Wittenbach was faster than analytical triangulation by up to a factor of 3. In general, this result was expected from other experiences, although not many direct comparisons have been published. But on the other hand, the elapsed time for triangulation using different digital systems varies. This could be attributed to the degree of automation of each system and to the different level of experience of each system operator. Especially, the post processing of the measurements provided many problems using HATS due to the large number of blunders in the measurements.

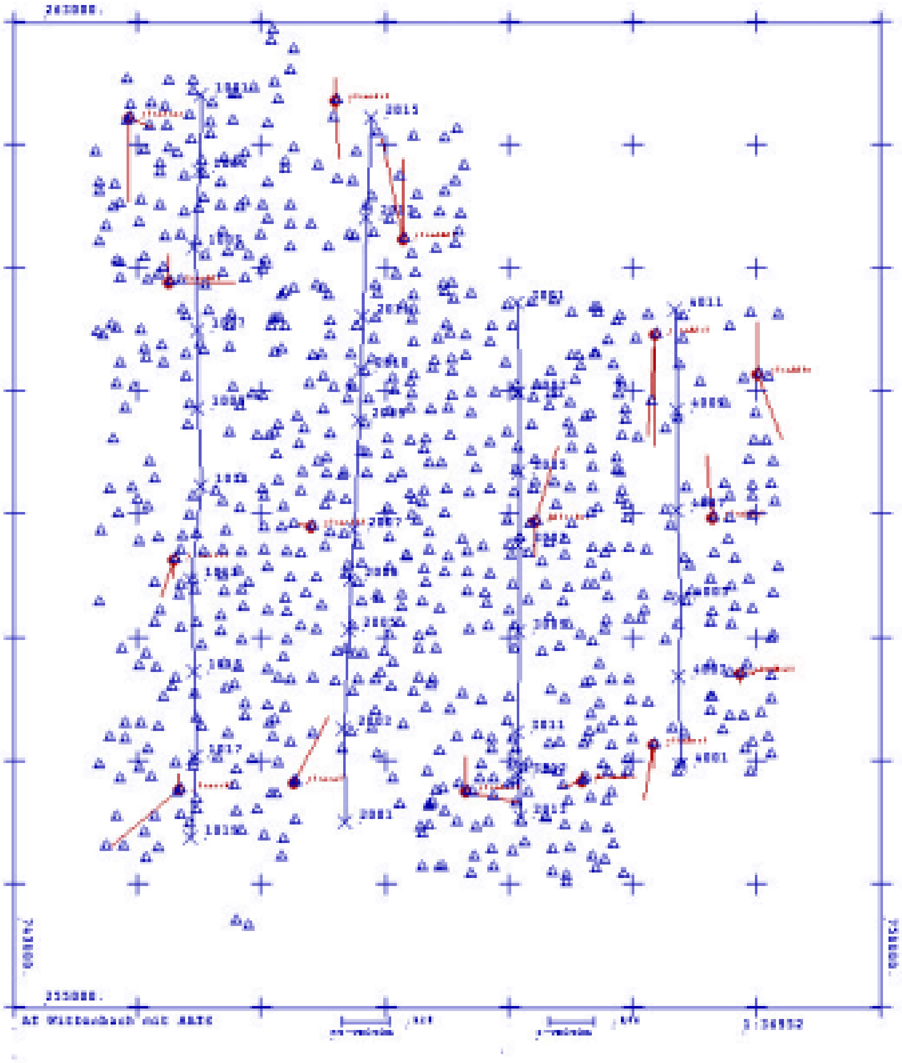

Fig. 5 – Digital AT with HATS

Other authors report good productivity for digital triangulation in flat terrain. DeVenecia et al. (1996) report a total working time of around 10 minutes per image, which was achieved with two test blocks using HATS. The two test blocks (Forssa and Wisconsin) have a large photo scale of around 1: 4000 and represent a very flat area with maximum height differences of 10 meters. In alpine and Nordic regions, a similar production rate for digital systems as summarised in table 7 was obtained by different authors (Kaeser et al. 1999, Kersten 1999, Urset and Maalen-Johansen 1999).

Table 7 – Elapsed operator time for AT (Wittenbach) with different software packages

AT processing steps	AP DSR14	DPW Match-AT	DPW Phodis-AT	DPW HATS
Preparation [h]	5.0	1.5	1.0	1.5
AT Measurements [h]	10.5	5.5	3.5	4.5
Bundle block adjustment and quality control [h]	2.0	0.5	1.0	3.5
Total elapsed time [h]	17.5	7.5	5.5	9.5
Number of images	35	34	34	34
Elapsed time per image [min]	30.0	13.2	9.7	16.8

6 Conclusions

Digital aerial triangulation of the Swiss test block Wittenbach could be performed using three different AT systems (Match-AT, HATS, and Phodis-AT). In comparison, the same block was triangulated at an analytical plotter (Kern DSR14 with ORIMA-T). The results (RMS, sigma naught aposterori σ_0, empirical accuracy, number of n-fold points), which were obtained using the four different systems with four different operators, were similar for all three digital systems and can be accepted as good for practical applications. With digital triangulation the same range of sigma naught could be achieved as for analytical triangulation. But, the efficiency of digital triangulation is much higher (approx. a factor 2–3). Furthermore, the adjusted orientation parameters are much more reliable than derived from analytical triangulation due to the higher number of measured points per image and their position in the image with the assumption, that all blunders are eliminated. In general, it is very difficult to compare triangulation software packages, if the triangulation is performed by different operators with different level of experience.

The comparison of HATS and Match-AT yielded the following results, which might be influenced by the author’s subjective opinion:

- Digital triangulation using both systems provides a reliable result of the photo connections within the block.
- The precision (sigma naught) of digital aerial triangulation using both systems is at the level of analytical triangulation.
- HATS provides more automation in the preparation by Swissphoto’s customised and modified approach.
- The quality of measured points by the combination of feature and area based matching is higher.
- The results obtained by both systems are similar, although the point distribution is different (point clusters vs. homogeneous point distribution).
- For the measurements of Match-AT less post processing is necessary.

- Digital triangulation with Match-AT is faster.
- The integration of bundle block adjustment software in the measurement phase (Match-AT) is the better solution.
- Both commercial systems do not provide an easy-to-use graphical user interface for quality control of the triangulation results.
- Both systems do not provide template matching of signalised points to achieve higher accuracy.

However, there is still potential for more improvements in digital AT to increase the productivity, so that a triangulation rate of better than 5 minutes per image could be possible in the future. This can also be achieved, if precise direct measurements of the orientations elements by GPS/INS will be available, to start with a better approximation for the automatic point transfer.

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Discussion

Results of digital triangulation using different software packages
(HATS/Match AT/Phodis-AT)
T. Kersten, Swissphoto, Switzerland

Andersen (Department of Mapping Sciences, Norway):
Nowadays the external orientation elements are an important output from aerial triangulation. Have you had a chance to compare the results from the different packages for those elements and not only the ground checkpoints?

Kersten (Swissphoto, Switzerland):
Good question, because sometimes you use analytical plotters to do mapping, you perform the aerial triangulation digitally and then you use external orientation for the analytical plotter. I have not had time to compare this, but it would be a good idea. But I do not see that there are great differences with the digital triangulation. On the other hand, when you transfer the orientation data to the analytical plotter, you always realise that there is a slight height shift and you have to adjust it. Perhaps someone else can comment on this too.

Grabmaier (ITC, Netherlands):
The transfer of exterior orientation parameters to other systems has its pitfalls. For example, it makes a difference whether or not you make a correction for atmospheric refraction; that can explain a datum shifting. It makes a difference whether you use conform transformation or affine transformation for inner orientation. If you use the former in one system and the latter in the other, you might end up with models which have parallaxes in the analytical plotter. So the exterior orientation parameters are sensitive to slight differences in the interior orientation which should normally play no role if you base the orientation on ground control; but they suddenly become very significant if you base your orientation on the parameters of the exterior orientation computed from aerial triangulation. Even atmospheric refraction makes a considerable difference; nobody minds if the projection centre is 1m higher or lower. But if you download the orientation parameters from an aerial triangulation, which was computed with correction of atmospheric refraction into a system, which does not correct for refraction, you get a datum shift. It is even worse if you try to get orientation parameters into analytical systems. Besides this fact, you have the problems with primary, secondary and tertiary axes.

Kersten (Swissphoto, Switzerland):
I mostly agree and can say that operators also have problems when they have to check the orientation on the analytical plotter and the points are measured automatically and some points are in the fields or on trees; they do have trouble in checking these points. That is why they sometimes complain about aerial triangulation.

Dörstel (ZI Imaging):
A comment on transferring orientation data to an analytical plotter. Our experience is that the trouble begins if you try to apply self-calibration in bundle block adjustment. I mentioned in my presentation that some customers get the best results by transferring a lot of three folded points instead of multiple folded points to the analytical plotter. Secondly, a remark on the height index; to my mind it is clear that an automatic matching algorithm has a completely different height index than an operator, so for normal data compiling we talk about 1/2m height index for each operator. This is the average we have in these algorithms.

Automated Triangulation in Nordic Terrain
Experiences and Challenges with MATCH-AT

A. Urset
Blom Mapping, Oslo

I. Maalen-Johansen
Department of Mapping Sciences,
Agricultural University of Norway, Aas

Abstract

Preliminary values for the tie point positions is the most crucial factor for success in the automated process of aerial triangulation. In steep terrain with considerable height differences, the preparation and pre-processing of data for the triangulation are required to obtain acceptable gain from automation. The paper discusses the workflow and presents results from different production projects.

Introduction

The Norwegian company Blom Mapping has used digital photogrammetry for orthophoto production and mapping since 1994 and for the last two years Intergraph's ImageStation has been the core of the digital production system. Digital photogrammetry has taken over the majority of the mapping market in Norway and digital orthophotos have become a product of considerable commercial interest. At the same time, the competition for the market shares has been substantial. One field to gain cost reductions with digital photogrammetry, is within the orientation process. With automation of the aerial triangulation, the time spent on manual point measurements can be reduced and transferred to other production tasks.

1 Project description

The triangulation blocks used vary a lot in size, shape and image scale, due to the variations in the current mapping projects. Two of the blocks were used for large-scale mapping, while the other two were meant for orthophoto production in smaller scale. The accuracy requirements for the orientation parameters are different for these two mapping purposes and it was also spent more time editing the blocks used for large-scale mapping. Thus the results of the triangulated blocks should not be compared directly to one another.

Table 1 – Description of blocks in project

Block	Image scale	Block size (images)	Overlap (%)	Height difference (m)	Pixel size (μm)
Tromsoya	1:3500	7x(7–19) (=93)	60/20	160	12.5 μm
Trollvika	1:6000	3 strips (=24)	60	280	12.5 μm
Malmo	1:15 000	19x12 + 3 cross strips (=163)	60/50	67	25.0 μm
Nordmarka	1:20 000	5x12 (=58)	60/20	530	12.5 μm

The terrain types range from dense, coniferous forest (Nordmarka, close to Oslo) with considerable height-differences, via flat urban areas (Malmo, Sweden), to deciduous forest in steep terrain on the coast in northern Norway (Tromsoya and Trollvika). The images from two latter areas are not optimal due to late spring photography and too much leaves on the trees. GPS positions were included in the setup of all the blocks, but DTM's were not used in any of these projects. Trollvika consists of three connected strips along a road.

2 Description of the used software

2.1 ImageStation MATCH-AT (ISAT)

ImageStation MATCH-AT (ISAT) is an automated aerotriangulation package combined with editing facilities. MATCH-AT is a fully automated aerotriangulation and bundle block adjustment package provided by INPHO GmbH of Stuttgart, Germany. The objective of MATCH-AT is to automate point transfer and tie-point measurement operations, thereby minimising manual work and operator intervention. In addition, ISAT supplies editing facilities that seamlessly integrate MATCH-AT with Intergraph's ImageStation photogrammetric products.

MATCH-AT is designed for fully automatic aerial triangulation. Its main features are feature-based and least-squares matching procedures and an integrated bundle approach which rigorously and automatically adjust matched points by using robust statistics.

2.2 NLHBUNT for bundle block adjustment

NLHBUNT is a bundle block adjustment software developed by Department of Mapping Sciences, Agricultural University of Norway and Norkart AS of Norway. This software provides more statistical data than ISAT, and has possibilities for adjustments with GPS-positioning and self-calibration built in it. Stripwise estimation of additional offset and drift-parameters is available.

When we started using MATCH-AT, there were some problems with integrating GPS-data in the processing, so in order to get these measurements in to the adjustment, we had to use an external software package. Besides we have also experienced that ISAT sometimes throws out control points and tie points which are correctly measured, without any warnings at all. Of course it is possible to bring the measurements in to the adjustment again, but it is easier to control the adjustment using NLHBUNT.

3 Workflow

3.1 Project setup

The input data for the project includes project-, strip- and camera-parameters, and control point coordinates. We use to copy the project and camera parameters from existing projects, and then use the editing facilities to adjust them.

Setting up the strips is done by the Strip Wizard command. This tool allows you to edit parameters related to the bulk creation of photos. Approximate exterior orientation is assigned to the photos during this process, normally by adding the GPS-positions for the first and last photo of the strip.

To get a more accurate approximate orientation, we finally import the GPS-positions for all the photos in the block . This is done by the import exterior orientation command. This is not mentioned as a step in the workflow for ISAT by Intergraph, but we have experienced better matching results by using this in our workflow.

3.2 Interior orientation

Interior orientation (IO) is the first step in the orientation process. The normal procedure is to measure all of the fiducials in the image, and to use affine transformation for the IO solution. The program has functionality for reviewing the residuals and transformation parameters, and remeasure, delete, withhold, or reinstate individual fiducials at any time. When you save the IO solution, the software saves the results for restoring the orientation later.

ISAT does also have an automatic interior orientation functionality – Auto-IO. The Auto-IO tool requires that one of the images in the block is manually measured and uses this as a template for the automatic measurements.

3.3 Control point measurement

We usually measure 5–6 well distributed control points in the block before we start the automatic matching. The rest of the control points are measured after we have got a successful adjustment. Then it’s easier for the operator to locate the points, because the initial positions are more accurate.

3.4 Initialize ISAT

In this step you start specifying the block you wish to process. Then the system initializes nominal tie-points (TPCs) using a 3x3 pattern of von Gruber point positions. The ground coordinates of these TPCs are derived from the approximate exterior orientation values and the average ground elevation value for the entire project.

You can also use approximate DTM- and GPS-data for this initialization. Then the elevation values in the DTM will be used instead of the average ground elevation value. According to *Madani/North* (1998) you should use DTM-data if the Ground Elevation range within the block is more than 20 % of average Flying Height.

If you do not have a DTM covering the area of the block, you can extract just a few points from a map, and use these points to make a DTM. In version 2.0 of ISAT these points had to form a regular grid, but in the latest version this requirement has been removed.

3.5 Adjust settings

It is recommended to inspect and edit the resulting TPCs using Point Measurement facility in case of large relief displacements and imprecise projection centres. The pull in range of the matching algorithms is approximately 10x10 pixels and if the positions of the TPCs are out of this range, the computation will fail.

You can manually move the TPCs and it seems to have an effect on the points. But if you check the generated xyz-values for the TPCs which are stored in the *.prj file, this really has no effect on these coordinates.

3.6 Matching and block adjustment

Proper settings and options for the processing of the block is selected in the MATCH-AT Driver. We normally use preliminary matching during the computation. It is recommended to use this if DTM-data is not available. Then the automatic matching and block adjustment is done.

For processing of large blocks it is useful to try running ISAT only for the first two or three levels in the image pyramid. Then we get an indication of whether the positions of the TPCs are inside the pull in range for MATCH-AT or not.

3.7 Analysing and editing

MATCH-AT provides statistics in the Review Results facility and the aat.log file. Normally we start to analyse the results by browsing the aat.log file, to get an indication of the quality of the adjustment. If the phi and omega values for an image exceeds 4–5 grads, this is an indication of blunders in the block. This log file also include statistic on number of measurements per image, residuals for the control point measurements, and tie point measurements.

If blunders are detected in the block, this is often caused by errors in the GPS-data for an entire strip. Otherwise the estimated kappa value in the preliminary exterior orientation can be out of the pull in range of the program. The most efficient solution in such cases is spending some time trying to establish better preliminary values and try initialising and re-running MATCH-AT, instead of editing the blunders in the existing measurements.

If the log file does not have any indication of blunders, the Edit Suspect Points tool should be used to go through the list. In this list you will find the TPCs with either to few measurements or blundered measurements. If the list is very long, it can be useful to check if there is special areas in the block which have many errors. This may also indicate that the preliminary values for exterior orientation is too weak, and that they may be edited and the matching re-runned instead of editing all the suspect areas on the list. The rest of the control points are then to be measured.

3.8 Post block adjustment

After editing the suspect areas and measuring control points, we use to do a post block adjustment. This is done by the MATCH-AT driver. The next step is reviewing the results, to see if there still are blunders in the block. Since ISAT has automatic blunder detection, the blunders will be withheld. If it is enough good measurements in the areas where these points are placed, you may ignore these blunders. If there is few measurements you have to edit the blunders or measure additional points to strengthen the block. Withheld control points must also be re-measured.

3.9 Post block adjustment in NLHBUNT

The last step of ISAT is normally to write the adjustment results to the project files by running the Bulk Orient tool. Instead of this, we export the image measurements, and do a bundle block adjustment in the NLHBUNT software. This is done because we get more statistical results out of this software, so we better can control the adjustment. It is also possible to do a stripwise estimation of additional GPS parameters, if necessary.

The final step of our workflow is then to import the adjustment results back into the project files by Import Exterior Orientation.

4 Results

The most central results from the adjustments in NLHBUNT are shown in table 2. As mentioned before, two of the blocks are established for mapping purposes and two for orthophotos. Since the results are taken from actual production projects, there was none proper check points available. Comparable projects triangulated manually in analytical instruments usually have sigma nought between 4 and 5 µm.

Table 2 – Results from bundle block adjustments

Block	Image scale	Sigma nought (µm)	RMS Control points xy (m)	RMS Control points z (m)	Number of tie points	Number of control points
Tromsoya	1:3500	5.01	0.074	0.028	1626	20
Trollvika	1:6000	4.95	0.035	0.045	201	8
Malmo	1:15 000	6.17	0.097	0.026	2700	11
Nordmarka	1:20 000	6.04	0.088	0.020	1100	10

The results in all four projects are inside the current requirements. The height accuracy is apparently better than the planimetric accuracy for three of the blocks. This is a known effect from earlier projects with GPS-controlled blocks. The number and location of the control points follow the recommendations for GPS-controlled blocks, i.e. points in each corner of the block and in the end of each strip sidelap area.

Since we do the final adjustment in NLHBUNT, we have little experience with the effect of self-calibration on the blocks in ISAT. In the NLHBUNT adjustments the effect of additional parameters was not found to be significant.

5 Problems

During our first 5 months with ISAT we have experienced several problems with the software. Most of them were either caused by operator faults, or problems which we could get around by doing the steps in another way than the manual suggested.

We had major problems to get the GPS-data into the project during the initialization of the block. It turned out that we had to put the GPS-file in to the block-directory on the disk, but since this directory is established during the initialization, we had to initialize the block twice to include the GPS-data. Another problem was that the eccentricity values of the GPS-antenna had to be entered with positive values. We did get around this problem by writing the negative value in a text editor and then copy this into the box in the menu. This problem is fixed in later versions of the software.

We have also experienced some problems with the Auto-IO function, as we in two different blocks got large residuals for the GPS-positions for an entire strip. It turned out that the automatic fiducial measurement for the images in these strips had failed with approximately 1 cm! Since we had problems including the GPS-data in our first projects, this was an error we could not escape, unless we had manually controlled the images. The reason for this error is probably that the images were scanned on a Leica Helava DSW300 roll scanner, and when changing from one roll to another, the positions of the fiducials were placed differently in the image files. Then the template-image differs too much from the image that is about to be measured, and the measurement fail. It is not unusual that the automatic measurements fail, but normally the program refuse to measure the image at all.

Besides, we have also experienced that ISAT during the robust estimation throws out control points and tie points which are good measured, without any warnings at all. Of course it is possible to bring the measurements in to the adjustment again, but it is easier to control the adjustment using NLHBUNT.

Precision measures in ISAT are also unreliable. The sigma can be small although many blunders are still in the data set. Clusters of tie-points can have considerable systematic shifts from one image to another and still be regarded as good points.

MATCH-AT provides statistics in the Review Results facility and AAT.LOG file which are used to identify weak areas in the block. Tie-points measured in only one image per strip are not identified in this procedure. Areas in the blocks with poor tie-point distribution can be missed due to this malfunction.

6 Time consumption

The time registered on the operator in the current projects, including all necessary production steps down to oriented images, is shown in table 3. The figures are taken from the internal project accounts.

Table 3 – Time consumption

Block	Block size (no. of images)	Elapsed operator time (hours)	Elapsed operator time pr. image (hours)	Comments
Tromsoya	93	32	0h 20min	
Trollvika	24	21	0h 52min	Incl. DTM-testing
Malmo	163	35	0h 13min	
Nordmarka	58	32	0h 33min	

Time consumption strongly depends on the accuracy of the preliminary orientation and on the terrain type. In the projects including coastline or lakes (Tromsoya and Trollvika) the need for manual interaction was considerable.

The Trollvika block contains of single strips only, and most of the measurements had to be edited. Since the number of images was only 24 it was faster to do it manually instead of spending time on finding errors in the preliminary EO values. We even tried to make a DTM with a spacing of 500 meters just to check if this could help the matching, but it did not seem to have any effect at all.

7 Suggestions for improvements

Most of the problems are already addressed in the text above, but a summary of possible improvements are given here.

To get a more accurate approximate orientation, all the GPS-positions for photos in the block should be possible to import in the setup step.

The blunder detection and removal in ISAT should be more able to handle clusters of ill-matched tie-points.

In the initialisation of the nominal tie-points, it should be possible to apply different tie-point patterns to handle different overlap.

8 Practical Conclusions

ISAT performed acceptable accuracy for the investigated blocks after different quantities of operator contribution.

Time consumption strongly depends on the accuracy of the preliminary orientation and terrain type. Semi-automated triangulation applying the recent function for matching-assisted point measurement is a cost effective method for smaller and potentially problematic blocks. A semi-automated approach should be applied in projects with considerable height differences or poor preliminary orientation parameters. Blocks including different kappa rotations inside each strip are not suited for automated processing.

A general trend in photogrammetric systems is to remove most photogrammetric parameters from the interface in order to obtain a broader use of such systems among “new” user groups. This also leads to less possibilities for project-wise adaptation. In automated triangulation experienced operators are required to locate and solve problems. They should also have the possibilities to set up optimal parameter sets and analyse the adjustment results.

Further investigations should focus on the underlying reason(s) for smaller RMS in height than in planimetry for the control points.

References

Intergraph Corporation: ImageStation MATCH-AT User Guide, versions of July 1998 and January 1999.

Intergraph Corporation: ImageStation Model Setup User Guide, version of July 1998

Intergraph Corporation: ImageStation Photogrammetric Manager User Guide, version of February 1998.

Madani, M. and North, S., 1998: MATCH-AT: Some Fundamental Workflow Issues, InterGraph note.

Discussion

Automatic triangulation in Nordic Terrain-experiences and challenges with Match-AT
Anne Urset, Norway

Heuchel (Inpho):
Just a small rectification: I am not quite sure that this actually does happen, that correctly measured control points are eliminated without warning. You are warned regarding automatic points when they are eliminated. But, for all those that are manually measured, that means the control points for them, you also get a warning in the log file. We should find out what happened there exactly, but I have to correct it. The opposite happens when you have manually wrongly measured tie points; during the adjustment those points get eliminated, but only for the adjustment, as they remain in the data sets. Maybe this could explain the problem because if you export the data to your local or your block adjustment programme PAT-B, then you will get a higher sigma naught. This happened to some users.

Hoschtitzky (ITC, Netherlands):
I believe there is a simple explanation as to why the system puts you back into the water; I think that there are details and the points are chosen according to a mathematical criterion and the latter will have the same outcome when the procedure is repeated. In LH Systems, if you do not lock a point and force the system to replace a point which you already deleted by a new point, it will bring you back to the same point and repeat the same blunder: that is logical.

Urset (Norway):
But this is caused by the tiepoint position, it says in the manual that you should move these points, but earlier today I have heard that this does not work and I have also realised this during practical work.

Heuchel (Inpho):
I think she is right: this is a problem about which a lot of users complained. The reason is that we implemented at the beginning a possibility to edit this tie point centre. So your editing was only used for the beginning, but later on if the system detects that it could not find any points in that area of the photo, it tried again to project a new tiepoint into the original area. Hence the user gets the impression that the system ignores the editing of the user. I think that we will sort this out.

Nicoletti (Intergraph):
Another remark on what Tobias Heuchel (Inpho) has said: regarding the software used for this test. There is a problem for the repositioning of tiepoint areas and if there are not enough points found inside that mesh, the main tiepoint area must be moved back again. So now the tiepoint has been fixed and it is working. But a new problem emerges related to the GPS file. So this is another way for the direct import instead of running through all the operations again. To avoid this there is a workflow that you can follow. You can use the same GPS file that you used for value matching AT to allow you to import the orientation parameters and even to compute the Kappa.

Urset (Norway):
Yes, I used this file but I had to put in the Kappa. I had to compute the Kappa value myself, the programme does not do this.

Nicoletti (Intergraph):
There is a special way that I have to show you.

Boberg (Royal Institute of Technology, Sweden):
I was surprised to find that your root mean square errors in planimetry were up to 2 or 3 times higher than in height: do you have an explanation for that?

Urset (Norway):
I have already discussed it with some colleagues and I think it is because there are very few control points in the GPS block. It seems to be the nature of such blocks and I myself wondered why this effect happens, but it seems to happen often in such projects.

Digital Aerotriangulation for Map Revision with Match-AT

C. Käser, T. Czáka, T. Kunz
Swiss Federal Office of Topography
Wabern, Switzerland

Abstract

First experiences with automated AT (Match-AT) show that the introduced method (supported by GPS projection centers and the digital elevation model DHM25) is operational for revising 1 : 25 000 maps.

The quality of the AAT was checked in an area of 210 km^2 on an analytical plotter BC3 with 367 height check points. A special effect is that the height differences towards the edges of the model normally increase. To reach the demanded standard deviation of 1.5m in height, additional height check points have to be introduced.

Due to the missing graphical overview for the block control in Match-AT, a tool called VisAT was developed which allows a graphic search for weak connections or regions with high residuals in planimetry or height.

The direct import of Match-AT orientation elements into the BC3 creates parallax zones along the edges of the model. These can be removed by recalculating the model bundle parameters on the BC3 with 30 automatically measured tie points.

1 Photogrammetric systems

For about ten years the photogrammetric restitution of the National Maps (scale 1 : 25 000) has been done on 6 analytical plotters BC3 from Leica with the software MAPCEI from Aviosoft. In 1996 the Federal Office of Topography acquired a digital photogrammetric system consisting of 1 roll film scanner from Zeiss (SCAI-SCAW with PHODIS SC on SGI O2), 1 data server from Silicon Graphics (HW: SGI Origin200 with 162 GB hard disk, processor R10000, 180MHz, 640 MB RAM, SW: Match-AT, PHODIS OP and OrthoVista) and 1 Digital Photogrammetric Workstation (HW: SGI O2, SW: PHODIS OP, TS, ST30 and PhotoShop).

To be able to keep up with the general trend of the photogrammetric system suppliers towards solutions on Windows NT, one NT workstation with PhotoShop and ArcView with Image Analysis was bought last year.

2 General block information

The entire photo flight equipment is from Leica: The camera system RC30 with girostabilized platforms PAV30 and the GPS-aided flight management GIM. In general, the camera lens is a 153 mm cone. To record the flight path and the event marks, a GPS receiver from Trimble (4000 SSE) is used. Since 1998 the images are being flown in color, usually with RDP II from Fuji film.

The image scale for map revision 1 : 25 000 is 1 : 30 000 with a forward/side overlap of 70% / 30%. Thus, the flying height is between 4000 and 7000 m. All control points are non-marked natural points, measured by GPS. There are no cross stripes for a block, but a pair of flight lines are fixed together by 2 GCP regions, one at the beginning and another one at the end of the lines. One GCP region normally consists of 5 points. The a priori block accuracy (RMS) is 0.5 m in planimetry and 1.0 m in height.

The images are scanned with 14µm (1814 dpi) scan resolution directly on the roll. The image data format is TIFF tiled. Match-AT supports only gray-scale images, thus color images have to be reduced to 8 bit.

Because the orientation elements are used later on analytical plotters, the adjustment of the block is compensated without self-calibration. Drift compensation parameters are introduced to improve the quality of the GPS observations.

3 Match-AT results of Block C: Escholzmatt

The area is 24 km x 35 km (840 km^2) located in the Swiss Plateau (Emmental). The terrain is a hilly agricultural region with small villages, frequently alternating between open fields and forests. The block was flown in 6 lines (direction E-W) on 20.06.1998. 123 color images were taken. The image data volume for the block is 48 GB (gray-scale images with image pyramids). Overall there were 38 GPS ground control points in 6 regions.

RMS without drift compensation	East	North	Z
Terrain points [meter]	0.163	0.206	0.605
GPS observations [meter]	0.773	0.489	0.828
Check points [meter]	0.301	0.326	1.034
	Omega	Phi	Kappa
Rotation [mgrd]	2.4	2.0	0.8

Fig. 1 – The results with 24 control (11 in height) and 14 check points

Sigma0: 4.20 micron = 0.30 pixel = 0.131 meter
Number of observations / unknowns / redundancy : 30186 / 14244 / 15942
Number of tie points per photo: average = ~120, minimum = 80, maximum = 194

The computation time for the whole block was 33:15 hour:min. or 16.2 min. per image.

4 AT check on stereo models of Block C: Escholzmatt

10 stereo models were checked on the analytical plotter BC3. At first there were some regions along the edges with parallax zones.

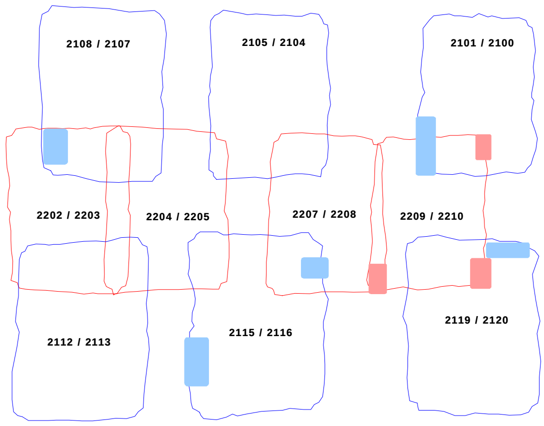

Fig. 2 – Model orientations on the analytical plotter: parallax zones

In that case the orientation elements (in *.md files) were directly imported. After recalculating the bundle parameters of the stereo model on the BC3 with 30 automatically measured tie points, the parallax zones were gone.

The quality of the automatic AT was checked with 367 height check points (non-marked cadastral fix points) in the upper left block quarter. Overall the standard deviation was ± 1.35 meter (medium = +0.8 m, minimum = –3.9 m, maximum = +3.3 m). Per model the standard deviation varied between –1.3 m and +1.8 m. The model 2115/2116 was very good with an average of 0.0 m and a standard deviation of 0.15 m. In general the height difference was within the tolerance and very good in the center. A special effect was that the height differences towards the edges of the model normally increased by up to 2–3 meters (Fig. 3).

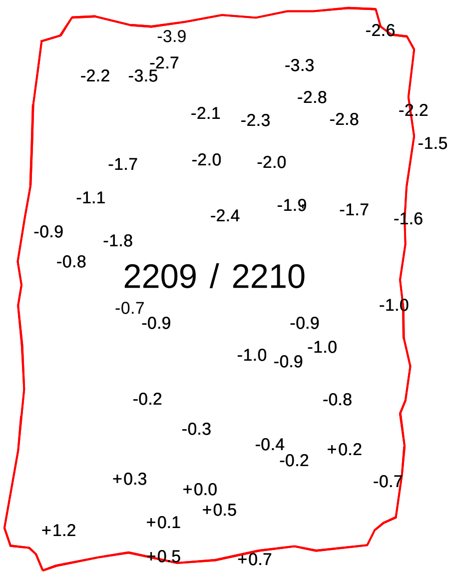

Fig. 3 – Model orientation on the analytical plotter: height problems along the edges of the model

In addition, the quality of the automatic AT was checked by a private photogrammetric office on an Intergraph ImageStationZII with 100 height check points (non-marked cadastral fix points) in the upper left block quarter as well. The standard deviation was ± 1.1 meter (average = –0.4 m, minimum = –2.6 m, maximum = +1.7 m).

5 Conclusions

5.1 Positive

Automatic aerotriangulation AAT is operational

The automatic tie point measurement by matching techniques works in most cases. Normally the tie points are correctly located and on the ground but some dubious matches like points in lakes and points on top of trees (Block C) still remain.

Initialization of tie point regions with GPS projection centers and digital terrain model

The automatic definition of homologue tie point regions in all photos works very well because of the approximate coordinates of the camera position through GPS and the known terrain characteristic from the digital terrain model of Switzerland DHM25.

Block stabilization with GPS projection centers

We have reduced the number of ground control points significantly by using GPS to determine the projection centers and introducing them as additional observations in the AT. Although the results of the AT look very good, there are still some large corrections on the initial projection centers (1–2 m in planimetry and height).

Time expectations

Overall, a digital AT takes about the same amount of time as the classical method, but there is a gain in time due to unattended processes running overnight. Earlier, the computation time was very fast, about 5 min. per photo for Block A Saane-Sarine, but has now slowed down now to 15 - 20 min. per photo for the newer blocks.

Data input and output

In our heterogeneous environment the data transfer from PHODIS to MATCH-AT (interior orientation, image pyramid) and back to PHODIS (exterior orientation) works. The export of the exterior orientation to the analytical plotters BC3 and the documentation (hardcopy) of the ground control points works too.

5.2 Negative

Block definition: additional height check points

The block configuration described under chapter 2 (see Fig. 4 without height points) caused several problems: the RMS's of heights (1.5 m) were larger than expected and the maximal error was up to 3 m. In another region with few tie points (large forests), the observations from the GPS projection center and the control points were not strong enough to keep the photos in the right places and they were displaced by up to 100 m in planimetry and height. This displacement also created mismatches for 2-fold tie points.

Because of that we will introduce a new block configuration: additional height control points in every block corner. In order to be able to check the block accuracy more reliably, additional height check points are introduced at the beginning and end of the flight lines and in the center of the block.

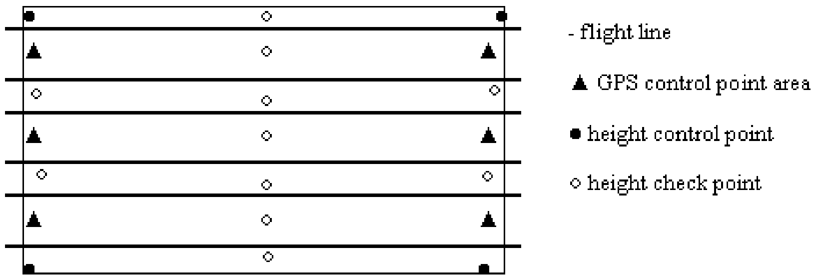

Fig. 4 – Block definition with additional height points

Search for weak connections

In Match-AT, a good tool to control the distribution of the tie points and to search for weak connections between the photos is missing. The Match-AT function "Analysis" for finding tie point areas with 0 connections is not designed for overlapping tie point areas. But that is the result of our matching strategy with multiple tie point areas and 100 and more tie points per photo.

To overcome this situation we created a tool called VisAT (Visual Basic tool with database access running on Windows NT). VisAT just gives a graphical overview of the whole block without any image information. The projection centers of the photos are shown in blue and the tie points of the whole block are displayed in different colors indicating the number of photos connected. To check weak connections there are functions for zooming in and displaying the rays to the connected photos per tie point available.

Manual measurement of new/tie points

It is very easy to measure ground control points with Match-AT because of the known positions. It is much more difficult to measure new points. The selection of all involved photos, identical regions and identified points has to be done manually. Only the final measurement of the point in all images can be done with LSM when the point approximation is good enough.

Exclusion zone

In Switzerland there are a lot of lakes and forests. Match-AT matches tie points on lakes and on top of trees. To avoid such matches, it would be nice to be able to introduce vector data for exclusion zones like lakes or large forests.

Graphical overview of block adjustment results

In Match-AT, the results of the block adjustment are just shown in a log-file. What is missing is a graphical overview of the results with, for example, the residuals in planimetry and height for control, check and GPS projection centers.

Orientation problems on the analytical plotter BC3

The direct import of Match-AT orientation elements (*.md files) creates parallax zones along the edges of on the model. After recalculating the bundle parameters (for the stereo model) on the BC3, there still remain significant height differences along the edges of the stereo models (up to 3 m), but the parallax zones are gone.

Discussion

Digital Aerotriangulation of Map Revision with Match AT
C. Käser, Switzerland

Kölbl (EPFL, Switzerland):
It is very interesting to see your experience, but when I see your recommendation for the control point distribution I think it is quite common. If you have only a 30% sidelap then the effect of instability is too large and this cannot be a problem with the programme. You should use cross strips.

Käser (Swiss Federal Office of Topography, Switzerland):
I agree that this is not due to the software, but due to the block configuration. We do have a problem in mountainous areas, we cannot fly cross strips on the same day as we have to fulfil the flight program, but it would be a solution.

Andersen (Department of Mapping Sciences, Norway):
During the block adjustment, did you use additional parameters to compensate for things such as film distortion etc?

Käser (Swiss Federal Office of Topography, Switzerland):
No, we do not work with self-calibration.

Torre (ICC, Spain):
In reference to the parallaxes: did you observe in the last block, where you found a parallax, any correlation between lack of points in the area or bad point measuring and the parallaxes. Are the parallaxes you detected in a complete model or in that part of the model where there are not enough tiepoints? The other question is about self-calibration parameters: did you find later problems in using the results as orientation data?

Käser (Swiss Federal Office of Topography, Switzerland):
First question: the parallax has shown up just in a part of the stereo model, not in the whole stereo model. But I do not know if there were good tiepoint matches in the region where parallaxes appeared, that is something we have to check. For the second question, I do not intend to use self-calibration in that environment because of the analytical plotters.

Madani (Intergraph):
My first comment is that we always recommend, after the bundle block adjustment is done, that you perform the so-called “back-up after the orientation” to readjust so that you obtain a parallax free model on the analytical plotter. A question: you mention having difficulties in manual measurement of new points and tiepoints but why is that? Which software was involved in these measurements and in the processing of bundle block adjustment ?

Käser (Swiss Federal Office of Topography, Switzerland):
Manual measurements of tiepoints are not supported by Match AT. This means that you have to start again for all the images involved, by locating identical regions. Then you have to manually survey these regions and finally locate the new tiepoints you would like to measure

Heuchel (Inpho):
A remark on the orientation problem: if you transfer the adjusted co-ordinates for image measurement and you perform a model orientation on the analytical plotter everything seems to be fine. The problem emerges when you directly take the orientation matrix. Your question is whether this is an implementation problem, on our part, concerning the interface to the analytical plotter. What I assume is the following: if you take the adjusted co-ordinates and the image observation and perform a bundle block adjustment, then you should be able to reintroduce these points as free points and you will get exactly the same orientation points. I am sure about that. Same orientation matrix, same co-ordinates of the different projection centres. So my diagnosis is that it is an interfacing problem which comes afterwards.

Baltsavias (ETHZ, Switzerland):
I believe this is wrong. If you transfer the object co-ordinates to the analytical plotter everything should work because the object co-ordinates should be precise enough as they come from bundle block adjustment. The problem is with the orientation which is calculated in the bundle block adjustment using a mathematical model which is different than that used in the analytical plotter. If you have drift parameters as Christoph Käser mentioned, then they influence the values of the exterior orientation; the same applies to the self-calibration parameters, the same to the interior orientation mentioned before. That is why the direct transfer of these values does not work. So the solution would be for the *manufacturers* of the analytical plotters, who are often the same as those of the digital systems, to make software for the analytical plotters that is compatible with the results of the digital aerial triangulation.

Experiences on Automatic Digital Aerotriangulation

B. Masala
Ing. ESGT
Cabinet Philippe Rollin, Marseille

Abstract

The aim is to set out some practical aspects of Automatic Aerial Triangulation using Phodis AT software. Following the workflow step by step, difficult aspects of this new method will be shown. Results achieved will help to conclude and to finally show the advantages of a fully automatic tie point determination.

1 Introduction

To start with, let me tell you I will not explain how an Automatic Digital Aerotriangulation works.

This has been exposed generally by several specialists and particularly for Phodis AT by Zeiss Engineers.

In brief, tie points are extracted from images with the technique based on features base matching, using geometric and radiometric criteria, then a robust bundle adjustment is used to eliminate outliers.

In the next step, the accuracy of the measurement is obtained using Least Square Matching method.

That's all for theory.

My purpose is to tell you about my experience after one year using Automated Aerotriangulation on several projects. Of course, I will present some results but first, let me specify the way I got them.

Theory is one thing and practice is another.

The procedure to get the photo exterior orientation digitally is constituted by several steps which offer several options.

I will make remarks for each step and then present you some projects and the difficulties encountered.

2 Block preparation

In this step, we must define approximate location of images, such parameters as camera characteristics and scanning resolution and of course ground control points coordinates.

The software design is based on a block architecture.

This means we needn't repeat some actions for each image. This is a good way to save time and to avoid mistakes.

3 Interior orientation

Automatic, semi automatic and manual interior orientation is available depending on the quality of the camera.

Easy to prepare, it works very well with modern cameras but, with an old RC10 and only 3 fiducial marks, we have to proceed manually.

4 Automatic tie point generation

This is the most important step in AAT, especially since it is time consuming when a traditional method is used, whereas it can be automated.

Really easy to run, with very few parameters to define, we have only to wait.

Leaving the office at 6, we should find next morning over 100 images equipped with tie points.

If the process continues throughout the day, its low priority will allow us to work interactively as for measuring ground control points.

Using a good material, it works without any effort.

If it doesn't, we'll have to spend times to analyse the results and measure additional tie-points.

Even correlation controled by an operator will not always work.

There is always an explanation. Here are some illustrations:

- The area may be fully covered by trees, clouds...

  We'll get a few points but the block adjustment will remove most of them.

- It may be a great difference of date for the flight.

- It could be an old camera with a poor lens, or a great difference between kappa of images and flight direction or even a dirty copy of the film.

  Then the poor contrast will limit the features collection, especially between strips where the overlap area is narrow.

- Finally, it may also be a scan with inappropriate parameters; in this case, some information will be definitely lost.

Standard conditions are not always met in a project.

In the examples I'll comment on, these problems were encountered and we'll see the great improvement of the last version of PHODIS AT.

Three remarks:

- Even with poor conditions, the AAT is able to define enough tie points inside strip but it seemed to be very difficult to transfer these tie points to the neighbouring strip. I did not understand why the same feature produced a 2 or 3 fold point different in each strip.

The consequence in practice was to spend time transferring these tie points on every photo concerned.

With the new version, We'll show you in the examples the results are really better, even with a poor material.

– The results of auto tie point generation are not detailed enough to analyse if we get enough 4 or 5 fold points to ensure a good geometry of the block.

  Managing this amount of data takes a long time and it is tedious to have to go back to the previous step again, trying to find the good parameters. But we're beginning to think experience will make up for this.

– In case of using this results for a compilation on analytical stereoplotter, the operator will have to measure his operator height constant. To do this, he will need tie points to measure. As automatic tie points are not always adapted to human measure, we have sometimes to proceed to the measurement of additional points in each model for this purpose.

5 Ground control points measurement

This step is easier and faster compared to traditional aerotriangulation.

The display of the approximate position helps us to decide.

The autocorrelation works almost in every case. This is also true for additional tie points.

But sometimes, in very few cases, the correlation doesn't work and, for this, we like to measure this point in stereoscopic conditions, like a stereocomparator. This is possible but not easy to manage.

However, this is not the most difficult step in the workflow.

6 Block adjustment

Data are exported from Phodis AT to several bundle block adjustments easily. It is also useful to be able to select only one portion of a block.

Then difficulties should be pointed out.

If the recent versions of bundle block adjustment can ensure the computation of a large amount of data, the parameters to be set before beginning the computation are still the old ones. The human interface has been the same for the last 10 years.

But the worst is the printout of the results which is not adapted to the huge amount of points. Of course there is a critical points list but it is arranged according to increasing point number and not to decreasing value of residuals... This list could represent a hundred screens to display.

Also the photo connection, especially important between strips, is not easy to check.

Then the gross error detection doesn't work very well and we are compelled not to use it sometimes. To solve this, we would like to filter tie points measurements using a residual criterion. As this doesn't exist, we have to load results inside a database, wait for a long time before removing highest residual measurements and export data back to bundle block adjustment. This step is time consuming and the risk is to forget some aspects between two runs.

In our view, this step should be managed inside the block adjustment, already especially designed to handle this type of data.

It could be a kind of semi automatic gross error detection, offering to validate or not some decision proposed by the software.

7 Conclusion

To conclude, let me insist that the most important for us is to be able to analyze the results when the software encounters difficulties to work properly.

The quality of images and the accuracy of the ground control points is still essential.

Scan resolution should be adapted to the quality of the material. This would often avoid difficulties.

Then we have to confirm AAT saves time for almost 3 times. As we have to pay for the scan, this is economically interesting when we have to produce ortho images. In other case, the time saved will make up for the cost of the scan. We really think this system will be more and more economically attractive by practical experience of users and improvement of the software.

Now, let's have a look at some projects we carried out this year:

Of course, when we get good material in the best condition, it's like a demo.

That's why I specially selected projects containing several problems.

BLOCK NAME	**BONDOUKOU**	**BEOUMI**	**DAOUKRO**	**VENELLES**
PHOTOS	50 B&W	220 B&W	70 B&W	21DIACOL
STRIPS	4 //	4//cross5//	6 //	3 //
SCALE	50000	30000	30000	10000
FOCAL LENGTH	152 mm	152 mm	152 mm	152 mm
SCAN RESOLUTION	15µ	30µ	15µ	30µ
POINTS	2584	5133	1594	1655
4 FOLD	1%	9%	13%	4%
5 + 6 FOLD	1%	12%	10%	2%
PHOTO MEASURES RMS	9µ	9µ	7µ	6µ

The first three projects were done with an old camera, bad weather conditions, in a woodland, a difference between Kappa and flight direction of 15° for some strips, a difference of date of three months to one year (you can imagine the effect on vegetation in tropical countries with shadow going from North to South), copies with a low contrast and many scratches.

We can explaine the better result of the projects BEOUMI and DAOUKRO by the new version of Phodis AT. Especially if we take in account that the BONDOUKOU flight was done the same day and the contrast was better than the followings. We can see even with a better resolution that the 4 fold points are not so frequent and the rms is less than the third project which was done with the same resolution.

The last project was done with a good camera, good weather conditions but with the previous version of Phodis AT. These explaines the 4, 5 & 6 fold points are very few.

We can give you now the time we spent on project DAOUKRO. We were not able to do this estimation with accuracy on the other projects and they were done with the previous Phodis AT version.

This project contains 2 strips with a difference of one year. The connection between these strips and the others had to be done manually.

The elapsed time for the whole aerotriangulation was 36 hours of operator and 10 hours of processing time. That means more or less half an hour per image. By an analytical method, this material quality should represent one hour and a half per models. The saving of time is significant but we hope to be faster in the future.

Discussion

Experiences in Digital Triangulation with Phodis AT
B. Masala, France

Andersen (Department of Mapping Sciences, Norway):
I just conclude, from your presentation and from the previous one, that badly planned and executed flight projects create a lot of trouble afterwards. I think it is very important to do the planning and execution with great care to avoid the sort of problems you have had and the trouble Christoph Käser (Swiss Federal Office of Topography, Switzerland) had with block no. 2, which was flown across the lake instead of around it.

Masala (Cabinet Philippe Rollin, France):
It is true that, in Africa especially, the weather does not always allow one to fly in good conditions.

Digital Aerial Triangulation with HATS

T. Kersten
Swissphoto Vermessung AG
Regensdorf-Watt, Switzerland

Abstract

Digital aerial triangulation is increasingly being carried out in photogrammetric production environments as greater efficiency is being attained through increased automation. In this paper, a customised and modified approach to digital aerial triangulation using the Helava Automated Triangulation System (HATS) is introduced. HATS is used as the basic triangulation measurement tool for the aerial triangulation of the swissphoto block of more than 6000 images covering the entire area of Switzerland with photo scales varying from 1:22 000 to 1:54 000.

For the whole block Switzerland, aerial triangulation was performed from October 1995 until July 1998 in 43 sub-blocks using between 82 to 333 images per block. The results of seven selected triangulation sub-blocks are presented. Furthermore, the limitations of digital triangulation in difficult terrain as given in Switzerland, especially in alpine regions, are summarised and suggestions for improvements are discussed.

Introduction

The transition from analytical to digital photogrammetry has already been established in private photogrammetric companies. One of the major advantages of digital photogrammetry is the potential to automate production processes efficiently, thus substantially improving the price/performance ratio for photogrammetric products. Today, the key to an efficient photogrammetric production environment is the degree of automation in data production processes.

Image processing and computer vision techniques have successfully been employed for facilitating automated procedures in digital aerial images such as interior orientation *(Schickler, 1995; Lue, 1995; Kersten and Haering, 1997a)*, relative orientation *(Schenk et al., 1990)*, point transfer in photogrammetric block triangulation *(Tsingas, 1992)*, and the generation of Digital Terrain Models *(Krzystek, 1991)*.

Digital aerotriangulation including image import and image minification, interior orientation, point transfer, control point measurements, bundle block adjustment and quality control, is one of the most complex processes in digital photogrammetry and the automation of this process was one of the challenges in the photogrammetric community in the early nineties.

Investigations in automatic digital aerotriangulation have been performed in scientific institutions like Ohio State University *(Agouris and Schenk, 1996; Toth and Krupnik, 1996)* and University of Stuttgart *(Tsingas, 1992; Ackermann and Tsingas, 1994)*, by system providers like LH Systems *(DeVenecia et al., 1996)* and Zeiss *(Braun et al., 1996)*, and by software providers like Inpho, Stuttgart *(Krzystek et al., 1996; Krzystek, 1998)*. Currently, there are a few software packages for automatic digital aerial triangulation commercially available: Helava Automated Triangulation System HATS (LH Systems), PHODIS-AT (Zeiss), MATCH-AT (INPHO and Intergraph), and since 1999 IMAGINE OrthoBASE (Erdas), ORIMA/APM on NT (LH Systems), and Virtuozo. But only few users *(Kersten and Stallmann, 1995; Beckschaefer, 1996; Kersten and O'Sullivan, 1996b; Hartfiel, 1997; Kersten and Haering, 1997b; Kersten et al., 1998; Kaeser et al., 1999; Masala, 1999; Kersten, 1999b; Urset and Maalen-Johansen, 1999)* have reported their experiences in digital aerotriangulation using a commercial photogrammetric system, although many systems are already in use world-wide. A comparison of different triangulation software packages is presented in *Kersten (1999a)*.

Since 1995, Swissphoto Vermessung AG, the former Swissair Photo+Surveys Ltd., is using digital photogrammetric stations from LH Systems (LHS). For the project *swissphoto (Kersten and O'Sullivan, 1996a)*, a block of 6063 aerial images covering the entire area of Switzerland with a photo scale between 1:22000 and 1:54000 was triangulated from October 1995 until July 1998. Seven representative sub-blocks from the block Switzerland are presented in Chapter 2. The customisation and modification of the Helava Automated Triangulation System (HATS) through the implementation of additional software and graphical user interfaces (developed by Swissphoto Vermessung AG) is introduced in Chapter 3. This approach increases the automation and efficiency of the commercially available system in Swissphoto's digital photogrammetric production environment. Some results (Chapter 3) and the production rate (Chapter 4) of seven different blocks are presented. Furthermore, problems and limitations of digital triangulation, especially in difficult terrain as given in the Swiss alpine regions, are discussed and improvements for the digital triangulation software are suggested in Chapter 5.

The customisation of commercial systems can be achieved by the following steps: (i) automation of procedure by batch processing and additional software specially for quality control, (ii) system integration by setting up the optimal hardware and software for each processing step, and (iii) optimisation by tuning the different system components through interfaces and a defined data/work flow.

The implementation of the digital photogrammetric production environment, its tuning and customisation, the current status and its performance are described in this article. This paper also briefly introduces the company Swissphoto, its history, services, and its transition to digital systems.

Triangulation blocks and photogrammetric systems used

Triangulation block Switzerland

For efficient triangulation, also with respect to the available hardware and software performance, block Switzerland was divided in 43 sub-blocks between 82–333 images per block. All sub-blocks were connected to each other with an overlap of three images in strip direction and one strip across strip direction.

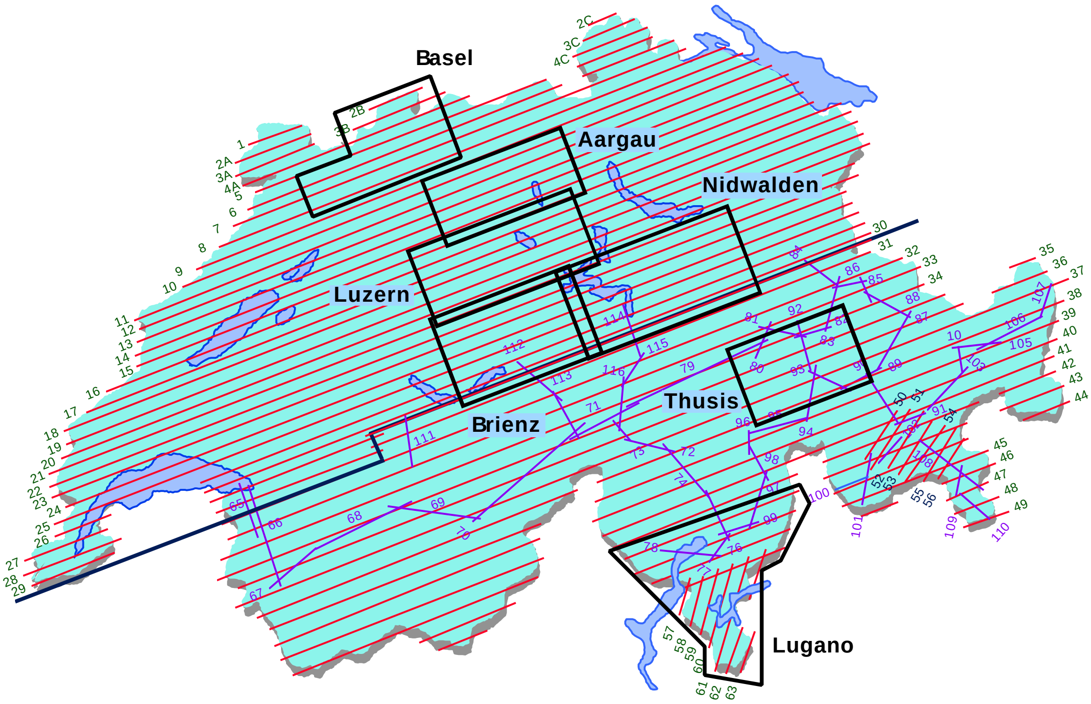

Fig. 1 – *swissphoto's* triangulation block Switzerland including seven selected sub-blocks

For the project *swissphoto (Kersten and O'Sullivan, 1996a)*, Switzerland was flown in three phases using colour and infra-red films simultaneously. Figure 1 illustrates the flight lines which were flown in 1995 and the perimeters of the seven sub-blocks. In phase 1 the urban areas and the northern part of the country were flown between June and August; in phase 2 the Alps and all valleys in the southern part of the country were flown between August and October 1995, while in phase 3 some small areas of Switzerland were re-flown from July to September 1996 due to hazy and partly cloudy air conditions during the 1995 flight. The regular flight lines were flown from east to west as parallel flight lines and in the opposite direction with an azimuth of ~70 resp. 250 degrees. The valleys in the southern part were flown in the directions of the valleys. The photo scale was approximately between 1:22000 and 1:28000 in the non-mountainous areas including the separate flights in the southern valleys and between 1:34000 and 1:55000 in the Alps. During the flights, camera stations were recorded by DGPS using a Leica GPS receiver in the aircraft and at each of three reference stations on the ground. Additionally, 104 well distributed points of the new Swiss GPS primary network LV'95 were signalised as control points.

In this paper, seven triangulation sub-blocks of Block Switzerland are introduced, which represent different terrain characteristics and block size. Block Aargau consists of 152 images (6 strips, average photo scale 1:28200) and represents agriculture and hilly terrain characteristics with varying ground height between 350–900 m a.s.l. Block Basel has almost the same block size (150 images, 7 strips, photo scale 1:26700) as Block Aargau, but represents urban areas and hilly terrain characteristics with a varying ground height from 250 m to 1300 m. In block Lucerne (216 images, 7 strips, photo scale

1:26700) the terrain varies between hilly and mountainous (ground height from 380 m to 1800 m). These three sub-blocks represent the Swiss midland, while the following blocks represent mountainous and alpine terrain characteristics: Block Brienz (270 images, height differences between 450 m and 2600 m) consists of 11 regular flight lines and one strip from a valley flight, which causes large photo scale differences from 1:22000 to 1:41000. Block Thusis (185 images) includes five valley flight lines and five regular east/west strips with large photo scale differences from 1:22000 to 1:52000 (height differences between 430 m and 2900 m). Nidwalden is the biggest sub-block (333 images) of the all 43 *swissphoto* sub-blocks. Its terrain characteristics are similar to Block Brienz including the lake Lucerne. This block consists of 12 flight lines with a photo scale of approximately 1:24000 and one line with 1:40000. Four lines were flown in 1996 to replace images with clouds from 1995. Block Lugano (261 images) is the most southern block with 7 flight lines (photo scale 1:27000) in north-south direction, 7 lines (photo scale 1:51000) in east-west direction (four lines from 1996 with a photo scale of 1:40000), and 5 lines along the valleys (photo scale 1:23000). The area of this block is characterised by mountains, steep valleys and some lakes. The image quality of this block was not optimal due to hazy weather conditions during the flights. Furthermore, the recording of the GPS camera station data did not work successfully during the overflight of this area.

Table 1 – Flight and block data of seven *swissphoto* triangulation sub-blocks

Block	**Area covered [km^2]**	**Ground height [m]**	**Terrain**	**Photo scale (average)**	**Forward/Side overlap [%]**	**Date of flight (days)**
Aargau	1262	350–900	agricult., hilly	~1:28 200	70%/30%	Jun./Jul. '95, (3)
Basel	1203	250–1300	urban, hilly	~1:26 700	70%/30%	Jul./Aug. '95, (4)
Lucerne	1735	380–1800	hilly, mount.	~1:26 700	70–90%/10–30%	Jun./Jul. '95, (4)
Nid-walden	3726	400–2900	alpine, lakes	~ 1:24 000 – 1:40 000	70–90%/10–30%	Jul.–Oct. '95, Jul. '96 (9)
Thusis	1800	550–2900	alpine	~ 1:22 000 – 1:52 000	70–90%/10–30%	Oct. '95 (7)
Brienz	2080	430–2650	alpine	~ 1:28 000 – 1:40 000	70–90%/10–30%	Jul.–Oct. '95, Jul. '96 (7)
Lugano	3477	190–2600	alpine, lakes	~ 1:24 000 – 1:51 000	70–90%/10–30%	Aug.–Oct. '95, Sep. '96 (7)

Each block includes flight lines with different exposure dates which varied from some days to more than 1 month up to 1 year (e.g. Block Nidwalden, Brienz and Lugano) and consequently vegetation changes from strip to strip are partly occurring. Flight and block data of the seven introduced *swissphoto* sub-blocks are summarised in table 1.

Digital image data

In total 7081 colour images were scanned within the project *swissphoto* on a Digital Scanning Workstation DSW200 of LH Systems in RGB mode from August 1995 until January 1998. During seven months in 1996/1997, a second rented DSW200 was used in parallel production. For high quality scanning, the two scanners (XY stage) were installed in a separate room, containing air-conditioner, air-humidifier and a dust filter, to minimise dust and dirt on the photos and on the glass plate of the scanner. The turnaround time for scanning each photo was about 30 minutes using a SUN Sparc 20/71 in the beginning resp. 20 minutes using a SUN Ultra 1. The resolution of the images was 25 µm, which corresponds to a footprint of 0.6–1.3 m on the ground. For triangulation of the *swissphoto* sub-blocks, the digitised colour images were converted into greyscale images in order to reduce disk space usage. The file size of each greyscale image was about 80 Mbyte.

Hardware

The aerial triangulation was performed on a digital photogrammetric workstation DPW670 (Mono-station) of LH Systems (Fig. 2). As a computer platform a SUN Ultra 2 (167 MHz) was used. In total 105 GByte disc storage capacity was available for the triangulation data. Three sub-blocks in the southern part of Switzerland (St. Bernard, Zermatt and Maggia) were triangulated with Match-AT from Inpho (Stuttgart) on a Silicon Graphics (SGI O2, R5000) in order to test an alternative triangulation software package in production.

Software

For triangulation of all sub-blocks the software release 3.1.2, 3.2 and 4.0 of SOCET SET (Softcopy Exploitation Tools) was used. HATS is a module of SOCET SET for performing block triangulation of suitably overlapping images. The tedious process of selecting and measuring image coordinates of pass and tie points is highly automated, with the possibility of operator override. The system flags unacceptable tie points and displays the required images for measurement without operator intervention. All the operator has to do is to re-measure these unacceptable points by moving the floating mark to their proper locations, if requested.

Fig. 2 – Digital aerial triangulation station at Swissphoto Vermessung AG

Digital aerial triangulation

In an automated production, the digital aerial triangulation (AT) is divided into several processing steps, which include data preparation (photos and control points), automatic data import and image minification, automatic interior orientation, automatic AT measurements, GPS supported bundle block adjustment, and quality control. To facilitate the use of the highly automated AT processing modules by the operator, some additional software for batch processing and easy-to-use graphical user interfaces (GUIs) were developed by Swissphoto Vermessung AG.

Data preparation

The data preparation includes configuration of the photo block (providing images, loading digital images from tape, if not available on disk) and providing control point data (co-ordinates, overview plot, available sketches). To obtain sufficient ground control points, five different sources are used for all *swissphoto* blocks:

- signalised points from the new Swiss GPS primary network LV'95 (accuracy in xyz = 0.3m),
- points from additional GPS campaigns (accuracy in xyz = 0.3m),
- vertical control points from the 1:10?000 Canton map series (accuracy in z = 1.5m),
- vertical control points from the Swiss 1:25?000 map series (accuracy in z = 1.5m),
- horizontal control points from official cadastre maps (accuracy in xy = 0.5m).

The majority of the signalised control points in the southern part of Switzerland were destroyed before the flight could take place due to a long time period between signalisation and flights. Thus, many control points were subsequently determined by GPS measurements using well-defined points in the digital images. Ground control preparation for the *swissphoto* triangulation blocks was a very time consuming process, which varied from block to block. This part of the triangulation required the most intervention resp. preparation by the operator.

Automatic data import and image minification

Before starting the measurements, the image import into the photogrammetric station and the minification of the images (generation of image pyramid levels for measurements, display and zooming) were performed fully automatically in a batch mode, which took up to 60 seconds per image on the SUN Ultra 2. The GPS photo centre co-ordinates of each image were also automatically imported to provide approximate values for the overlaps between images in the blocks. Additionally, the preparation of the triangulation files which contain all parameters for the automatic measurements, were performed automatically. Thus, using such customisation, the operator input was significantly reduced in comparison to when using the non-enhanced commercial software package HATS.

Automatic interior orientation

Before starting HATS, the interior orientation must be determined for each image. To avoid the time consuming semi-automatic measurements of the interior orientation, a fully operational automatic interior orientation (IO) of digital aerial images was developed at Swissphoto Vermessung AG and integrated into SOCET Set on the DPW670/770. This operation can be performed in batch mode without any operator intervention. The IO of an unlimited number of images related to one specifically defined camera type can be automatically determined in one step including quality control. The speed of the measurements and IO determination is approximately 5 seconds per image. The algorithm used is described in *Kersten and Haering (1997a).*

Automatic AT measurements

The processes of AT measurements, as currently used in HATS, are divided into four steps which include Automatic Point Measurement (APM), Interactive Point Measurement (IPM), Simultaneous Solve (Re-measurements) and Blunder Detection.

Before running APM, a tie point pattern was selected and edited to obtain a well distributed point configuration in each image for connecting the block. A very dense tie point pattern consisting of 98 points was used as a standard pattern for all described blocks. APM runs as a batch process mostly overnight or during the weekend. APM takes approximately 10–30 minutes per image on the SUN Ultra 2. After APM, a rate of 64–94% successfully measured points could be achieved for the blocks, depending on the terrain characteristics, the variation in the photo scale within each block and flight date differences between strips (Aargau 94%, Basel 89%, Lucerne 80%, Nidwalden 53%, Brienz 64%, Thusis over 60%, Lugano 34–75% for APM in each single strip). The success rate of APM was clearly higher for blocks in the northern part of Switzerland.

Ground control points and additional tie points were measured with IPM in a semi-automatic mode. If the datum is fixed by measurements of three control points or by GPS camera stations, the program drives the operator to the approximate positions of the subsequent ground control points automatically.

The triangulation of most sub-blocks in the northern part of Switzerland could be performed with APM. If necessary due to bad connections of strips, additional points were measured manually with IPM in a semi-automatic mode. In sub-blocks with mountainous terrain and valley flight lines the success rates of APM were often so bad that it was decided to measure all these blocks with a new strategy: APM was performed for each flight line and the lines were connected by manual measurements of additional tie points with IPM in a semi-automatic mode. The manual connection of these strips was time-consuming. The problem of APM failure in sub-blocks with mountainous area and additional valley flight lines can be attributed to extreme height differences and to the large photo scale differences between the valley flight lines and the regular strips.

After all measurements were performed, the observations were adjusted using the „Simultaneous Solve“ module of HATS. Instead of re-measuring all errors, a rigid blunder detection routine, which was developed by Swissphoto, eliminates all observations with residuals over a user-specified threshold. Simultaneous solve and blunder elimination were performed in an iterative mode until a certain specified precision was obtained. This blunder detection uses only an user-specified threshold criterion and assumes high redundancy in the observations. But with this method it happened that too many observations, especially between strips, were eliminated due to bad quality points from APM. Nevertheless, areas of weak block connections were detected later in the quality control, and gaps without any points had to be filled-in by semi-automatic measurements. Unfortunately, simultaneous solve was often disturbed by so called „pseudo“ observations, where the system tried to connect images to each other without overlap (software release 3.2). These gross errors influenced all other observations significantly and it was always time consuming to remove all these blunders. As a better quality control solution, the computations of spatial intersection for each point would clearly indicate big blunders for subsequent automatic elimination, which is not yet implemented in HATS.

Bundle block adjustment

After a rough adjustment in HATS with simultaneous solve, all measured image co-ordinates of each sub-block were exported in a PATB-format and transferred from the DPW670 to a PC, where the bundle block adjustment was performed for each sub-block. All observations (image co-ordinates, control point co-ordinates and GPS photo centres) were adjusted in a bundle block adjustment with self-calibration using the bundle block adjustment program BLUH of the University of Hannover. After each run of the bundle block adjustment, an additional automatic blunder elimination was performed to eliminate all image points with residuals over a specified threshold (e.g. over 30 microns).

The results of the adjustments are summarised in table 2. For the seven *swissphoto* blocks the root mean square (RMS) values of the control point co-ordinates are between 0.3 m and 0.9 m in X and Y, and between 0.8 and 2 m in height, while the RMS values of the station co-ordinates are better than 0.6 m in X and Y, and better than 0.4 m in Z. The σ_0

from the adjustment varies between 11.5 and 12.6 micron, which corresponds to approximately 1/2 of the pixel size. These results are representative for all other blocks measured with HATS. For the three sub-blocks measured with Match-AT, σ_0 from the adjustment varies between 6.1 and 7.7 micron, which corresponds to precision of approximately 1/4 to 1/3 of the pixel size.

Table 2 – Results of the bundle block adjustments of seven *swissphoto* sub-blocks

Block	**Strips/ images**	**Control H/V**	**σ_0 [μm]**	**RMS X [m]**	**RMS Y [m]**	**RMS Z [m]**	**RMS X_0 [m]**	**RMS Y_0 [m]**	**RMS Z_0 [m]**
Aargau	6/152	12/107	12.2	0.45	0.44	0.79	0.48	0.40	0.18
Basel	8/150	80/159	11.5	0.59	0.62	0.78	0.37	0.31	0.11
Lucerne	8/216	22/144	11.8	0.55	0.64	1.01	0.59	0.57	0.13
Nidwalden	13/333	11/180	11.5	0.60	0.39	1.24	0.44	0.35	0.13
Thusis	11/185	10/108	12.6	0.45	0.35	1.25	0.29	0.22	0.36
Brienz	12/270	13/128	11.7	0.26	0.31	1.04	0.47	0.34	0.13
Lugano	19/263	13/137	12.4	0.88	0.57	1.96	0.24	0.49	0.22

The level of precision of digital AT with automatic point transfer depends significantly on the matching algorithm applied. With feature based matching a precision of 0.3–0.5 pixels can be assumed for point transfer, while with least squares matching a precision of 0.1–0.2 pixels can be achieved. More details about accuracy considerations of digital AT are contained in *Ackermann (1996).* A precision of 1/2 of the pixel size was achieved with the *swissphoto* sub-blocks using the cross correlation algorithm in SOCET SET (see table 2). The reasons for the results achieved with these *swissphoto* sub-blocks could be addressed to bad ground control quality (especially the height control from the maps) and the large number of measurements (many tie points with bad quality) in each block, which also include points with residuals larger than one pixel (25 μm). However, the large number of measured points per image and their good distribution in the image provide a high reliability in the adjusted camera station co-ordinates. The results from triangulation were used for digital orthophoto production.

Quality control

After the final bundle adjustment, an update of the orientation data for each image support file and the measured image point files is performed at the DPW670 using interfaces between BLUH and SOCET SET. The geometric quality control for the block is given by the results of the bundle adjustment (σ_0, RMS, etc.). Furthermore, due to high automation of the measurements and gross error elimination, it is absolutely essential to check the photo connections within each strip and across the strips, in order to confirm a reliable point distribution and connection in the triangulation block. Therefore, an additional software module was developed by Swissphoto Vermessung, which provides a fast and easy-to-use visualisation of all point connections in the block (Fig. 3). Using this module, the operator is able to scan quickly through the block, photo by photo and strip by strip, to check visually the number of rays per point, the distribution of points in each photo, and, by clicking on the photo number in the display window, the connections to each neighbouring photo. Thus, the operator is able to analyse the connections within the block and to measure additional points in weakly connected areas after the measurements (APM and IPM) and after the bundle block adjustment. In figure 3, the following information is displayed: image perimeter of image 16_137, all measured points of image 16_137 (e.g. 4 indicates the number of rays, i.e. this point is connected to three other images), point position in image 16_137, all images connected to image 16_137 indicated as image number (e.g. 17_128). The operator checks the connections between images by clicking on one of the image numbers around the displayed image perimeter (e.g. 17_128) with the mouse. All points, which are measured in both images, are highlighted in blue colour in the displayed image perimeter.

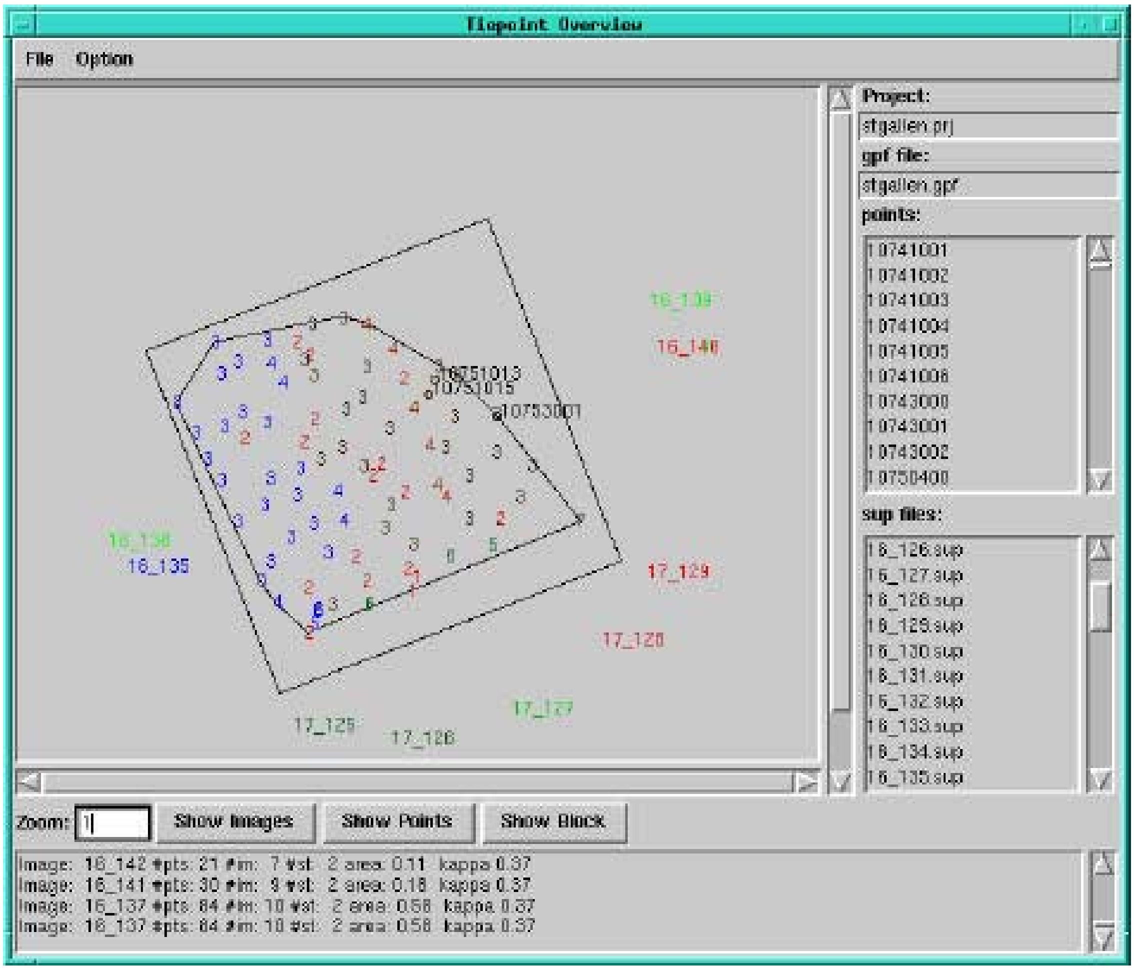

Fig. 3 – Quality control of aerial triangulation by visualisation of photo connections

Time required

The time required for digital aerial triangulation of each introduced block is summarised in table 3. In this table, only the operator's time is counted, while the computation time of the computer for running batch processes, which is mostly done overnight, is neglected.

In our investigations for triangulation of the block Switzerland using HATS, a total time of 9 min per photo required for the triangulation of block Aargau, excluding scanning and ground control preparation, was the best result achieved. For the sub-blocks Aargau, Basel and Lucerne, a high degree of automation was achieved through successful automatic point transfer, due to good terrain characteristics in these blocks and little interaction of the operator in the data processing and quality control.

A slightly worse result (16 to 38 min per image) with respect to efficiency was achieved with the *mountainous* sub-blocks Nidwalden, Brienz, Thusis and Lugano. The problems of these blocks for the automatic point transfer were: (a) extreme height differences in the alpine region (steep valleys), (b) photo scale differences between strips, (c) the time intervals between the flight dates of the strips (up to one year), and (d) strip overlap sometimes less than 10%. The production rate of other *swissphoto* sub-blocks was sometimes worse.

The productivity rate obtained with these seven triangulation blocks is significantly worse in comparison to the results achieved with the triangulation of other Swiss blocks. *Krzystek (1998)* reports about the triangulation of a Swiss block (400 b/w images, scale ~1:30000, area Bern-Fribourg-Interlaken) in mountainous terrain using MATCH-AT. For this block, a production rate of better than 5 minutes per photo (operator time) was achieved. However, other authors, *Kaeser et al. (1999) and Urset and Maalen-Johansen (1999),* report that a similar production rate for triangulation in alpine and Nordic terrain was achieved using Match-AT compared to the aforementioned production rate of the *swissphoto* sub-blocks using HATS (see table 3).

Other authors report good productivity for digital triangulation in flat terrain. DeVenecia et al. (1996) report a total working time of around 10 minutes per image, which was achieved with two test blocks using HATS. The two test blocks (Forssa and Wisconsin) have a photo scale of around 1:4000 and represent a very flat area with maximum height differences of 10 meters. *Beckschaefer (1996)* reports about 66 images per eight hour shift as the best result for digital aerotriangulation on the INTERGRAPH ImageStation, which corresponds to a production rate of 7.3 minutes per image.

Table 3 – Elapsed time for digital AT using a customised and modified approach of HATS

AT processing steps	Aargau	Basel	Lucerne	Nidwalden	Thusis	Brienz	Lugano
Preparation [h]	4.0	5.0	7.5	12.5	20.0	9.0	13.5
AT Measurements [h]	13.0	16.5	29.0	69.5	90.0	78.5	57.0
Bundle adjustment [h]	5.0	3.0	7.0	6.5	7.5	15.0	4.0
Total elapsed time [h]	22.0	24.5	43.5	88.5	117.5	102.5	74.5
Number of images	152	150	216	333	185	270	263
Time/image [min]	8.7	9.8	12.0	15.9	38.0	22.8	17.0

Algorithmic aspects

The quality of the results and the efficiency of triangulation are dependent on the quality of automatic point transfer and correlation (measurement algorithm), which again depend mainly on image quality (including scanning and weather conditions) and terrain characteristics (e.g. land-cover and height differences). In summary, the following aspects caused problems for the correlation algorithm in our investigations:

- Extreme height differences in the images resp. block
- Strips with different flight dates (vegetation changes in summer)
- Shadows from early morning flights (bad quality terrain representation)
- Densely forested areas and lakes
- Triangulation blocks with variable photo scale within the block (from strip to strip)

To improve HATS with respect to speed, precision, robustness, flexibility, and user-friendliness the following software improvements are suggested:

(1) An easy-to-use GUI for providing and checking initial orientation values of images to build the triangulation block including the overlap of each image. The success rate of APM depends significantly on good initial values for the image orientation.

(2) The use of an existing DTM (Digital Terrain Model) in APM speeds up the APM process and increases the precision and robustness significantly, especially in mountainous and alpine regions, so that the rate of successfully measured points can also be increased.

(3) The implementation of a combined matching technique using feature based matching for rough measurements in low image pyramid levels and least squares image matching for precise measurements improves the precision of the overall measurements slightly. A small disadvantage due to slightly reduced speed should be ignored due to the increasing performance of each computer generation.

(4) The use of GPS data, additional parameters and an efficient band ordering algorithm for the re-linearisation of the normal equation system in simultaneous solve provides better approximations and accuracy, more flexibility and speed-up of the adjustment module.

(5) The use of on-line quality control by computation of spatial intersections of the measured points after the measurements reduces the number of blunders significantly.

(6) The integration of bundle block adjustment or the use of on-line triangulation algorithms (sequential estimation in bundle block adjustment and data snooping in blunder detection) during APM to increase the quality of the automatic point measurements through elimination of gross errors during the measurement phase *(Gruen, 1985a).*

Conclusions and outlook

For the block Switzerland with more than 6000 images, digital aerial triangulation using HATS has been successfully performed in terrain with varying characteristics. During the aerial triangulation processing of the 43 sub-blocks, the commercial triangulation software used was customised and modified by development of additional software and GUI's to obtain a higher degree of automation in the workflow of digital aerial triangulation and to reduce the intervention of the operator to a minimum.

However, it could be also shown that the production rate for triangulation in alpine regions is much worse than in flat or non-difficult terrain. This demonstrates that the production rate resp. the efficiency of digital aerial triangulation is mainly dependent on the type of the terrain and the block configuration. In particular, the variation of the photo scale within the block and extreme height differences in terrain like the Swiss Alps cause problems to the correlation algorithm. This leads to a bad performance in the automatic point transfer. To fulfil the requirements for successful digital triangulation in difficult terrain, improvements of the automatic point transfer approach must be done. E. g., the use of an initial DTM and an on-line triangulation algorithm including quality control could reduce the problems in automatic point transfer. But a major problem for the automatic point transfer, the variation of the photo scale, will still occur, which might require interactive point measurements in semi-automatic mode.

However, we believe that, in general, there is potential for more improvements in digital AT with respect to productivity so that a triangulation rate of better than 5 minutes per image could be possible in the future, even with difficult terrain characteristics as in the Swiss Alps. Currently, it seems that analytical aerial triangulation is still competitive to digital AT in difficult terrain like in the Swiss Alps, if also variable photo scales occur in the blocks.

Today, the integration of bundle block adjustment in the automatic point transfer module is the modern trend, but is not implemented in all commercial triangulation software packages. The automation in digital aerial triangulation must include automatic quality control to obtain high reliability and efficiency. Nevertheless, direct measurement of exterior orientation by GPS and Inertial Measurement Units (e.g. Applanix system, *Lithopolous, 1999*) will be increasingly performed during aerial flights. But it can be assumed, that the combination of digital aerial triangulation and direct measurement of exterior orientation by GPS/INS will be a good solution for reliability reasons and quality control.

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Discussion

Digital aerotriangulation with HATS
T. Kersten, Swissphoto Switzerland

Hoschtitzky (ITC, Netherlands):
Some of my experiences with HATS seem to confirm your experiences, even though you have tailored your software for interior orientation. You mentioned that in your system the interior orientation is fully automatic and autonomous. Without it, you end up with a lot of lengthy and unnecessary information to read whether the measurements were successful or not. I think something ought to be done about this because the user does not need to read all those long messages if the correlation *was* successfully achieved. Another thing is the number of correlation points for the automatic point transfer; you used about 100 points per photo and a regular pattern. I did this too, with up to 100 points per image, with a success rate of 60% which you also got for the Alpine areas and 80% for the hilly areas. The question arises: what are you going to do with the unsuccessful points? Do you measure them manually? Now, when we look at some of the Alpine blocks, there are 100 points times 100 photos of which 40% failed. It means that you have to measure 4000 points manually. In other words, you should determine automatically so many points so that you can afford to lose many of them without worrying. Another issue in automatic measuring: the system can recognise if it is successful or unsuccessful and you have 4 possible combinations of inconsistency. I have experienced that some points were indicated by the system as being unsuccessfully measured while they were successful, and vice versa, in all possible combinations. Furthermore, the density pattern is such that when you indicate, 100 points for example, there are many points chosen with different points numbers that have identical positions so you have 36–1, 36–2, 36–3 all in the same position; the system has taken the same point several times. As far as pass points are concerned, there is one thing that is typical in one or another system. I have triangulated a block well-known to our French colleagues from ENSG: it is a block in their fieldwork area in the south of France. In that block there is a large number of height control points, derived from the "Reseau National de Nivellement", the National Levelling Network. These points are situated in positions which are very good to measure for the classical photogrammetric operator and are not suitable at all for automatic measurements. If you compare the manual and automatic measurements of these points, you see that they have different height values. This means that the internal consistency of photogrammetric data measurements through the workstation is correct, but it is incorrect with respect to the true height on the ground.

Kersten (Swissphoto, Switzerland):
First, the answer concerning the automatic interior orientation: we had already developed this software when I was at the ETH in Zurich and we adapted it later to the Helava System and admitted it is very powerful. Now, it is important to know that if you have automation in the processing you must also have it in the quality control. In the interior orientation we have a very easy-to-use tool to see if all the images are measured and if the automatic orientation is successful. Your second comment was that there are long lists of results that are hard to analyse. We managed to reduce this to a minimum by writing graphical user interfaces so the operator can use this by pressing keys. In between this we

also created more or less automatic quality control. Now, on the question of point measurements, we do not measure all the points which failed after the automatic point transfer. The system says there are 500 points for manual measurement: we ignore this and go through the block to see what the connections are like. This is done with the help of the connection checking graphical user interface. If we realise that we need more points then we go there and measure them in the interactive point measuring mode and there, the operator has to sit down and fix them. The critical thing is not in strip direction but across strips where the system often fails and we have to connect the strips manually. That is why we have a longer processing per image.

Hoschtitzky (ITC, Netherlands):
What about the height pass points?

Kersten (Swissphoto, Switzerland):
We measure all the control points manually, i.e. the fully signalized and the height control points. We have different types of height control points: some are very easy as they are in flat areas or in streets, others are more critical such as house roofs for example, which have to be measured in the stereo mode. All this is done in a purely manual mode.

Reiss (Bayer. Landesvermessungsamt, Germany):
Going back to the issue of vertical control points: it is not a problem of automatic point block transfer, but of bundle block adjustment. Even if you are working with a comparator, you cannot use quality control without clearly defined xy co-ordinates. So we have a problem switching from the model adjustment to bundle block adjustment. Moreover, there has been a change in philosophy in aerial triangulation. In the past we had the application to densify a control net for subsequent stereo compilation for example. Now automatic aerial triangulation does not give the new points for subsequent measurement, but primarily gives us the orientation elements of the images and of the models. This causes trouble in measuring new points, as was mentioned on several occasions before. Several states in Germany are building up a control network to be used for flights to be done in some years, but this does not work if you use points on roof tops for example. These are very stable points and therefore useful for orienting an image, but are not suitable for automatic aerial triangulation and for correlation, because you have to measure them stereoscopically and interactively. As far as this aspect is concerned, there is not much support from the systems, because the stereoscopic measurements are not integrated well enough into the systems.

Kersten (Swissphoto, Switzerland):
I completely agree with your comment.

Madani (Intergraph):
You said that you used self-calibration in bundle block adjustment. But when you use additional parameters to set up the model on an analytical plotter or a digital workstation for DTM collection, how do you remove the effect of additional parameters which are not supported by the mathematical models?

Kersten (Swissphoto, Switzerland):
Good question, because afterwards we do an update of the orientation parameters in the Helava stations. This is done thanks to an interface in BLUH to the Helava station and

here we use the adjusted co-ordinates of all the object points and the final external orientation as initial variants and we do a resection in space for each image. So we try to compensate the influence of the additional parameters afterwards.

Madani (Intergraph):
So basically you use the adjustment values, then you use the same projection equation and do the adjustment again?

Kersten (Swissphoto, Switzerland):
Yes, it is an adjustment, but this time it is a special resection per image.

Torre (ICC, Spain):
A question to Mr. Madani (Intergraph): is there any provision in the Intergraph environment to take advantage of self-calibration parameters in stereo data compilation? In the analytical environment it does not exist and I do not think it exists in the digital either.

Madani (Intergraph):
I mentioned already that we had "bulk adjustment", which should solve the problem regarding the digital line, but the parameters for self-calibration cannot be taken into consideration. As you know, self-calibration bundle adjustment is performed by extending the co-linearity equations with some additional parameters (APs) to “model” the systematic errors. After the adjustment, the significant APs are estimated. The real-time loop of almost ALL analytical plotters and digital photogrammetric workstations use only co-linearity equations, therefore the results of self-calibration bundle adjustment (exterior orientation parameters) cannot be directly used. One must remove the effect of these APs from the EO parameters. That means running bundle adjustment without APs once more, but using all 3D object point ccordinates estimated during self-calibration as control points. This is the way used in MATCH-AT.

Torre (ICC, Spain):
It is because in the past someone put the request to the analytical vendors to modify the software in order to include self-calibration parameters. Now that we are moving into the digital, I extend the same request to you.

Madani (Intergraph):
As I mentioned above, the effects of APs must be removed from the extereior orientation parameters before they are used in the real-time loop of digital photogrammetric workstations.

Digital and Analytical Aerial Triangulation
a Comparison Test

R.Kaczynski, J.Ziobro
Institute of Geodesy and Cartography
Warszawa, Poland

"Digital Aerial Triangulation gives a great push concerning accuracy, economy and cost reduction" – Prof. Ackermann

Abstract

Analytical Aerial Triangulation has been performed at the Institute of Geodesy and Cartography (IGIK) in Warsaw for over 12 years. Digital photogrammetric methods have been introduced in IGIK since 1996. The results of Aerial Triangulation performed on Planicomp P-1 Zeiss by analytical method and on ImageStation 6487 INTERGRAPH with the use of semi-automatic digital method are presented in the article. Two software packages from Inpho; namely PAT-MR and PAT-B were used for spatial block adjustment.

The accuracy achieved with the use of digital aerial triangulation (sigma nought 4.9 – 5.5 μm) is about 20 % better than that achieved with the use of analytical method (sigma nought 5.8 – 8.1 μm).

Digital aerial triangulation of a block of already scanned aerial photographs is achieved in one-third of the time needed to perform the job with the use of analytical method.

Data used

The comparison test was performed on 93 color aerial photographs taken in 9 strips at a scale of 1:8000 with Zeiss LMK 3000 camera (with FMC system) with focal length 305 mm, 60% end lap and 37% side lap from a height of h = 2400 m. Geodetic network consisting of 69 well distributed natural GCP's has been identified and measured in the field with GPS techniques, with the accuracy RMSE x,y,z = +/– 10 cm.

Analytical aerial triangulation

Analytical aerial triangulation was performed on an analytical plotter (Planicomp P-1 Zeiss). This instrument, with sophisticated software from Zeiss and Inpho has been used in the Photogrammetry Department in the Institute of Geodesy and Cartography in Warsaw for more then 10 years.

Interior orientation was done on 8 fiducial marks. Vertical parallax py was eliminated on 10 well distributed points in each model. Mean error of vertical parallax py for each model during relative orientation was about 3 μm.

On each model there were 10 well distributed tie points; altogether there were 333 points in the block. The total number of observations of tie points used to complete the block was 1325. The measurement was done stereoscopically by an experienced operator.

PAT-MR Inpho software was used for gross error elimination and block adjustment by independent models.

PATB Inpho was also used for bundle block adjustment. The results have then been used for comparison with the results of block adjustment done with digital aerial triangulation method.

Semiautomatic aerial triangulation

Digital Aerial Triangulation has also been performed in IGIK. Our team has already successfully used this method with some of the results of digital aerial triangulation being presented at the ISPRS Symposium Comm. IV in Stuttgart in 1998.

The color aerial photographs for the test were scanned (Photoscan PS-1 Zeiss) with pixel size 22.5 μm in the density range 0.7 to 2.3 D. Scanning was done with photoalignment angle, compression by JPEG (with compression factor Q=20) and a full set of the overviews. Only the red band was used for digital aerial triangulation.

Data compression using the JPEG board installed in the ImageStation has a great advantage especially for large blocks.

For all scanned photographs, besides raster image data, also an ASCII file with the header containing file format, scan origin (upper left), number of lines, number of pixels per line, number of pixels per scan (dpi), photo identification number, date of acquisition of photographs, scanner type, gamma curve of the scanner and all camera parameters has also been recorded. Scanning format was COT (Intergraph) with a tile size of 256, and full set of overviews.

The scanned data was then transferred to the ImageStation 6487.

Inner orientation was done on 8 fiducial marks automatically. Mean square error after affine transformation was 4.3 μm.

It had been earlier empirically proven by the authors that 18 natural tie points were the optimum number for one model. Therefore, only 18 tie points were measured on each model. All 631 tie points were measured in the block. Each photo was tied with overlapping photos using about 30 tie points. Natural points give practically the same accuracy as signalized points when area based matching is used. Altogether 2590 semi-automatic measurements were recorded on the ImageStation 6487 (Intergraph). Points were selected on the image by the operator, and then transferred to the neighboring photos by correlation methods. Two image matching methods were applied. In the first method tie points are transferred automatically with the fast, but of lower accuracy (0.5 pixel) cross correlation (CC); in the second method with high accuracy (0.1 pixel) least squares matching (LSM) was used. Matching is done within window size 33 by 33 pixels. Natural GCP's have been measured by the operator on the screen. RMSE of transferred points is about 0.1 pixel. In case of low contrast area where tie point have been selected, the Interest Operator has also been used. Our other tests have shown that in the case of high image contrast, we can achieve sigma nought 6.3 μm without using the Interest Operator. In case of low contrast images sigma nought 6.3 μm can only be achieved with the use of Interest Operator.

The test block was adjusted using PAT-MR (by independent models) and also PAT-B (bundle adjustment).

Results and conclusions

The results are shown in table 1.

Table 1 – Results of analytical and digital AT

RMSE		**Planicomp P-1**		**ImageStation**	
		PATM	PATB	PATM	PATB
Sigma nought [**μm**]	**xy**	8,1	5,5	5,8	4,9
	z	28,2	–	22,3	–
On GCP's [**cm**]	**XY**	7,3	8,4	9,3	10,9
	Z	5,7	5,3	6,3	6,9
On tie points [**cm**]	**XY**	4,6	4,9	3,4	3,9
	Z	15,3	15,4	13,2	12,1

Digital aerial triangulation is very accurate. The accuracy is generally at the same

level as the most accurate analytical method executed on the high precision analytical plotter Planicomp P-1 by a very experienced operator. Digital aerial triangulation gives also fast results, is less expensive and even more accurate than analytical.

In the case of this test the results of digital aerial triangulation are about 20% better then the results of analytical aerial triangulation.

Sigma nought for horizontal is 5.5 μm in analytical method and 4.9 μm for digital method adjusted both with PATB.

RMSx,y of adjusted points is 4.9 cm with the analytical method and 3.9 cm in digital both adjusted by PATB. This value is equivalent to about 0.2 pixel size. RMSz is about 4 times less accurate then in planimetry due to use of the camera with ck= 30 cm.

RMSxy in GCP's is 8.4 cm for analytical method and 10.9 cm for digital. The identification of GCP's on digital images was less accurate then on Planicomp due to not optimal choice of GCP's for digital aerial triangulation in the field by GPS team.

Vertical accuracy for GCP's is 0.02‰ h.

Labor time needed for digital aerial triangulation is about 3 times less then that needed to perform the work by the analytical method, even though the number of observations has been doubled (2590 in digital comparing to 1325 in analytical). Requirements for experience of operator are much lower than in case of analytical method. Semi-automatic approach to aerial triangulation of large scale photographs gives promising results, especially for built-up areas.

For production of DEM and digital orthophotos, the elements of outer orientation have higher priority then the geodetic coordinates of individual points. Due to this, digital aerial triangulation is already used in IGIK on a broad scale. This is also why we have recently purchased MATCH-AT for our new Intergraph system installed on a Windows NT workstation.

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Paper has been presented also on ISPRS WG III/1 Workshop "Integrated Sensor Calibration and Orientation". June 16 - 17, 1999, Portland, Maine, USA

Part 5

Orthophoto Production

Chairman

O. Kölbl

The input data for orthophoto production, exchange of orientation parameters, DTM/DSM quality and representation. Radiometry, scanning problems and image quality, radiometric colour enhancement, dodging and homogeneity. Mosaiking, printing techniques, standards for orthophotos

Practical Aspects of Digital Orthophoto Production

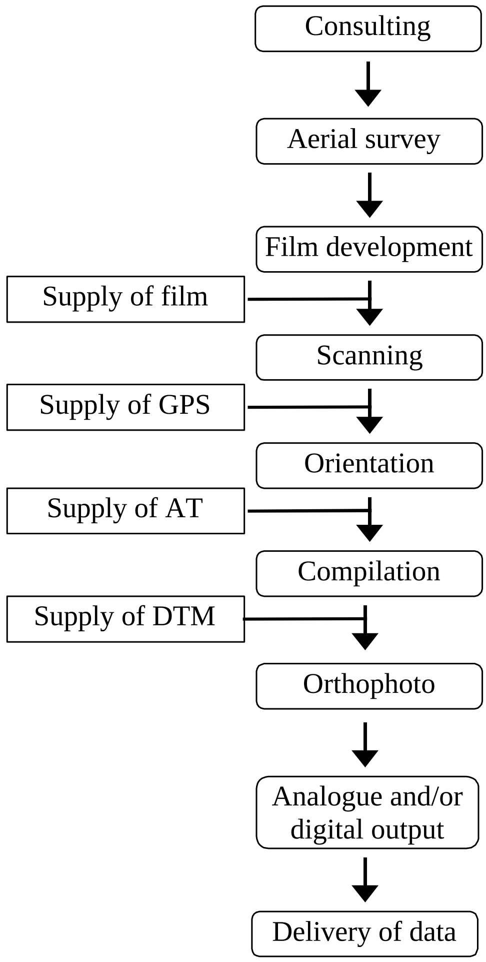
U. Weidner
Hansa Luftbild GmbH
Münster, Germany

Abstract

Digital orthophoto production can be considered as an operational process in a digital photogrammetric production environment. Nevertheless, there should be always efforts to improve the functionality in order to better fulfill the requirements in a practical workflow. Therefore, the aim of this paper is to discuss some general aspects of orthophoto production from a practical point of view. The main focus is on mosaicking and radiometric aspects, because most problems arise in these fields rather than in the geometric part of orthophoto production.

1 Introduction

Digital orthophoto production provided – compared to analogue production techniques – a larger flexibility taking mainly advantage of digital image processing techniques. Furthermore, the digital output opened a larger variety of applications, e.g. in a GIS environment. Both aspects influenced the production workflow changing from analogue to digital, and thus, allowing to take advantage of the inherent capabilities for automation. Looking at the workflow of orthophoto production starting from aerial survey, scanning, aerial triangulation, DTM capturing to orthophoto computation and mosaicking, the orthophoto computation itself is an easy and straightforward task compared to the others. Nevertheless, there are still some open problems encountered concerning automated mosaicking, treatment of radiometric properties and data handling in a production environment. Handling hundreds or thousands of aerial images as input and facing the requirements of the customers and users is still not an easy task. Examples of these requirements are seamless image data and its radiometric appearance, both arising from the use of orthophoto data in GIS.



The major advantage of orthophotos is that they can be produced in short terms in order to provide up-to-date information. This is especially true assuming that the terrain surface is subject to minor changes only and thus the DTM needed can be updated – where necessary – locally and used again. Up-to-date orthophotos can be applied e.g. for urgent planning purposes within short time, whereas elaborated line maps with a definitely longer production time would not be at hand. However, if vector information is necessary, it must be still extracted. Digital orthophotos offer the user the possibility to extract this information by himself. This possibility is of great interest, if the accuracy requirements are not too high and the task needs special knowledge for interpretation which may not be common to a photogrammetric operator.

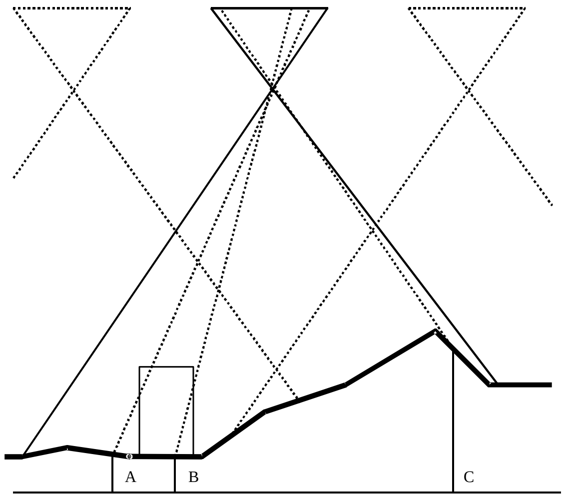
Besides the property of a shorter production time, orthophoto production is also less expensive than line mapping. This is due to its high degree of automation. Thus, orthophoto data is of interest, if the customer can not afford the time and/or the money for line map production. Therefore, orthophoto data can be used as primary source of information either to focus the production of line maps or to focus their update if already existing. Furthermore, it provides complete georeferenced information for purposes of documentation.

The use of orthophotos in a GIS often implies seamless image data. Therefore, the paper will shortly discuss some geometric aspects of orthophotos (Section 2). The main focus will be on mosaicking, thus on questions related to either radiometry alone (Section 3) or radiometry and geometry in combination (Section 4). This sequence is in line with the workflow of most of the software packages for orthophoto production, which strictly separate the rectification process from the mosaicking process. Despite this it might be helpful to integrate geometric information of the DTM into the mosaicking part or just integrate both processes, which is almost necessary in case of orthophotos with city models as underlying geometric description. Although this is recognized as an interesting topic, the paper is not meant to give an overview of recent developments or details of existing systems, but to discuss general questions that arise in a workflow for orthophoto production.

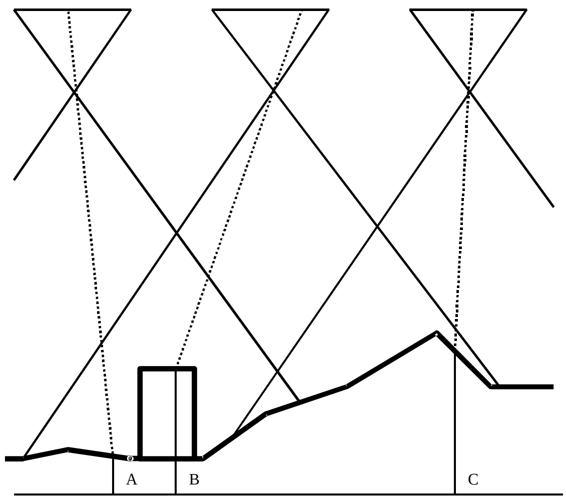
2 Geometry

Orthophotos belong to the group of georeferenced imagery. In this group we can distinguish between aerial images with footprints – coordinates of image corners assuming a mean terrain height – or images that are georeferenced by coordinates of the nadir point and an azimuth, furthermore rectified imagery applying a projective transformation, conventional orthophotos and true orthophotos. For the computation of true orthophotos, the underlying surface description does not only contain information about the terrain surface, but also about man-made structures such as buildings and other objects of interest protruding the terrain surface. For the production of true orthophotos, all the objects of interest must be extracted before the actual computation, thus reducing the advantage of fast production. Therefore, true orthophotos may be of interest in downtown areas, but will hardly be produced for larger areas. In the sequence of the paper, we will restrict to conventional orthophotos based on a surface description of the terrain and value added conventional orthophotos, if some selected types of man-made objects such as bridges and fly-overs are incorporated in the surface description. In order to fulfill the requirements for the representation of such surfaces, a TIN data structure, e.g. based on a constrained Delaunay triangulation, is necessary. The incorporation of breaklines also is required in order to describe rough terrain in an adequate manner. This is vital for the quality of the orthophoto, since the DTM accuracy (measurement and modelling accuracy) is decisive for the quality of the end product. Therefore, it is doubtful, if automatically derived DTMs can be used when a high geometric quality has to be assured, especially for large scale orthophoto applications.

Geometry of conventional orthophoto



Geometry of true orthophoto



Besides the quality of the DTM, the approach applied for orthophoto rectification – in particular anchor point philosophy or strict use of the collinearity equation – has an impact on the result. The principle of anchor points is applicable for smooth surfaces only. The use of the collinearity equation for every orthophoto pixel is favourable and even necessary in case of rough terrain and in case man-made objects are included in the surface description. With state-of-the-art hardware, however, there is no longer a significant difference with respect to computation time. Therefore, the collinearity equation should be used and this approach should be introduced as standard.

The geometric quality of orthophotos is also influenced by the sensor set-up. Focal length of camera, scale and overlap of aerial images have an impact on the result. In order to reduce leaning effects and positional errors (misplacements) due to deficiencies of the DTM, a flight with 60 % end and side lap may be used, which permits the use of only the central parts of the images. Another possibility is to use a camera with a longer focal length. However, this leads to a higher flight height and may increase negative effects due to atmospheric conditions on the sharpness of features and the overall radiometry. Since a longer focal length decreases the accuracy of DTM measurements, it is recommendable to use in this case already existing DTM information. Finding the right set-up will therefore always be a technical compromise in order to fulfill the specifications of a project.

An adequate geometry of orthophotos is taken as granted by the customer and user. Standards for the geometric properties can be easily defined, because they are based on strict mathematical formulas. Nevertheless, sometimes irritations arise with regard to the geometric properties of orthophotos, especially when the pixel size or ground sampling distance and the accuracy are mixed up. The pixel size is more or less related to the required interpretability (which features shall be visible, which size do these features have, scanning resolution), whereas the accuracy (positional accuracy of a pixel) depends on the geometric set-up only (accuracy of DTM, accuracy of orientation parameters, accuracy of ground control,...). A strict definition and clear separation of these terms is necessary. Orthophotos with the same pixel size may be computed based on input data differing by decreased scale of aerial imagery (e.g. 1:5000 vs. 1:10000) and scanning pixel size (e.g. 28 vs. 14 microns), but the accuracy and quality will hardly be the same.

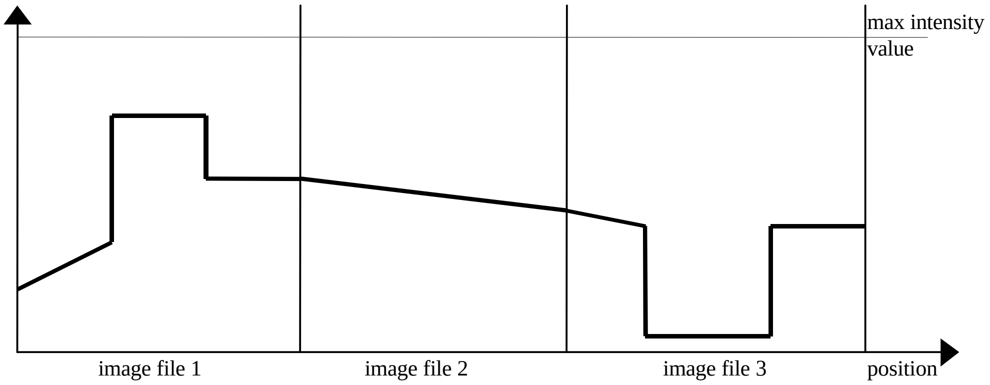
3 Radiometry

The treatment of radiometry, i.e. brightness and colour in particular, has always been a challenge - not only in a digital workflow, but also in an analogue production environment. This is due to effects inherent to aerial photography, but also to the subjectivity of defining the quality of radiometric appearance. It is certainly not a problem to tune the radiometric appearance of a single image, but the problems increase with the number of images and the number of applications. Unfortunately, this increase of problems to be solved does not seem to be linear, not only because of larger numbers of images and possibly more varying conditions during the flight, but also due to variations of the image content over larger areas.

Clearly defining in which way radiometry should be treated, is quite of importance. Film development, scanning and the entire digital radiometric processing will be effected by it. Therefore, the first step is consulting the customer for his application. His requirements may vary from an overall good looking radiometry with seamless appearance to a more emphasized visibility and interpretability of features in more or less homogeneous regions, both for analogue output and visualization in a GIS environment. The latter requirement is a question of calibration, which has to take into account the different characteristics of output media. These different characteristics can be used to compute for each output media a specific look-up table. Although, this seems quite trivial, in practice problems may arise, because it literally implies calibration and thereby definition of look-up tables for all the screens and plotters in the customer's office. In order to adapt to the needs of users, it would be helpful, if the GIS environment of the customer offers some image enhancement techniques, e.g. contrast enhancement, to discern details e.g. in shadow regions that still carry information.

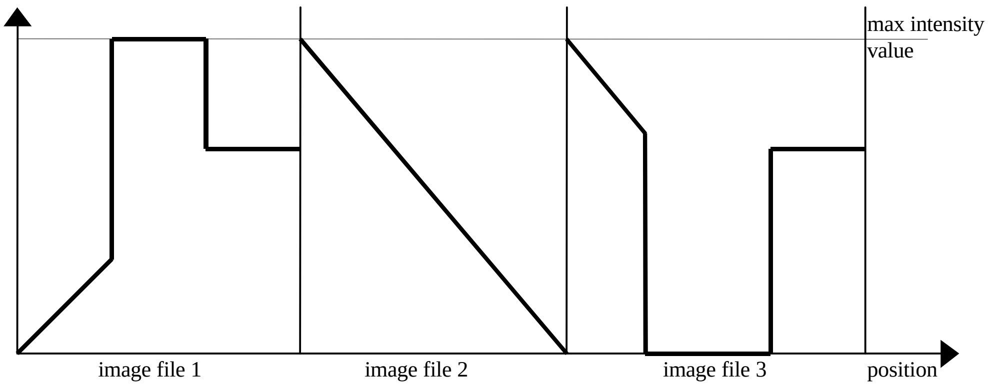
The requirements of a homogeneous appearance of the entire orthophoto data set over larger areas with varying image contents and the visibility of details also in quite homogeneous regions are competitive. In the first case, the darkest and the brightest regions in the area almost define the density range, assuming that no saturation is allowed. This may cause problems, if these minimal and maximal values result in a narrow histogram for the homogeneous regions. In the second case, the requirement can only be fulfilled, if the contrast is enhanced locally, or if again the darkest and brightest spots are taken to define the range, but this time for each image. The two cases lead to the question, which scan philosophy should be applied: tone matching of images already during scanning by taking sample images as reference or scanning according to the density properties of each image. Both approaches (see sketches) do have advantages. The first approach simplifies mosaicking from the radiometric point of view while the latter is trying to adapt to the radiometric properties of each image and thereby gaining as much radiometric resolution as possible. Which one is to be preferred with respect to the overall photogrammetric workflow ranging from automatic aerotriangulation and DTM capturing to orthophoto mosaicking? According to our experience, tone matching during scanning has the advantage that a homogeneous appearance can generally be achieved. It is, however, sometimes difficult for the scanning operator to assure this homogeneous appearance,

Tone matching strategy



because of tremendous radiometric differences between the diapositives of subsequent images. Nevertheless, the compensation of remaining offsets is part of the subsequent radiometric processing. The minimum/ maximum approach leads to larger differences in the radiometric appearance of quite similar image parts, which may cause problems during radiometric mosaicking. Therefore, a rigorous investigation and more information about the treatment of radiometry within the different orthophoto software packages would be necessary in order to ease the decision which approach should be applied. Nevertheless, these findings have to be checked and evaluated for every project again.

Minimum/maximum strategy



Orthophoto production has to face the well known effects inherent to aerial photography – radiometric roll-off, hot spot and sun glint. The radiometric roll-off, i.e. the loss of intensity at image edges and chromatic changes, is due to properties of the optics, e.g. lens density, but also due to external conditions such as haze. Hot spot and sun glint depend on the sun angle and reflectance properties of surfaces, e.g. leading to directed reflections. The magnitudes of these effects depend on the scale of aerial photography. Some of the effects can be easily modelled, e.g. light fall-off assuming a pattern of concentric circles. Some of the effects interfere with each other making the separation of effects difficult. Therefore, some approaches treat the different effects by analysing the frequencies within the images and assuming that the effects mentioned above cause the low frequencies. In most cases this frequency analysis leads to acceptable results. Nevertheless, there are cases in which the frequency analysis fails, because the image content is likely to mimic the radiometric effects, e.g. an image with bright objects at one edge of the image and darker parts at the other. Such problems could be overcome by involving some user interaction into the processing, e.g. exclusion of areas which may cause problems or qualitatively defining the effects. The main problem is that the software user does not always have information at his hand which compensation approaches/functions are used and which ones are activated under which toggle button. Thus, not only a description of the keyboard input, but also background information is required. At least it should be provided for those who are interested. Automatic determination of parameters is useful, but should take the magnitude of effects and its significance into account. Furthermore, the achieved results should be crossed-checked with results for other images assuming the conditions for taking and processing the photographs were approximately the same. In cases the results are doubtful, the user should be able to apply predefined parameters or use parameters of adjacent images.

In order to use a software system properly, the user has to know the methodology, including terms and input parameters. This is not only true for the proper handling of a system, but even more necessary for the evaluation of results. The question the user has to answer is: Can I achieve better results applying another offered strategy within the software package or are the radiometric effects system inherent? An example are the colour spaces: Which colour spaces are used? Are there favourable colour spaces for special tasks within orthophoto production or why is a specific colour space used for a special task? What side effects have to be taken care of?

Besides these basic questions there is another practical one: Compressed or uncompressed? It is well understood that compression has impact on the entire workflow, including e.g. aerial triangulation. Compression is favourable with respect to the amount of data which has to be handled. Nevertheless, in order to allow for the comparison of effects the compression has the final result and not only on radiometry, information and clarification of input parameters for compression algorithms is needed, thus, a first step towards standardization.

4 Geometry and Radiometry

Most of the software packages for orthophoto production strictly separate the rectification process from the mosaicking process, although it might be helpful to integrate geometric information of the DTM into the mosaicking, e.g. assigning a higher weight to image information of surface patches with surface normals close to the ray of view. The geometric part of mosaicking mainly consists of defining an appropriate seamline between adjacent images and blend in the images by feathering - presuming that some radiometrical image processing has already been done. Software packages offer a wide range of mosaicking tools. Some of them are fully interactive with respect to seamline definition, others operate fully automatic. Automatic techniques are needed when taking into account the huge amount of data that will have usually to be processed within a project. However, automatic techniques may fail in complex scenes, where also a human operator has difficulties to define a seamline. Therefore, the main question is to which extend and at which point human interaction is required and integrated - only at the start and the end of an entire production step, i.e. editing of the data, or also in between. The second strategy is preferable from a practical point of view, because it reduces editing at the end, which might be cumbersome and prohibitive with large data sets. In case of seamline definition, a system could generate a proposal automatically and guide the operator to those regions where the system's quality measures indicate problems. The operator could then interact, correct and define new seamlines or seamline corridors, and finally start the process of merging the images together. Although, the result of final merging has still to be checked, this strategy seems to be more effective than checking and editing the end product only.

The guidance of the operator to critical regions is definitely helpful during processing of the data, but also to effectively check the quality of the results, e.g. continuity of features and results of mosaicking. Besides this guidance functionality, editing functionality is needed of course. This editing functionality is usually not sophisticated within the orthophoto systems as they rely on automation. Therefore, it may be necessary to switch among different systems leading to new problems: Interfaces. Different systems support different formats (image formats, orientation parameters, georeference) which leads to additional expenses if exchanging data between software packages during the work flow becomes inevitable. Standards, which are not only defined but also introduced, or at least descriptions of interfaces and formats would be beneficial for producers and customers.

5 Conclusions

Digital orthophotos offer a solid foundation for a large variety of applications within GIS environments. Examples for these applications are planning tasks and change detection in order to focus further mapping work. Dependent on the resolution, orthophotos provide more comprehensive and complete information than traditional vector maps. Therefore, they are often used as stand-alone products leaving further interpretation and information extraction to the customer and his specialized staff. Orthophotos are also used in combination with vector data as back-drop. In the latter case, orthophotos can be produced more or less as by-product, if vector data and DTM are compiled by means of photogrammetric restitution.

Digital orthophoto production can be considered an operational process in a digital photogrammetric production environment. Almost all photogrammetric software packages offer this functionality. Whereas the geometric part of orthophoto production is well defined and no severe problems normally occur, the radiometric part still poses problems.

The geometric accuracy of orthophotos mainly depends on the quality of the underlying surface description. Therefore, a user of orthophoto data should be aware of the effects inherent to orthophotos such as misplacement of objects that are not modelled by the DTM. Furthermore, the terms accuracy and pixel size should be strictly separated. Metadata about the orthophoto including information about the input data directly connected to the orthophoto would be helpful in order to avoid the use of orthophotos for applications where the accuracy of orthophoto data is not sufficient: Orthophotos may be computed with a quite small pixel size for the sake of interpretation, but their positional accuracy may be less.

The treatment of radiometry still poses problems, especially when dealing with colour imagery. The reasons for this may be the subjectivity of radiometry and that the focus of developments was more directed towards the geometric part. Nevertheless, a good radiometric appearance is becoming more and more important and therefore more efforts are required to provide image enhancement techniques that are applicable for the compensation of the effects inherent to aerial imagery.

Orthophoto production meanwhile reached a high degree of automation. This is not only true for the orthophoto rectification, but also for mosaicking. Nevertheless, automation mainly fails within complex areas. In such cases, editing and interaction functionalities are needed. The necessary actions for critical areas should be guided by the system. Thus, the systems should be provided with some self-diagnosis functionality. Furthermore, the user should not only be given information on which toggle button has to be pressed, but also be provided with background information about the underlying approaches. Only if this information is available, the user can really check and evaluate the results. Clear and legible manuals or on-line help and more interpretable error messages would do a great job to cool down the software companies' hotlines.

Discussion

Some Aspects of Digital Orthophoto Production
U. Weidner, Hansa Luftbild, Germany

Vögtle (Univ of Karlsruhe, Germany):
How do you handle urban areas with tall buildings where there is a sidelonging effect, even if you only use the middle part of the images but you cannot exclude it totally? Do you use a special DTM including the buildings?

Weidner (Hansa Luftbild, Germany):
No, normally not. It depends on the requirement of the user. One way is to stick to the area near to the nadir point for example. Another way is to produce 2 orthophotos but the cost is high if you have to restitute all the information. If someone can afford it we will do it.

Simmons (Simmons Mapping, UK):
A comment about meta data problems that we have all the time. I am sure you have the same problem in Germany as we do in England with customers who lose their chain; nobody knows how it was done before, they lose reports. If there was something attached to the data, then the problem would be solved.

Weidner (Hansa Luftbild, Germany):
I think it would be nice to have an image format which has this additional documentation. So ground control is not done only by spatial resection; it is a rectified image using cadastral information, so the output is different. All of this should be recorded.

Colomer (ICC, Spain):
I want to comment on tracking down the history, the heritage of any image. We store all the relevant parameters from the beginning to the very end. Then of course, we cannot use a standard because we are a small group and cannot dictate our standards, so we have been forced to develop our own format which has a lot of special features. You then transform and store the transformation parameters, the radiometric and geometric parameters. The other approach is to store the information in a database, but then you need to keep the data base together with the files.

Weidner (Hansa Luftbild, Germany):
The problem with this is, what does the customer do?

Automation in Rural Orthophoto Computation

D. Moisset
I.G.N. France

Complete automation

Photogrammetry and also DTM are preliminary components of the orthophoto.

Only after the problem concerning automation in aerotriangulation has been solved and also the problem concerning automation in DTM calculation can we say that it is possible to calculate a digital orthophoto in an automatic way.

Technically, when you have a triangulation result, you have in the same time the relationship between the ground and each image.

As soon as you have defined the pixel size you want for your orthophoto you can follow the DTM shape for each pixel and use this relationship in order to get the radiometric value on your original image, and to fill the orthophoto.

Of course, this description is very schematic but it works and it is entirely automatic. We do it at I.G.N.

You will find below an example of a question to which direct answer is given by such orthophotos automatically set.

Imagine a customer in a photographic library who maybe does not know anything about orthophoto and maybe does not care about its properties. He just wants a pretty photo in the center of which he can find his house or the project he wants to show at an exhibition. He can confuse a photo with an orthophoto.

We use the properties of an orthophoto to make a small assembly for him.

Of course, we have to perform a radiometric equalization to combine, in only one document, radiometric values coming from different images because, it is known that each of them has its own distortion in its original radiometry.

Most of the time such a job concerns a very small area, and we can say that we do very well on this radiometric equalization, using a simple algorithm based on the calculation of a mean image.

In such a case, when the orthophoto is used as a photograph and because the required quality is only visual, it is easy for the customer to check the result and we can say that complete automation works very well.

Automation and accuracy of the result

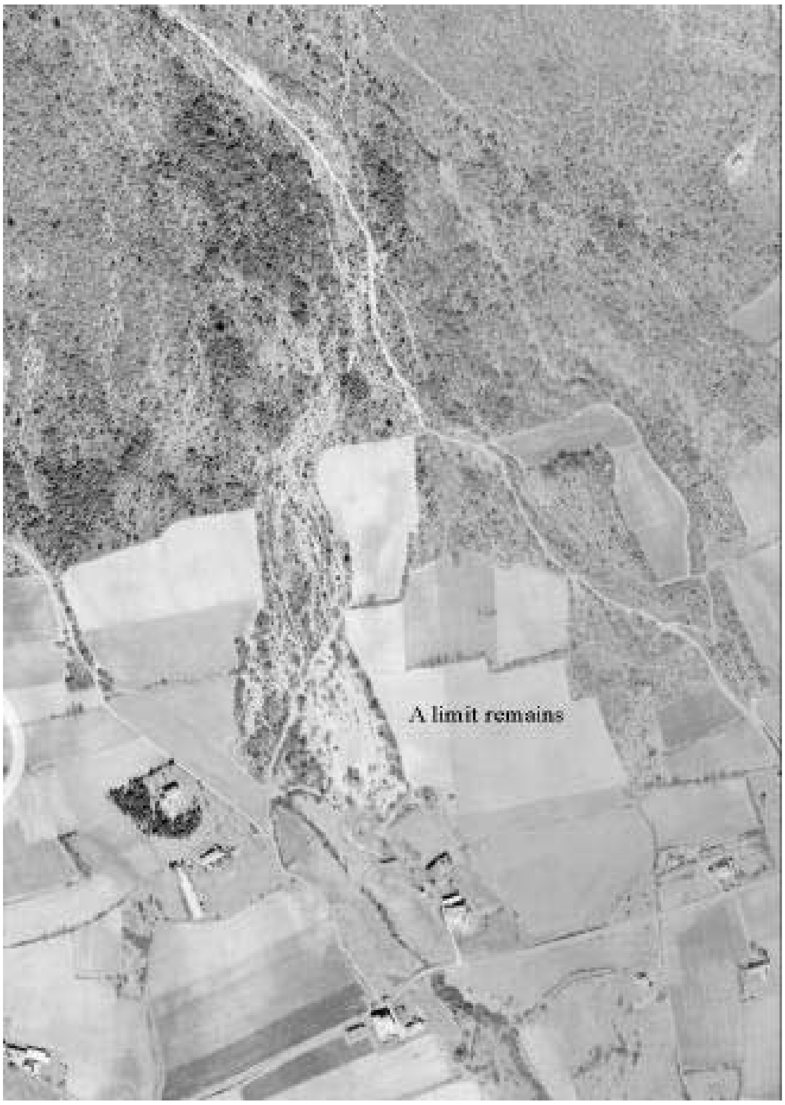
A second example concerns people who want to use the orthophoto as a tool that allows to draw in the ground referential system.

Lithuanian people for example, use the orthophoto to draw maps on a rural area. They are not looking for a pretty orthophoto because they don't intend to put it on the wall. They only want to have an accurate enough tool to make interpretations on it.

When an edge appears on the orthophoto, they want to be able to find out if this edge is the ground feature or not. And if it is, they want it to be accurate enough to complete their maps.

If an edge remains on its orthophoto mosaic, after radiometric equalization it can't disturb such a user as long as he is able to differentiate this limit from the ground feature.

For him, an automatic answer can be given in terms of radiometric equalization without much of a problem even if the covered area is very large.



For such users the main question concerns the accuracy of the DTM done automatically and consequently, the accuracy of the automatic aerotriangulation results.

It is very important for them to have the means to define it and also to check it.

I saw technicians who prefer to use the classical way instead of the automation we proposed in order to ensure they keep control on the result.

They want to be able to decide themselves about the compromise between the time they spent and the quality they obtained.

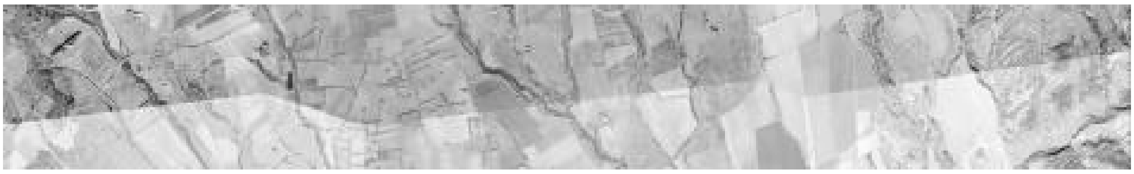
In my opinion, the more your aerotriangulation is automatic, the sharper and the easier to use must be the means you give to check it and to interpose on it.

It is the same for the automatic DTM calculation and we can say that automation is efficient as long as it is under control.

Automation and the aspect of the mosaic

A third family of users want their orthophoto to coincide with the whole map and want it also to be as pretty as a photograph (both qualities at the same time!)

When the orthophoto mosaic covers a large area a simple equalization algorithm does not work very well. It is disturbed by homogeneous parts of the landscape and limits remain on the mosaic which remind us that orthophoto is not a photograph.



One manual solution can be used and it consists in excluding some homogeneous parts of the landscape from the radiometric equalization.

Another more automatic possibility can be given if we use a more precise algorithm for the radiometric equalization.

We expect a lot in an algorithm given by M. H. Le Men which put into play physical parameters like the position of the Sun when the photograph was taken, the shape of the covered ground and the nature of the elements that occupy the field.

We are developing such an algorithm at I.G.N. and at the same time, we are trying to improve the visual aspect of the orthophoto mosaic automatically following natural features as boundaries of the mosaic to switch between one image and its neighbor.

For such users, the automation in radiometric adjustment must also be under control and must allow manual interposing in order to eliminate lake from radiometric adjustment or to correct some boundaries manually.

Another way: ”Take the box, your information is inside “

We have seen some limitations in automation coming from the user’s requests

Because the orthophoto contains all the information from the photograph and a part of information we could find on a classical map, we can say it contains the right answer for lots of user requirements.

It is a cross between a photo and a map. It is like a map, without the cartographer’s interpretation.

However, users want this orthophoto to be a proper map and it seems they expect too much from it.

That is true except if the user is able to extract the information that he needs himself.

For him, maybe the right automatic answer could stay in a box (or computer file) that could contain the whole photogrammetric data and also some stereoploting possibilities by using a PC for example.

I know it already exists on the market.

Proposal for the Demonstration of the Orthophoto Software at the OEEPE Workshop

O. Kölbl

1 General Objective:

- Demonstrate the possibility of an optimal adjustment of the colour of neighbouring images (image cutting length predefined grid lines, without feathering)
- Show how to correct images for a general light fall off (Est Ouest)
- Correct the vigneting effect of the image
- Show the possibilities for image cutting length features and the feathering effect
- Give indications on the optimal pixel size of the resulting Mosaik and show how to conserve the original image sharpness
- Use of filters in order to increase image sharpness and colour appearance
- Show facilities for the production of sub images of a fixed size (3x3km) of the resulting mosaik
- Show on your own images how breaklines (TIN) can be incorperated, bridges properly modelled and eventually how to rectify houses
- Available output format: Geo tiff, datacompression
- Discussion of the workflow

2 Picture Material

The images were taken with a Leica RC30, wide angle lens on Kodak film, flying height nearly 5000m, picture scale 1:27,000. They form a small bloc of 2 x 2 images with 60% longitudinal overlap and 40% lateral overlap (Picture numbers: 14058, 14059 (1st Strip), 15057, 15058 (2nd strip)).

The picture are on CD-ROM and were made available by Swissphoto Zürich.

3 Image Orientation

The images were scanned on a LH-Systems scanner DSW 200 with pixel resolution of 25µm. The orientation stems from an aerial triangulation, in which a RMS in planimetry in the control points of 0.5 m was obtained; whereas 1m resulted in height.

4 Digital Terrain Model

The digital terrain model was taken from the national height model 1:25,000 of Switzerland with a mesh width of 25m. The precision of the DTM is indicated with ±2m. The data can be made available only for the presentation at the workshop of OEEPE and were gracefully put at our disposal by the Federal Office of Topography.

5 Description of the Tasks

Elaborate orthophotos of the area covered by the 4 photographs of the following area:

Upper Left corner:	E: 629500	N: 228000
Upper right corner:	E: 636000	N: 230000
Lower left corner:	E: 632000	N: 220500
Lower right corner:	E: 638500	N: 222500

5.1 Demonstration of colour balance, by only global tone adjustment

Demonstrate the possibility of an optimal adjustment of the colour of neighbouring images **without feathering**. The image should be cut length the lines passing through the points:

Est_West: P1: E: 631000, N: 224000, P2: E: 637000 N: 226000

North-South: P1: 633000, N: 228000, P2: E: 635000 N: 222000

We ask you to show the colour adjustment in particular length the lines were a break will be apparent. We propose that you first correct the images for the light fall off in East-Oust direction and the vigneting of the camera. As for colour balance it is suggested to keep the area around the coordinates E: 633000, N: 226000 in image 14058 (Altbüron) as reference and leave this area unchanged.

5.2 Standard Mosaiking length features and feathering

Show the possibilities for image cutting length features and the feathering effect; make an optimal colour correction for the 4 images within the dimensions of the mosaik.

5.3 Sharpness of the mosaik

Give indications on the optimal pixel size of the resulting Mosaik and show how to conserve the original image sharpness

5.4 Use of filters for image sharpening

Show whenever possible how to increase the image sharpness and colour appearance by the available standard filters.

5.5 Output of the mosaik

Show facilities for the production of sub images of a fixed size (3x3km) of the resulting mosaik and specify the output formats (Geo Tiff, Compressed ?).

5.6 Miscellaneous

Show on your own images how breaklines (TIN) can be incorperated, bridges properly modelled and eventually how to rectify houses

5.7 Workflow

Show on the example of the “optimal” mosaik the recommended workflow.

Editors Note
For technical purposes, the vendor's presentations, are reproduced at the end of the proceedings, in part 7.

Discussion after the Demonstration

Vendors demonstration mosaicking (Helava, Intergraph, Zeiss)

Kölbl (EPFL, Switzerland):
I understand that you used mainly dodging for colour balancing in image correction?

Miller (LH Systems):
Customers tend to use a variety of tools and if they have drastic colour problems they do not sort them out by the dodging program. But if there is a subtle colour problem, the dodging can work well when it is run in an independent fashion where all the green, red and blue bands are processed together in separate colour batches. In the case you mentioned it was effective but it is not in all cases.

Remarks on the Quality Control of Digital Orthophotos

M. Wiggenhagen
University of Hanover,
Institute for Photogrammetry and Engineering Surveys

Abstract

The application of quality management rules is important to control the production of orthophotos and to ensure the quality of output products like orthophoto images and orthophoto mosaics. The working group „NaBau“ of the German Institute for Standardisation „DIN“ develops standards in the area of photogrammetry, image processing and remote sensing (DIN 1, 1995, DIN 2, 1996, DIN 3, 1997).

As a member of the working group „orthophoto requirements“ the author is collecting material, ideas and definitions for a the new DIN standard named „Digital orthophoto“.

1 Motivation

Current hardware and software tools allow the fast processing of digital orthophotos based on precise digital elevation models. To inform the applicants about the product history and quality the whole orthophoto production process has to be investigated and to be described in the new DIN standard. For quality control circles process relevant parameters have to be defined and outlined in specifications. The result of the development of new standards should include state of the art methods and products which can be compared with results currently offered on the market.

2 Status of the definition phase

After the collection of information the following details will be included in the new standard:

- Image data (Digitized aerial photographs)
- Numerical data, (Interior and Exterior Orientation)
- Digital Elevation Model (Surface model, object model)
- Methods (Interpolation, resampling)
- Output data (Digital product, Analog product)

The processing steps for digital orthophotos will be described in detail in the annexes of the DIN Standard. The quality management definitions are already defined and can also be used for the new standard (*DIN 4*, 1995). For quality control purposes it is necessary to investigate and to define the main contents of the production line. This ensures the producer of orthophotos to be able to supervise the quality of the output product. Main steps are the scanning of analog input images, setting up the interior and exterior orientation and the generation of digital elevation models.

3 Specification of parameters

Main parameters of the orthophoto production are the desired object resolution, the radiometric resolution and the defined output region. Depending on the size of the output region in most cases orthophoto mosaics instead of single orthophoto scenes have to be produced.

The output resolution of digital orthophotos depends on the influence of the resampling process and the resolution of the digital input images. Photogrammetric scanners with geometric resolutions between 7 and 12 µm and radiometric output in 8-bit per channel are considered in the production process. The accuracy of interior and exterior orientation parameters is not critical for the production process using modern aerotriangulation and adjustment programs. The critical topic is the quality of the used digital elevation model. The required accuracy can be calculated by the known focal length and the radial distance in the input image and the allowed maximum ground location error:

$$\Delta h = f \Delta x / x \qquad \text{with}$$

Δh = accuracy of elevation model

Δx = maximum ground location error

f = focal length of the input image

x = radial distance in the input image

The new standard for digital orthophotos will contain further accuracy calculation rules to enable the user to clarify the main dependencies in the production process. The calculation will consider the input and output pixelsize, the desired map scale and e.g. the amount of data to be stored for the digital product.

For this purpose several annexes are planned to be added to the main standard text.

These annexes are:

Annex A Specifications for the digital orthophoto

Annex B Description of the production process

Annex C Description of orthophoto parameters and functional dependences

Annex D Error theory accuracy requirements for production parts

The specifications in appendix A will be e.g. the resolution of the digital input image, the resolution of the digital orthophoto and the border coordinates of the output image.

Details of the annexes B to D are still under investigation.

The quality of digital orthophotos has to be investigated in two separated ways.

The geometric quality will be investigated with control points, measured control distances, with additional overlapping orthophotos and with vector data for visual quality control.

The radiometric quality will be controlled with white and dark areas in the images (radiometric control points), with additional overlapping orthophotos and with statistical parameters like mean greyvalue, standard deviation, and histogram analyses.

4 Summary

The collection of definitions and process relevant parameters for the production of digital orthophotos is still not finished. Main topics like image scanning, generation of digital elevation models and resampling have already been investigated. In near future some new definitions are necessary to consider current processing methods, parameters and products.

5 Conclusion

To control the quality of photogrammetric products a new standard is under investigation for digital orthophotos. In addition other standards e.g. for aerial flight planning and image scanning are under development.

For the market it is very important to clarify the main production dependencies and to define all quality relevant parameters. The evaluation processes will be based on those quality parameters. In the production process the additional quality circles will ensure a stable and reliable product accuracy.

References

DIN 1, 1995: DIN 18716-1: 1995 – 11
Photogrammetrie und Fernerkundung – Teil 1: Grundbegriffe und besondere Begriffe der photogrammetrischen Aufnahme.

DIN 2, 1996: DIN 18716-2: 1996 – 07
Photogrammetrie und Fernerkundung – Teil 2: Besondere Begriffe der photogrammetrischen Auswertung.

DIN 3, 1997: DIN 18716-3: 1997 – 08
Photogrammetrie und Fernerkundung – Teil 2: Begriffe der Fernerkundung.

DIN 4, 1995: DIN EN ISO 8402: 1995 – 08
Qualitätsmanagement – Begriffe (ISO 8402: 1994) dreisprachige Fassung EN ISO 8402: 1995

Discussion

Remarks on the quantity control of digital orthophotos
M. Wiggenhagen, Institute of Photogrammetry,
University of Hannover, Germany

Kölbl (EPFL, Switzerland):
When can we expect these standards to come out?

Wiggenhagen (Univ of Hannover, Germany):
We will be finishing the first phase of definitions this year. Then you will have to wait another year or a year and a half for the specifications process under the DIN Standard. They will then be completed and published. So hopefully, you will be able to get the paper by mid 2000.

Kölbl (EPFL, Switzerland).
In radiometric control: how far will you go, what will it look like?

Wiggenhagen (Univ of Hannover, Germany):
Personally, I would like to see a grey scale in all aerial photographs. So the photographs together with the ground image would contain a grey scale. Thus, the photographic development process would be integrated in this grey scale. This would later allow one to focus and get a normalised image. This would be in the camera frame, not on the ground. Today this is the only method to do a densitometric and sensitometric control and measure the negative and normalise them. On top of that, if one could get radiometric ground control points, it would be even better. But who wants to do the measurements on the ground?

Kölbl (EPFL, Switzerland):
I am a little hesitant because, for the normal user, you are not interested in having a proper tone reproduction from the photograph to the orthophoto, you want it only to control the photographic process. Now, if you publish your DIN and I am not satisfied with the orthophoto, then the one responsible will say that he had respected the DIN norms. What I need is a good image corresponding to my needs. Indeed, it is possible to define standards and once I had to do it when I tried to work out standards for the density of specific objects; I defined a road which should have a density of 10 on my aerial photographs on my negative. It is simple, it must be done with some tolerance but there are ways and these objects are very uniform. Whether it is in France or Switzerland they are about the same. Should this not be taken into account?

Wiggenhagen (Univ of Hannover, Germany):
Yes, I agree with you, but the problem arises when you have difficult customers who do not know what they are talking about. If you have experienced customers we can take their requirements into account and do dodging etc. In the DIN you will find methods and parameters which will justify what you had done to an ignorant customer. This is because you have to consider both sides: the producers and the customers.

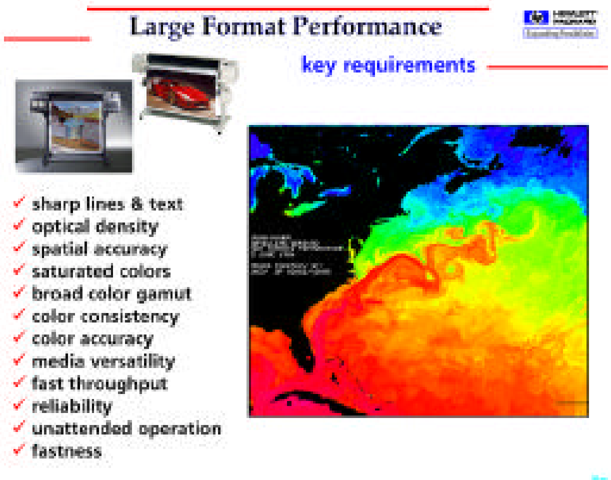
Grabmaier (ITC, Netherlands):
With respect to sensitometric control, to my mind it does not make sense to put one sensitometer strip on one side of the photo, this should be done all around the image. As Professor Kölbl said, this could be done anyway. The nice thing about it is that it displays what has been done to the image. For instance blue was taken out, red was added or more stretched than green, etc. It is not so vital to see on the final image that everything appears grey, there is no tone etc. You can do the same things with the orthophoto as now, but later on not much documentation is needed, as the sensitometric strip will indicate what has been done.

Large Format Printing
with HP JetExpress Technology

Text by R. Allen
Hewlett-Packard Laboratories

Presented by R. Raychoudhury
Hewlett-Packard BCD

This paper presents an overview of Hewlett-Packard's new JetExpress technology and discusses how it contributes to the speed and productivity of HP's new DesignJet 1000C Series large format printers. The ink jet printing process is discussed in terms of its basic elements of storage, addressing, transfer, and fixing. After reading this paper, you should understand why HP is committed to thermal ink jet as the technology of choice for high quality, high throughput, and reliable large format printing.



This figure shows some of the important aspects of high quality imaging for a large-format printing system, whether it is the HP DesignJet 1000 Series or the HP CP Series. These characteristics are important in all applications of large-format printing, and the engineering that goes into the writing system is focussed towards meeting these product performance objectives.

HP's thermal inkjet technology, called "TIJ," was invented in 1979 at Hewlett Packard Laboratories in the Printing Technology Department. HP's first TIJ printer was ThinkJet, introduced in 1984, and HP still manufactures ThinkJet print cartridges today.

This figure shows key characteristics of HP's TIJ technology. TIJ delivers very high printing throughput: it produces drops at high frequency and its compact design allows a large number of drop generators[1] to be placed on the printhead. An energetic process for drop ejection and integrated power and interconnect electronics are key to high reliability and high performance in a TIJ printing system.

Unique among printing technologies, ink jet provides economical, robust solutions across the full range of applications. This includes inexpensive portable printers, photographic-quality desktop printers, workgroup color printers, and large-format printers. HP's TIJ printers, inks, and ink delivery systems provide solutions in all these market segments.

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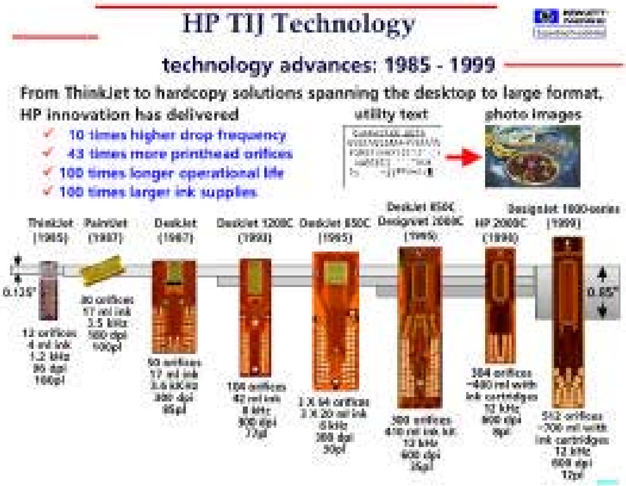
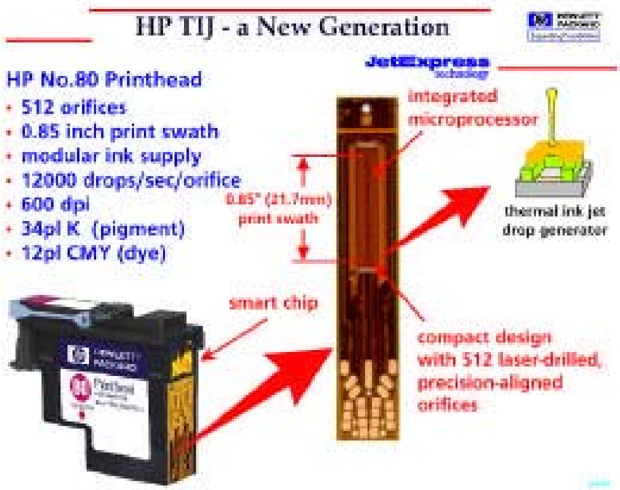
[1] A drop generator is the structure that produces a drop of ink. An orifice (or "nozzle") is part of the drop generator, and it is the tiny hole through which a drop emerges. The terms "orifice," "drop generator," and "nozzle" are often used interchangeably when counting the number of independent drop generators on a printhead.



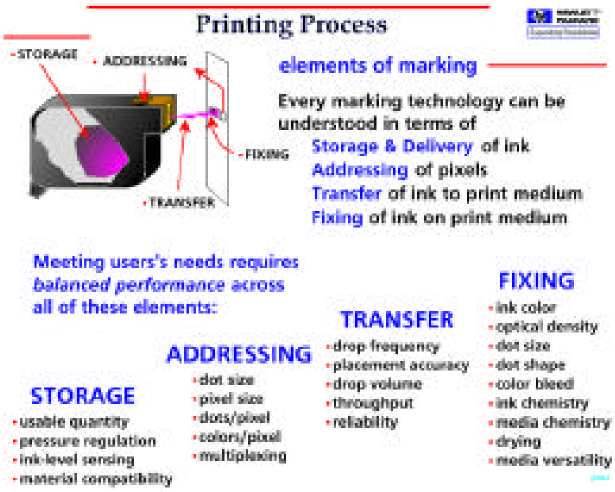
HP ink jet innovation is built upon an R&D investment of billions of dollars. And, since the introduction of ThinkJet 15 years ago, HP has made orders-of-magnitude improvements in printing performance. This figure shows some of HP's ink jet printheads from ThinkJet to the HP No. 80 Printhead for the DesignJet 1000-series. They are shown in relative size and with their key specifications.

Since 1985, HP technology has advanced from printing utility text to photographic images. Drop ejection frequency has increased by a factor of 10, and the No. 80 printhead has 43-times more orifices on a silicon chip that is smaller than the chip used for ThinkJet. Compared to ThinkJet, current drop generator designs deliver over 100 times as many drops during their useful life, and ink cartridges hold 100 times more ink.



This figure gives an overview of the newest TIJ generation representing the state-of-the-art in ink jet technology: the HP No. 80 Printhead with HP JetExpress Technology. Introduced in the HP DesignJet 1000 Series, this printhead has a high (12KHz) operating frequency, 600dpi print quality, 512 orifices for a wide (21.7mm) print swath, and small drop-volumes. Its modular ink delivery system features pigment-based black and dye-based color (CMY) inks.

The orifice plate is part of the polyimide tape used for the electrical interconnect. HP uses an excimer laser to drill and precisely align each orifice to the drop generator chamber. The printhead is fabricated on a silicon chip with an integrated microprocessor to monitor printhead operation. This assures high throughput under all printing conditions.



In order to understand a complex technology like inkjet, with so many interacting components and processes, it is useful to consider four basic elements of a printing process[2].

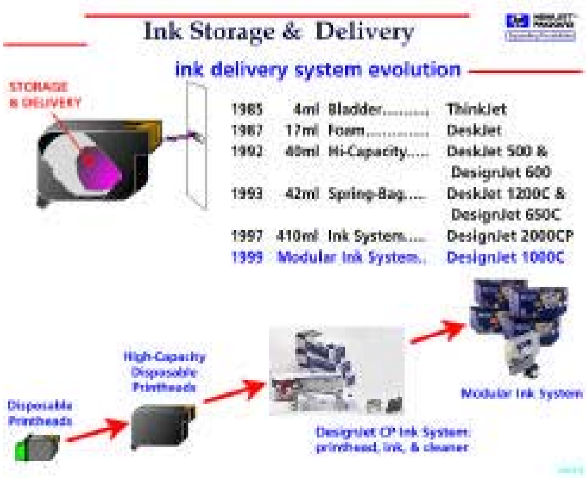
- storage **and delivery of ink;**
- addressing **of pixels;**
- transfer **of ink to the print medium;**
- fixing **of ink onto the print medium.**

Printing technologies[3] can be compared in terms of how each implements these four processes.

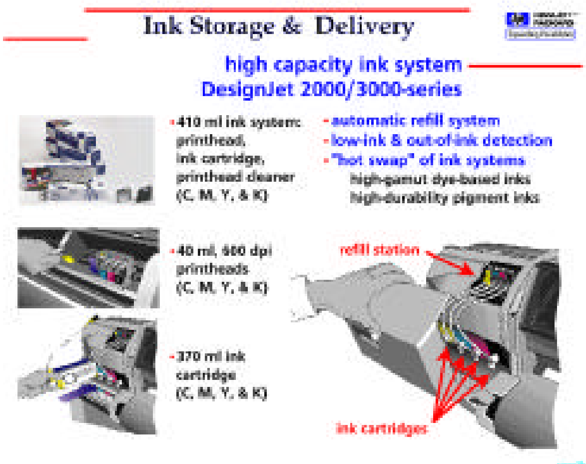
In order to meet customer needs, it is important that the printing system offer *balanced performance* across storage, addressing, transfer, and fixing. This figure lists some important aspects of each element, and these must be considered together for balanced performance. For example, a good design is not simply achieving the highest possible resolution (i.e., **addressing**: small dot size) but must take all the other factors into account. Balanced solutions are the focus of HP engineering and product design because they do not compromise performance in one area (such as throughput) for the highest possible specification in another (such as small dot size).

[2] The term "ink" is used here to represent the colorant whether it is actually a liquid ink, electrophotographic toner, or other material used to record a mark.

[3] For example electrophotography, dye-sublimation, thermal transfer, conventional photography, lithography, and others.



Consider the **storage** of ink. This figure shows the evolution of HP's ink delivery solutions over several product generations. In 1985 ThinkJet delivered 4 ml of ink in a disposable print cartridge. With a disposable printhead and ink supply, HP achieved a breakthrough in usability: the user could service the most critical element of the writing system simply by replacing it. The reliability and operating life of drop generators increased over the years from breakthroughs in printhead design and manufacturing processes. These advances provided the foundation for the long-life ink system on HP's DesignJet 2000 and 3000 Series in 1997. This system delivers 410 ml of ink, 100 times more than ThinkJet. Today, the No. 80 Modular Ink System in the DesignJet 1000C offers another advance in performance and user convenience: an HP No. 80 Printhead will deliver 700ml, two 350ml No. 80 Ink Cartridges, before replacement.

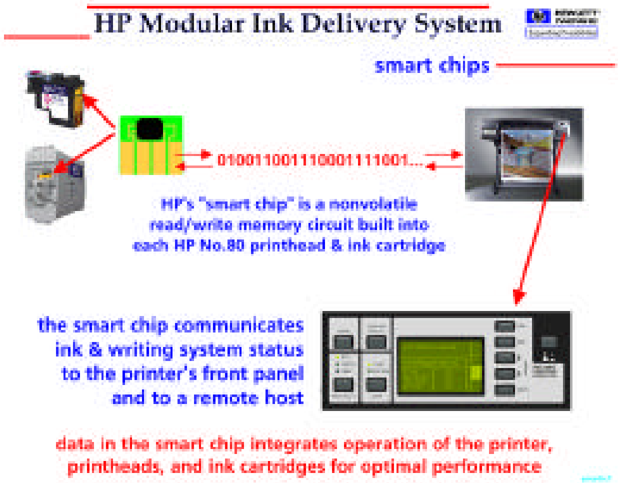


Let's review the features of the HP DesignJet 2000 and 3000 Series and compare them to the 1000 Series to understand the differences.

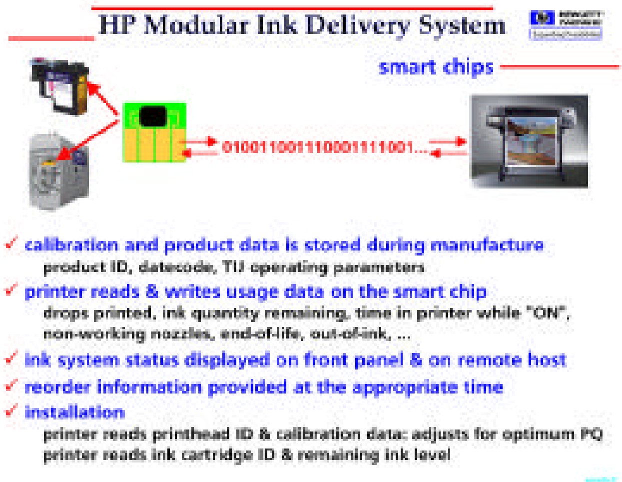
The DesignJet CP ink system contains a printhead, an ink cartridge and a printhead cleaner for cyan, magenta yellow and black. Each system supplies 410 ml of ink. When the ink is consumed, all components are replaced together. Two types of ink systems are available: a dye-based system, offering highest-quality color, and a pigment-based "UV" ink set for high durability (i.e., water- and lightfastness). Each ink cartridge automatically refills its printhead (using the printhead's internal pressure regulator as a pump) in a simple system that provides low ink detection.

A practical feature of the CP ink system allows the user to swap between dye and pigment ink systems from one print to the next. This capability is valuable to the markets and applications served by the CP DesignJets where flexibility (in ink and media) and productivity are important. The printhead, ink cartridge (with its ink supply tube), and printhead cleaner are simply removed, stored, and replaced with components of the other ink type. No intermixing between dye and pigment inks can occur, and no cleanup or flush cycles are required.

The HP No. 80 ink system for the DesignJet 1000 Series has three components: a print-head cleaner, 175ml and 350ml ink cartridges, and a printhead for each color: cyan, magenta, yellow, and black. It features automatic refill and ink level sensing, but the key difference between it and the CP system is its modular design and performance. The No. 80 Printhead has a longer life and will use several ink cartridges before replacement. Another innovation is a "smart chip" for the printhead and ink cartridge.



The "smart chip" on each HP No. 80 printhead and ink cartridge is a non-volatile, read/write memory circuit with a serial data connection to the printer. It stores and communicates information that integrates the operation of printer, printheads, and ink cartridges for optimal performance. This information is important for reliable unattended operation, high print quality, and convenience in consumables management. For example, remaining ink quantity and printhead performance can be displayed on the printer's front panel and remotely on pop-up windows on the host computer.



The smart chip performs many useful functions. It stores calibration and product data such as when the products were manufactured (assuring fresh supplies), where they were manufactured (for quality control), and information about the operational history of the ink cartridge and printhead. It provides the user with product identification[4] useful for reordering supplies.

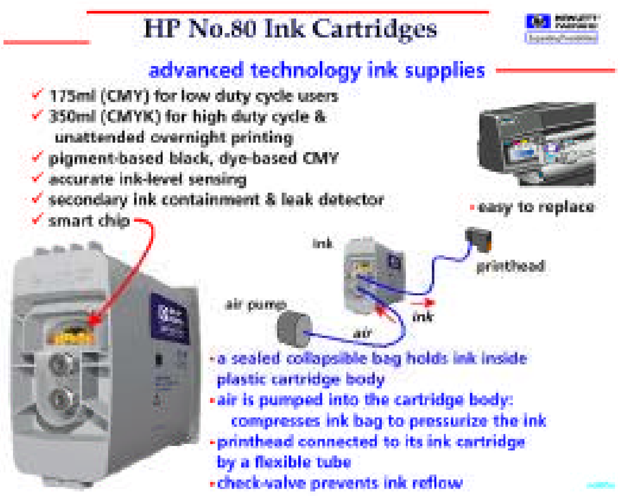
During operation, the number of drops printed, the ink quantity remaining in the cartridge, the date of first use, and the number of non-working nozzles are recorded on the

[4] part numbers for ink cartridges and printheads.

smart chips. Since this information stays with each cartridge and printhead, a partially used module could be taken out of the printer and replaced with a new one for a long unattended print job. Later, the original module could be placed back in printer to use its remaining life under attended conditions.

When a printhead is installed, the printer reads calibration data to adjust operating parameters for optimum print quality and checks for remaining life. When an ink cartridge is installed, the printer reads the remaining ink quantity and expiration date.

Writing system status stored in the smart chip can be displayed on the printer's front panel and on a remote host. This capability improves the management of consumables: whether the printer has low- or high-duty-cycle use, the user can accurately determine how much longer supplies will last and when and what supplies to reorder.



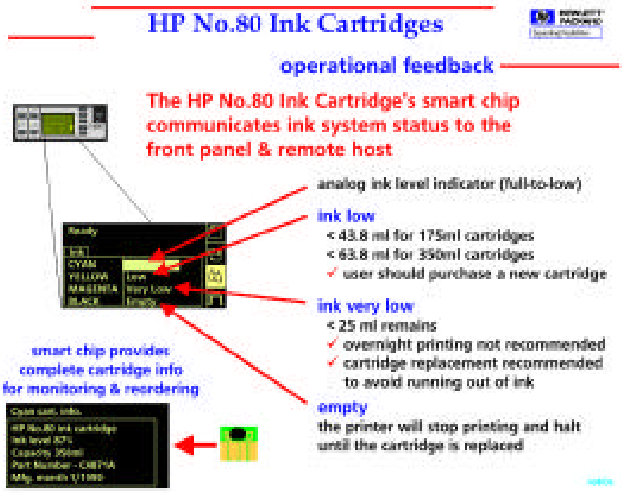
The HP's No. 80 Ink Cartridges come in two sizes: 175ml (CMY), for low duty-cycle use, and 350 ml (CMYK) for high duty-cycle and unattended printing. The black ink is pigment-based for high optical density and fastness; the color inks are dye-based for high color saturation and gamut. Ink is contained in a collapsible metalized-plastic bag inside the rigid cartridge body.

The smart chip on the ink cartridge keeps track of the number of drops printed by the printhead while it is attached to the cartridge. Multiplied by the drop volume, this gives an estimate of the quantity of ink consumed.

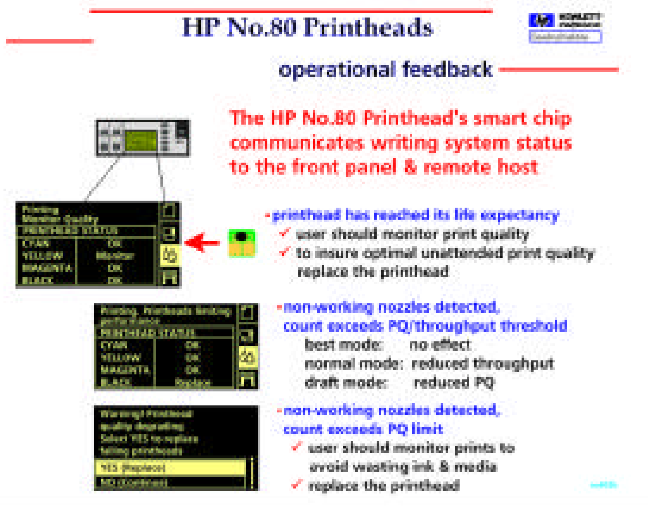
In the figure above, you can see two septa[5] on the ink cartridge. One connects to the ink bag to supply ink to the printhead through a flexible tube. The other connects to a small air pump in the printer to allow pressurized air into the cartridge body. Pumping air into the cartridge squeezes the ink bag and forces ink out to the printhead. The printhead is continually refilled from this source of pressurized ink, and its internal regulator accepts only as much ink as needed to meet printing demand. A check valve inside the cartridge prevents flow of ink back into the ink bag.

[5] A needle and septum is used for a make-break fluid connection.

This simple and reliable system also provides a second measure of remaining ink quantity. As ink is consumed, the ink bag collapses and the empty volume inside the cartridge increases. When air is pumped into the cartridge body, the change of pressure with time depends on the flow rate from the air pump and the empty volume: as the empty volume increases, the pressure increases more slowly. By measuring the pressure change with a sensor, the amount of remaining ink can be calculated very accurately. The smart chip keeps track of this, too.



The printer's front panel and pop-up windows on the host provide operational about the ink cartridges with analog ink level indicators ("gas gauges") and warning messages. For example, **ink low** warns the user that a new ink cartridge should be purchased soon. **ink very low** warns that overnight printing is not recommended. And, when **empty** is displayed, the printer will stop printing and not resume until a cartridge containing a usable quantity of ink is installed. The smart chip tells the user how long the supplies have been in printer, how long they are expected to last, and what to reorder.



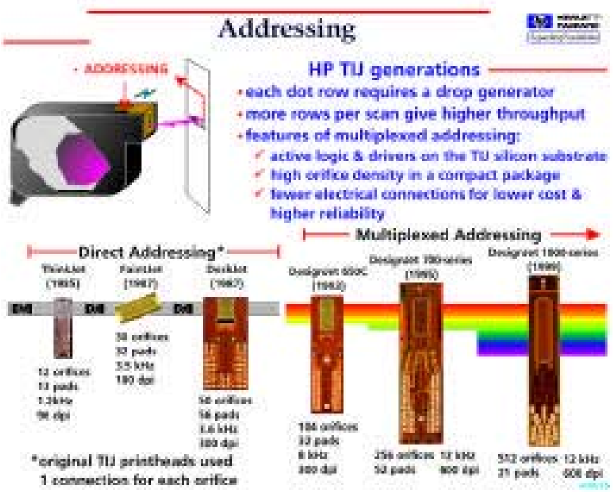
Printhead status is also communicated to the user. When a printhead approaches the end of its useful life, a message is displayed to alert the user that print quality should be monitored and the printhead should be replaced before long, unattended print jobs are attempted. This is important for unattended operation, where poor print quality could waste a large amount of ink and media.

The smart chip works with the DesignJet 1000 printhead service station to keep track of how many orifices are not operating within specifications. In the service station, a drop detector measures flight parameters of ink drops, and a drop ejection test is periodically performed on each orifice of each printhead.[6] Because the "Normal" and "Best" print modes compensate for non-working orifices, the printer can maintain full throughput and high print quality as long as the number of non-working orifices is less than a certain value.[7] When this number is exceeded, the user is warned that reduced throughput (in Normal Mode) and reduced PQ (in Draft Mode) will result. If additional failures are detected, the user is advised to monitor the quality of the output and replace the printhead when necessary. This avoids wasting ink and media and losing data in real-time applications.

In summary, the ink supplies for the DesignJet 1000 Series and CP series share common features such as automatic printhead refill and large in-printer ink supplies. The key differences are in writing system performance, the type of inks available, and the smart chip. The smart chip helps the user manage consumables and optimizes system performance and productivity.

[6] The waste ink is stored in a chamber ("spittoon") within the Printhead Cleaner.

[7] A list of nonoperational orifices is kept in the smart chip and used by printer firmware to print dots with only the good orifices. In "Normal" and "Best" modes, different rows on the printhead pass over the same area on the recording medium. This completely compensates for nonoperational orifices because good orifices are available to print at all dot positions.



This figure shows how HP technology has enabled more drop generators to be placed on the printhead through advances in **addressing** technology.

Unlike piezo printheads, HP's thermal ink jet printheads can print at their full vertical resolution *in a single pass*. To do this, there must be a drop generator for every row. For example, this means that 600dpi vertical resolution requires orifices spaced 1/600th inch apart on the printhead. And, for higher throughput, each new generation of printheads operates more orifices. The challenge in building large printheads is to operate a large number of drop generators with the fewest electrical connections between the printhead and printer.

In HP's early designs, each drop generator had a direct electrical connection to an electrical pulse generator in the printer. This is called *Direct Addressing.* For ThinkJet, 12 orifices required 13 electrical lines and connections (one line was a common). Thirty orifices on PaintJet required 32 electrical connections (2 commons). In the original DeskJet design, 50 orifices required 56 electrical connections (6 commons).

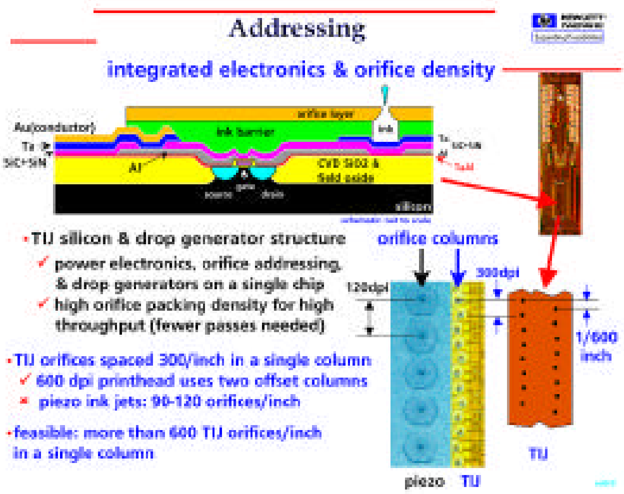
Referring to the figure, the drop-emitting part of the DeskJet printhead is the gold-plated orifice plate. The interconnect area (the arrangement of round gold-plated pads) on the polyimide tape is over ten times larger than the orifice plate. With *Direct Addressing*, the printhead's interconnect area was becoming large and expensive as the number of orifices increased. As all electrical engineers know, connections are among the most unreliable components of electronic equipment. And, as print cartridges are replaced, those connections are made and opened many times over the life of the printer. With *Direct Addressing*, the number of connections was growing as fast as the number of orifices, and this presented a real challenge to reliability and to minimize interconnect area, printhead size, and cost. To take the next step to printheads with a hundred or more orifices, a new technology was needed.

In 1993, HP introduced the first printhead with *Multiplexed Addressing*. This allows fewer electrical connections to control more orifices: 104 orifices were controlled with only 32 connections on the DesignJet 650C printhead. The silicon fabrication technologies for NMOS and thermal ink jet were combined to build transistors and diodes on the same silicon chip as the TIJ heater resistors. This allowed more drop generators with higher printing resolution to be placed on a chip. The benefit to printer design was to increase interconnection reliability and decrease printhead width.

Minimizing printhead width is important! Printhead width directly translates into the size of the printer on a desktop: for every 1 mm additional print cartridge width, a printer using four print cartridge becomes 8 mm wider. This is because the printer carriage has to move the assembly of print cartridges across the width of the paper, and then completely off the paper's edge on each side. Additional width is required to allow the printhead carriage to decelerate, stop, and accelerate back across the page. Minimizing printer size is a key customer value for the desktop market.

In the HP No. 80 Printhead, 512 orifices are controlled with only 21 electrical connections. The area for interconnect pads is now significantly smaller than the silicon area of the printhead. Without *Multiplexed Addressing*, the interconnect area would be about 10 times larger than the 1987 DeskJet's interconnect, and that would be completely impractical.

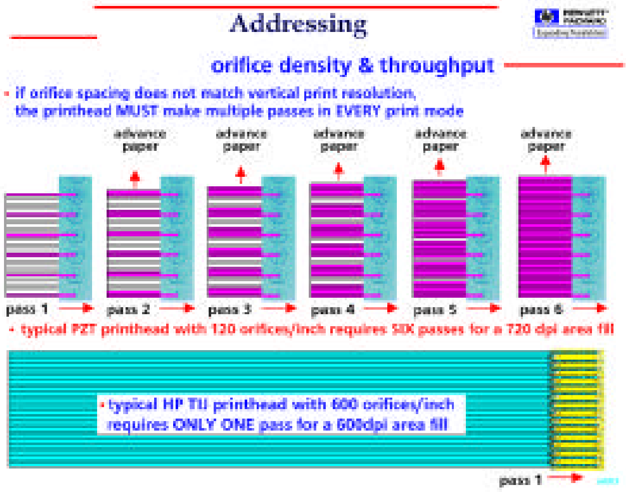
In 1985, HP's ThinkJet printhead had 12 orifices, printed at 96 dpi, and produced 1200 drops per second out of each orifice. That works out to 14,400 drops per second. In 1999, the HP No. 80 Printhead's 512 orifices print at 600 dpi and operate at 12KHz for 6,144,000 drops per second.



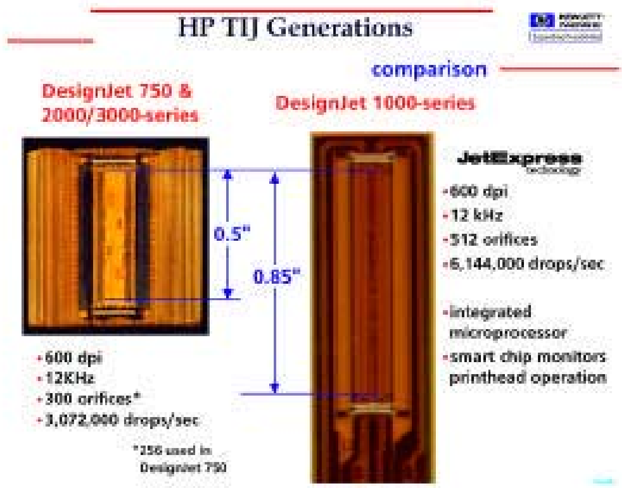
This figure shows a schematic cross-section of the silicon chip used in HP's multiplexed addressing printheads. NMOS transistor technology and the TIJ heaters share metal and insulator layers in an integrated structure. This places the power switching electronics on the printhead, unlike earlier designs where the switches are in the printer.

600 dpi printing is achieved in a single pass by placing two columns of orifices close together. The drop generators are spaced 300 to the linear inch in each column, and the two columns are offset from each other by 1/600". This gives one drop generator for each printed row spaced 1/600" (600 dpi) apart. HP's R&D has shown that it is feasible to place 600 TIJ drop generators per linear inch.

Another important TIJ design feature allows the orifices in each column to be slightly offset in the direction of motion as the printhead scans across the page. If the drop generators in a column were arranged in a straight line, they would have to fire all at once to print a vertical line. But this isn't practical for electrical and fluid mechanical reasons. The offset compensates for the nonsimultaneous and nonsequential[8] orifice firing order and allows accurate placement of drops at high carriage scanning velocities.

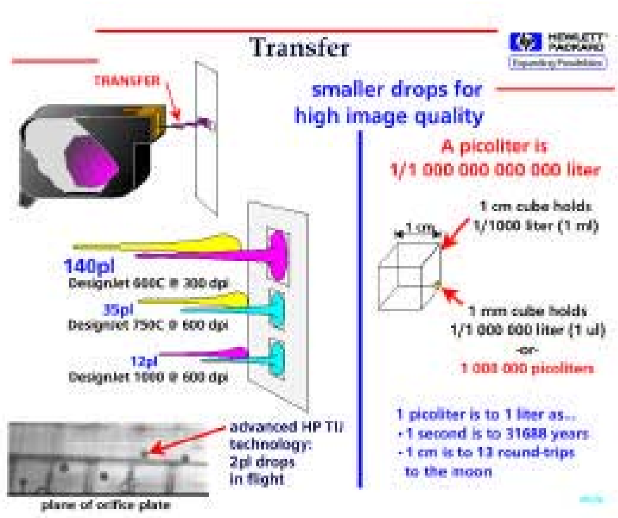


Some piezo manufacturers claim 720 dpi vertical resolution, but their printheads require as many as **eight** passes to completely fill an area. This is because their orifices are spaced only 1/90" apart on the printhead. In some newer generations of piezo ink jet, orifices are spaced 120 to the inch. But, that requires **six** passes to full an area at 720 dpi for all print modes. With HP's true 600 dpi printheads, a full area fill can be achieved on **one** pass. That enables HP printheads to achieve very high throughput.



[8] In order to prevent hydraulic interference between orifices that could affect drop volume and velocity, a firing order is chosen to assure that adjacent orifices do not fire in sequence. This allows each drop generator to refill and be undisturbed by its neighbor before it is fired.

This figure compares the printhead in the DesignJet 750 and CP Series with the HP No. 80 Printhead. It shows how much HP inkjet technology has advanced in one generation. JetExpress doubles the rate of ink delivery to the media, and it has a built-in microprocessor on the same silicon chip as the thermal ink jet drop generators. The processor measures printhead temperature, print density (number of orifices firing), and computes the optimal operating parameters for the drop generators. This maximizes throughput and maintains consistent image quality. In fact, if you think of HP's JetExpress printhead as a microprocessor that prints with tiny droplets of ink, that gives you a accurate idea of the amount of information handling, data processing, and the material science that is part of each printhead.



Consider the **transfer** of ink from the printhead to the recording medium. Drop volume is an important performance measure of the transfer process. Smaller drops generally produce smaller dots, and this is useful both for higher resolution binary printing and for halftone printing. In halftone printing, multiple drops are placed in each pixel to achieve more printable colors and gray levels per pixel. This is the principle of HP's PhotoREt technologies used in desktop color printing. With PhotoREt II, up to 16 drops of ink are placed in each pixel to give hundreds of colors per pixel. This process minimizes grain and tone breaks in color images.

For a given dot size, developments in ink technology can reduce the required drop volume. This has real benefits to the user. Less ink is used in an image, and drying times are improved without the use of heaters and fans. This reduces the cost and complexity of the printer and contributes to a low cost per page.

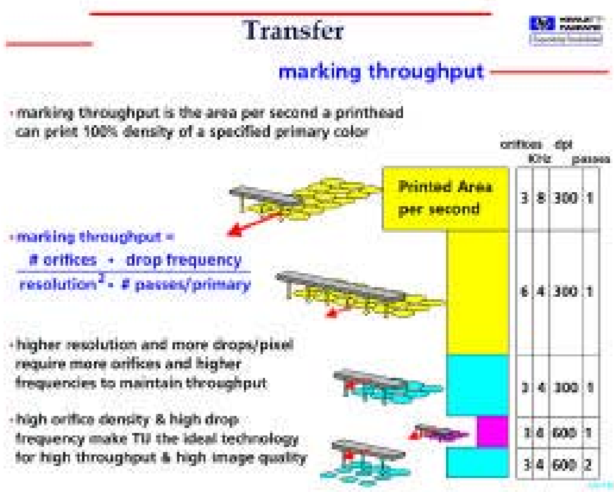
This figure shows the trend from the DesignJet 600C to the 750C and to the 1000C: from 140 picoliter drops at 300 dpi to 12 picoliter drops at 600 dpi.

Picoliters (pl) are units of volume and nanograms (ng) are units of mass. Both are used to specify the quantity of ink ejected in a single drop. For pure water, 1pl = 1ng. Because TIJ inks are 70–95% water, the two measures are often used interchangeably.

How much is a picoliter? A picoliter is 1 millionth of a millionth of a liter. That's a very small volume. To appreciate how small that is, consider a cube *1 centimeter on a side*. This cube holds 1 thousandth of a liter, or one milliliter. Milliliters are a familiar unit, used in doses of medications. Now, if you take a cube *1 millimeter on a side*, it holds 1 microliter, or one millionth of a liter. There are 1 million picoliters in a microliter: 1 million picoliters inside a cube that is only 1 mm on a side. And, with each drop, an HP ink jet printer delivers a few picoliters and places them precisely on the print media to produce an image. It would take 83,333 12pl drops to fill a 1 mm cube – about 7 seconds of continuous operation for a single orifice on an HP No. 80 color printhead.

Here are a few more ways to think about how tiny a picoliter is. Consider a ratio where a picoliter represents something familiar. For example, if a picoliter were like 1 second, then a liter would be 31,688 years. So, take a second to say "one thousand one," and then sit back, relax, and wait halfway through a typical ice-age (60,000 years) to get the idea how a picoliter relates to a liter. A picoliter is to 1 centimeter as, what?, a liter is to the distance from San Francisco (California) to Barcelona? Well, a little more than that: how about 13 round trips to the moon?! Now that is a very incredible number! But the moon is only 400,000 kilometers away, *only* 40,000 million centimeters, and the ratio is one million million.

In the future, drop volumes will become even smaller. HP's current generation of desktop color ink jet printers use 8 pl drops, and 2 pl drops have been demonstrated by HP R&D. Why are the volumes so small, and how small does drop volume really need to go? 4 pl CMY drops are invisible to the eye at normal reading distance on a glossy white background. Does that make 2 pl drops even more invisible? The objective is to print many drops in each pixel to achieve continuous-tone printing. A 2 pl drop should produce the same quality as a commercial phototypesetter - better than about 4800 "dpi." At this point, the pursuit of ever-smaller drop volumes will probably reach a practical limit.



This figure shows how throughput is related to printhead design, and it hints at new directions in printhead technology.

Marking Throughput the area per second a printhead can print a specified primary color at 100% density. There is a simple but very useful *Equation for Marking Throughput* in this figure. Let's see what this means with some simple examples.

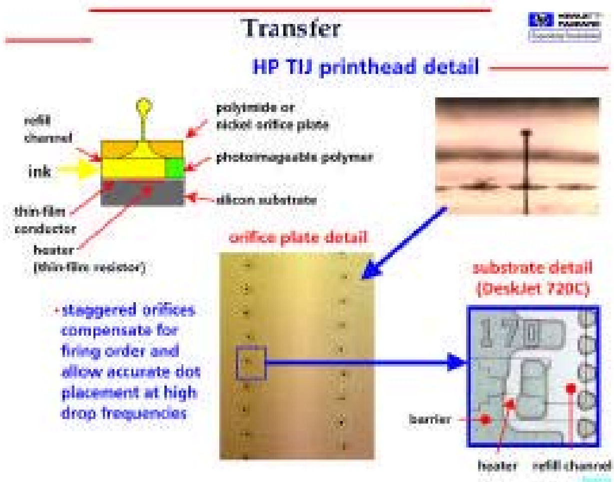
Start with the basic printhead: it has three orifices (remember: we're keeping it simple!), it operates at 4 kHz and prints for 300 dpi. Now, in 1 second it can print one square as shown in the figure. To print faster, either double the number of orifices or double the drop frequency. In this case, *twice* the area is printed each second compared to the basic printhead, or two squares in the figure.

What happens if the resolution is doubled from 300 to 600 dpi? With other design parameters unchanged, the equation shows that only *one quarter* the area is printed each second: $^1/_4$ square.

Why does HP have to invent and deliver new technologies to put more orifices and faster orifices on the printhead when resolution is increased? It is because resolution appears as a squared-term in the denominator in the *Equation for Marking Throughput*: when resolution *is doubled*, throughput *decreases by a factor of four*. Customers expect that higher print quality will not come at the expense of throughput, especially a dramatic decrease like this.

When HP introduces a new generation of high performance printers, like the DesignJet 1000 Series, increasing throughput at high resolution requires placing more orifices on the printhead and operating them at the highest possible frequency. If you understand this, you understand what drives ink jet technology innovation.

HP believes that thermal ink jet is uniquely suited to provide the solutions dictated by the *Equation for Marking Throughput*. In the future, TIJ will deliver much higher drop frequencies as HP's technology meets even more demanding requirements for image quality and throughput. Theoretically, TIJ can deliver over 100,000 drops per second from each orifice, and it can do that because, unlike other ink jet technologies, there are no moving parts except the ink itself.



This figure shows a detail of a typical thermal ink jet printhead[9]. The printhead is built using the same "thin film" processes used in integrated circuits. A silicon substrate (i.e., "chip") has a heater resistor and electrical conductors for each drop generator. A **drop generator chamber** is formed around the **heater** (square feature on the silicon) by

[9] It is the HP DeskJet 720 black printhead.

openings in a layer of photoimageable[10] polymer to make a **barrier**. This film and the structure formed around the heater are seen as the light blue material in a top-view in the lower-right of this figure. (The open area where ink can flow is “white.”) Notice that in this design, ink can enter the drop generator chamber on two sides, and the **refill channe**l has a group of post-like structures that act like a **filter** to trap any fine particles that may be in the ink. An **orifice plate** made of gold-plated, electroformed nickel or a laser-drilled polyimide tape forms the top of the drop generator.

In HP’s thermal ink jet, drops are ejected perpendicular to the surface of the orifice plate. This can be seen in the photo in the upper-right of the figure: a drop[11] emerging from the orifice plate is shown under stroboscopic illumination.

This figure shows some of the key technologies in the HP No. 80 Printhead. The printhead has an internal pressure regulator that allows the printhead to be continuously refilled from the ink cartridge (c.f.: **storage**) by admitting fresh ink as it is needed. The regulator also controls the supply pressure of ink to the drop generators. This pressure is slightly below atmospheric pressure to prevent ink from dripping out of the orifices.

The HP No. 80 printhead represents today’s most advanced technology in drop-on-demand ink jet: its integral pressure regulator, smart chip, long operating life, and JetExpress Technology define the state of the art.

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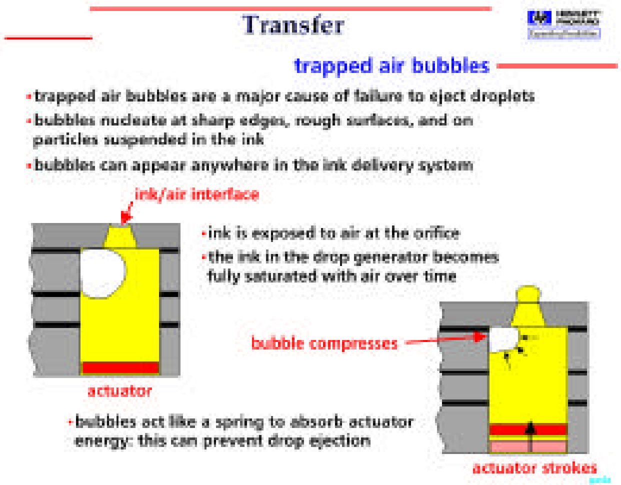
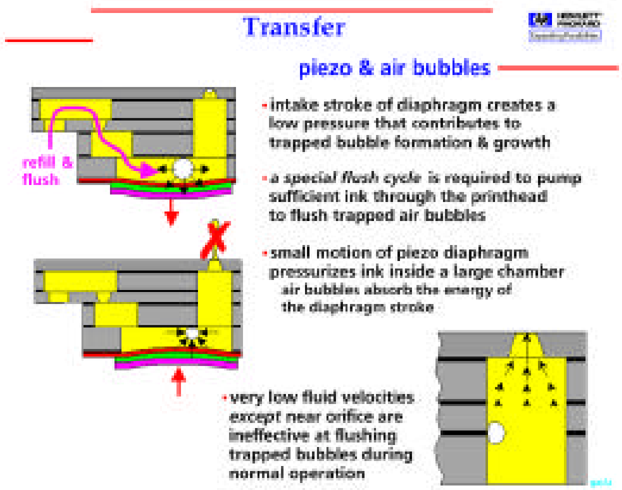
[10] “Photoimageable” means that openings in the polymer layer are defined by projecting an image of the desired solid and open areas onto the polymer layer and then chemically “developing” it. During development, some of the polymer is etched away leaving an opening producing chambers, channels, and posts.

[11] Actually, this is not a single drop: it is many hundreds of drops imaged together by a repeating stroboscopic pulse captured on a single frame of film. A single drop appears because the drops are virtually identical.



Trapped bubbles of air or other gases are the major cause of failure to eject ink droplets. Bubbles present a significant problem for piezo ink jets. Bubbles *will* appear anywhere in the ink system: it is practically impossible to keep all the ink degassed, especially ink near the orifices. When bubbles appear inside a printhead, they absorb the energy needed to reliably eject a droplet.

A drop-on-demand ink jet works like a piston ("actuator") in a cylinder, forcing ink out a small hole (the "orifice") as the piston moves into the cylinder. The ink is nearly incompressible, so when the piston strokes quickly in and out, a droplet is ejected. But, an air bubble is very compressible, so instead of pushing out the ink, the bubble volume decreases as the piston strokes. When the bubble absorbs most of the motion of the piston[12], a drop will not be ejected.



This figure shows a cross section of a typical piezo inkjet printhead. This design has a large internal volume of ink; in fact each drop generator has more than 100 times the

[12] More precisely: when the volumetric displacement produced by the piston is equal to the decrease in bubble volume.

volume of a comparable TIJ drop generator. And, that means three things that are bad news for reliable drop ejection: there is more surface area for a bubble to form and attach, more volume of ink (and dissolved gas) to form a bubble, and the velocities inside the chamber are too low to purge air bubbles.

This printhead works like an old-fashioned oil can: a large diaphragm moves a very small distance to cause ink to squirt out of the orifice. The piezo actuator deforms when a voltage is applied across it, and this moves the diaphragm into the chamber a few millionths of a meter. The geometry of the piezo drop generator chamber makes it a hydraulic transformer where the input and output volume changes are the same. That means that the large area of the diaphragm moving a small distance causes the small area in the orifice to move a large distance[13] to produce a jet of ink. This works fine when there are no air bubbles to absorb the change in chamber volume produced by the diaphragm's stroke.

In practice, the diaphragm first strokes out of the chamber (creating a low pressure) to fill it with ink, then into the chamber (creating a high pressure) to eject a droplet, then out again (low pressure) to cause the drop to break-off. These low pressure cycles, an essential part of the piezo ink jet process, facilitate the growth of air bubbles in the chamber by a process known as *rectified diffusion*.

The small motion of the diaphragm in a large chamber filled with ink leads to another problem: the velocities in the ink are virtually zero except near the orifice. There is no fluid flow to sweep bubbles out of the chamber. This is the reason why piezo ink jets waste so much ink: ink must be periodically pumped through the printhead to flush air out. This uses a significant quantity of ink: in fact, studies show that *200 times more ink* is required for printhead servicing in piezo printers than for HP's thermal ink jet printers.[14] It is not an accident that HP ink jet requires far less ink to purge air bubbles.

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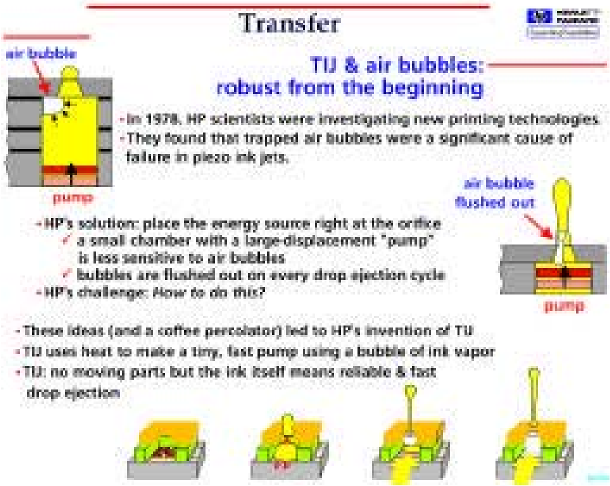
[13] Think of the ink droplet as a small diameter cylinder that moves a large distance out of the orifice as the diaphragm acts like a large-diameter cylinder that moves a small distance into the chamber. With no air bubbles and no flow back through the refill channel, the volumes of the two cylinders are the same.

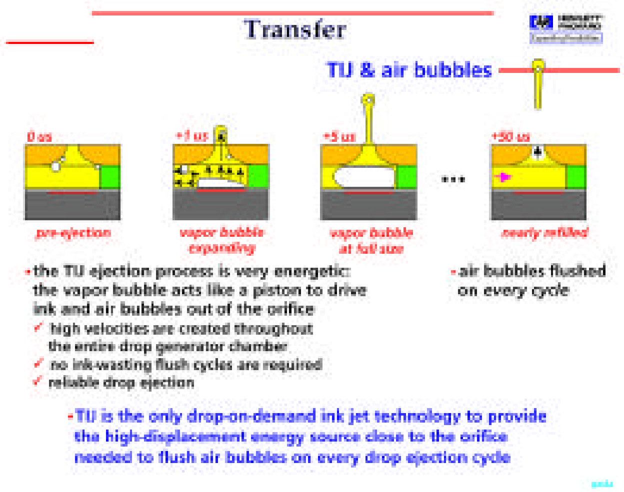
[14] This conclusion is based on measurements during disassembly of piezo and TIJ desktop ink jet printers: the volumes of the ink disposal pads were compared.



The first principle leading to the invention of thermal ink jet was that trapped air bubbles are a fact of life for ink jet and a significant cause of failure in piezo inkjet printers. Scientists at HP Laboratories were looking for a new technology based on a small ink chamber coupled to an energetic, large displacement pump. They wanted to place the pump right at the orifice to flush air bubbles out with every drop.

Here is the more or less official story of how HP invented thermal ink jet. One of the scientists working on new printing technologies at HP Labs in 1978 was John Vaught, and he drank a lot of coffee. John drank so much coffee that he had to have his own coffee maker on his desk. Now, a percolator is a thermal pump with *no moving parts but the coffee itself*. There is a heater at the bottom of the pot, a funnel covering the heater that has a tube to carry liquid up and out the top to a basket of coffee grounds. Heating the water in the bottom of the pot forms big bubbles of steam that push water (coffee) up the tube and out over the coffee grounds. One day, as John was waiting for a fresh cup of coffee, he recognized that he could use this principle to make an inkjet printer where heat, rather than a mechanical pump, ejects the ink.

After six years of work in material science, chemistry, heat transfer, fluid mechanics, and product development, and after millions of dollars of investment in R&D and manufacturing, HP introduced the ThinkJet printer in 1985.



The key to TIJ reliability is its unique, energetic drop ejection process powered by a vapor bubble[15] in the ink. High fluid velocities throughout the chamber purge air bubbles on each cycle. This minimizes the amount of ink used in printhead servicing, and that contributes to lower cost of use. And, thanks to John, there are no moving parts except the ink itself.

The HP No. 80 Modular Ink System uses a Printhead Cleaner for each printhead, and it serves as a component of the service station in HP DesignJet 1000 Series printers. It is replaced with the printhead to ensure reliability and consistent print quality.

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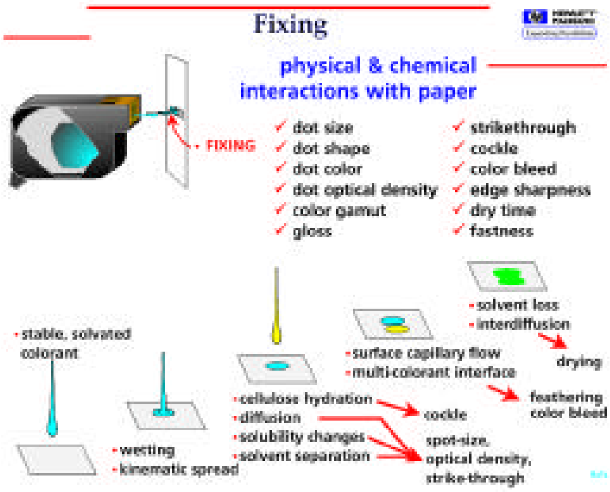
[15] The bubble is produced by a vapor explosion resulting from heating the ink at *100 000 000 ºC per second*. The heating is so rapid that heat penetrates only about 0.1 millionth of a meter into the ink, so most of the ink remains cool. This process is completely different from boiling, because the ink is a superheated liquid until is spontaneously changes to a vapor at its superheat limit, about 340ºC. Boiling occurs at about 100ºC.

The Printhead Cleaner has a cap that seals against the orifice plate when the printhead is idle. This minimizes the loss of volatile ink components and prevents ink from crusting in the orifices. An elastomeric ("rubber") wiper is used to periodically clean the orifice plate and remove paper dust and dried ink spray that can affect print quality and prevent drop ejection.[16] The Printhead Cleaner also has a spittoon[17] to hold the waste ink produced when the printhead ejects droplets to test orifice function and to refresh the ink in the orifices after the printhead has been idle.[18]



Fixing is the final process of marking, and it involves complex physical and chemical interactions between the ink and paper. This figure shows some these interactions and the effects they have on the quality of the final print. Ink design has many competing performance requirements. For example, the ink must remain a liquid in the printhead orifices, where it is exposed to air, yet dry very rapidly on the print medium. The fixing process requires that the pigment or dye separate from the ink solvent at the surface of the paper to achieve high optical density. But, the colorants must remain in solution[19] during the storage and useful life of the print cartridge and in the orifices. Otherwise, clogs will prevent droplet ejection.

[16] The black printhead uses a pigment-based ink, and the black No. 80 Printhead Cleaner provides a special wet wipe using a solvent to clean off any pigment that has dried on the orifice plate. For the dye-based CMY printheads, the ink itself is a good enough solvent to remove dried ink from the orifice plate.

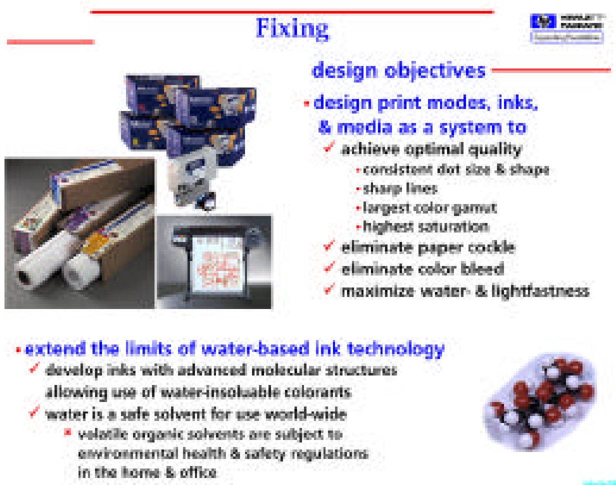
[17] "Spittoon" is not a very nice word, but ink jet engineers use it anyway: it is the container into which ink is ejected. You can also find spittoons near the bar in cowboy movies.

[18] The ink in the orifices loses water and other volatile components over time and becomes more viscous. Also, the loss of volatile components concentrates the colorant. So, a drop ejected after the printhead is idle will have different fluidic and marking properties. To insure consistency, fresh ink is maintained in the orifices by periodically "spitting" a few drops into the "spittoon." An algorithm in the printer determines when to spit based on the time the printhead has been uncapped, the number of swaths printed since the last spit cycle, and several other factors.

[19] Pigments are dispersed in a stable *suspension* – they do not "dissolve" in the ink.

Typical markets for large format graphic prints made by ink jet printers include advertising, retail sales and promotional signage, and reproductions of fine art, photographs, and graphic artworks. Durability of the print is an important attribute because the value of the print in these applications far exceeds the cost of ink and media. *Lightfastness*, the resistance to fading under extended exposure to light, particularly light with strong UV components, is an element of durability.

HP DesignJet CP Ink Systems UV deliver pigment-based cyan, magenta, yellow, and black inks that have been formulated for exceptional fade-resistance – they provide outdoor durability up to 2 years on certain media. Testing by an independent laboratory, Wilhelm Imaging Research, Inc., determined that prints made by HP DesignJet CP printers using HP DesignJet CP Ink Systems UV have an expected indoor display life exceeding 100 years before noticeable fading occurs.[20] Prints made with the HP DesignJet CP Ink Systems using dye-based inks show no noticeable fading up to 5–6 years on certain media tested under the same conditions.



[20] Indoor conditions are taken to be 450 lux for 12 hrs/day.

The design and development of ink is one of the most technically challenging parts of ink jet printing, and it requires a system approach involving the chemistry of the ink vehicle and colorants, and design of the printhead, ink delivery system, service station, print modes, and media. These elements all work together, using strengths in one area to compensate for limitations in another. For example, multiple-pass print modes play a significant role in reducing or eliminating cockle and color bleed: they limit the rate at which ink is applied to the print medium. This allows some solvent to evaporate between passes, and minimizes the opportunity for ink to flow between adjacent wet pixels.

HP’s TIJ inks are 70–90% water. As an ink jet vehicle (i.e., solvent and carrier for the colorants), water has several useful properties: it is nonflammable, nontoxic, reasonably inexpensive[21] and has high surface tension (to keep the ink in the orifices) and low-viscosity (to facilitate drop ejection). It is also a safe solvent for use in the home and office: worldwide environmental health and safety regulations limit the use of volatile organic solvents. But, water also presents a number of challenges: it interacts with cellulose fibers in paper to cause cockle[22], its high heat of vaporization[23] makes it difficult to remove water from the print medium, and many colorants that provide the highest color saturation, gamut, and fastness are not water-soluble.

HP has solved many of the challenges of water-based inks through innovative chemistry and a system approach. For example, HP chemists have developed ways to make water-based inks using colorants such as pigments and solvent dyes. Pigments are tiny solid particles that do not dissolve in water. But, when special molecular structures are attached to and surround each particle, a stable dispersion of the particles can be made. When the pigment is delivered to the recording medium, it attaches to the surface and is very waterfast and lightfast. The colorful, waterfast, and lightfast dyes used in clothing are solvent dyes – they are not soluble in water. But atomic structures called “functional groups” can be added to the dye molecule to provide water solubility. The goal of advanced ink research at HP is to extend the capability of water-based inks to meet the requirements of the most demanding applications.

Since photographic image quality is important in both desktop and large-format printing, it might be useful at this point to briefly discuss the role of media. Papers can be roughly categorized as *plain*, *coated*, and *glossy*. And the media surface is very important to image quality. The two primary characteristics are whiteness and how light is reflected.

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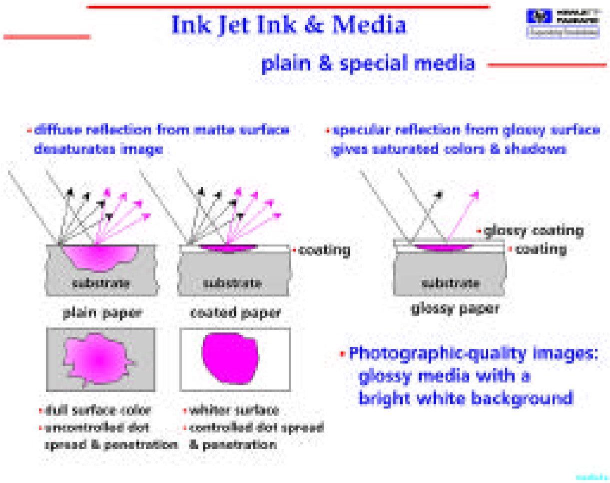
[21] Water used in ink jet ink must be highly purified.

[22] This is the uneven surface that results when uncoated paper is moistened: water molecules disrupt hydrogen bonds linking cellulose fibers, and internal stresses are released causing the paper to wrinkle.

[23] This is the amount of thermal energy needed to change a liquid into a gas.



The color and brightness of a printed image depend on the whiteness of the paper.[24] If the paper is yellowish, all the colors will have a yellow hue. If gray, the colors will be dull and desaturated. A coating on the media insures that the background is bright and white. It can also control the size of the dot produced by the ink drop, and hold the colorant at the surface to produce high color saturation. On uncoated papers, the ink drop can produce small, large, or irregular dots (depending on surface chemistry and physical properties) and it can penetrate into the paper leaving too little colorant at the surface for adequate optical density.

Both plain and *matte* coated papers produce *diffuse reflection* of light from their surfaces. That means that a ray of light is scattered at the surface: not all of the color absorbed by the printed dot is reflected into the eye of the observer, and rays from nearby regions are scattered into the eye mixing with and desaturating the color.

A glossy surface produces *specular reflection*, where almost all the light from the colored dot enters the eye. This produces more saturated color and blacker blacks.[25] The limitation with a glossy print is that it has a narrower viewing angle than a matte print – light sources from the room can reflect off the print's (mirrorlike) surface into the eye.

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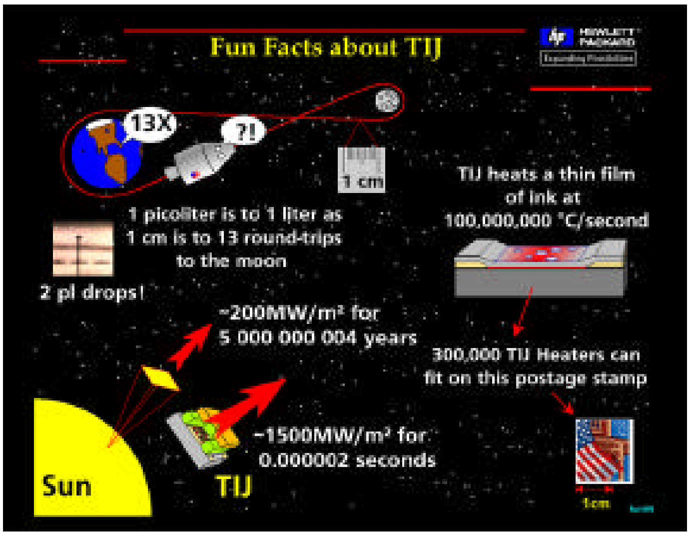
[24] In subtractive color printing, the colorant acts as a filter to subtract wavelengths of light and the whitest white is the background color of the print medium.

[25] As an experiment, have matte and glossy prints made from the same photographic negative. The glossy print will have the sharpest image, the highest color saturation, and the best detail in the highlights and shadows. The only difference will be specular versus diffuse reflection.

This figure shows some of the media available for the HP DesignJet 1000 Series. HP's Bright White Inkjet paper is now available in a 91 meter (300') roll for unattended printing applications, and a new High Gloss Photo Paper has been designed for the 1000 Series.



This figure contains a number of surprising and fun facts about thermal inkjet. It is really an amazing technology that operates on a scale outside of our everyday experience.

First of all, let's consider the power involved in making TIJ work and compare it with the Sun. From each square meter on the Sun's surface 200 million watts of power flow into space. That is enough power to heat and light a small city. But, the surface of a thermal ink jet heater outshines the Sun: it heats the ink with the power of 1500 million watts per square meter – $7^1/_2$ times more power per square meter than the Sun! Now it can't sustain that for very long or it would vaporize. While the Sun has been burning its nuclear fuel for about 5,000,000,004 years[26], a thermal ink jet heater must be turned off after about 2–3 millionths of a second to prevent it from getting too hot.

At the upper right in the figure is a schematic of a TIJ heater in cross-section. The silicon chip (gray) has thin-film layers of electrical conductors (gold), the heater resistor (red), and protective coatings (gray). Passing an electrical current through the resistor heats the ink at 100,000,000ºC per second. It takes this heating rate to generate a superheated vapor explosion; otherwise the ink really would boil. The heating is so rapid, only a layer of ink about 1/10th of a millionth of a meter thick is warmed. The ink actually does not have time to boil: it is heated so fast it reaches its superheat limit as a liquid and then explodes into a vapor.

This incredible amount of power and heating capability, more powerful than the Sun, operates silently and safely on your desktop because TIJ heaters are very tiny: about 300,000 could fit on a postage stamp.

Finally, the quantity of ink ejected with each drop is incredibly tiny, and in the upper left of the figure you get another amazing sense of scale. TIJ can eject 2 picoliter droplets, and a picoliter is to one liter as 1 cm is to 13 round trips to the moon. It's an incredibly tiny quantity of fluid that can be ejected 10's of 1000's of times each second by each TIJ orifice.

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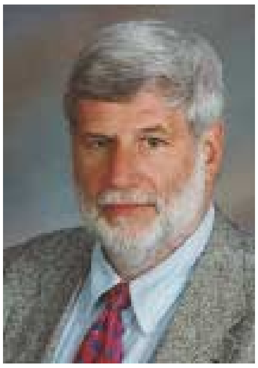
I hope that this presentation has given you a better understanding of the thermal ink jet process and an appreciation of the incredible technology that goes into HP's ink jet printers.

Ross R. Allen



Ross R. Allen is a Project Manager in the Printing Technology Department of HP Laboratories in Palo Alto, California. He has worked at HP Labs since 1989 on projects involving advanced ink jet inks, new sensor technologies for ink jet and laser printing, digital image capture, and information appliances. His team invented and developed the technology for the HP CapShare 910 document capture and communication appliance.

[26] I made the first version of this slide four years ago, so it's now about 5 billion and four years.

He joined HP San Diego Division in 1981 to become part of the original group of researchers developing thermal ink jet (TIJ) for HP’s first color graphics printer, PaintJet, in 1985. At HP he has worked on almost all aspects of TIJ including device physics, computer simulations, design, testing, and optimization of printheads, and new ink delivery and electrical interconnection methods.

Dr. Allen studied at the University of California at Davis, earning a BS, MS, and Ph.D. degrees in Mechanical Engineering. In 1996 he received the Distinguished Engineering Alumni Award from the U.C. Davis College of Engineering. Dr. Allen has been awarded 28 US and European Patents, and has published over 20 technical papers. He has given presentations in over 25 countries on HP's ink jet technology.

Discussion

Principles Printing Technique
R. Raychoudhury, Hewlett Packard

Colomer (ICC, Spain):
You mentioned the Iris colour printer. It actually has software for colour calibration to the real output i.e. offset printing. Do you provide anything comparable in your 2000 and 3000 series?

Raychoudhury (Hewlett Packard):
Hewlett Packard does not provide an external colour calibration system for our printers, so we tend to concentrate on the printers as output devices. Our printers are mainly sold by resellers, their added value is the plotter software. There are a number of software vendors that sell software for production workflow and this includes very similar software for calibration as you mentioned. So the answer is yes, but not by H.P.

Grabmaier (ITC, Netherlands):
You mentioned true 600 dots per inch. Are you using a matrix of 8 by 8 dots to produce 65 different shades of grey including white = 0 and black = 64?

Raychoudhury (Hewlett Packard):
What I meant by true 600 dots per inch was that the printer can produce true 600 dots per inch at 600 dots per inch output with a single pass of the printer head. There are other agent systems around from competitors that can achieve similar or higher resolutions but they have to make a lot more passes. To make this clearer, imagine a 600 dots per inch grid: then they may replace drops accurately within the grid, but the drops are too big: they may cover more than one grid cell, so they have to make more than one pass to fill the grid. So, a *true* 600 dots per inch is like having 600 dots per inch size dots on the 600 dots per inch grid.

Grabmaier (ITC, Netherlands):
Would that mean that you have only 60 pixels ?

Raychoudhury (Hewlett Packard): No, 600.

Kölbl (EPFL, Switzerland):
I think there is a confusion here: they print dots, but how you get the grey values later is a question of the driver.

Raychoudhury (Hewlett Packard):
The matrices can be of different sizes, the one used by the printer is 256 by 256 and there is a different logic for each colour to enable us to disperse the dots that overlap each other for the pearl greys. This can be done by the printer or externally, so the software you are using to drive the printer can choose to do it in whichever way it wishes.

Kölbl (EPFL, Switzerland):
You insisted very much on the question of having stable ink. You have explained to us perfectly well the dye based ink and the pigment ink. Are these two different printers or can you choose?

Raychoudhury (Hewlett Packard):
The 2000 and 3000 printer supports two different ink systems. One buys the printer and with it one can buy a dye-based ink system and a pigment-based ink system. You can change these within 10 min. So, changing from one to the other removes all the dye-based components and installs pigment-based components and vice versa. Those printers have an acute characteristic of allowing the user to change everything that touches or contains ink

Kölbl (EPFL, Switzerland):
The expression 3M, is this a pigment system or something else? I was impressed by a demonstration made of putting an orthophoto into water and the ink remained intact. This was a demo of 3M with a special ink.

Raychoudhury (Hewlett Packard):
It is a pigmented system. This one typically has water fastness. The durability of the print to water is a function of the ink and the media. Our policy is to enable the widest range of media to be used in our printers and we actively work with media manufacturers to enable that. So currently for the HP design jet 2000–3000 printers there are about 130–140 different media including water-fast ones even with our inks.

Production of orthophotos

A practical approach on the critical success factors of the production process

M. Gubler, D. Gubler,
Gubler Imaging,
Märstetten, Switzerland

Summary

The analysis of the value chain shows the need for the consistency of data throughout all sub-processes from beginning until the orthophoto. The reliability and the careful evaluation of the subcontractors is essential: unprofessional modifications of the original file or ungoverned conversion processes at the beginning of the value chain cause costs in following processes that are reversible only at hight cost or are not reversible at all.

With the current technology of Cymbolic Sciences`s Direct Digital Printing it is today possible to expose digital data basically without any loss of information on a photographic media. This technology allows to take advantage of the strengths of the photographic media.

Concerning the costs we must learn that the direct digital printing on photographic media (as for instance the RA-4) is less expensive than comparable inkjet-plots. The selection of the digital printer has to cope carefully with terms like "required amount of data (megabytes) per file", "resolution at the edges of an image" etc. Rather wide is the quality range of the alternative products of various manufactories of digital printing equipment as Gretag, Cymbolic Sciences, Durst, Epson, Roland, Hewlett Packard etc.

In terms of the selection of the optimal output media there is only the Ilfochrome© material meeting all the crucial quality requirements of the enduser.

The question of costs is irrelevant in terms of alternative output media`s. The selected output media and/ or the selected printing/ plotting technology causes only a marginal part of the entire project costs but it strictly determines the applicability of an orthophoto. At this point we should discuss the qualitative aspects of the final product rather than the costs of separate sub-processes.

1 Value chain: Process analysis of the orthophoto

The production of the orthophoto contains a number of processes which are closely related to each other. It is essential to know that the aspects of quality

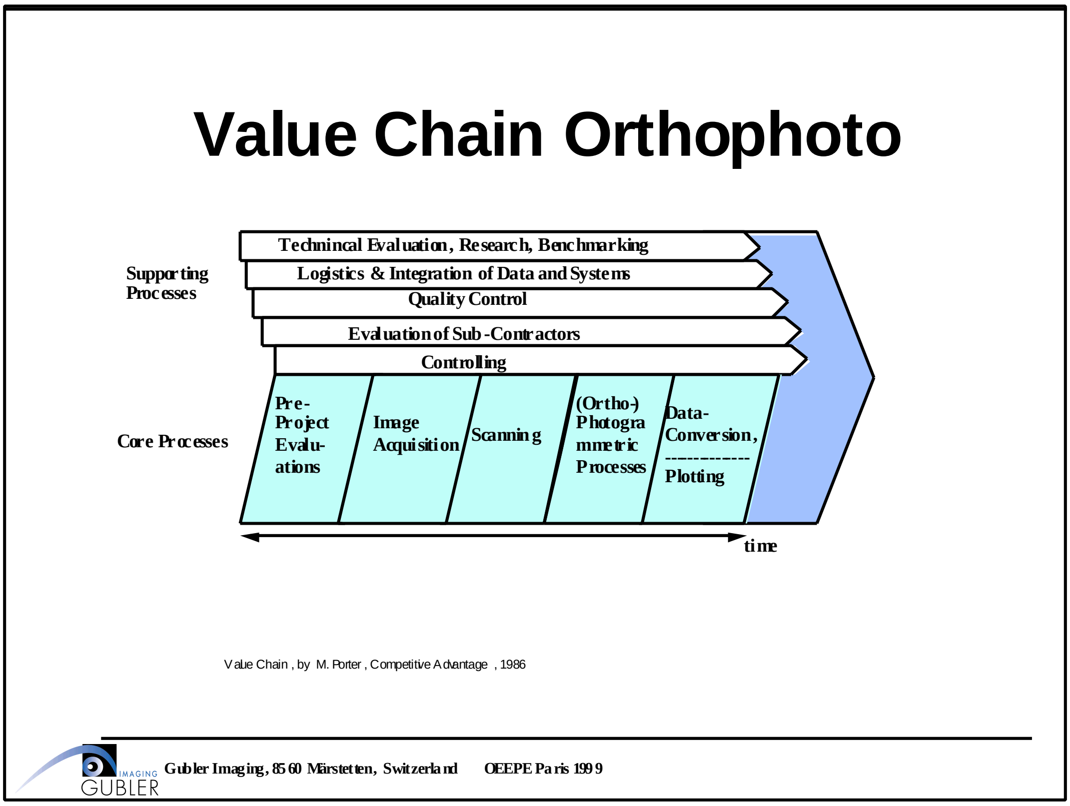


Figure 1 – Value chain of an orthophoto

and costs of the sub-processes are determined decisively by the preceding processes. As an illustration we use the concept of the value chain by Michael Porter[1], which bases on the idea of allocating all sub-processes alongside their evolution, independently of organizational units.

Pre-Project evaluation

The photogrammetric acquisition of a geographic region typically starts with an evaluation phase. This evaluation phase requires a considerable amount of specific knowledge, it is time consuming, it involves sub-contractors and it specifies milestones and parameters for the further proceeding.

[1] Vgl. David Gubler, Systempartnerschaften zur Realisierung kurzer Durchlaufzeiten, Diplomarbeit Universität St. Gallen HSG, 1997

Image acquisition

As it is a representative media for further processing we use the film (color, reversal or false color, etc.) as taken on aerial photography.

Scanning

A rather simple definition of scanning could be as the following: “Transformation of the analog information provided by the film (...) onto a digital file which contains all the relevant data: resolution, details, measure, tone reproduction, etc.

Orthophotogrammetric processes

The orthophotogrammetric processes represent the variety of processes added to the raw-scan as for instance: Aerial triangulation, DTM, DEM, Tone reproduction, etc.

Plotting

Plotting describes the visualization of orthophotogrammetric data by a hardcopy. Thereby the hardcopy faces a number of relevant criteria’s according to its employment (see 3, Qualitative analysis: Ilfochrome© vs. RA-4).

2 The visualization of the orthophoto[2]

For the visualization of the orthophoto we will take a closer look at the digital exposure on photographic paper. This digital printing is done at Gubler Imaging Switzerland with the LightJet 5000 of Cymbolic Sciences Ltd, Canada. The statements on the comparison of different plotting techniques as well as the examinations of the critical success factors are based on the wide practical experience of Gubler Imaging Switzerland. It is not subject of this paper to analyze in depth any alternative technique as inkjet, thermal transfer or dye sublimation. Instead we will show some practical results.

2.1 Direct digital printing with the LightJet 5000

As these samples show it is today possible to transform the digital data directly and without any loss of information onto a hardcopy, e.g. a photographic paper.

2.1.1 Direct digital printing

The herewith introduced Ilfochrome©-material allows reflective as well as transparent photographic media. It is actually a normal paper as known from the classical photography except for some upgrading characteristics in respect of laser light exposure. The RGB-Laser is then exposing directly to the light-sensible paper. This very technique originates in the well known digital film printing. Its therefore that the developed laser exposure technology of the Cymbolic Sciences LightJet prints with an apparent resolution of 300 or 400 dpi, 12 or 16 lines per millimeter respectively. Compared to the

[2] In this paper we use the term „orthophoto“ for the digital file containing orthophotogrammetric data as well as for the orthophoto-hardcopy, e.g. the digital print, the plot, the photo.

human eye which distinguishes about 8 lines per millimeter the 12mm apparent resolution of that very photo printer is capable of continuous-tone images without pixels, without any visible pattern. The half-tones are therefore continuous-tone images compared to the various inkjet technologies, where each half-tone is an combination of various dots (CMYK).

2.1.2 Amount of data required

In our practical work we noted one very interesting fact: even though we print at an apparent resolution of 300 dpi (400dpi) the amount of data is considerably smaller compared to the data required by common printing techniques, which is due to the integrated hardware RIP of the LightJet 5000. The herewith shown sample of an Ilfochrome© orthophoto originates of a 150 MB TIFF file. Its not until the original file is transformed by the hardware-rip simultaneously to the printing process that the file amounts to its temporary 700 MB. Its therefore absolutely sufficient for an image of the size of 1 square meter to work with some 150 to 200 MB TIFF files.

2.2 Key success factors alongside the value chain

In this section we will focus on the critical success factors of the production process of the orthophoto. Its substantial to understand the impact of early processes of the value chain on the cost explosion in later processes.

2.2.1 Image acquisition, aerial images

The selection of the proper combination of lenses, film-material and mostly the proper exposure time are key to achieve maximum results in terms of tone reproduction and contrast. A subsequent correction of white and dark points or modulation of the gradation curve is not only time consuming but can also distort critical half-tone information. We will not mention the relevant aspects of different film material even though the use of positive, false color or reversal film has notable impacts on the following scanning process.

2.2.2 Scanning

In the process of scanning we distinguish the term “raw-scan” and the term “fine-scan”. The raw-scan is the transformation of the (raw) information of the film into a digital file, whereas it is crucial that there is no loss of any information. Its only the fine-scan which takes into account the correct e.g. the individually necessary fine-tuning as tone reproduction, color adjustment, retouch, image compilation etc.

As we noted from our experience it is very important not to “overcorrect” any raw-scan: the tone reproduction is hardly a core competence of each firm. Therefore the early modulation of any file must not lead to a loss of the original content of information of any film, raw-scan respectively. Otherwise the original data is lost and can not or only with extensive costs be rearranged.

2.2.3 Orthophotogrammetric processes

The same criteria's as for the scanning are valid in terms of the orthophotogrammetric processes. Special alert is necessary by the use of different software and different conversion modes: conversions from one data type to another one may lead to deformations of resolution, accuracy and tone reproduction.

The above mentioned argument is valid as well: the subsequent re-correction of data is expensive.

2.2.4 Data conversion, fine-modulation, image combination, tiling

compare 2.2.2 and 2.2.3

2.2.5 Digital Printing

In order to understand the critical success factors of the printing process we have to focus on the technical sequences: we have to distinguish between the process "fine-modulation" and the process "printing". The process of printing is a governed process which follows some sort of "standard operational procedure", the critical factors are steady systems and the result is determined mostly by the quality of the input, e.g. the quality of the incoming file.

In consequence we need to focus on the "fine-modulation": the interpretation must not be a random one but has to meet professional criteria's in terms of tone reproduction, color management and it has to correspond with the original scene of the original aerial film.

3 Qualitative analysis: Ilfochrome© vs. RA-4 vs. Inkjet

3.1 Ilfochrome©

Strengths of the Ilfochrome©

- The achievable green-modulation equals about the one of the euroscale
- Light resistance: substantially higher than alternative technologies as e.g. Inkjet or RA-4
- Light diffusion: detail of dark parts become very well visible due to the fact that we the laser exposes into the black medium[3]
- Physical stability: very high accuracy in terms of measurements since the Ilfochrome© material is based on polyester and not on paper. Humidity or changing climates cause not the effects known form paper-based media's

[3] The differentiation in the dark tones already exists in the Ilfochrome© material whereas all printing techniques have to first build up the positive dark spectrum!

Critical aspects of the Ilfochrome©

- Relatively high costs of the raw material
- Small number of professional providers of the Ilfochrome©-production-process

3.2 RA-4

Strengths of the RA-4

- Very favorable costs
- For limited needs an absolutely sufficient alternative
- Many providers
- Fast process, short development time
- Good drawing/ resolution in the bright aeries

Critical aspects of the RA-4

- Less color modulation than the Ilfochrome©
- Lower light resistance than Ilfochrome©
- Limited stability: due to its paper-based medium the RA-4 print is not stable at changing humidity
- Light diffusion: limited resolution/ tone reproduction in its darker aeries since the RA-4 process –in contrary to the Ilfochrome©- is exposing light into a white media

3.3 Inkjet

Strengths of the inkjet

- In-house-production is possible due to lower fix costs of the plotters compared to the infrastructure-intensive photographic technologies
- Large number of suppliers of plot-services

Critical aspects of the inkjet

- Low light resistance. The special inks and papers amount up to costs even exceeding the Ilfochrome©!
- Limited stability: due to its paper-based medium the inkjet print is not stable at changing humidity
- Upgrading the "normal" inkjet by using special paper- and ink-combinations leads to material costs even higher than the costs of RA-4 photographic paper

- A diffusing variety of very different qualities of inkjet-products is existing on the market

3.4 Finishing

Most media's as Ilfochrome©, RA-4 or any inkjet can be coated by laminate or lacquer in order to meet superior requirements as light resistance, protection against humidity and damage, cleaning etc. However those treatments can not overcome with the basic weaknesses of the different printing and plotting technologies. This conclusion has its means especially for the evaluation of inkjet-plots in terms of stability and price.

4 Quantitative aspects of plotting technologies

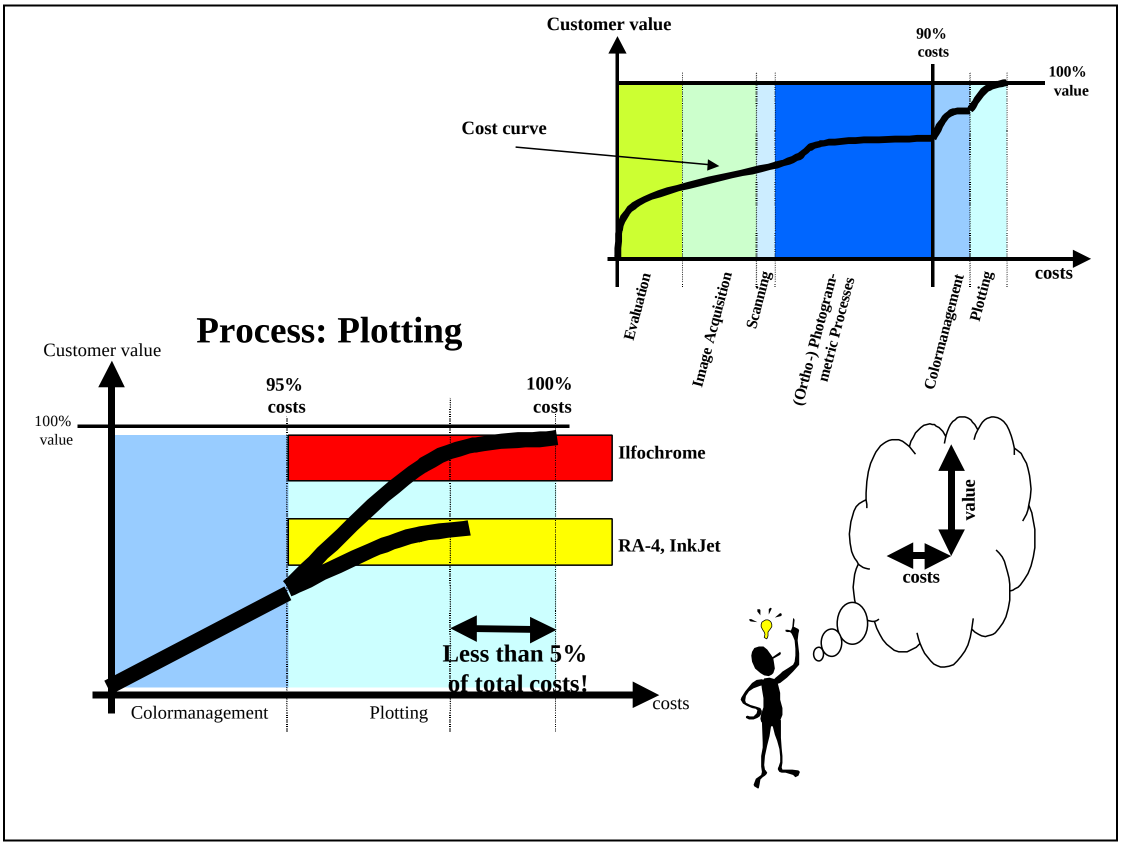


Figure 2 – Costs vs customer value

4.1 Costs and gains alongside the value chain

In this section we will focus on how costs and gains are growing along the development processes of an orthophoto. Together with the analysis of the alternative print- and plot media's of sections 2 and 3 we will then extract some crucial conclusions on the evaluation of different print- and plot techniques:

Requirements of the orthophoto:

- Applicability in the field
- Stability in terms of measures
- Light resistance
- Stability in terms of traction
- Water/ humidity resistance
- Reproducibility of the original halftoning (e.g. green of vegetation, red of false color films, ...)
- Resolution, visibility of details
- Availability of post-orders

We can say that the direct digital printing on Ilfochrome© materials is the only technique which covers all aspects. The RA-4 and the inkjet have weaknesses especially with measures, light resistance, color and tone reproduction.

As shown in figure 2 we estimate that at the point where the digital file of an orthophoto exists the costs of an orthophotographic project have risen up to some 90% or above of the total project cost. So, if we take into consideration to produce a hardcopy as well –e.g. an orthophoto plot or a direct digital print inclusively the necessary color management- we only deal with some 10% or less of the total project costs!

Furthermore we must notice that about half of the costs of the plotting/ printing is caused by the "preparation" (color management, tone reproduction, data transformation,...) of the files. So there are two sub-processes to be distinguished: first at all the "color management" consisting of all necessary "preparation" of the digital file and second the process of "plotting" or "digital printing".

As a result we note that some 5% of the total costs of a orthophoto plot is due to the color management etc which is necessary in any case, independent of the chosen type of plotting, printing or media.

Shortly: the decision on which technique is being used for plotting/ printing – or the question whether to use Ilfochrome© or RA-4 or any other alternative technology – only affects 5% of the over all project costs but it has a major impact on the benefit of the final product!

4.2 Irrelevancy of costs of the printing technology

From figure 2 and from the conclusions under 4.1 we can see that there is no relevant impact on the total cost of the project by selecting one or another printing technology.

On the other side we face crucial requirements of an orthophoto given by the enduser. These requirements are "conditio sine qua non" to the enduser. So the 5% of total costs are to be measured with the benefit faced by the enduser.

In other words:

The selection of the output media as well as of the printing technology has a crucial impact on in the usage possibilities. But this decision only affects some 5% of total costs. The careful evaluation of the needs has to put the benefits and the costs of different solutions in relation not only to one sub- process but in relation to the entire value chain – in relation to all the sub- processes.

The investment decisions are not to be taken under the aspect of one single sub-process but under regards of all the pre- and post-processes in order to optimize the total costs over the entire value chain.

Discussion

High Quality printing with Cibachrome
M. Gubler, Switzerland

Colomer (ICC, Spain):
How handy is the orthophoto? Can you write on it with a felt pen and can it be folded? How handy is it in the field ? The second question is the price.

Gubler (Gubler Imaging, Switzerland):
Cibachrome paper is not handy and you can perhaps fold it once but to find out just how handy the orthophoto is in the field you will have to ask the end user.

Grabmaier (ITC, Netherlands):
You contrasted the film writer output and ink jet output. Do you have any experience with dye sublimation printers?

Gubler (Gubler Imaging, Switzerland):
First, the original technology included film printing machines and now this is applied to larger format paper. We also expose on transparency material such as Ilfochrome translucent or opaque paper.

General Discussion in Orthophoto Production

Kölbl (EPFL, Switzerland):
Since we are getting to the end of this session about orthophotos, let us think about what we have already discussed: production, DTM, printing. But something is missing: the drivers. You use either a TIFF format or you print online on your machine and get the information quickly. At the office, you have a variety of printers and you need the program and colour proofing. Would it be useful to invite the vendors to give their view on the issue and show what they offer?

Nicoletti (Intergraph):
I am not a specialist in printing but Intergraph has a wide variety of products. For printing products we provide specially developed drivers which give good results in colour and grey scale output, this is at the low end. Then we provide high level systems for plotting such as photoplotters in which you do the process of colour separation, you plot separate colours, separate films and then these films are sent to a very high-level typing system to get the end product. So, we cover the whole production line with low-end products to very high colour resolution products.

Miller (LH Systems):
We investigate and provide recommendations on tenders but generally we are not experts on printing.

Dörstel (ZI Imaging):
Our policy is and must be to rely on standards. So we see for vector output that this could be Postscript for example. For us, the output would be – from my point of view – TIFF or GeoTIFF. What comes next is a question of what the actual plotters can produce as a good final output.

Raychoudhury (Hewlett Packard):
I would agree with Mr. Dörstel (ZI Imaging) who said that standards are the answer. This might not be the case in the graphic art industry. However, what we see happening is that the people who invented Postscript as a format have been moving now to PDF format and have made a certain number of improvements in the PDF language, so now it is better to be able to handle larger formats and to deal better with colour. What I can predict for the mid-term future is that PDF will become the standard interchange format and that there will be an increasing use of the Internet to directly send your PDF files to vendors. Thus, I can see Dolby and PDF leading the way in standardising to isolate to a certain extent the specific nature of software.

Part 6

Logistics, Management and Financial Aspects

Chairmen

R. Héno **J. Colomer**

Major bottlenecks in digital photogrammetric workflows. Running production workflows in an heterogeneous environment. Translators, standards. Development tools: libraries, macro languages, documentation. Workflow management tools. Migration/upgrading: protecting the investment – hardware /software/ data. Maintenance, availability, reliability, training.

Swissphoto's Automated Digital Photogrammetric Production Environment

T. Kersten, W. O'Sullivan, N. Chuat
Swissphoto Vermessung AG
Regensdorf-Watt, Switzerland

Abstract

In recent years digital photogrammetric systems are increasingly used in photogrammetric production to significantly improve the efficiency of the production processes. However, for each specific production the systems require tuning and customisation by additional software developments, specially for automation and handling of large data volumes in big production projects.

In this paper, we present the implementation and establishment of a digital photogrammetric production environment in the private company Swissphoto Vermessung AG, formerly swissair Photo+Surveys Limited. A high efficiency of the production environment was achieved by automation of the data flow, integration of systems from different vendors and optimisation of the work flow through interfaces and hardware. The establishment of the digital production environment was influenced by the requirements of the project swissphoto, i.e. the production of digital colour orthophotos over the entire area of Switzerland.

1 Introduction

The transition from analytical to digital photogrammetry has been underway in private photogrammetric companies since 1992. One of the major advantages of digital photogrammetry is the potential to automate photogrammetric production processes efficiently, thus substantially improving the price/performance ratio for photogrammetric products and services. Therefore, image processing and computer vision techniques have successfully been employed for facilitating automated and automatic procedures using digital aerial images such as orientation (*Heipke* 1997), point transfer in photogrammetric block triangulation (*Tsingas* 1992), and the generation of Digital Terrain Models (*Krzystek* 1991). But today, the key to an efficient photogrammetric production environment is the combination of the following criteria: (i) the degree of automation in each data production process including self-diagnosis and quality control, (ii) the level of system integration, (iii) and the optimisation of the data and work flow using large data volumes. In order to achieve adequate productivity, extensive refinement, improvements and additional software developments for commercial digital photogrammetric systems are required. Consequently, the user can customise the commercial systems to his own technical specifications.

The customisation of commercial systems can be achieved by the following steps: (i) automation of procedure by batch processing and additional software specially for quality control, (ii) system integration by setting up the optimal hardware and software for each processing step, and (iii) optimisation by tuning the different system components through interfaces and a defined data/work flow.

The implementation of the digital photogrammetric production environment, its tuning and customisation, the current status and its performance are described in this article. This paper also briefly introduces the company Swissphoto, its history, services, and its transition to digital systems.

2 The company and its history

Swissphoto Vermessung AG is the largest provider of photogrammetry, engineering surveys and geoinformatic services in Switzerland today. There are more than 75 people employed in the head office in Regensdorf-Watt and in the two Swiss branch offices in Zollikon (Zurich) and Altdorf (Canton Uri). The company was founded in 1931 by W. Mittelholzer, a Swiss flight pioneer, under the name Swissair Photo Ltd. In 1972 the firm merged with Karl Weissmann Vermessungen AG to form Swissair Photo+Surveys Ltd. After 66 years as a 100% subsidiary of the national airline 'swissair' a management buy-out was performed in 1997. Under the new name 'Swissphoto Vermessung AG' the company is active on the national and international geo-data market. For the international market strategic partnerships have been founded. In July 1997, Swissphoto Vermessung AG achieved the ISO-9001 quality certificate for the new developed and implemented quality management system.

Swissphoto Vermessung AG specialises in acquisition, processing, management, analysis and presentation of spatial data. The company combines its more than 60 years of experience in aerial photography and engineering with the modern digital know-how of a leading supplier of comprehensive geographic services. The result is a wide range of services and products which cover all aspects of spatial information processing. The services of Swissphoto include aerial photography, analytical and digital photogrammetry, digital image processing, scanning and plotting, digital cartography, engineering and cadastral surveying, navigation charting, training and consulting, and geoinformatics. Archive products include aerial photographs from 1917 until today, digital terrain models and orthophotos covering the whole of Switzerland.

3 The digital step

In the following some key points for the implementation of digital systems at Swissphoto are summarised:

- increasing demand for digital information, specially for digital orthophotos
- technical progress and innovation by new techniques and systems
- rapid progress in the development of the computer performance
- efficiency to meet the market requirements for fast and high quality data production
- chance for innovation by new type of products and services, and its flexibility

Nevertheless, the major influence for the development of a digital photogrammetric production line was given by the large national orthophoto project *swissphoto*, which had to be realised in a reasonable time period. Consequently, this required a high level of automation in all production processes, e.g. scanning, aerial triangulation, DTM and orthophoto generation, mosaicing, data management, etc., for efficiency, time and cost saving reasons. The orthophoto project *swissphoto* was started in spring 1995 under private initiative, in order to provide up-to-date geo-data covering the entire area of Switzerland (42'000 km^2), derived from aerial images. Within three years digital colour orthophotos with a pixel size of 0.75 m at ground scale were produced for the whole country using commercial digital photogrammetric equipment.

The project *swissphoto* is described in *Kersten* and *O'Sullivan* (1996b).

4 Current digital photogrammetric systems used

For the production of the *swissphoto* orthophotos, digital photogrammetric equipment was used from LH Systems (UNIX based scanning and stereo stations) and from ISM (NT based orthophoto stations). The continuous progress in upgrading the hardware components of the production systems is described in chapter 5. The current digital photogrammetric production environment of Swissphoto Vermessung AG consists of several workstations using three different operating systems: UNIX, NT and MacIntosh. All workstations are integrated in a fast, wide SCSI ethernet network (100 Mbit).

The major parts of the current digital production environment are summarised in the following (see Fig. 1):

- *UNIX workstations* (one Digital Scanning Workstation DSW300, three Digital Photogrammetric Workstations DPW770, and one administration workstation using SUN Sparc 4 as computer platform),
- *NT workstations* (one Image Server including YAMAHA CD-Writer and 46 GB hard disk, three Digital Orthophoto Workstation DOW, one Backup Server using DLT Quantum 2500 with 5 tapes DLT4000),
- *Mac workstation* (one Digital Image Processing Workstation).

Additionally, two analytical plotters, Leica SD2000 and Kern DSR14 are in use in analytical photogrammetric production.

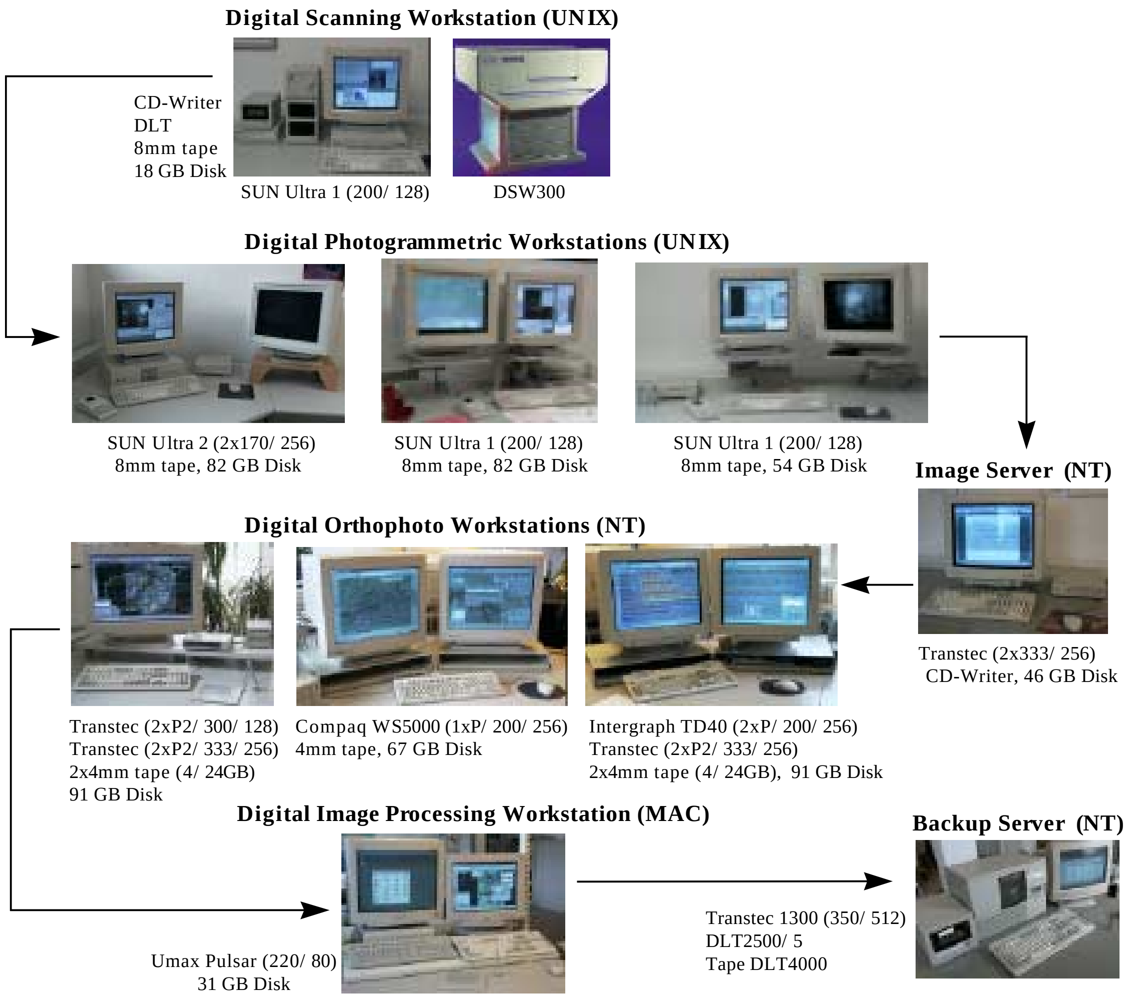


Fig. 1 – Swissphoto’s digital photogrammetric production environment 1999

5 Procurements of digital systems (technological update)

Continuous upgrade steps are necessary to meet the requirements for a highly efficient digital production environment. Consequently the latest software releases of the current photogrammetric systems used are implemented to increase the production performance. But in addition, the speed of production is highly influenced by the performance of the computer hardware. Swissphoto have consistently achieved high output within the production environment through continual hardware upgrading as well, as described below.

Swissphoto started the transition from analytical to digital photogrammetric production systems after the ISPRS congress in Washington D.C. in October 1992, when the first producer licence of the software SysImage was purchased from ISM. The hardware used was a PC 486 with 33 MHz frequency and 1 GByte hard disk. At that time, the system was capable of producing only b/w orthophotos. The continuous technological update is summarised in the following:

- *August 1995:* implementation of integrated production systems (one dual station DSW200/DPW770, one stereo station DPW770, both running on SUN Sparc 20) from LH Systems (former Leica/Helava),
- *October 1995:* split up of the dual station to a scanning station DSW200 and to a DPW770,
- *July 1996*: increased scanning production by renting a second DSW200 station until January 1997,
- *December 1996*: purchase of the third photogrammetric workstation, a mono-station DPW670 (SUN Ultra 2 with two processors of 170 MHz each and 256 MByte RAM),
- *January 1997*: installation of a digital image processing workstation (Macintosh system UMAX with 200 MHz, 80 MByte RAM, 2 GByte internal disk and 31 GByte external disk) for improvement of the radiometric quality of the digital orthophotos using Live Picture as the image processing software,
- *May 1997*: upgrade of all three SUN Sparc 20 to SUN Ultra 1 (200 MHz/196 MByte RAM),
- *1996/1997*: purchase of the second and third SysImage licence for the NT based orthophoto workstations,
- *February 1998*: upgrade of the network from 10 to 100 MBit per second as a major breakthrough for the UNIX and NT based production environment,
- *February 1998:* installation of a NT image server (2x 350 MHz and 512 MByte RAM) as the interface between the UNIX DPW's and the NT orthophoto workstations,
- *February 1998:* two PC based orthophoto workstations were equipped with two PC's each, where each of the PC uses a dual pentium processor (350 MHz, 256 MByte RAM). One station is equipped with a 24 inch monitor, while the second station has two 21 inch monitors. The operator uses a switch box to manage all processes of the orthophoto workstation on the two PC's,
- *April 1998*: exchange of DSW200 to DSW300,
- *July 1998*: upgrade of the mono-station DPW670 to a stereo station DPW770,
- *February 1999*: installation of a NT backup computer system (350 MHz and 128 Mbyte RAM) using a Quantum DLT 2500 with five 40 GByte DLT tapes for all NT orthophoto workstations.

During the whole phase of upgrading the hardware systems additional hard disk were purchased when needed. At present, a disk capacity of 562 GByte is in use.

6 Refinement of the systems (automation, integration and optimisation)

6.1 Scanning

From August 1995, images were scanned on a Digital Scanning Workstation DSW200 of LH Systems with a pixel size of 12.5/25.0 micron (b/w or RGB). For high quality scanning the scanner (XY stage) was installed in a separate room, containing air-conditioner, air-humidifier and a dust filter, to minimise dust and dirt on the photos and on the glass plate of the scanner. Since April 1998, the new scanner DSW300 is in use. The geometric and radiometric performance of both scanners, DSW200 and DSW300, was evaluated in several tests (*Baltsavias* et al. 1997; *Baltsavias* et al. 1998). Using the latest software release SCAN 4.1 (March 1999) the system is capable of performing re-sampling of the images on-the-fly during scanning. In general, quality control of the scanning is guaranteed by periodic radiometric and geometric calibration of the scanner. For each specific scanning project, the quality of the scanned images is guaranteed by visually checking of each minified image on the screen. All scanned images are transferred to internal workstations on-line, but can be delivered on Exabyte tapes (4 and 8 mm), on DLT or on CD-ROM depending on the image file size.

6.2 Aerial triangulation (AT)

Depending on the project size and the final products, AT will be performed on the analytical plotter or on the digital photogrammetric stations. In an automated production, the digital aerial triangulation (AT) is divided into several processing steps, which include data preparation (photos and control points), automatic data import and image minification, automatic interior orientation, automatic AT measurements, (GPS supported) bundle block adjustment, and quality control. Due to inadequate automation and quality control at the time for the processing of large data volumes using the commercial Helava system, some additional software for batch processing and easy-to-use graphical user interfaces (GUIs) were developed by Swissphoto Vermessung AG. Thus, the use of the highly automated AT processing modules could be facilitated for the operator. The digital aerial triangulation for the project *swissphoto*, its data flow and results, and the additional software modules used are described in the following papers: *Kersten, Th., O'Sullivan, W.* 1996a, 1996c; *Kersten, Th., Haering, S.* 1997b; and *Kersten, Th., Haering, S., O'Sullivan, W.* 1998.

In the following the AT processing steps are briefly introduced:

- *Data preparation*: configuration of photo blocks (providing images, loading digital images from tape, if not available on disk), providing control point data (co-ordinates, overview plot, available sketches).

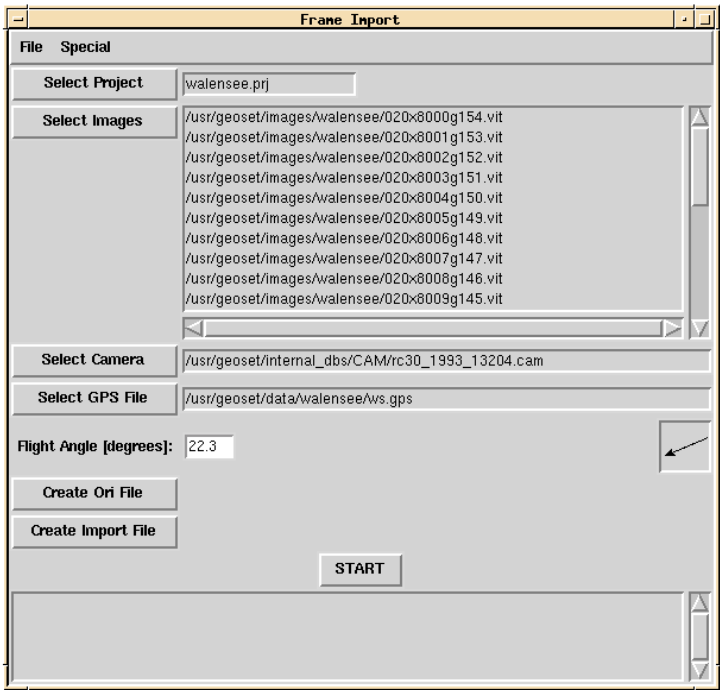


Fig. 2 – Graphical user interface for batch frame import

- *Automatic data import and image minification*: image import into DPW770 and minification of images (building-up image pyramid levels for display and zooming) in batch mode (see Fig. 2), input of GPS photo centre co-ordinates of each image, preparation of the triangulation file (set-up of AT parameters) in batch mode.
- *Automatic interior orientation:* fully operational automatic interior orientation (IO) of digital aerial images as integrated module of SOCET Set on the DPW670/770 (see Fig. 3) developed by Swissphoto Vermessung AG (batch mode without operator intervention, see *Kersten* and *Haering* 1997a).

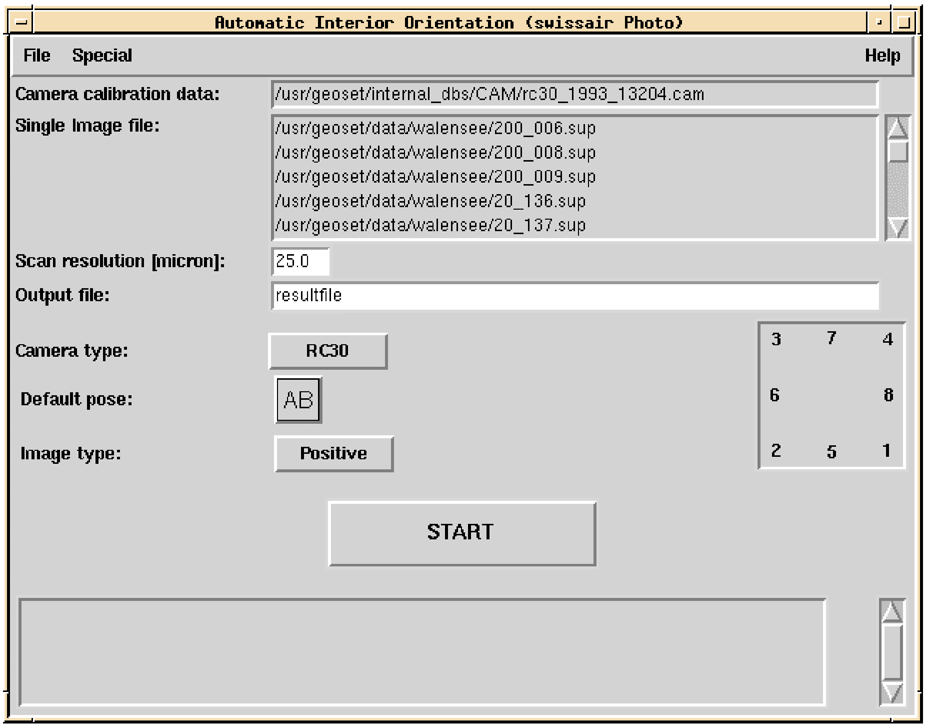


Fig. 3 – GUI for automatic interior orientation

- *Automated AT measurements:* Automatic Point Measurement (APM) using a very dense tie point pattern consisting of 98 points as a standard pattern, Interactive Point Measurement (IPM) only of ground control points and additional points in a semi-automatic mode, and Simultaneous Solve (including re-measurements).
- *Threshold blunder elimination (necessary):* Automatic blunder elimination of observations with residuals over a user specified threshold using results of a bundle block adjustment.
- *(GPS supported) bundle block adjustment:* file export in PATB-format, data transfer from DPW to PC, bundle block adjustment with self-calibration using BLUH (bundle block adjustment program of the University of Hanover).
- *Update of orientation data:* interface between BLUH and SOCET SET resp. ORIMA for updating orientation data at the digital photogrammetric stations resp. analytical plotters
- *Quality control:* software module for fast and easy-to-use visualisation of point distribution and photo connections within and across strips, developed by Swissphoto (Fig. 4).

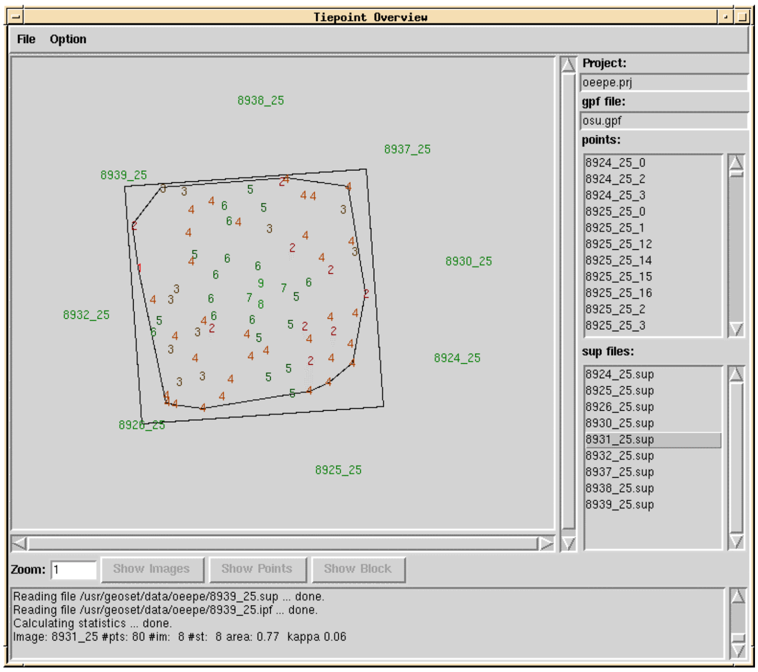


Fig. 4 – Graphical user interface for AT quality control

6.3 DTM generation

For orthophoto production the digital terrain models are generated at the digital photogrammetric station DPW770 by digital image correlation using the software module SOCET SET ATE (Automatic Terrain Extraction). The following processing steps are used:

- *Set-up:* definition of the used images, correlation strategy (adaptive or non-adaptive), grid space and other parameters, generation of a MSL-file.
- *DTM generation:* batch processing using a Swissphoto GUI
- *Quality control:* (i) rough quality control by generation of a shaded relief and its visual inspection, (ii) fine quality control by visual 3-D inspection and editing of the contour lines in each available image stereo model of the defined project area.

For DTM editing, a fast and easy-to-use GUI for loading of the images (stereo image pairs) on the extraction or console monitor was developed by Swissphoto.

6.4 Stereo plotting

Currently, stereo plotting is performed at the analytical plotters for map revision in 2-D (e.g. 1:10?000 maps of the Swiss Cantons), for official mapping of the cadastre in 2/3-D (1:500/1:1000), and for vector data collection in special projects.

6.5 *Orthophoto generation and mosaicing*

The orthophotos are generated image by image at the DPW770 by batch processing. The relevant parameters are set in a Swissphoto GUI (see Fig. 5). For the project *swissphoto* the pixel size of the colour orthophotos was 0.75 m, while for large scale projects the orthophotos were generated with a pixel size of 10–25 cm. For mosaicing all orthophotos generated at the DPW's were transferred via the network to the image server of the NT based digital orthophoto workstations (DOW), which use SysImage from ISM for mosaicing and data export. The advantage of SysImage compared to the SOCET SET software of the DPW770 is the fast visualisation of large data volumes on the monitor for semi-automated mosaicing and on-line quality control. Further processing steps are the following:

- Distribution of orthophotos from the image server to the NT workstations
- Conversion of orthophotos from VITEC to SysImage format in batch
- Mosaicing of orthophotos by manual seamline generation and manual colour balancing using brightness, contrast and gamma correction for each single orthophoto
- Generation of huge block files (< 2 GB) containing multiple orthophotos by automatic seamline feathering
- Saving of the block files in SysImage format

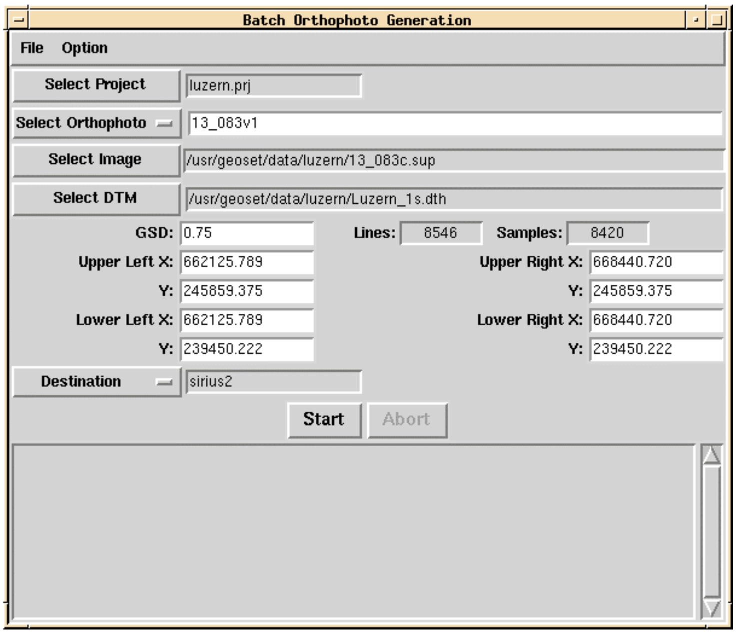


Fig. 5 – GUI for batch orthophoto generation

6.6 *Data management and export*

Finally, the orthophotos are saved as mosaic blocks with a maximum file size of 1.9 GB (NT system limitations) or with a maximum number of 37 orthophotos (SysImage limitations). These block files are saved on DAT tapes or on DLT tapes on the backup server.

For specific projects or customer requirements, the final orthophoto data is usually exported in the following tile sizes (sheets) using TIFF format:

- 3 km x 3 km with a pixel size of 0.75 m (project *swissphoto*)
- 4375 m x 3000 m with a pixel size of 0.625 m (project *swissphoto*)
- 500 m x 500 m or 1000 m x 1000 m for large scale projects with a pixel size of 10–25 cm

For the orthophoto export, the relevant block files are virtually mosaiced with SysImage and the export of regular tiles is performed by batch processing using a DGN file with the pre-defined tiles and special software which was developed by Swissphoto.

The DTM of the project *swissphoto* is saved in 15 km x 15 km tiles on the disks of the DPW's and on Exabyte tapes (8mm).

6.7 Image processing

The orthophotos can be delivered in three different quality standards: (i) raw data from SysImage, (ii) GIS quality for data processing on the monitor by image processing with Photoshop or Live Picture, or (iii) high quality for printing of maps by further image processing. The image processing can be performed with Photoshop on the NT workstation or with Live Picture on the MacIntosh workstation. Using Photoshop image processing with a maximum file size of up to 500 MB only can be performed, while with Live Picture image processing with a file size of up to 1.9 GB is possible.

7 Performance of the production environment

The following performance of the digital production environment is nominally estimated from results of the project *swissphoto*:

Table 1 – Estimated performance of the digital production environment

Process	Scanning	Digital AT	DTM/Edit	DOP	Mosaic	Export
Photos/hour	6	6	0.5	4	4	10
Photos/day/shift	50	50	4	35	35	80

In general, the performance depends on both the photo scale and final pixel size of the orthophotos.

Using the above described production environment, the orthophoto project *swissphoto* was realised within three years. Currently, Swissphoto produces a digital surface model of Switzerland with a grid size of 10 m by digital image correlation on the DPW770 using the photos of the project swissphoto (1995/1996). Simultaneously, digital colour orthophotos of the Canton Jura (840 km^2) with a pixel size of 25 cm are generated on the DOW using SysImage.

8 Conclusions and outlook

Digital photogrammetric systems have been successfully implemented at Swissphoto in recent years. These systems complement the analytical production line consisting of two analytical stereo plotters. Today, a modern and up-to-date digital photogrammetric production environment is in use at Swissphoto Vermessung AG, which utilises the latest technology and software releases, and highly skilled and motivated staff. Concepts for the implementation of such digital systems are driven by economic requirements of large projects for data production. The pressure of time and costs for the management of these projects requires software and hardware implementation and training-on-the-job. The increase of the production rate through automation, integration and optimisation of the Swissphoto photogrammetric production environment compared with analytical methods cannot be quantified in percentage, but we believe the following aspects, among others, summarise the general improvement:

- implementation of user friendly and easy-to-use graphical user interfaces
- reduction of operators intervention (and errors) through batch processing
- expansion of the production time by batch processing overnight and during weekends
- invaluable software tools and skilled operators for large project processing
- guarantee for higher quality control capability as an integral part of the production
- competitive within a high cost environment.

However, the transition phase from analytical to digital technology is still ongoing. With due respect of the dramatic progress to date, digital photogrammetric systems are still at an early stage of development, with great potential for improvements and further developments. Gruen (1999) foresees possibilities for short-term improvements, and actions, that would require more time to obtain adequate results:

Short-term improvements

- Simplification of user-interfaces/better on-line help
- Design of parameter „macros“
- Robustification of key functions
- Inclusion of self-diagnosis
- Provision of quality measures for all results
- Simplification and more flexibility with data import and export.

Middle- and long-term improvements

- Implementation of on-line triangulation
- Simultaneous processing of n images (n>2)
- Integration of automated image interpretation (use colour, texture, etc.)
- Usage of a priori knowledge, i.e. existing data (GIS, DTM, etc.)
- Establishment of more advanced post-processing and editing tools
- Implementation of semi-automated algorithms for object extraction
- GIS integration.

Nevertheless, a future vision could be a fully automatic digital photogrammetric system, which performs aerial triangulation (including scanning of photographs if digital images are not available, import of digital image data, interior orientation, point transfer through large blocks, measurements of control points, bundle block adjustment), and generation of digital terrain models and orthophotos including mosaicing and data export. One must be aware that the more automation the systems provides, the more automatic quality control must be also implemented between all processing steps - a control which today is carried out mostly by the operator - in order to guarantee accurate and reliable results.

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Discussion

The Automation, Integration and Optimization of Digital Photogrammetric Production Environment
T. Kersten, N. Chuat, W. O'Sullivan, Swissphoto, Switzerland

Siman-Tov (Ofek Aerial photography, Israel):
About your last image processing system with Live picture, how is the system resampling pictures? You work on vector layers and change the image; how good is the quality control of your orthophoto?

Kersten (Swissphoto, Switzerland):
With image processing, you always have to be careful not to destroy your data. Photoshop is very well-known and you can always find someone to explain how to use it. With Live picture in Switzerland, we could not find anyone to explain its use, so when we bought the software we did self-training to find this out. In this system, it is important to change the format, so you go from TIFF to the internal format, but the problem is that you do not know what format it is; it could well be that there was some image compressing there. That is what we checked by comparing the original data with the final one and saw that there was a slight compression. But for this processing we used this data as it had only been used once, and we saw that the quality is as good as with Photoshop and with other systems. The only thing that we did was to analyse it visually, but no statistics about the pixels have been drawn up.

Dowman University College London:
You have focused on those aspects of automation which work very well. You said little about extraction of vectors from stereo imagery. Is this because you are happy with what is being done at the moment or that you do not see any prospects for automation in that field?

Kersten (Swissphoto, Switzerland):
This is what I would call the digital production line for orthophoto generation in DTM. We still do all the vector data collection on analytical plotters because the resolution for the aerial images is much better than on the digital one, even if it is scanned with a higher resolution than 12.5µ. So the analytical plotter is still being used for vector data collection and the high tech machines for automated data processing. We realized that in Switzerland there is a high demand for digital orthophoto. This is why in this production line we concentrated on the UNIX system and the NT Systems for the orthophoto and DTM production.

Grabmaier (ITC, Netherlands):
You have just said that you did the collection of vector data on analytical plotters, but do you do the aerial triangulation by digital means or do you do the whole process analytically?

Kersten (Swissphoto, Switzerland):
It depends on the project size. For a large project we always do automatic aerial triangulation. With small blocks, let us say of 10 images only for cadaster data collection, on a scale of 1:5000 or 1:8000, we triangulate analytically. But at present we do not do any vector data collection digitally. But I think we will do it in the future, because the younger generation will agree to switch to digital systems.

Logistics and System Integration
Experience of 'France Ingenierie Topographie'
Digital Photogrammetry Integration and Production Optimization

G. Toth, D. Lenne
France Ingénierie Topographie, Soisy /Montmorency, France

Abstract

This paper describes the DPW system integration from HELAVA within the FIT's photogrammetry workshop, the work optimization and their quality control.

1 F.I.T presentation

France Ingenierie Topography is a company specialised in topography, cartography, photogrammetry and consultancy. It is a branch of the ITI Group.

ITI (Engineering, Topography, Data Processing) is composed by 3 other companies with which FIT has close links and that are working in the fields of environment, regional planning, GIS and housing.

ITI head office as well as F.I.T's one is located in Nantes. As a all, the Group gathers more than 400 employees of which 110 are employed by F.I.T.

In order to give the best answer to its customers, F.I.T is present in 4 different regions:

- Nantes
- Ile de France
- Valance
- Corrèze

F.I.T's turn-over was for 1998 of 7,3 millions euros (48 millions FRF).

2 Digital photogrammetry integration

2.1 Photogrammetry workshop

Photogrammetry is a traditional activity of F.I.T Ile de France. When created F.I.T took over a photogrammetry workshop and developed it. At the end of 1991, the photogrammetry workshop was using 3 analytic stereoplotter and 2 analogic stereoplotter:

Leica SD3000
Leica DSR11
Matra Traster
Wild A7 and A8

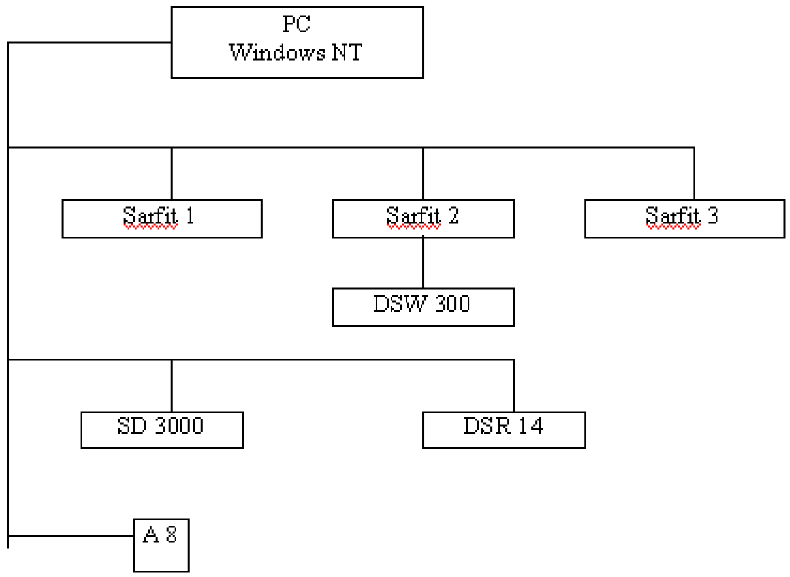
The workshop was reorganised at the beginning of 1995 while at the same time F.I.T was integrating digital photogrammetry.

In 1996, F.I.T took the decision to equip itself with Leica materials. We bought a DPW 770 on Sparc 20 with a storage disk of 40 GB.

During the first year we had good results and have noticed an evolution on the French market. We decided then to develop our photogrammetry activity.

The current situation is:

FIT Workshop



Our Equipment and software

	Hardware	Software
Sarfit 1	Sun Ultra 30 512 MB RAM Creator 3D Solaris 2.6 Stereoscopic screen 67 GB disk Handwheels Exabyte	SOCET SET 4.1 Pro DPW + microstation Easy Copy Image Alchemy
Sarfit 2 + DSW 300	Sun Ultra 60 256 MB RAM Creator 3D Solaris 2.6 Mono exploitation 58 GB disk Exabyte	SOCET SET 4.1 Scan
Sarfit 3	Sun Ultra 60 512 MB RAM Creator 3D Solaris 2.6 Stereoscopic screen 117 GB disk Handwheels DLT	SOCET SET 4.1 Image Alchemy
Station NT	NT PII 400 128 MB RAM	SOCET SET NT Flykin Suite + Orima Soc Microstation

2.2 Optimization of the photogrammetric production

The Digital production line is used for those tasks:

Aerial triangulation	5–10%
Data capture	15–20%
Orthophotography	70–75%

2.2.1 Aerial triangulation

Work organisation:

The Work preparation is done in a traditional way

Scanning
- scan setting in accordance to the final product
- scanning on Sarfit 2
- moving of the images on disks to the final location (and archiving)

Job preparation – (Swissphoto tools)
- import-batch
- internal orientation – batch/control

Aerial triangulation observations (sarfit 1 and sarfit3)
- semi-automatic method: pattern 3x5 with automatic correlation with new measures of wrong points or manual observations.
- relative orientation and validation
- observation of the ground control points

Computation is done with the tools we have:
- Hats on sarfit1
- Orima Soc: station NT (with a very fine block analysis)
- Data conversion between sarfit 1/2/3 and the anlytical stereoplotters is provided by the “convert tool “ of LHS

Conclusion:

For a large scale site with average quality photos and by using the automatic possibilities we have an out put of 5 stereomodels per hour.

2.2.2 Vector Data capture

Work organisation:

Work preparation is done with PRO 600
- Project settings and libraries are the same than for the analytical line.
- Programming of the keyboard for the shelf functions.

Data capture
- Vector projection on the stereoscopic field - for control.
- Automatic windows refocusing

Conclusion:

Similar output in classical data capture
20% improvement in updating

2.2.3 Orthophotography

Work organisation

- "Dodger" on the concerned photos
- DTM – automatic correlation by zone at night (on sarfit 3 machine)
  adaptive strategy use without any preparation;
  smoothing and if necessary integration of the existing vector before treatment;
  interactive terrain edition on the 2 stereoscopic stations.
- Orthorectification and mosaicking: we use the OrthoMosaic tool of Socet Set with or without ADRA for the "work units" creation.
- Cutting out and reformating the "working units" for delivery.
- Graphic production: vector preparation is done in the microstation environ–ment. Plot files are created with "Image Map" and print with "Easy Copy".

2.3 Quality control

Quality control is a problem in a field where terminology is not yet well defined and where there is no well established standards.

Our quality plans, adapted to each project, aim at 3 purposes:

project integration, deadline respect, work quality.

In order to maximise the guarantee offered, F.I.T expresses its quality approach thanks to 4 elements:

- human resources
- technical means
- control processes
- methods and organisation

2.3.1Control made during the execution of a project

Work phases	Control description	Documentation
Shots	Site covering Overlap respect Density control	Control form
Stereopreparation	Points repartition Quality and accuracy of points' survey	Listing of points' origin and their accuracy
Scanning	Scan geometrical calibration Picture visual control Mark sensors absence Histogram analysis Internal orientation Validation	Calibration form Scan form Internal orientation file
Aerial triangulation	Tie points dispatching and quality Orientation control Results graphical analysis	Listing of qualitative calculus analysis
DTM	Stereoscopic validation Statistical analysis	Production control form
Orthophotography	Visual control with Existing vectors by superposition	Production control form

2.3.2 Quality action board

Work phases	Objective	Point	Participant	Control
Shots	Reception		CP, RT, OP	CP
Stereopreparation	Determination of ground control points		OP	CP
Scanning	Digital photos	PC	OP	CP, RT
Aerial triangulation	Block computation	PA	OP, RT	CP, RT
DTM	Extraction and validation	PC	OP	RT
Orthophotography	Orthorectification and mosaicking		OP	RT
Delivery	Final preparation	PA	OP	CP, RT

CP : Chief project
RT : Technical responsible
OP : Operator
PA : Stop point
PC : Check point

Data exchange

Personalised customers' services and ready to use Image Data Base

- Arcview : image pyramid
- Mapinfo : 8 bits tiled with a image pyramid
- Microstation : Descartes Hmr format or Cot format for Iras
- Geoconcept : 24 bits tiled with a image pyramid
- APIC : 216 colours xwd format
- ArcInfo Bil format
- Star
- Autocad
- etc...

As far as there is no existing standards for georeferenced images delivery is not only some CDs but a real service for our customers.

Financial Aspects and Economics of Tenders

J. Piedfort
Johan Piedfort Photogrammétrie, Lausanne, Switzerland

You all have surely noticed that prices of various tenders for one and the same job are very different.

Some firms are offering very low prices. Impossibly low. Prices I cannot afford to work for with my firm, and many of my colleagues have the same problem. Some colleagues of mine told me they won't even make a tender for certain mandates because they don't have any chance of getting the job anyway.

Clients often choose the lowest price, but at the end they expect the highest quality.

Result:

This tendancy of lowering prices has caused the bankruptcy of many companies these last two years.

I myself know several of them. Firms that lowered prices even below cost, believing that this was the way they would stay competitive.

But the investment in equipment, training costs and staff remain quite expensive.

My opinion:

I decided that I would not get into this game of lowering prices over and over and that I don't have to because by offering a certain quality and by responding exactly to the client's demand.

Reasons:

We are in a very specialized branch, where high quality is important – and it is possible to realize it. Now, we see firms doing low quality work offering low prices, because it's their only trump. Or, european firms offering very low prices because in fact they do not have the equipment they pretend, but are having the job done abroad at low wages, impossible in Western Europe.

The poor knowledge of photogrammetry and the lack of information in our profession, I believe, make these abuses possible and are at the root of the price evolution.

It is very important when making tenders to understand the client's demand right. Big price differences between tenders come from the fact that competitors interprete the demand differently and are thus offering different products or services. Often, invitations to tender are not detailed enough and leave too much space for interpretation by the competitors.

Example: Project 1 – 1998 (about 800 km^2)

Sometimes, when offering exactly what the client asks for, one can make a product which is finally not useful to him.

Example: When the pictures are taken in summer, in order to make nice orthophotos, it is difficult to make a detailed DTM of them which can be used for other purposes also. If the DTM has to be very strict, there will be gaps and this is problematic for the orthophotos.

Again, this can lead to abuses, where firms are deliberately offering the minimum, for of course lower prices that its competitors.

And you can only compare prices when talking about the same products or services.

Needs for changes:

From the clients' side, there is a need to determine his needs and formulate them correctly and in detail.

But, photogrammetrists should intervene to enable possible clients to do so.

Often, clients have only a far-off link with photogrammetry, they may know only their own application. They will not ask for certain products and services because they are not familiar with them. Or, on the contrary, they will ask for certain precision or specifications because they heard of it or used them in the past, but forget that this was in a totally different context.

It would be interesting for the clients to consult a photogrammetrist or even to make a pilot project with the help of a photogrammetrist before starting a big project.

I have myself been consulted several times to develop with the client the method for the works they intend to have done and do a test job on part of the concerned territory.

This may seem expensive at first, but may help to save a lot of money afterwards by outlining the product according to the client's needs.

When receiving tenders then, the client would do better to control and analyse them. This way it would become clear where price differences come from. This could avoid problems afterwards. What are the different tenders really offering and is this what they need ? Clients could also visit competitors offices and check whether they really have the equipment they mention or whether in fact they are one of those having the job done abroad at low cost.

To do so, however, a better knowledge of photogrammetry is necessary.

And it is up to photogrammetrists to introduce these ideas with potential clients, giving them a chance to get to know better the possibilities and applications of photogrammetry and by explaining the interest for them to use photogrammetry in order to enable them to formulate their demands more precisely.

Unfortunately, again one should be aware of abuses. I heard of an expert advising against certain firms pretending they did not have any experience in photogrammetry and recommending all the time the same company, that got this way several important jobs. Moreover, it seems impossible to get information about the expert's identity.

Again, the client's lack of information was at the root of this.

Very important in the information is the terminology, the definitions.

Example: I know people selling imagery as orthophotos. Of course, at a much lower cost than a real orthophoto.

(Project 2 –1999 – about 80 km^2 – flying scale 1/4000)

Conclusion

As to demonstrate all this, a friend of mine running a photogrammetry firm after having tried some time to get work at very low prices, decided to bring them up again and managed to get a lot more of work. Because many clients have had a bad experience with low quality work and prefer to pay for good quality and service again.

To sum up, I just would like to repeat that I believe that photogrammetry should and can remain a high quality and specialized field, at a certain cost level,

and that by promoting and introducing the field to possible client groups, one can even extend the applications of photogrammetry.

By making the clients conscious and sensitive to quality differences and abuses, we can come to a balanced position again, where there is no space for the low budget photogrammetry.

I thank you all for your attention and hope to get your reactions.

Comparison of prices between tenders

Project 1 – 1998

Prices in Swiss Francs

Company	Scale	Total Price
A	1 : 18’000	907’682
B	1 : 15’000	709’634
C	1 : 15’000	340’595
D	1 : 20’000	285’326
E	1 : 20’000	219’390

Company	Flight	DTM	Orthophoto
A	100’000	434’000	188’000
B	44’000	472’000	90’000
C	69’000	63’000	128’000
D	41’000	124’000	58’000
E	28’000	92’000	54’000

Comparison of prices between tenders

Project 2 – 1999

Prices in Swiss Francs

ORTHOPHOTO

Company	Color	Black/White
A	212’850	80’625
B	181’200	152’208
C	125’725	96’052
D	18’812	16’125
E	17’033	11’957

PRINT

Company	Color	Black/White
A	10’750	8’600
B	5’798	4’711
C	5’798	2’319
D	3’225	2’150
E	5’798	3’986

FLIGHT PRICES

Company	Color	Black/White
A	43’875	28’075
B	37’600	–
C	33’280	25’000
D	32’800	21’800

Discussion

Financial Aspects/ Economics of Tenders
J. Piedford, Switzerland

Kamper (Danish National Survey and Cadastre, Denmark):
As you said, the idea of companies tendering extremely different values springs from the fact that most organisations are not specifying what they want. In France there are mechanisms whereby the government participates in large orthophoto projects. Mechanisms through which one could tie down tenders well with good specifications should exist, but you do not see that really happening. However, in the EU tenders, there is an attempt to draft quality control requirements and rules and that could be taken up and in France the opportunity exists. So national mapping organisations like IGN can promote the idea that public organisations should have a fairly comprehensive set of rules to enable them to tie down requirements. If this happens, we would not be floating between various conceptions of what makes up an orthophoto. So, I think that the initiative should come from national mapping organisations headed by the EC.

Piedfort (Piedfort Photogrammétrie, Switzerland):
I agree, there should be a standardised control system applied by every member country of the EU. There are countries in Europe with strict quality control rules, so when a supplier is called upon to carry out an order , all the details are discussed beforehand, so that the customer knows exactly the what and how of his orthophoto production and what are the technical specifications.

Kersten (Swissphoto, Switzerland):
This is why I think the mapping organisation should impose these specification requirements on the supplier companies, to make sure that everybody knows that the access to orthophotos is easy.

Piedfort (Piedfort Photogrammétrie, Switzerland):
I think that smaller companies should have their word to say in this because the national organisations usually work projects concerning large areas and do not necessarily share the same experience as small offices of photogrammetry. This is why I think this should come from every part of the profession.

Kersten (Swissphoto, Switzerland):
I would like to comment on the dialogue between the data provider and the client. As you mentioned, the client often does not know what he wants and is not able to specify it. This is entirely our fault as it is. I think our task is to provide these people with the best service and advice, to tell them what they might require and what to expect from the data they get. This is what vendors are doing with us now and what we, as suppliers, should do too.

Schroth (Hansa Luftbild, Germany):
My comment is that the lack of standardization is one thing, but the major problem is high competition in the profession in Europe, the result being that there is not enough work for all of us. In several countries like the NL for example, the standard of the products delivered is high but the pricing is exorbitant too. The reason why national mapping organisations are coming on the market is that they are forced to earn their own

money now. This creates additional competition. If you compare central Europe with southern Europe, you will see that in Germany, for example, there are 80 companies working in photogrammetry, whereas in Spain or Italy the number goes up to 200 on top of the national agencies. On the other hand, demand for work is not increasing: we are told by the GIS community that there is more of it, but it is not true. I have looked into this in detail.

Hoschtitzky (ITC, Netherlands):
Over the last 33 years I have seen dozens of very large mapping projects, including whole national territories. It seems to me that it is not primarily the lack of clarity on the product specifications that are to blame. In many of them, the specifications were very clear. The huge pricing differences from one company to the other come from enormous differences in the cost structure of those companies. So this explains why, for the same product, the costing in two companies can be in a relation of 1 to 3. Moreover, companies have jobs to do overseas; this means that, if they are not geographically close to the area on which they are working, they will for example have to wait for the right flying weather which can drastically increase the cost of production compared to a company which is located on the spot. Therefore, these disparities in prices from one firm to another are often perfectly justifiable. This will always be the case. What I do not agree with is the competition between the private and the state-subsidised companies. In the latter, the policy is non profit-making so the prices they offer are sometimes arbitrarily low, whereas in the commercial company, it is a question of making a living. So I find it strange that the EU allows such unfair competition to exist within the European Community.

Logistic Problems at the Institut Cartogràfic de Catalunya

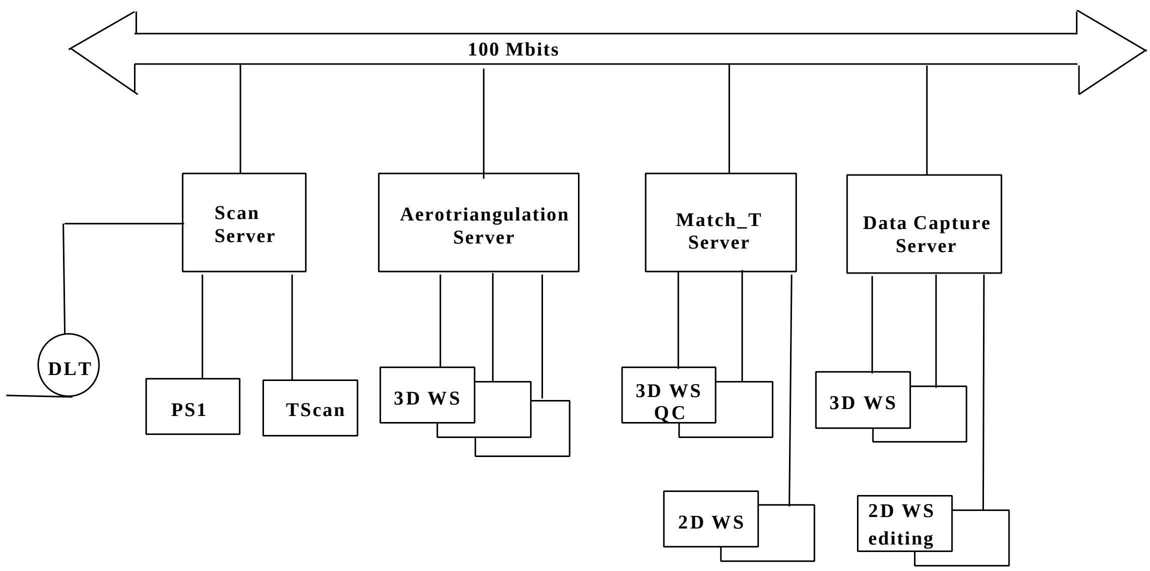
M. Torre, A. Magariños, J.L. Colomer
Institut Cartogràfic de Catalunya
Barcelona-Spain

1 Introduction

Our work had two goals: first, to reduce the operator interaction as much as possible to save time and lessen errors and second, to centralize data and run batch processes in servers. We believe that although the tools built are very specific to the Intergraph environment, the paper can bring some ideas for users of other systems.

2 System architecture

Nobody will argue against the benefits of keeping files on-line for the duration of a job step. For example, in point transfer we measured 4% of the operator time devoted to data management. So we decided to configurate generously our servers with as much as 100 GB to 300 GB per server as shown in the figure below.

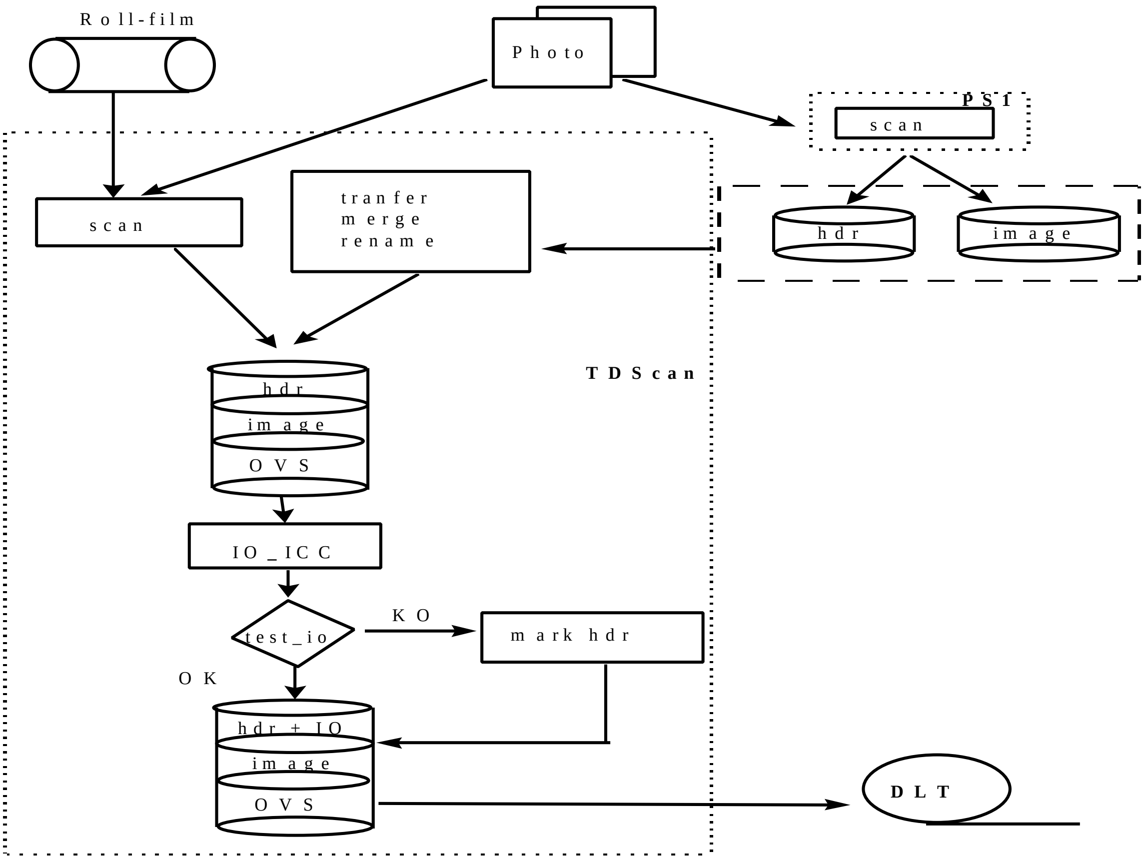


Note that we assign a server to each of the digital photogrammetric tasks: scanning, point transfer, DTM generation and stereoplotting. Batch jobs are prepared in 2D workstations and executed on the servers. Point transfer and visual checking of Match-T results are performed on workstations with files mounted remote on the servers. Stereoplotting is still performed with the images on local disks.

3 Scanning

We operate now a PS1 and a TDSCAN with the Autowinder feature for scanning rolls of films in unattended mode. For a long time we have been waiting for the possibility of adding our own information to the header of the raster files. Besides storing standard information related to the scanner and the scanning process, we wanted to store any type of information that could optimize our workflows or could be of use for long term archival. Right now, the TDSCAN software provides for this capability

However, this is not the case for the PS1, which stores the information of the scanner and the scanning process in a separate ASCII file. In addition, the file headers can be only accessed with a piece of software that is only available on NT. Therefore we had the problem of homogenizing the header of the raster files. We solved it by transferring the image file and the associated ASCII file to the NT environment and then use the file access library (CFL) for storing the ASCII data into the header. We also wanted to extend the file name to allow better identification and automation in the workflow, so we take advantage of having the file in the NT environment for extending the 14 character UNIX file name.



We also wanted to store the measurements of the fiducial marks and the parameters of the inner orientation, and we wished to do this automatically. Although Intergraph provides a tool for doing inner orientations, we implemented our own which uses a library of cameras with templates of the fiducial marks, calibration data and a threshold for the residuals of the inner orientation. The software performs a check of the wrong/right reading of the film, locates and measures the fiducials and performs the inner orientation. If the residuals are above the thresholds, a flag is set in the header.

The result is a normalized raster file with a meaningful file name and a header containing the inner orientation. This file is stored on a DLT and catalogued in a tape library for later use.

4 Design of the photogrammetric project

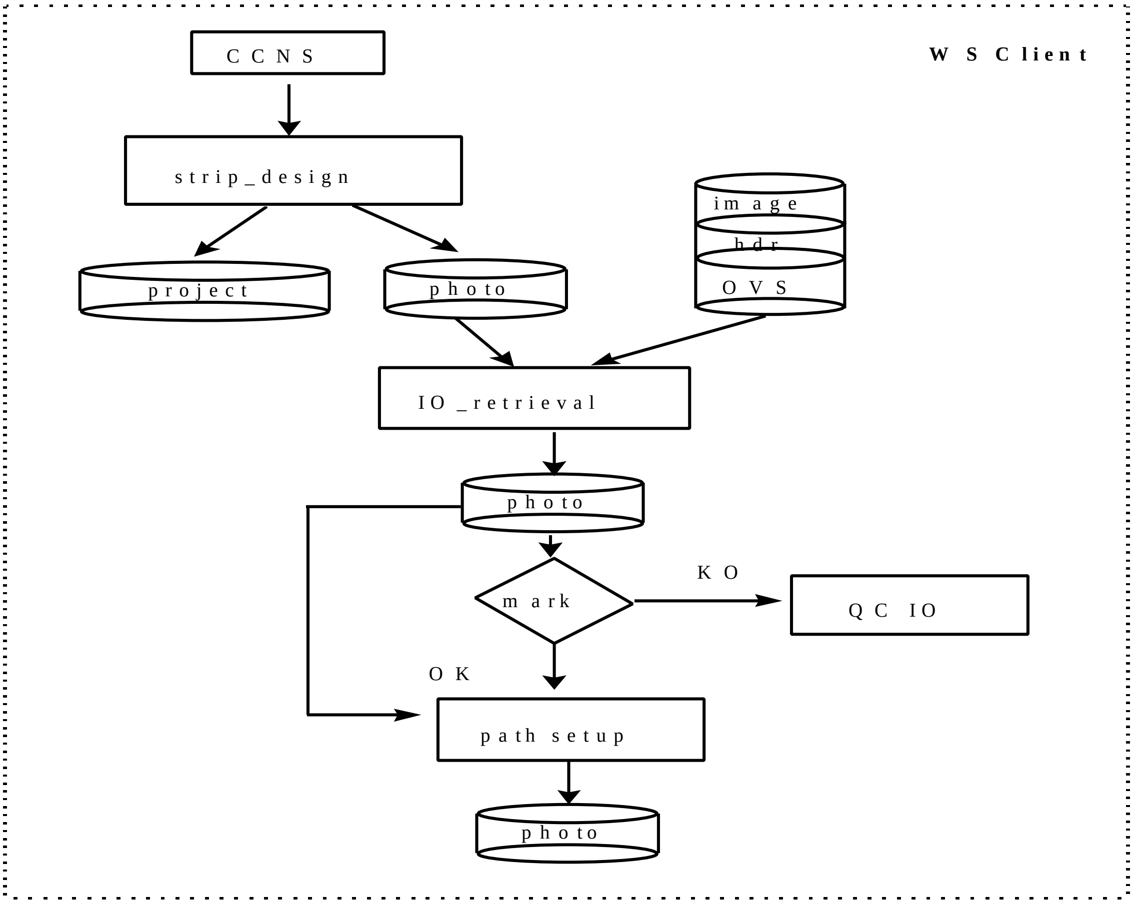
Point transfer and aerotriangulation are the next steps. As stated before, the point transfer is performed with all the image files of a photogrammetric block mounted remote on the 300 GB server. The Intergraph software needs to create two files for this step:

- a *project* file that stores general information and the parameters and defaults of the project,
- a *photo* file that has an entry for each photo with the path to the image file, the footprint of the photo, the coordinates of the projection center, the image coordinates of the fiducial marks, the IO transformation parameters and the measurements of the pass and control points in image coordinates.

In the standard environment, the operator uses a GUI to define the strips and create the files. Instead, our “strip design” software automates this by:

- creating the file with one entry for each photo, ordered stripwise,
- automatically creating the file path by searching for the file name in all the volumes mounted (this utility is used on relocating files in other volumes/directory and is based on AI techniques to speed up the search),
- retrieving the IO measurements and parameters from the header of the image file, checking the error flag that was set if the residuals were below tolerances, branching to interactive actions if error, and storing the IO in the *photo* file,
- reading the output from the Computer Controlled Navigation System (CCNS-IV) storing the GPS centers of the photos and computing and storing its approximate footprint. This information is used by the Intergraph software to help the operator in locating the conjugate points by driving him automatically to the overlapping areas.

The result is a *photo* file ready for the interactive point measurements task. When complete, we run the block adjustment using our GeoTex software and transfer the adjusted points back and update the *photo* file.



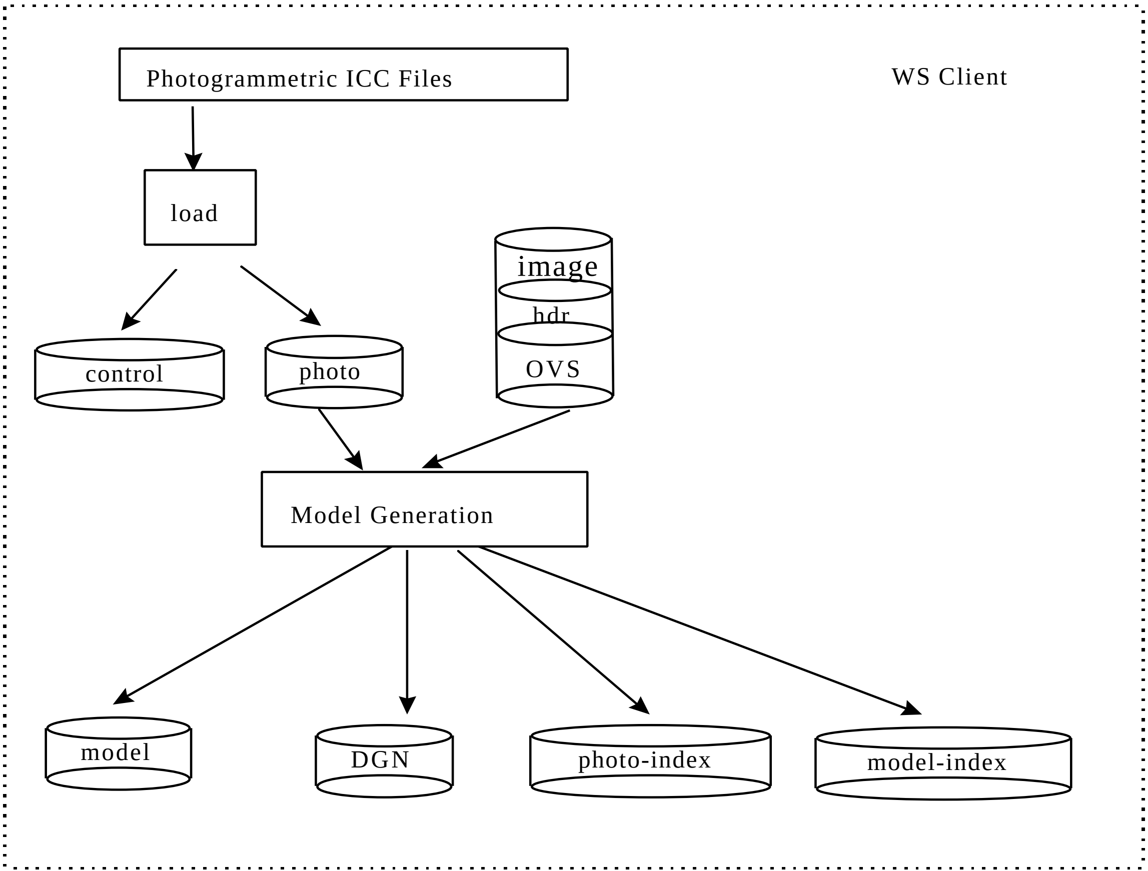
Two utilities are available for:

- printing a sketch of the measured points of a photo on a DIN-A4,
- creating a photoindex by extracting the 1 MB overview from the image pyramid of each photo in the block. This photoindex can be displayed on the screen with Intergraph or MicroStation software and/or plotted on a HP DIN-A0 plotter. Each thumbnail is 15x15 cm on the plot.

5 Preparing Data for stereoplotting and DTM generation

First, the *photo* file is updated with the adjusted photo coordinates of the pass and control points. In addition, we transfer from the GeoTex the external orientations and the self-calibration parameters (there is more information such as the covariance matrix of each observation and the reference systems used, but unfortunately the *photo* file cannot store it).

The software requires also a *control* file with the ground coordinates of the points and a *model* file containing an entry for each model. Each entry stores the identifiers of the images forming the stereopair and the collinearity parameters of the model.

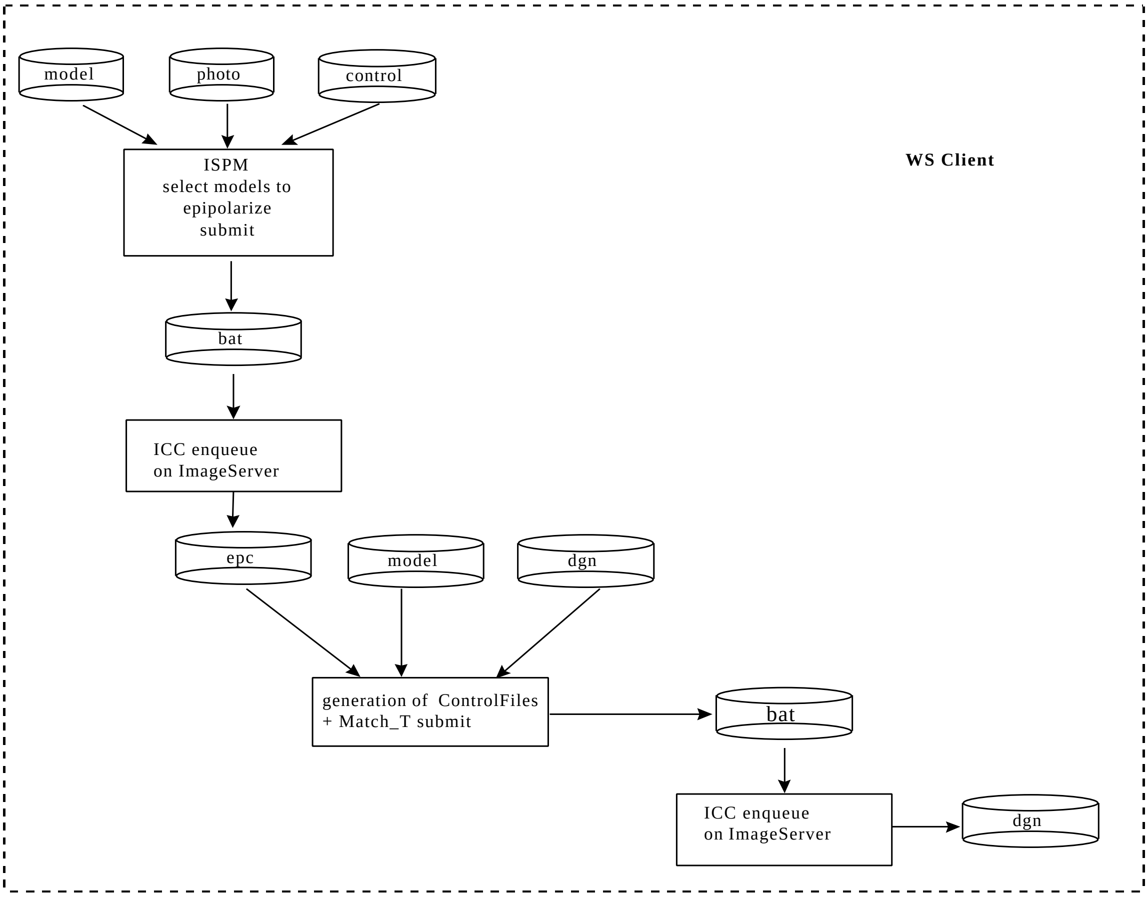


Again, the operator can use the standard GUI to define the stereopairs or our utility that creates entries for all the possible models with overlap between 50% and 85%, the percentages defined by the operator. Optionally, a DGN per model (the stereoplotting canvas) can be automatically created. Another one can be created with all the pass and control points for checking during stereoplotting.

6 Queuing Epipolar + Match_T ImageServer process

The first step is to have the model sampled into epipolar geometry. We use the standard GUI to create a file containing the command lines for the epipolar process. With the BatchManager software this file can be enqueued to run in the server, with all the image files mounted locally.

For launching Match_T we do not use the standard GUI either. Instead, we prepare the required control and parameter files automatically and enqueue it for execution on the server.



The results of Match-T are stored in a DGN file. The 3D visual quality control is done with all the files mounted remote on the server.

The last improvement in our workflows has been reducing the time spent in exchanging execution reports among production units. We have tried to standardize these forms as much as possible and have improved the error reporting, to be aware of errors as soon as they appear.

7 Final Remarks

As the time goes the amount of data grows larger and the hardware changes at a high rate. This leads to a continuous development effort and therefore systems and software have to be flexible to absorb the changes easily. This means easily extensible and changeable, fast traceable for debugging, and portable among environments. We would argue that the Object Oriented Programming is becoming the best development platform to meet these requirements.

Discussion

Logistics Problems at ICC
M Torre, ICC, Spain

Reiss (Bayer Landvermessungsamt, Germany):
Since there is no standardization, I presume you have created your in-house standard. How do you store these data, what format is used?

Torre (ICC, Spain):
We are working with the COT format from Intergraph. In order to deliver or to provide information, we use the TIFF format. The internal working format is a tiled file, 8 bits per pixel, multi-channel so you can handle both black and white images as well as hyper spectral information on the same file. It also allows for compression but it does not work for pyramids; this is the shortcoming of the internal format we use. After the processing is completed, we can switch to whatever standard is required by the customer. Of course, the idea of keeping a history of how the images were obtained is for internal purposes.

General Discussion: Advances since Lausanne 1996

Chairmen
R. Héno, IGN, SIT, France
J. Colomer, Institut Cartografic de Catalunya, Spain

1 Introduction

There is a need among users to reduce the logistic problems as much as possible, so that photogrammetric experts and operators can concentrate on topics within their field of competence.

Many things have indeed been improved since the last Workshop (Lausanne – March 1996), but critical points remain along the production process.

Solving the logistic problems is of course a question of personal organisation, and people here are invited to share their experience to enable other people to benefit from it, whatever equipment they use.

Vendors could help too, if they improve their installation / training / advice / maintenance services. Suggestions are given below.

As far as image and data management are concerned, users and vendors are invited to prepare standards together.

All the topics mentioned below are what we perceive to be critical in the production process. Some of them have been discussed during the meeting. The debate is retranscribed after the questions.

2 Points to be discussed among users

2.1 Improvements in the logistic aspects

Most of the logistic problems that were discussed in Lausanne – March 96 are now less constraining in the production process:

2.1.1 Image storing

Technology has improved: DVD (4,7 Gbytes, but not a real standard) versus CD-ROM (644 Mbytes, and a true standard), Mammoth (40 Gbytes) versus Exabyte (5 Gbytes), etc ...

a) More images can be stored on fewer tapes, but does it really make the job easier?

b) How do we locate and retrieve images?

c) Do we need a viewer?

d) How can we benefit from a database to manage the ever increasing number of tape cartridges?

e) What should be the main characteristics of such a database?

Madani (Intergraph):
Obviously, the answer here is ISIS (ImageStation ImageServer). Many of these issues are being addressed by the ISIS project. (Mr. Madani performs a live demo of the product.)

Shears (Erdas):
Our philosophy with image storing and archiving is to reduce the storage burden by introducing the concept of calibrating an image. So, instead of resampling an image to an output projection system, we store the imagery once only which is in its raw format, in TIFF or bmp and all we store is the results of the final aerial triangulation with the images. So, if you do not want to resample it, it just applies the transformation as what is required, either for display or map production purposes. The advantage of that is that you only store the data once and in its original format. The other principle benefit is that you obtain the spatial integrity of the data. So, if you are using imagery for vector digitising for example, you want to ensure that you do not use sampled imagery, but raw imagery. That is an additional advantage, but the significance on storage is that you only store the original format and only once, rather than trying to store a rather oversampled orthophoto mosaic which could run to Giga bytes.

Heuchel (Inpho):
Good idea to store raw image data. What about the image pyramids. Do you add that or can you do it on-line or on the fly? It has to be done, doesn't it?

Shears (Erdas):
We store the pyramids with it as well, so there is no sacrifice in the zooming in or out . The pyramid structure we use occupies about 8% of the original file format, so we are working with additional compilation techniques to reduce the amount of additional overhead a raw image would have. We are currently at the 8% level but it is coming down, so it is not a huge overhead which has to be stored.

Coulombe (DVP Geomatic Systems, Canada):
In DVP we have a function that as long as you are in the working area and you have the disk space, you can have the whole model of the block tied together, accessible at any place on the “stereo mosaic”. So all the surrounding area of the block is accessible to the operator just as Mr. Madani (Intergraph) described; we already have that in the DVP.

Simmons (Simmons Mapping, UK):
This is something that is going to be needed as we expand our systems to get more and more scans, produce more and more projects. Is LH Systems planning anything in that domain?

Miller (LH Systems):
Image storing is a real issue as we move to digital cameras; it now becomes a crisis if you lose a scan, you cannot go back and scan again. We see this in databases and physical hardware; how automated is it to back up and restore data? Right now we do not get much demand for long-term data storage but perhaps there are some people here who are going to be in the business of long-term safekeeping.

Shears (Erdas):
This is something related to the national mapping agencies who are not working on a contract basis but are selling volumes of data to the general public or businesses etc. This will have to be linked with the Web too.

2.1.2 Storage of Image Data:

Local networking has improved. Ethernet 100 is now available at the price of former Ethernet 10. Giga Ethernet is coming. Images are easier to distribute among users.

Disk space on the workstation is getting cheaper. There is software which lets several disks appear as one large disk, and there are 18 GB and new 36 GB disks (and 50Gb by the end of the year?).

a) Has data management become simplier or already disappeared?

b) Is an average network powerful enough to allow remote visualization?

c) Does a fast network enable client/server type of computing in photogrammetry (i.e. processing on workstations with files mounted on an image server)? Is this alleviating data management?

Dörstel (ZI Imaging):
I think present-day networks are not powerful enough to allow for only one central server, because, on the one hand, our requirements grow daily and, on the other, the amount of data increases daily too. So we as vendors have to supply a good and flexible concept to manage this and to exchange the network behind it to take full advantage of this innovative technology.

Madani (Intergraph):
The problem of large data storage has always been the concern of big companies not small ones. The difference between digital and analytical photogrammetry is in scanning and keeping track. Regarding the networking problem, we can connect our project and review the results, zoom in the image which might be difficult through the local network, but now there is the Internet. There is the concept of shadowing i.e. cashing the imagery once and then requesting that portion of the image as it is needed, therefore the network is not going to play a big role. So if anyone is interested in seeing what this shadowing is and how the image is retrieved through the Internet or the network we can discuss it after this meeting.

2.1.3 Image compression:

Image compression is not yet obvious for all the vendors, nor for all the users.

a) Is compression still needed?
Not all the software is necessarily capable of reading / writing compressed files.

b) Is there an overall agreement for JPEG compressed images on TIFF tiled files?

c) What about the new JPEG 2000 standard based on wavelet compression?

d) Does the « Q-factor » value have the same effect in all systems?

Madani (Intergraph):
I believe that image compression is needed; even though disk/tape/CD space is getting cheaper, it is not without cost. Also, it appears that data grows to fit available storage space. I have recently come across wavelet compression files (MrSID) that are in the order of 17 Gigabytes in the uncompressed form for each image. Regarding the question of the general acceptance of JPEG compressed images on TIFF tiled files, my answer is: this seems to be the best format for photogrammetry, but perhaps not necessarily for remote sensing. In reference to your question about the new JPEG 2000 standard based on wavelet compression, the answer is that it is not finalised yet, or is it? In any case they will have to go a long way before beating MrSID's penetration into the market with their current wavelet compressor. If they can have a royalty-free algorithm (no patents) and freely available source code, as we did with JPEG, then it will be a success. If either one of these two components are missing, the format will only be accepted if the government adopts it and forces it on the people. As for the Q-factor, our answer is NO. The concept of Q-factor is not in the JPEG specifications. Therefore, every application vendor and every file format creator can come up with their own unique definition of a "Q-factor". In the CFL world , INGR Q-factors are different from TIFF and JFIF Q-factors, which are both different from NITF Q-factors. However, as long as you stay in the CFL world, there should be no differences between NT and CLIX.

Miller (LH Systems):
I think that many vendors have agreed that TIFF has become a uniform standard and most of them exchange it very well, though it has taken some time to transfer different types of TIFF files as there are so many of them around. JPEG is supported by most of them and there is a general consensus that wavelet compression offers advantages, so there will probable be a move to wavelet, but this will take some time. Moreover, there is no agreement on the Q-factor and though this is not causing any trouble, it would be nice if they did agree. TIFF seems to have difficulties maintaining momentum; it is not making money. Perhaps it is preferred by the world-wide community because it is not profit-making, but whether or not it will be successful is uncertain.

Stojic (Erdas):
Erdas started as a remote sensing company in 1978 and we have specialized in that area for a long time. We have implemented wavelet compression (W.C.) recently, specifically MrSID. We have seen the advantages of this implementation and since we have released a new product called Orthobase which does the automatic aerial triangulation etc., we want to take the same concepts and transfer them to the realm of photogrammetry of both compression and decompression. Thus, Erdas is moving towards W.C. implementation via MrSID in our forthcoming technology.

Shears (Erdas):
Just a comment to Scott Miller's (LH Systems) remark on the capitalism and TIFF and MrSID. The reason why we are embracing MrSID is because it is a proven compression technology, but the concept they have about paying for compression is ethically O.K. It can be compared to UNIX's decision on their LZW compression to pay to uncompress, that is putting the burden on the user rather than on the data supplier. So, yes MrSID is making money but it is a slightly better concept of a business operation than UNIX had.

Siman-Tov (Ofek Aerial Photography, Israel):
I produce orthophotos and image files. What about copyright of the orthophotos. Do your companies give it a thought?

Dörstel (ZI Imaging):
Good point, we have not looked into it that deep. What is available now is to use programs accessible on the market to stamp copyright on the images.

Siman-Tov (Ofek Aerial Photography, Israel):
So what is done now to make a project copyright, is to develop yourself some system to prevent it from being copied. But it is not commercialised or generalised. We are expecting large companies to find a solution to this.

Shears (Erdas):
Are you suggesting that vendors should ensure that imagery is used once only? I think it is a data vendor issue rather than a software manufacturer one.

Siman-Tov (Ofek Aerial Photography, Israel):
I should have the option to protect the image or not.

Shears (Erdas):
I think it is your responsibility as data supplier to ensure that no one is infringing your copyright. None of our copyright is being infringed if your images are used. As far as data distribution goes with Erdas, we provide free data viewers for people like yourself who are producing data; it is a free-of-charge viewing technology that adds value to your data. So rather than selling a georeferenced TIFF image on a CD ROM, we provide you and therefore the end user with the ability to view, roam, annotate and make a map out of the data set. If needed, we can lock the viewer to the data, but I do not think copyright is a vendor issue.

Reiss (Bayer Landvermessungsamt, Germany):
I think that it is nowadays possible to bundle 3D data into a format so that it can only be read if you buy it. So it can be source of making money.

Taylor (Erdas):
We have thought about it. The data supplier can decide what he will charge for these data. Our viewer adds value to it but we have decided not to charge for the viewing.

Torre (ICC, Spain):
Going back to the Q factor in the JPEG compression.; because it depends on the format i.e. TIFF and on the operating system, will it work differently in each case?

Madani (Intergraph):
We have not done that.

Dörstel (ZI Imaging):
In this session we are talking about standardization and doing things like using different Q factors and image standards to run completely independently. Each vendor will find the best solution for himself. I am sceptical about such specific solutions and would therefore propose not to support this.

2.1.4 Installation

We always need advice on how to set up the new system within an already existing production line, according to experience gained at other user's sites.

We need a full installation of the product, a **complete** documentation of the product to be installed by a local system engineer, and a 24-hour hot line to assist a local system engineer.

New versions must be scheduled and documented in advance.

2.1.5 Migration/upgrading, maintenance

It should be possible to protect one's investment, and to benefit from the latest functionalities of the system at the same time.

Once again, new versions must be scheduled and documented in advance.

Old versions must be maintained during a decent amount of time. Users cannot change their production lines in a minute, since those are most of the time complex chains containing various products, coming from more than one vendor, linked to each other with home-made applications.

Moving from an OS to another is a very costly task, even with standards and if the files are compatible in an heterogeneous environment.

What type of migration services do the vendors offer? more free training? compatibility/porting tools?

Which to choose? workstations on UNIX, PCs on windows NT? The choice should be up to the user!

What about Linux? What about Java? Is this the prelude to a new change in OS?

2.2 Stand by

Some problems raised in Lausanne are still unsolved, or only partially.

2.2.1 Scanning:

Unattended scanning is now available, but scanning is still a tedious job.

a) Is it possible to have good radiometric parameters for the whole block? How?

b) What about storing more than 8 bits/pixel and adjusting the radiometry in a batch post-process?

c) Could the process be even more automated? Could the file naming be done automatically from what is annotated on the photo? Is it worthwhile?

d) How robust is the system in skipping the gaps of variable length between photos? Systems are now fast enough to allow simultaneous scanning and processing in the sense that there are no “time-outs” anymore.

e) Is post-processing (autododging, internal orientation, image pyramids, etc.) performed at the scanning station?

f) Do systems generate a thumbnail of each photo that can be used later as a visual index?

g) What information is stored in the internal/external headers? Do we need to store the status of the scanner, the scanning parameters, etc.? Internal or external headers or both?

h) What type of meaningful reporting tools are given to the user?

2.2.2 Multitasking

Some processes still require long computations that must be scheduled overnight and during weekends.

a) In a multiprocessor system, does the software take advantage of the multiple CPUs? Can the user allocate each processor to a different batch queue? Is there any license limitation?

b) Is the photogrammetric software multithreaded for maximum speed in multiprocessor systems?

Miller (LH Systems):
We are using multi-tasking and multi-processing in the scanner, in the NT products and the UNIX products. There is always a need of the user to maximise what he can get from the hardware, so there will always be a demand for those multiple processing as long as the computer producer uses the CPU systems.

Dörstel (ZI Imaging):
Our product does not currently support multi-tasking but we know products that would do it. It is made by our new partner, Intergraph. We are planning to make a product which will integrate the best of both firms.

Stojic (Erdas):
(Shows their stations and he explains that they use multi processor technology in stereo analysis and in 3D visualisation. They integrate vector data, raster data, topographic information, visualisations which implement multi-tasking capabilities. Open GIS has become a standard for 3D rendering and display).

Madani (Intergraph):
The Orthopro product I showed you and the image pipe technology are both multi-tasking. Firstly, we should get some numbers on our typical workflow. My belief is that most of our workflows are disc I/O bound and not CPU bound and adding another CPU or diverting the application may not increase the performance. So perhaps, improving the disc subsystem with faster drives and RAID striping may be a better way to spend money.

2.2.3 Display

a) Is roaming performance satisfying now? At what price?

b) Is there enough CPU/graphic power to enable some real time image processing (image enhancement, etc.)?

Heno (IGN, France):
We were told that at Swissphoto the plotting is done on analytical plotters because digitally there are accuracy and performance problems. The question of whether roaming performance is satisfying and if sub pixel measurements are available to ensure sufficient accuracy, is still a current issue.

Madani (Intergraph):
Firstly it would be valid to define “satisfying”. Roaming is not as smooth on NT as it was on CLIX. However, since we are using OpenGL based technology, all we have to do is slide in a faster graphics card, and roaming smoothness should improve, which makes this a good investment for the customer. All other aspects of the roaming are performing better now than before and at a lower cost.

Miller (LH Systems):
Sub pixel measurements are generally used in aerial triangulation, correlation, etc. Typically 1/6 pixel precision is a sub pixel system. The pixel precision is moving down to 1/8 of a pixel range. Some clients might also prefer to have sub pixel moving cursors within the images or the imagery moving to sub pixel positions behind the cursor. This is something that would be useful in our industry. We will see more of that as the graphics card performance increases.

Heipke (University Hannover, Germany):
In display technology there are some issues to be raised. One concerns the interlaced screens; when are we going to move away from this technique? The second is about image quality; most operators say that the clarity, brightness and separation of the images was much better in the old days. Are we to expect an improvement in image quality in future?

Miller (LH Systems):
I am not sure that most vendors have produced interlaced systems; LH Systems has not. Several vendors have produced full frame sequenced displays; they had to cut down the resolution of course. But then there is a lot of ghosting and bleed-through in these monitoring systems – that is to the detriment of the profession. The fact is that we were not able to get the occlusion in the stereo as we can get it in the analytical plotter. There has not been a good answer to that so far, unless you want to go for monochrome.

Stojic (Erdas):
Along with the progress in display technology, there are several manufacturers of monitors in the UK and the USA which do not need an emitter, crystallised glass; you can view stereo only by looking at the screen. So we have seen a movement towards alternative methods, not only for stereo display, but also for monitors and graphic cards etc. Moreover, the entertainment industry is moving forward with respect to 3D display systems; there are graphic cards that cost $150 each, which support stereo. We recommend some

of these cards to our users for certain applications. So this is an exciting moment, when manufacturers are decreasing the price so they are becoming widely used, not only in photogrammetry.

Nicoletti (Intergraph):
It is true that the drivers in the sequential frame are providing a lower resolution, but it is also true that if you compare the result on the vertical direction, there is an increase of around 30%, so the decrease is only in the horizontal direction. Regarding new technologies for viewing, I know of one but it can be used by one operator only.

Madani (Intergraph):
A comment to Prof. Heipke (Hannover, Germany). It is a valid point, as the calculation is simple. When it comes to 3D feature collection for digital mapping, the operator prefers to work on analytical plotters, because he sees a sharper image. So you look at what is available on the market, see if it is affordable and use it.

Coulombe (DVP Geomatic Systems, Canada):
At DVP we have not only developed software but use it also in production. We have had a project recently in which 12 operators were involved. We tried the Stereography New Vision in a real production mode. All the operators agreed that the screen was less tiring and they could work on it 8 hours a day. They had never worked on analytical plotters, so in a way they cannot be biased.

Grabmaier (ITC, Netherlands):
I have experienced this with my students who saw both digital and conventional systems. They are reluctant to go digital. But of course for digital orthophoto, for DTM, and for aerial triangulation, there is a lot of potential in the new systems.

Duperet (IGN, France):
At IGN our operators prefer to work on digital workstations than on analytical plotters.

Kersten (Swissphoto, Switzerland):
I agree with Mr. Grabmaier, the resolution on analog images is superior for precise plotting. Moreover, operators get headaches if they sit on the workstation for many hours. So their health is also an important consideration.

Colomer (ICC, Spain):
We have been running the digital systems for 7 years, and we have not had headache problems so far.

Miller (LH Systems):
We have to be careful before we jump to conclusions about either system. We can compare a 7–8 µm scan with an analog image, not any less. We have customers who scan in the 8–10 µm range and they are happy with the digital. But they are coming very close to the quality of analog images.

Colomer (ICC, Spain):
We should make the OEEPE work on this.

2.2.4 User interface

Real time interpolated zoom and multi-view interface are not available on all products yet!

a) What about voice input?

b) What about using a more sophisticated mouse, like in the world of virtual reality (something like: the more you press the button, the more you apply the tool)?

Heno (IGN, France):
Let us consider now a new user interface: voice input, new mice. At IGN we are using ITE from SOCET SET to edit our DTMs. We think that it could be convenient to have something like « the more you press the button, the more you apply the tool ». Any comments?

Shears (Erdas):
We feel the systems should be developed in other areas than that, i.e. in simplifying the workflow by streamlining it. We are trying to make the job available to a wider range of users. By way of an example, we introduced colour visual guides and created icons to this end.

Stojic (Erdas):
We have tried to adapt to the needs of a photogrammetric user. We tried to make user interfaces user-friendly, by opening the market to a wider audience. Thus, we have streamlined the whole photogrammetric workflow into 6 unique steps, only six buttons for automated processes. Moreover, we introduced all kinds of devices like the fact that all the colour codes are interactive, to bridge the gap between the user and producer.

Dörstel (ZI Imaging):
This tendency towards simplification is general and it was Microsoft who set the trend. To address the point of special input devices, I was involved in the construction of the P-mouse and so I know about the trouble of finding out the requirements and prices involved. We hope that the consumer market develops a demand so we do not have to look for new solutions.

Coulombe (DVP Geomatic Systems, Canada):
DVP tries to distinguish between a product that looks nice and one that is efficient. So, we want to reduce the number of clicks and clacks to carry out a project for example.

Heipke (University Hannover, Germany):
Voice recognition is beginning to be used in different areas. Can we expect to see it in photogrammetry soon?

Dörstel (ZI Imaging):
Yes, we have been looking for this technique for years. Voice input is going to come for office use, but for photogrammetric needs this is not very cost-efficient.

Madani (Intergraph):
Intergraph is working on it; we did use it in the past but it was not reliable enough then.

Baltsavias (ETHZ, Switzerland):
The issue here is not gadgetry; what we need is to have a user interface which is developed by people who have worked in the photogrammetric field. So for example, it is necessary to select the functions which are being used 99% of the time and get rid of the other hundreds of unnecessary buttons. There are public domain software cores which are oriented to the practical needs of the user, but I have not seen similar commercial software so far. Finally, something should be done with the thousands of parameters which are extremely complicated and need a high standard of education to be handled. So all this leaves a lot of room for the improvement of user interface.

Colomer (ICC, Spain):
We work a number of batch processes at night and we need something comparable to Excel to allow for thorough control of the processes.

Madani (Intergraph):
With respect to Mr. Baltsavias' (ETHZ, Switzerland) comment, I assure you that the authors of the software available do know photogrammetry well, and even if the systems are imperfect, we are trying to cater for the practical needs as much as we can.

Stojic (Erdas):
I disagree, not every one does. For example in North America, the level of photogrammetry teaching in higher education is desperately low compared with Europe. Many schools have closed down too. Across the world the standard is going down, so there are many users that have a poor knowledge of the science. Hence, the user interfaces have to be adapted to them too and we have to supply sufficient training, sufficient documentation.

2.2.5 Workflow management tools

a) What tools could be useful for planning/controlling WFs? For example a DB with the project defaults, indexes, thumbnails, footprints, naming rules, accuracy thresholds, prerequisite/corequisite conditions, alphanumeric and graphic reporting capabilities, etc.

b) Does a self-documenting system/language to define workflow exist? Could such a system control the execution of the WF? Would it be too inflexible?

2.2.6 On-line quality control

Quality control procedures should be included in any photogrammetric package. At every stage of the process, the software has to report errors and guide the user to the suspect data.

a) What kind of basic controls do we need in respect to conformity with the naming conventions, homogeneity of the input co-ordinates, size of the input data compared to the system capacities, etc ...

b) What about more sophisticated ones, like on-line triangulation, etc?

c) How much will those controls slow down the system?

2.2.7 Development tools: libraries, macro language

Development tools are needed: the user may develop his own applications, **in a relatively short time**, according to his needs and only his needs (no waiting for a complex application that would suit the needs of many other users!).

Libraries must be upgraded with the new versions of the software.

Documentation should be delivered in advance to allow the user to update his applications early enough.

Tools **for chaining and controlling batch jobs** are needed as well. The more images we process, the more time we need. Computers must be fully used. A good queuing system at OS level is required.

a) What are the improvements since Lausanne?

2.2.8 Training

Training must be adapted to the particular user's needs.

Self training must be possible through good documentation and various benchmarks. Individual tricky situations could be gathered as benchmarks to be shown during training sessions.

a) When possible, could training be enriched by another user, (provided he is not a competitor), since he has the « user's experience » that vendors sometimes lack?

b) What kind of training do we need ? Training for the operating system, the tools, the technique involved?

Heno (IGN, France):
Bruce Wald said at the beginning of this workshop that users are now becoming co-developers. In the same way, could a customer be used for a training course in another company?

Madani (Intergraph):
The training issue is crucial; it is difficult to satisfy everyone's needs. We have documentation on the one hand and it is useful in most cases. On the other hand, we ask the customers to either come to Intergraph or we go to their places and we work together on their individual requirements. Then we train them to use the software if they wish so.

Kölbl (EPFL, Switzerland):
Vendors cannot escape from the responsibility of training their customers. It is not enough to say that you had users who have been trained. Very often you need a general training to start with, then you need to do further training all the time as progress is very fast. To avoid the great loss of money due to lack of training, you need to ensure a thorough knowledge of the tools.

Coulombe (DVP Geomatic Systems, Canada):
At DVP we have tutorials with every new product that appears.

Dörstel (ZI Imaging):
We have understood the message: you need a well-documented user interface which requires less training. We are trying to work on this and there is some way to go, so results will not be immediate.

Shears (Erdas):
I agree with Prof. Kölbl (EPFL, Switzerland) and we have a number of international distributors whose responsibility it is to train locally. If they cannot cope, they refer back to Erdas who actually train trainers. This training is not only about how to present the software, but also about teaching skills.

Eder (Technical University Munchen, Germany):
Firstly, the software needs to be more self-explanatory for students who learn alone. Then, it would perhaps be useful to deliver a CD with a complete photogrammetric project to enable the user to see for himself how a standard project can be worked through.

Baltsavias (ETHZ, Switzerland):
The Internet could be used more widely for self-training purposes. Furthermore, users' meetings could be very fruitful for the exchange of experiences or opinions as well as for further education. This, in turn, could be used by the vendors to improve their products.

Madani (Intergraph):
In reference to what Prof. Kölbl (EPFL, Switzerland) said, it is true that second hand knowledge does not work. Even the video was used to train users but it failed to work. We are working on adapting the Internet for user/vendor, customer/customer interactions and it is a good media for this. Even though this is very helpful to both parties, we feel that physical training is needed, i.e. to sit down with the user and sort out his specific difficulties.

3 Need for standards

3.1 Running production workflow in a heterogeneous environment

Various software and even various hardware coexist in most mapping production lines.

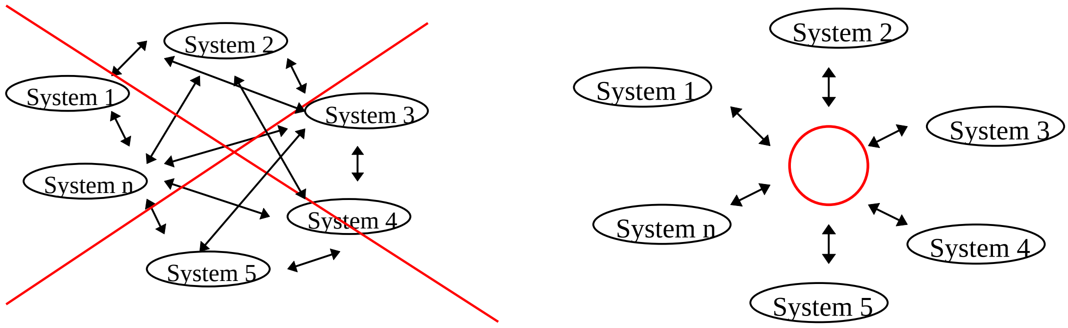
Advantage:

It is wise not to be fully dependent on a single vendor...
It is a liable solution to get the best from every vendor.

Drawbacks:

As far as logistic problems are concerned, running production in a heterogeneous environment has many drawbacks:

Most data are incompatible from one software to the next one. Converters must be written. Those home-made converters need to be rewritten as soon as one piece of the production line changes. Sometimes new formats need to be created!!! In IGN France for instance, they are so many data formats in use that a new format was created (FEIV), along with converters from and to this data format.



More skills are necessary to maintain the production lines: system engineers must know several operating systems, several hardware configurations.

More standards should help in this issue.

3.2 Translators, standards

Users of widely distributed products would like to be able to use only one image format at any stage of the process. This is up to the vendors of photogrammetric products. GIS vendors should also use the same standard, since most orthophotos we produce are meant to be used inside a GIS.

As far as data are concerned, things are probably more complicated, since vendors may want to keep their way of modeling the photogrammetry.

a) Is the uncompressed tiled TIFF format becoming the standard for images? Is this also true for Image Processing systems?
Besides formats, different software must agree or the meaning of parameters:

b) For example, is the range of values of the Q-factor for JPEG compressed images the same?
GeoTIFF is used for georeferenced images and is becoming the standard for orthophotos/orthoimages.

c) Is this true? Is it now common to deliver orthos in GeoTIFF?
Vendors do publish proprietary formats and offer routines/components to allow others to read/write data and parameters without translation. So, instead of translators, the vendors offer “data servers” to read other vendors' data.

d) Does this exist in photogrammetry?
In GIS AutoCad is a “de facto” standard and MicroStation is widely used for photogrammetric data capture. GIS systems usually import/export other formats in a quite rigorous way and the OGC, ISO/TC 211, CEN are concerned with standardising GIS data including “grid” type of data (including DTM).

e) What is the current status of these efforts?
OGC is proposing the use of rational functions as a general method to pass orientation of sensors.

f) What is the status of this? Are there concerns about a potential loss of accuracy?

Colomer (ICC, Spain):
The ISPRS WG II/7 has presented a draft to the ISO and the Open GIS Consortium (OGC). ISO welcomed the draft, but OGC's answer was less encouraging.

Dowman (University College, London):
I wonder if the OGC believes that a photogrammetric standard as opposed to a generic standard is worth fighting for.

Madani (Intergraph):
We had data exchange problems: it is a logistics nightmare. What are the solutions? One is standards, but what does this mean? If it means we should standardise an existing standard, I could not agree more. If you mean that the photogrammetry community should invent a new standard, then I think that the current raster standards fit the bill well enough, and we should get everyone to use one of them. We do not use more standards, we need less. Open photogrammetry is a better answer to this.

Part 7

Vendor's Systems Presentation

Vendor’s demonstration with standardised images in terms of preparation of the correlation, data checking and data editing. Vendor’s demonstration with standardised images in terms of the preparation of the aerotriangulation and the quality check. Vendors demonstration on mosaicking

LH Systems Current Production Workflows for Automated Triangulation, DTM, and Orthophoto/Mosaic Production

Scott Miller – LH-Systems, LLC
San Diego, Ca. USA

Overview

Improving automation in digital photogrammetry continues to be a challenging task. LH Systems digital photogrammetry products continue to undergo rapid change with improvements in automation occurring throughout the software. For the OEEPE workshop, we were asked to present current production workflows for automated triangulation, DTM, and orthophoto/mosaic production.

This summary covers these three topics by reviewing a recommended production flow when employing LH Systems SOCET SET software and related products. Below we will briefly cover workflows for:

- Automated Triangulation
    - ORIMA – Orientation Management software for automatic aerial triangulation
    - APM – Automatic Point Measurement software for tie point measurement and control point transfer
- Automatic DTM production
    - AATE – Adaptive Automatic Terrain Extraction
    - ITE – Interactive Terrain Extraction
- Ortho/mosaic production
    - Ortho-Mosaic

Users and readers should keep in mind that many workflows are possible with SOCET SET based software products. SOCET SET provides a large suite of tools. Production companies must link the tools together in different ways depending on the type of project and desired output. This paper merely reviews typical production flows for three general cases; triangulation, DTM, and orthophoto/mosaic production.

Triangulation with ORIMA and APM

SOCET SET provides three key products for automated triangulation; 1) APM-Automatic tie point measurement, transfer, and control point transfer, 2) MST – Multi-Sensor Triangulation, 3) ORIMA – Orientation Management software for aerial triangulation. Customers can choose which combination best suits their needs. MST provides flexibility to handle aerial images and satellite images while ORIMA provides for very efficient aerial image handling. Here we describe ORIMA and then present a typical production flow that exploits APM.

Goals of ORIMA

- Provide as much automation as possible
- Provide efficient interactive and manual capabilities
- Support very large numbers of points and images
- Provide extensive graphical support

Features of ORIMA

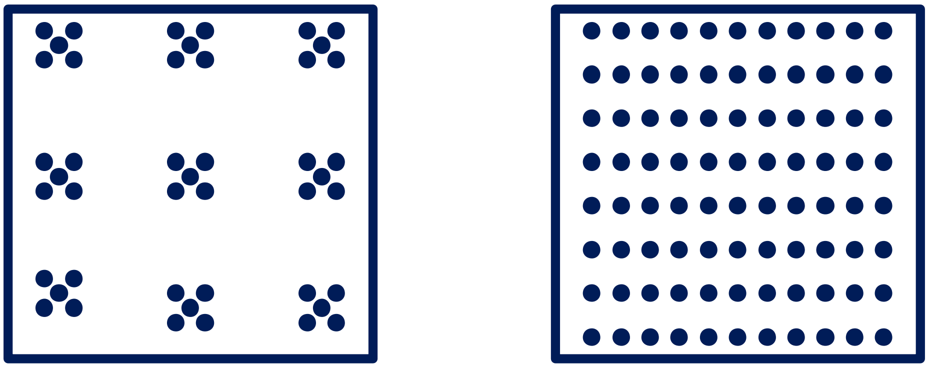
- Fully automatic or supervised interactive measurement with image matching
- Bundle adjustment with airborne GPS and self-calibration
- Highly automatic blunder detection
- Error analysis with powerful interactive graphics
- Interactive image measurement
    - Displays multiple images in pairwise combinations of split screen or stereoscopic views
    - Provides templates for placing tie points and point ID naming conventions
    - Automatically displays all overlapping pairs for a given ground location
    - Provides automatic matching on all images for a user defined location
- Automatic blunder removal by robust estimation
    - statistical blunder detection test
    - based on the residual, weight, local redundancy and σ_0, leading to a very realistic test
        - special, fast algorithms for computing inverse of normal equations
    - observations detected as blunders receive a smaller weight in the subsequent iterations
    - residuals of true blunders become larger in subsequent iterations

- applied to image points and control points
- GPS observations tested for blunders but not automatically removed

- Interactive graphical analysis
  - filters to select the objects for graphical display
    - type of object, ID, location, quality, reliability
- GPS profile separation and residual display
  - quality control
    - confidence ellipses
    - external reliability
    - reliable tie points
    - effectively used image format
  - perform measurement process from ORIMA if re-measurements/additional measurements required

Features of Automatic Point Measurement (APM)

- Initial block setup should be within 1000-2000 pixels
  - Overlap detection is performed at low resolution
  - DTM can be used to improve detection in rough terrain
  - Initial setup can be adjusted by initial 2D triangulation
- Tie point patterns can be clusters or evenly distributed



- Existing tie points and control points are transferred to all overlapping images
  - Scale variations are compensated by on-the-fly shaping based on current math model

    - Image matching is done in clusters
    - Initial point selection uses modified interest operator
    - Image matching uses multiple pairwise matching
    - Each point is derived from a cluster of points
    - Least squares blunder detection is performed on all pairwise clusters
    - Only small blunders are generally left after APM
    - Multi-ray points are created whenever possible by using overlap map to place points in multi-ray areas
- Difficult image conditions
    - Heavily forested imagery is often the most difficult
    - Bundle adjusted results can be fed back into APM for increasing the density of points
    - Manually defined point locations can be transferred automatically by APM…sometimes useful for very difficult terrain

Typical AT Flow

- Typically done with batch process

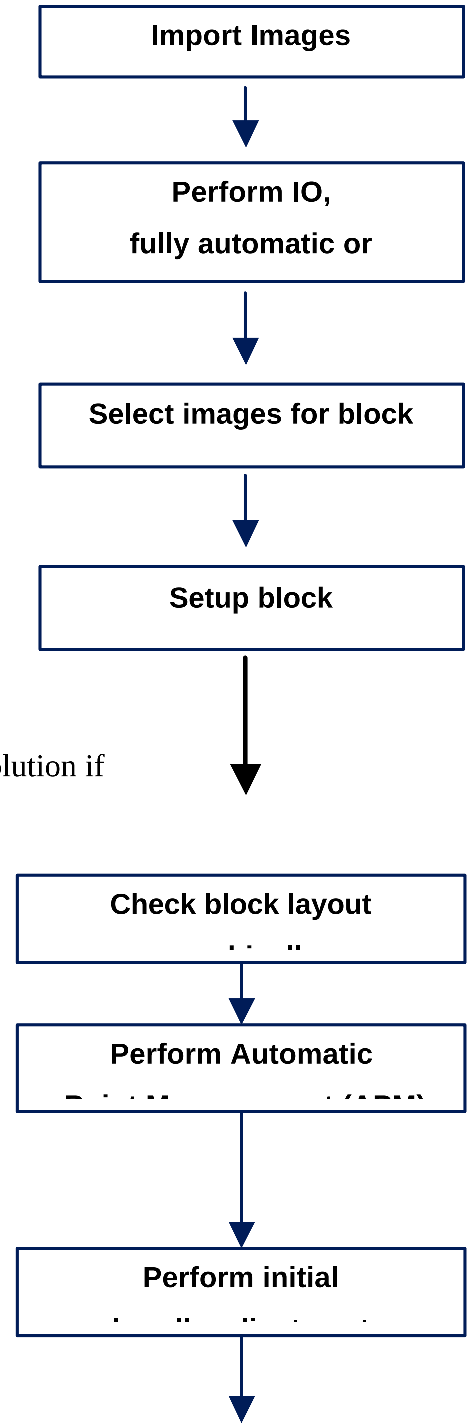
- If IO not already done by scanner, perform interactive or batch IO

- Select any group of images to be triangulated

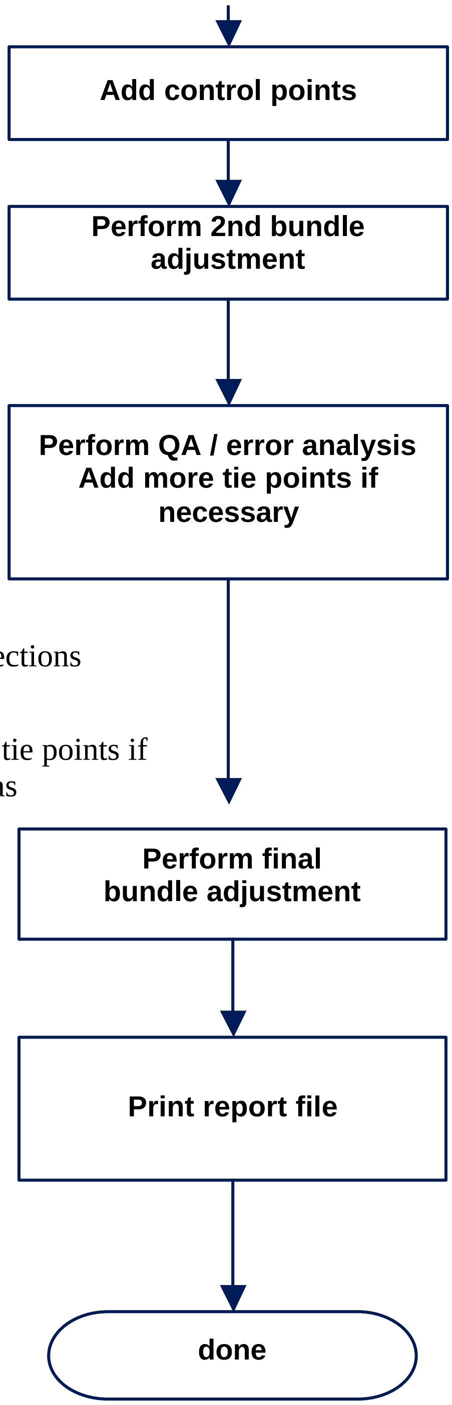
- Import GPS file, ASCII camera station file, or measure three tie points per image
  - Adjust Kappa graphically if GPS file
  - Measure 3 control points and perform 2D solution if starting from unknown position

- Typical graphical check to verify location and size of block

- Select Tie point pattern
  - Even distribution or point clusters
  - 30 to 150 points per image, typical
  - Select DTM if available
- Set apriori weights if necessary



- Automatically removes gross blunders by 2D adjustment
- Removes small blunders using robust estimation

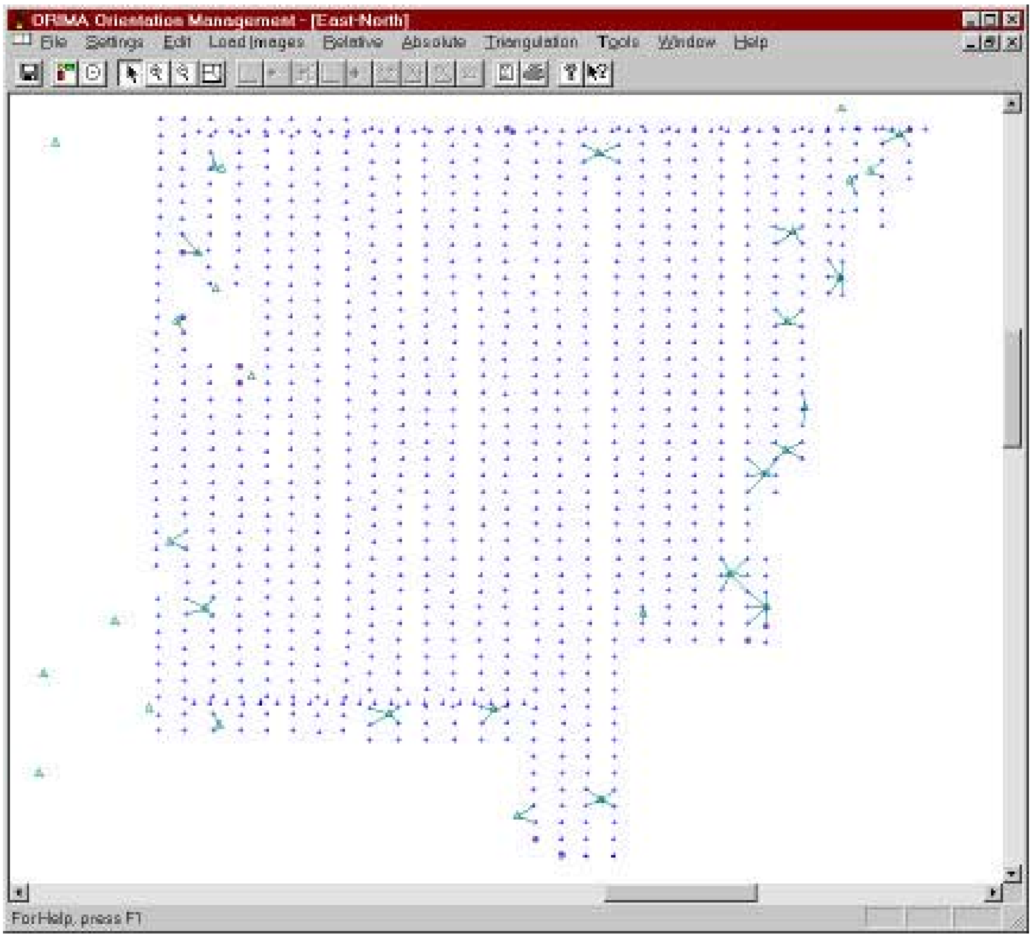


- Use image matching to measure control points if any
    - System will drive to and display multiple images
- Adjust apriori weights if necessary
- Error analysis
    - Check GPS profiles graphically, split or merge if necessary
    - Check accuracy and reliability graphically
    - Check quantity and layout of multi-ray connections graphically
    - Check block coverage graphically, add more tie points if required by clicking graphically on open areas
    - Add self calibration parameters if necessary
- If changes were done, perform a final bundle adjustment
    - review quality graphically
    - save results
- User can select desired items for report file

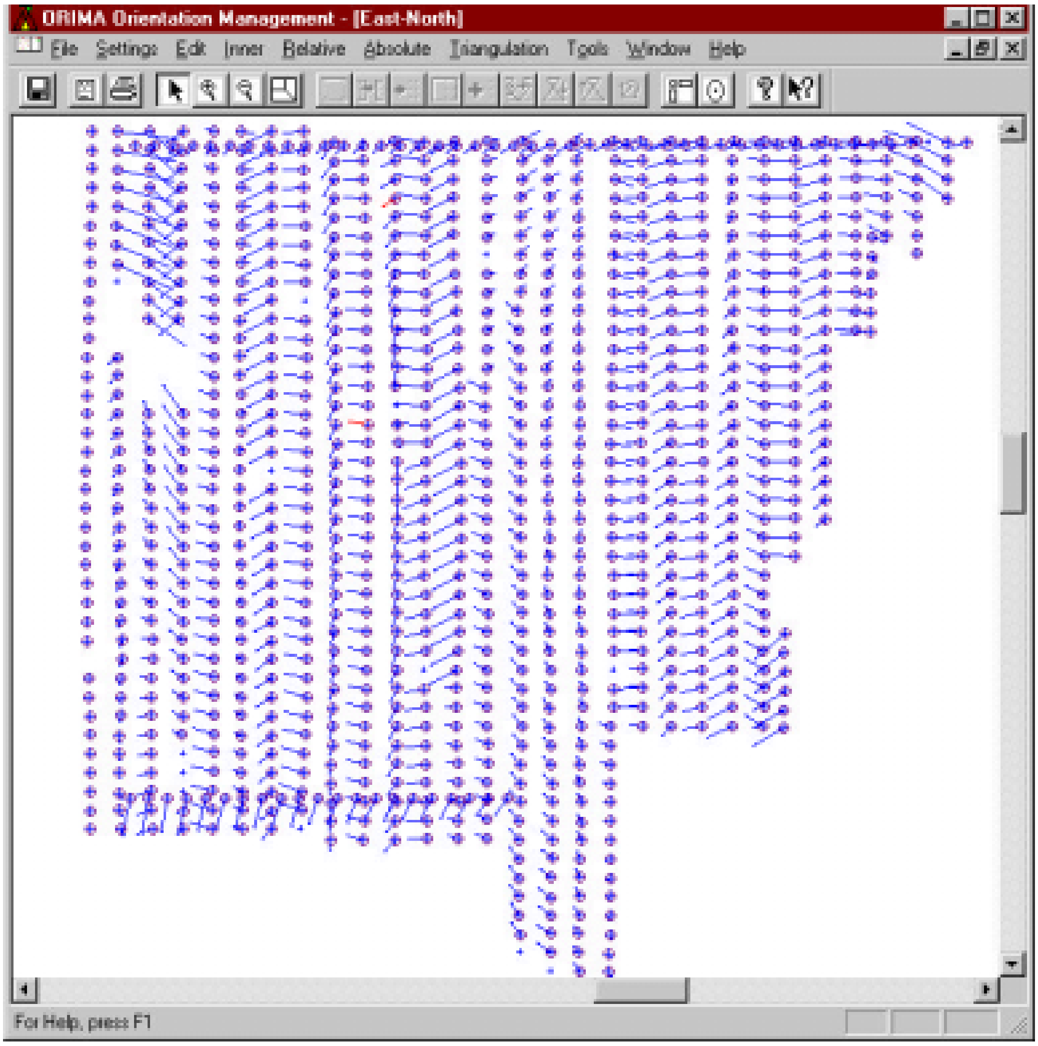
A Performance Example

Process	Automation	Time
Set up block with GPS file	Yes	Instantaneous
Set up kappa angles graphically	Partial	<1 minute per block
Tie point measurement	Yes	1-2 minutes per image (50 points)
Control point measurement	Partial	20-120 seconds per point
Bundle adjustment	Yes	<30 minutes per thousand photos
Graphical analysis and clean-up	Partial	Depends on complexity of block

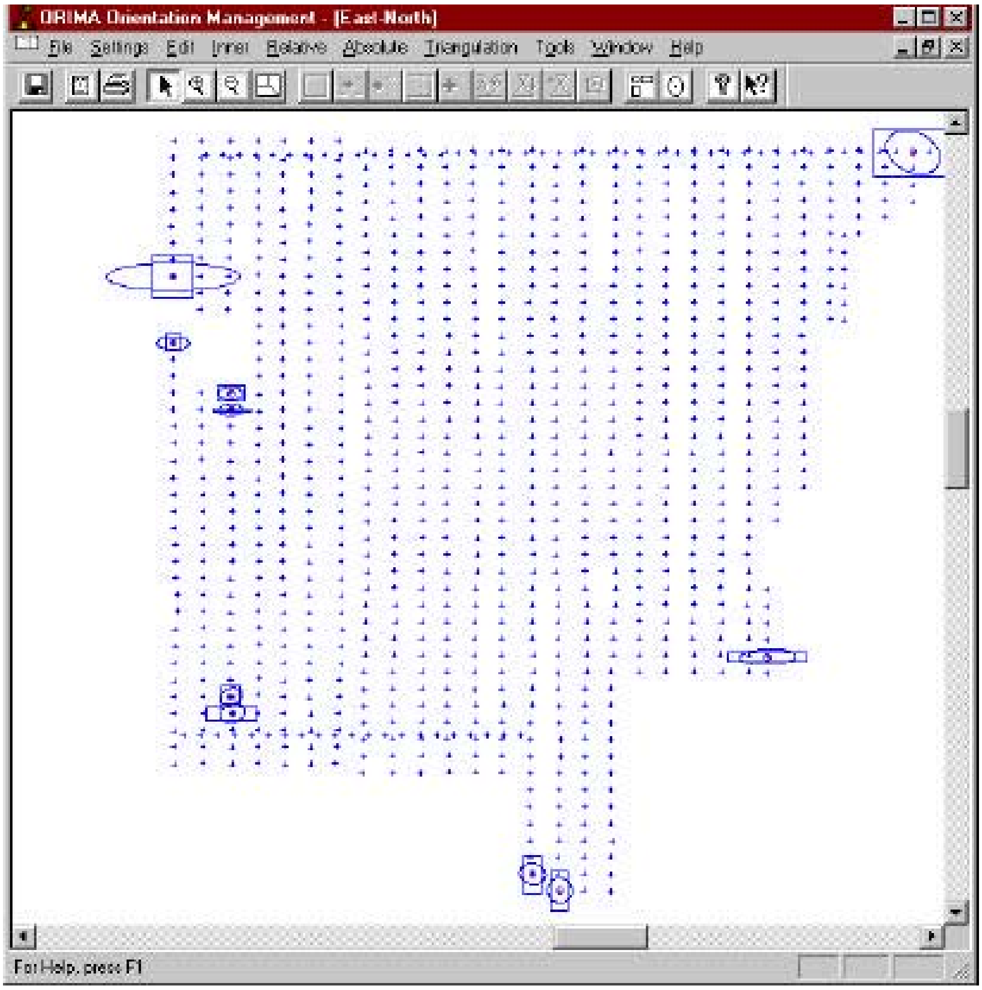
Block layout and GCPs



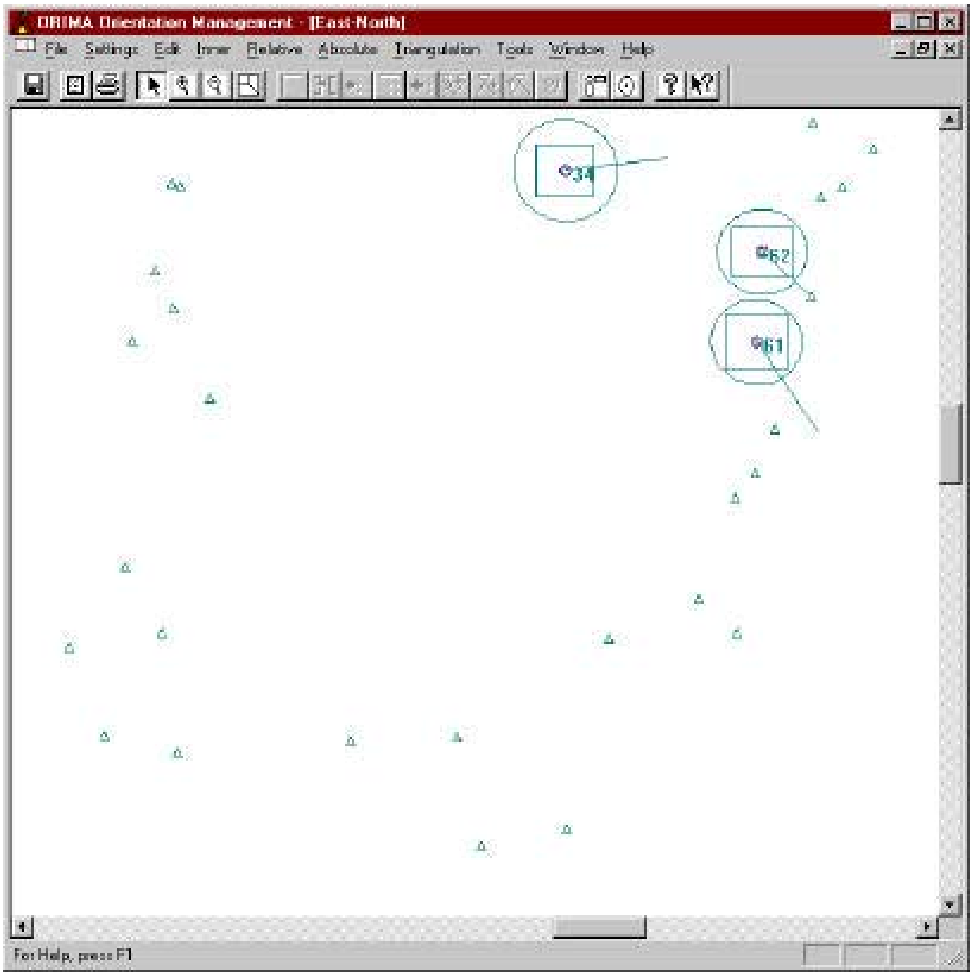
GPS stations with drift vectors



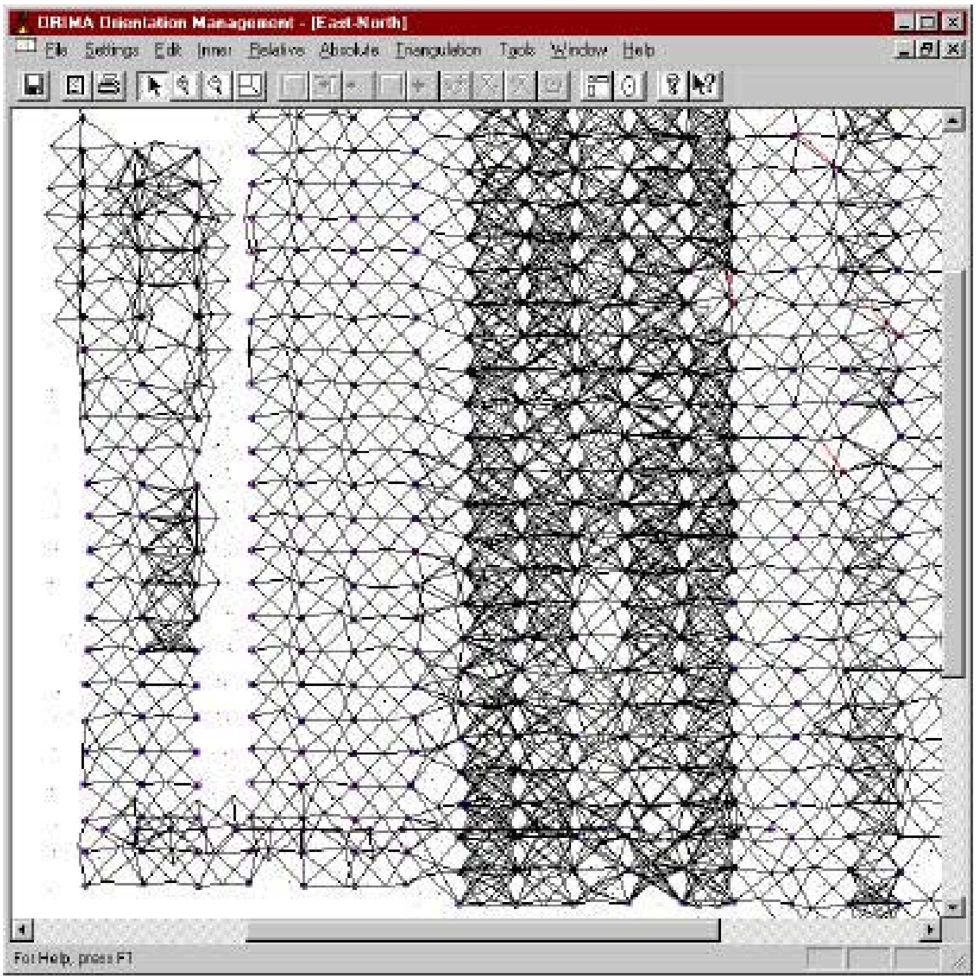
External reliability and error ellipses (unreliable proj. centers)



External reliability and error ellipses (check points)



Ray intersections geometry of (reliable) tie points



Summary

- Strong trend to automated triangulation
- Large numbers of points
- Comprehensive error checking is essential
- Automatic blunder detection/elimination and self-calibration are imperative; fast compared to manual data cleaning
- Use of Wizards allows automation for routine operations and increases throughput for manual operations when needed
- Powerful interactive graphics facilitate decisions that must be made by the user
    - find areas with insufficient tie points
    - ensure GPS profiles are properly defined

- conventional coarse quality criteria such as σ_0, rms and residuals are not sufficient to find weak areas

DTM Production

The following section briefly describes the SOCET SET DTM production tools and then provides a typical example workflow. This workflow is one of many possible flows. SOCET SET provides two key data types for DTM production: 1) Grid based or 2) Triangular Irregular Network (TIN) based. Typically, TIN based DTM production is more productive as the image scale becomes larger.

DTM production

- TIN or GRID
  - TIN may be the more efficient production method
  - GRID files can easily be made later from TIN files
- Breaklines, form lines, water boundaries, roads, etc
  - Breaklines can be extracted before and/or after automatic DTM production
  - If breaklines are extracted before, they can be used to initialize the DTM
  - If breaklines are extracted after, they can be merged into the DTM

Automatic DTM production

- Adaptive Automatic Terrain Extraction (AATE) uses an inference engine to adapt the methods for image matching to various terrain characteristics
  - Roughness, signal power, resolution, etc.
- Options
  - Use more than two images to get multiple views of sloping terrain
  - GRID or TIN with some automatic breakline output
  - Select weights for multi-banded image matching
  - Select precision, smoothness, filters

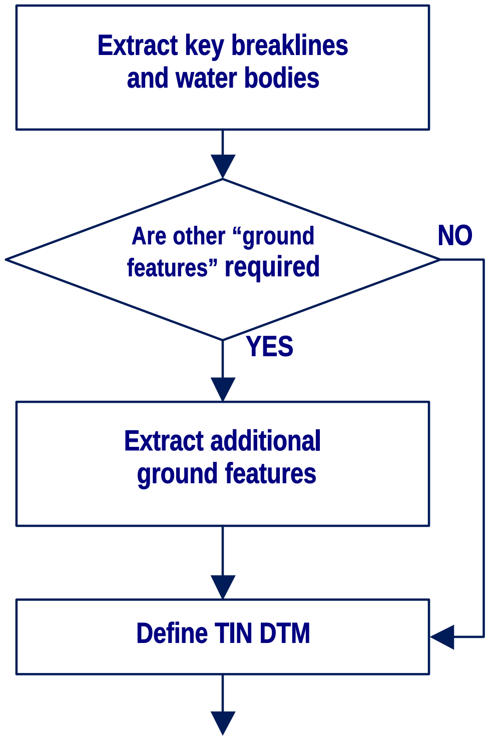
Interactive editing

- With the assistance of IGN, a near-real-time shaded relief display assists the user while editing
  - Excellent tool to check for over-smoothing, editing signatures, etc

- Start editing with global filters
  - Building and tree filters, noise reduction (thinning) filter, smoothing filter
- Sometimes, editing is easier with TIN
  - Start by deleting all bad areas
  - Add breaklines, form lines

DTM production: example flow

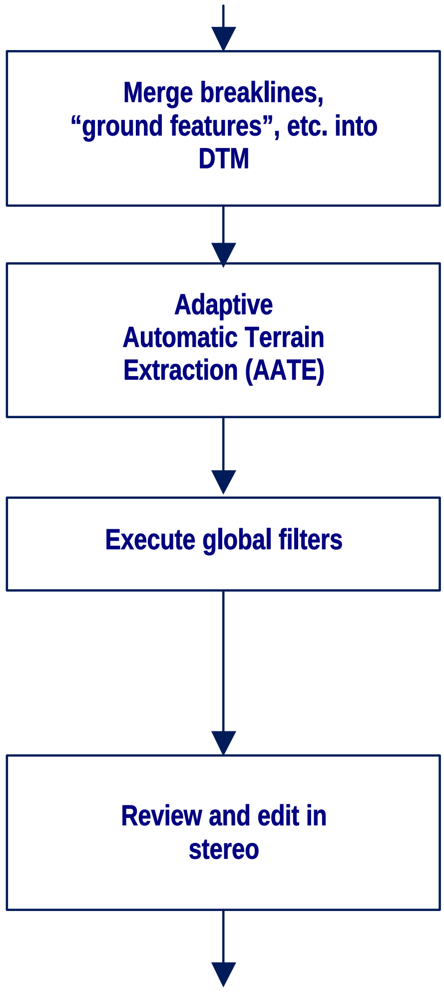
- Extract significant water bodies and break lines where poor image matching is likely
- If other "ground features", such as roads, are required for the project, extract those features next.
- Select multiple images for matching if possible. This allows the use of better viewing angles (thus better image matching) on sloped terrain**.**
- Break lines and water bodies can help the automatic extraction



- AATE is a batch operation over many images simultaneously; applies global filters if desired

- Editing strategy: Perform global and regional tools first
  - Tree and building filter, noise or thinning filter, smoothing filters

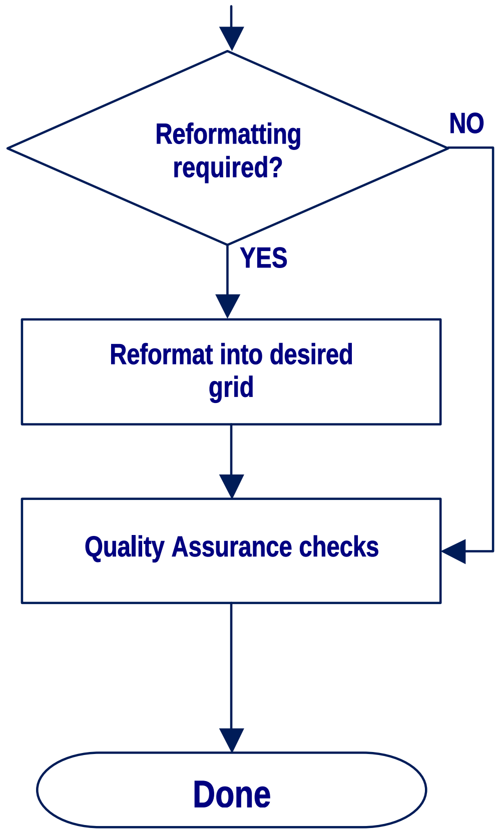
- Area and line edits
  - Delete “useless” TIN areas
  - Add breaklines, formlines
  - Delete and add points



- Format DTM into GRID or TIN as required

- Reformat is a batch operation: select region and spacing

- Use a sparse DTM or check points to compute mean and standard errors

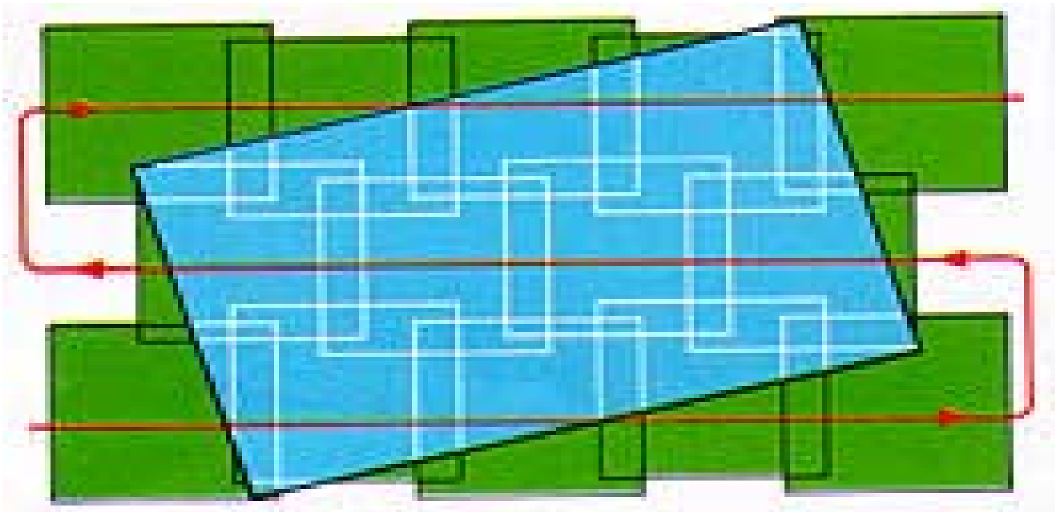


DTM production summary

- SOCET SET provides a rich tool set for DTM production

- Users must chain the tools together in an optimal way for the project's requirements
  - Accuracy?
  - Contours?
  - Buildings and trees or bare earth DTM?
  - Orthophotos only?
  - TIN or GRID?
  - Breaklines before and/or after AATE?

Ortho-Mosaic Production



SOCET SET provides several options for orthophoto and mosaic production. Software modules include True Ortho, Ortho-Mosaic, Layer Mosaic, Image Map, and Dodger. This section gives a brief description of Dodger and Ortho-Mosaic.

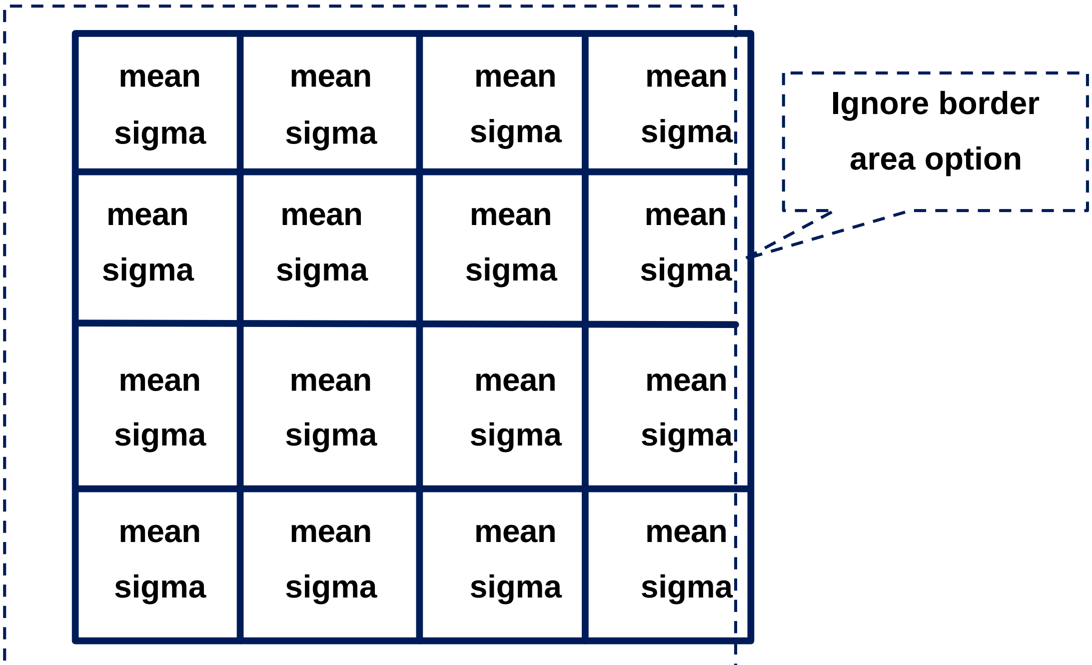
Image scanning

- The end product quality relies on high quality scanning, particularly for color imagery and color negatives
- Color quality is often highest from scanning negatives
  - Sharpness is retained, accuracy is retained
- Ideally, tonal transfer is kept consistent during scanning

Dodging and Balancing

- Raw images should be balanced and dodged
  - Remove hot spots
  - Remove vignetting
  - Balance colors
  - Balance contrast and brightness
- Images can be balanced to a common brightness and contrast and to common color content
  - Images with substantially different colors are very difficult to process

- Dodger inputs
  - Multiple input images
  - Parameter file
    - New desired brightness and contrast
    - Balancing by color band
    - Balancing across bands
    - Balancing across images
    - Constraints
    - Image pyramid generation
    - Image format
- Dodger processing
  - Each image is statistically characterized by a user defined tile size



- Dodger processing
  - Small tiles allow micro balancing
  - Large tiles allow global balancing
  - Some customers execute twice, once for global balancing, once for micro balancing

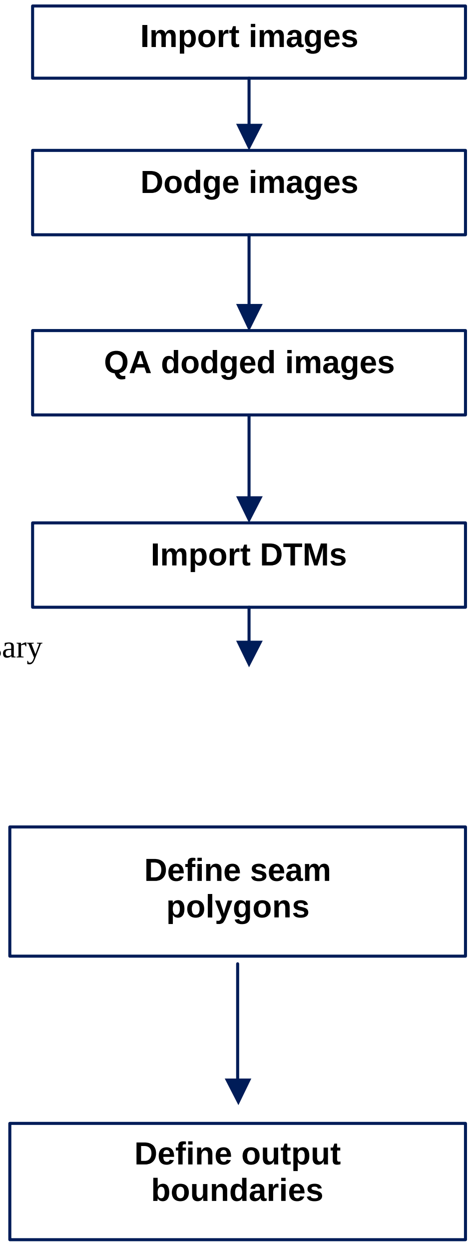
- Each tile of each image of each band can be "pushed" toward desired balance
  - Desired balance can be input
  - Desired balance can be computed from specific images or project wide
- Outputs
  - New or overwritten images, image pyramids

Ortho-Mosaicking – performs ortho-rectification and mosaicking in one step

- Inputs
  - Grid or TIN DTM or user defined Z
  - Output boundary (rectangle or polygon), pixel size
  - Triangulated images, or orthophotos
  - Polygon seam boundaries or automatic seams
  - Bilinear or modified cubic resampling
  - Macro feathering
  - Micro feathering
  - Output format e.g. Geo Tiff, Tiff
- Processing (Batch or interactive)
  - Modified cubic resampling
    - Compromise between optimal geometric resampling and MTF preservation
    - Preserves edges better than bilinear
  - Macro feathering (optional)
    - Uses difference in DN between overlap areas
    - Can be used for 1000s of pixel feather width
  - Micro feathering (optional)
    - Performs "blurring" within a few pixels of the seam line

One Typical Mosaic Flow

- Assumed triangulated images or orthophotos, or mosaics
- Batch process, usually in large groups
- Balance across entire project
- Check image balance visually by displaying multiple images
- Run Dodger “statistics only” to check statistics of images
- If DTMs are available, import them
- Edit DTMs if necessary, create DTMs if necessary
- User defined elevation if no DTM
- If desired, create seam polygons for entire project area
- Optionally use most nadir automatic seam polygons
- Place in batch files or enter into GUI
- Select pixel size

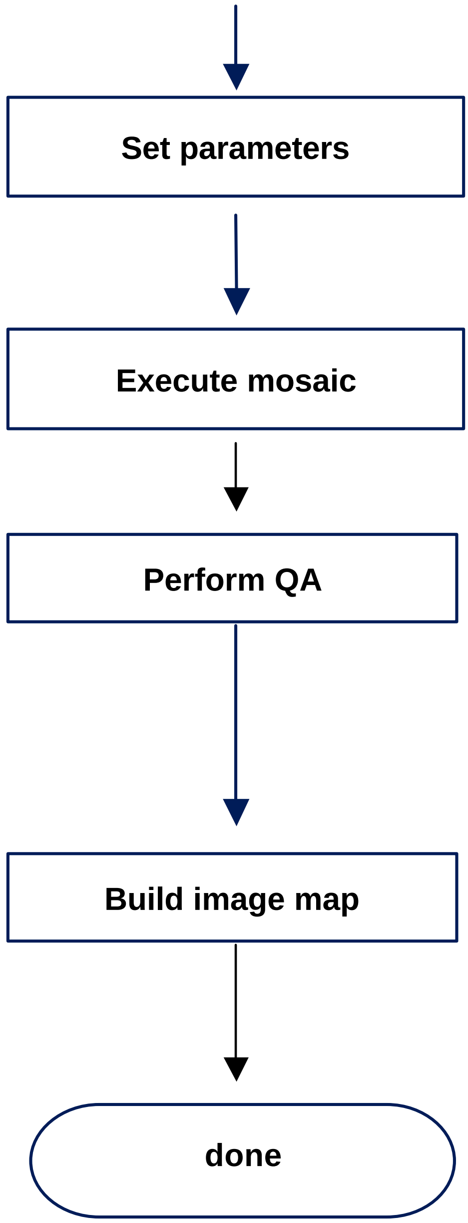


- Place in batch file or enter into GUI
- Select methods, resampling type, feathering type, etc.

- Batch or interactive, sheet by sheet
- Outputs GeoTiff, Tiff, etc.

- Display seamlines over mosaic
- Check radiometric and geometric extent
- Measure check points, produce statistics report

- Optionally, overlay grids, superimpose vector overlays, contours, symbols, legend, etc.
- Superimpose MicroStation files
- Output in PostScript, Tiff, etc



Summary

- Digital dodging can be used to balance radiometry across the entire project area
- Enhanced Cubic resampling can preserve edge characteristics
- Macro and micro feathering is optionally used to hide seams
- PhotoShop and similar packages can be used to edit scratches, dirt, etc
- DTM quality is the largest factor for geometric quality
- Scanning is the largest factor for radiometric quality

Overall Summary

This paper has given only a brief overview of triangulation, DTM, and orthophoto-mosaic production workflows. Many customers have created their own unique workflows and in many cases will use a variety of different software products from different vendors to achieve the best productivity for their needs. LH Systems products continue to improve in productivity and functionality. User feedback, including that from this OEEPE workshop, stresses the need for improved automated production. An especially critical need is improvements in batch processing. As we move forward, we have started work on several improvements for batch processing. Feedback from workshops such as OEEPE, provide a great deal of help in setting priorities for new software developments.

Z/I IMAGING[1]
The New System Provider of Photogrammetric Products

Josef Braun, Mostafa Madani and Klaus Neumann
Z/I IMAGING

Abstract

This paper provides an overview of the Z/I IMAGING photogrammetry systems. It shows that Z/I IMAGING is a system provider for photogrammetric hardware/software systems from aerial photography to 3D/GIS data capture.

To start with, a brief report on the formation of Z/I IMAGING, Inc. is given followed by its product strategy. Z/I IMAGING's major hardware and software configurations based on both NT and UNIX operating systems are described. Finally, brief descriptions about different digital photogrammetry workflows, such as camera systems, scanning, digital mensuration and triangulation, 3D feature and DTM collection, orthophoto creation, and solutions for mapping and geoengineering are provided.

1 Z/I IMAGING

Z/I IMAGING combines the potentials in hardware and software in the field of photogrammetry of the two companies Intergraph and Carl Zeiss and started doing business in Oberkochen on April 1, 1999. The new company is acting worldwide from the two core locations Huntsville/USA (Z/I IMAGING Inc.) and Oberkochen/Germany (Z/I IMAGING GmbH). Other locations are presently planned in Denver CO, France, England, Norway, Greece and Singapore. As successor to rights and obligations of Carl Zeiss and Intergraph, Z/I IMAGING is assuming the responsibility for the photogrammetric systems and their support and sale.

2 Product strategy

Z/I IMAGING offers hardware and software solutions for civil aerial photography, military air reconnaissance, analytical and digital photogrammetric plotting systems, grid data processing, data capture and output. In addition, solutions are available which permit data capture in GIS systems. Z/I IMAGING is thus offering a complete system, in state-of-the-art technology from one and the same provider, from aerial photography to the capture and output of topographical and GIS data.

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[1] Z/I Imaging Corporation a wholly owned subsidiary of Intergraph Corporation and Z/I Imaging GmbH a wholly owned subsidiary of Carl Zeiss are now operating, but completely independent. Upon approval of U.S. Department of Justice, Z/I Imaging GmbH will become a wholly owened subsidiary of Z/I Imaging Corporation.

To meet the requirements of our customers, an NT solution based on ImageStation and a UNIX solution based on PHODIS is being offered. Both systems were marketed successfully in the past.

Z/I IMAGING's strategy is focused sharply on customer satisfaction. For this reason, special consideration was given to the following aspects in the selection of our product portfolio:

- as complete a product line from one and the same supplier as possible
- service and support for all systems which have been manufactured in the past by Intergraph and Carl Zeiss to the extent to which this is economically reasonable and technically still feasible.

All products are sold in all Z/I IMAGING locations, and service and/or support provided for them, if possible. In the following, a presentation of the Z/I IMAGING systems is given.

3 Aerial and reconnaissance camera systems

3.1 RMK TOP the aerial camera system

For many decades now, camera systems from Carl Zeiss have been successfully used all over the world as high-performance systems for aerial photography. With RMK TOP, Z/I IMAGING has a camera system on the market which offers the following outstanding features:

- Modular design
  The most recent development of RMK TOP features a systematic, modular design. The individual components form logical functional units optimized to the needs of both practical application and economical use.
- High image quality
  The outstanding features of the lenses are:
    - very high image quality right to the corners
    - integration of internal filters into the optical system
    - high geometrical accuracy and very good color correction for the entire spectral range – from visible to near infrared
- Intelligent exposure control
  The automatic exposure control is based on the principle of –"image quality priority", which means that the optimum combination of aperture and exposure time is automatically selected for the prevailing lighting conditions, taking into account the specified film speed and filter factor.

- Constant access time
  The RMK TOP has a pulsed rotating-disk shutter with a constant access time of 50 ms. The benefits of this shutter are:
    - precise overlap control
    - direct exposure of single photos
    - exact triggering of exposure sequences

3.2 Reconnaissance camera systems

Although Electro/Optical sensors and other types of sensor systems have become more efficient over the time, photographic reconnaissance cameras still play a very important role in high resolution intelligence gathering. Z/I Imaging film reconnaissance camera systems implement and represent the results of collected experience in camera system design which meets and exceeds today's criteria of maintainability and reliability for use in modern military aircraft, pods, and drones.

Current programs include installation in aircraft such as in the GAF Recce Tornado, USN F-14 Tarps, and the CL-289 Drohne programs. Carl Zeiss has manufactured more than 1000 camera systems over the last 30 years. Z/I IMAGING will continue to produce and support these reconnaissance systems well into the year 2000 and beyond.

4 Analytical systems

Carl Zeiss was one of the world's first manufacturers of analytical systems. The PLANICOMP C series and P series systems have set the global standard in the field of analytical plotters. The C series was introduced into the market in 1976 and followed by the P series in 1986. The P Series has the following outstanding features:

- Maximum accuracy and quality level
- Superior optics
- High operating convenience, with P-cursor and tablet as the central control elements
- Universal hardware and software interfaces for connection of various plotting packages

The P series is a family of instruments:

- P1 Planicomp – the universal plotter of maximum precision, with extra large photo carriages
- P3/P33 Planicomp – high-precision analytical plotter, desktop instrument with vertically adjustable viewer

Z/I IMAGING offers the software packages PHOCUS and P-CAP for orientations, DTM collection and aerotriangulation measurement. Feature collection can be done either with PHOCUS or the P-Driver and MicroStation.

5 Image scanning

5.1 Introduction

The scanning of aerial photographs is a very critical step in the chain of digital photogrammetric image processing. Errors produced in scanning will propagate through the entire photogrammetric process. For a successful digital photogrammetry production, it is therefore vital to retain the precision of both the radiometric and geometric accuracy of the analog photograph.

Figure 1 – PhotoScan

5.2 Basic design principle

PhotoScan is a flat-bed scanner with a moving sensor and a fixed image carrier. This design eliminates the need to move the heavy film rolls (up to 7 kg). The high-precision mechanical scanning motion is simplified and the positioning accuracy of the system enhanced considerably.

Z/I IMAGING offers the scanner in a basic version (PhotoScan) and with a rollfilm option (AutoScan).

As optional scanning software, the program packages PhotoScan / AutoScan are available under Windows NT and the PHODIS SC program under UNIX.

The advantage provided by the modular scanner design is that a basic unit can be easily retrofitted with a roll film attachment. This permits the customer to be supplied with an optimally matched and low-cost configuration for his specific project, without being handicapped by technical restrictions or unnecessary costs.

5.3 Optics

The lens used is a high-speed mirror lens with a 1:1 image scale. It is based on a modified concentric Offner system and was developed by the Carl Zeiss optics specialist. The optics are manufactured with utmost precision by experienced experts.

The most important requirements such as

- no chromatic errors
- no symmetrical distortions
- telecentric imaging
- no optical vignetting
- very fast

are met.

This provides the user with a high optical resolution (72 LP/mm), high contrast and therefore an excellent basis for superb image quality. Users do not need to adjust the lens if the basic resolution is changed.

5.4 Sensor

A trilinear color CCD line serves as a sensor. For scanning, 5632 active pixels with a resolution of 7 µm are used.

In scanners, the solution using this line has the advantage over a CCD array that a higher scanning speed can be achieved for color pictures

The quality of the CCD line is always 100% and the line, contrary to the CCD array, displays no pixel errors. Because of these "blind" picture elements, the lost information in an array must be mathematically determined by means of a "defection map"

5.5 Electronics

A standard industrial PC is used to control the scanner, which is connected to the host computer via an SCSI II interface.

All resolutions (7,14,21,28,56,112,224 µm) have been implemented in the hardware, no resampling is required. The scanning speed increases if a lower resolution is selected.

This permits a fast survey scan of the complete image to be performed in just over one minute.

5.6 Roll film attachment

The scanner can be equipped with a roll film attachment for fully automatic scanning of uncut films. (*AutoScan*).

Using the appertaining software, complete film rolls scan be scanned in unmanned operation, for example during the night.

This allows production costs to be noticeably reduced. This option has been very well receive by customers.

As a second option, a RAID disk subsystem can be added to the Host workstation to provide sufficient disk capacity and a high scanning-data throughput for automatic roll film scanning.

5.7 Outlook

The launch of a newly developed CCD on the market has been a great success and constitutes a further improvement of the system. An independent test was performed at ETH Zurich by Dr. Baltsavias to demonstrate the system's efficiency. The radiometric quality was increased even further. The life span of the halogen lamp was drastically enhanced and now lies at 500 h. All existing instruments can be easily retrofitted.

The next development steps planned are a 10 bit CCD data option and an increase of the scanning speed.

Carl Zeiss, one of the world's leading manufacturers in precision engineering and optics, will continue to manufacture the PhotoScan for ZI/IMAGING.

6 Windows NT based Systems

6.1 Introduction

An integrated digital photogrammetry system is defined as hardware/software configuration that produces photogrammetric products from digital imagery using manual and automatic techniques. The output for such systems may include three-dimensional object point coordinates, restructured surfaces, extracted features, and orthophotos.

There are two major differences between a digital photogrammetry workstation (DPW) and an analytical stereoplotter. The first and perhaps the most significant is input data. Most problems arise due to the extremely large size of the digital images. This alone can almost cause the photogrammetric workflow to grind to a halt if the image file is not handled properly. The most efficient way to handle large image files is through smart file formats and image compression techniques.

The second change brought on by the digital photogrammetry system is a potential for automatic measurement and image matching that simply did not exist in the analytical stereoplotter environment. The automatic measurement and image matching techniques are the great value-added components that the new digital technologies bring to photogrammetry *(Madani, 1996).*

The advent of low cost symmetric multiprocessing computers and very high performance frame buffers allowed us to consider a new solution to the DPW design. The new DPW must satisfy both commercial and government photogrammetry requirements. Furthermore, it should keep pace with the rate at which computer technology is changing.

In this chapter, an overview of the Z/I IMAGING Integrated NT-Digital Photogrammetry System based on the Windows NT™ operating environment is given. The major hardware and software configurations of such a system are described. Finally, brief descriptions of digital photogrammetry workflows, such as scanning, digital mensuration and triangulation, three-dimensional feature and DTM collection, and orthophoto creation, are provided.

6.2 New DPW Design

When we considered options for the design of a next generation DPW, we recognized that a basic set of requirements must be fulfilled. Some of the main elements of the first generation ImageStation system were:

- Management of very large images
- Support for very large monitors
- Smooth and continuous roam across the entire image
- Stereo display in a window
- Stereo vector superimposition
- Fully functional data capture during roam

In addition to these fundamental requirements, a number of additonal requirements had to be met to satisfy the needs of government organizations. These additional requirements were:

- 16 bit per pixel panchromatic stereo processing
- Bicubic interpolation
- 5x5 convolution filtering
- Automatic convolution filter selection during zoom
- Automatic dynamic range adjustment
- N bit to 8 bit display mapping and gamma correction
- On–the-fly epipolar resampling

On-the-fly epipolar resampling would enable production shops to eliminate the time-consuming batch resampling of images prior to stereo exploitation. The remaining requirements would greatly enhance the quality of the displayed imagery and relieve the operator from the very tedious tasks of image enhancement during exploitation.

In-line software JPEG image compression and decompression eliminates the need to have the uncompressed images anywhere on the system. Software JPEG compression/decompression allows the system to uncompress the images on the machine only at display time, and only that portion of the image to be displayed. This capability enables operators to store, backup, and transfer over the network images that are approximately 1/4 the size for black and white images or 1/10 the size for color.

We also formed a set of design goals that were necessary to ensure that this system could keep pace with the rate at which technology was changing. Among these design goals were:

- Independence from custom hardware
- A single scalable executable
- Hosting on a platform with a large installed software base
- Hosting on a platform with a very high probability of maintaining backward binary compatibility

A careful review of these design goals led us to a symmetric multiprocessing (SMP) architecture. An examination of the workstation market for the late 1990s clearly indicated that the only "open" system supporting SMP that was suitable for technical processing was Windows NT. In addition, the Open Graphics Library (OpenGL) had been ported to the operating system. Thus, the architectural launch pad became:

- Windows NT
- SMP aware software
- Open Graphics Library (OpenGL) for raster and vector operations

6.3 Hardware Configuration

The Z/I IMAGING Integrated NT-Digital Photogrammetry System consists of the following hardware components:

- PhotoScan TD
- ScanServer
- ImageStation Z
- SSK Hardware Kit

6.3.1 ImageStation ZIII

Digital photogrammetry workstations (DPWs), powerful computers configured to do the work of an analytical stereoplotter, are very important components of a digital photogrammetry workflow. The DPW itself is the result of the digital photogrammetry requirements on the host computer having been integrated. These requirements include a high-quality stereo display, the ability to handle large images efficiently, and a productive ergonomic design. A high-quality stereo display is important both for comfortable stereo viewing and the accurate identification of image objects.

The current Z/I IMAGING's DPW is the ImageStation ZIII (Figure 2). The main features of this complete DPW are:

Figure 2 – ImageStation ZIII Configuration

- Dual 450 MHz Intel Pentium® II Xeon processors
- 512 KB cache for each processor
- 256 MB RAM, expandable to 2 GB
- RealiZm™II VX25 3D graphics accelerator, true-color, 2.5 megapixel maximum screen resolution
- 28-inch panoramic multi-sync, 24-inch panoramic multi-sync , or 21-inch multi-sync selectable resolutions from 640 x 480 1,980 x 1,200
- Dual screen options available for the above monitors (passive stereo option available for 21-inch)
- 45.5 GB disk storage (one 9.1 GB and two 18.2 GB hard drives)
- Stereo viewing kit; Ten-button two-handed cursor; Multimedia keyboard; 3-button mouse
- High-precision D-sized (34' X 22„) digitizing surface in a single surface table; Adjustable Cyborg chair
- One copy of Windows NT operating system

6.3.2 ImageStation Softcopy Stereo Kit

In April 1998, Intergraph introduced a new system to extend the range of its industry leading photogrammetry solutions. This system allows a customer to convert an Intel based workstation-level PC into a DPW.

Dubbed the ImageStation Softcopy Stereo Kit (SSK) and ImageStation Softcopy Stereo Kit Pro (SSK Pro), these kits include everything a customer needs to get started in high productivity for applications such as model orientation, stereo compilation, DTM collection and editing, except the PC and MicroStation^{TM} (Figure 3).

SSK highlights include:

- High-quality stereo display on your stereo-capable, 21-inch (or smaller) monitor
- Smooth stereo roam in a PC window
- On-the-fly epipolar resampling
- In-line software JPEG compression/decompression for smaller image sizes and faster file transfer

Minimum system requirements:

- Single 200 MHz Pentium Pro processor (dual Pentium II processors recommended)
- 128 MB RAM
- 3.3 volts on PCI bus
- Monitor that can stereo synch at 120 Hz (for best performance)
- Parallel port for software runtime protection

Hardware components

- Intergraph's Intense 3D Pro 2200S stereo frame buffer for stereo display
- CrystalEyes (liquid crystal) stereo glasses and emitter
- 3D mouse for precision digitizing in X, Y, and Z

Figure 3 – ImageStation SSK Hardware Kit

6.4 Software Configuration

The Z/I IMAGING Integrated NT-Digital Photogrammetry System software is designed for a complete end-to-end digital workflow. This workflow may be divided into two separate operations, visual database creation and visual database exploitation. The visual database creation deals with photo scanning, image mensuration and triangulation (orientations and/or bundle block adjustment), and epipolar image generation, if necessary. The visual database exploitation deals with 3-D feature /DTM collection, CAD model generation, and orthophoto creation (Figure 4).

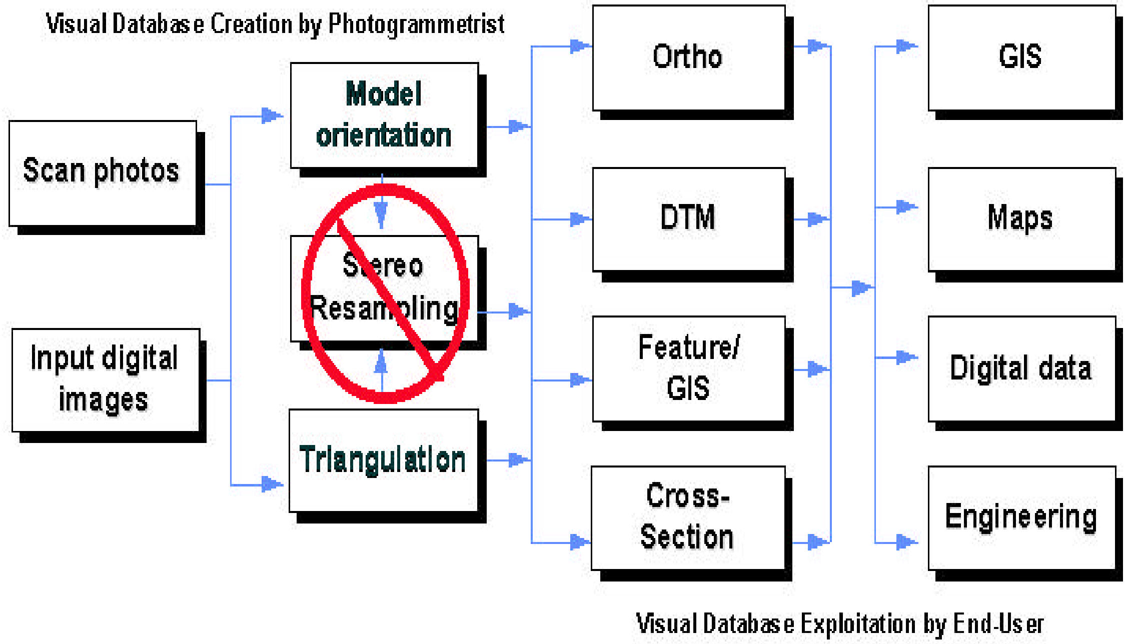

Figure 4 – Digital Photogrammetry Workflow

In general, the major digital photogrammetry workflows are as follows:

- Mensuration and triangulation
- 3-D Feature and DTM extraction
- Orthophoto Generation

6.5 Mensuration and Triangulation

ImageStation Photogrammetric Manager (ISPM) provides photogrammetric data management tools required for the production workflow. It provides entry/edit menus, the bulk input/output of photogrammetric data, and various import/export options for several third-party photo triangulation packages. It also has the interfaces between the ImageStation Z applications.

Orientation and/or triangulation of digital imagery (frame and satellite) can be accomplished by the following four products:

1) ImageStation Model Setup (ISMS)

2) ImageStation Digital Mensuration (ISDM)

3) ImageStation MATCH-AT (ISAT)

4) ImageStation Multisensor Triangulation (ISMST)

6.5.1 ImageStation Model Setup

ImageStation Model Setup (ISMS) is a simple, easy-to-use measurement environment for Interior, Relative, and Absolute orientations and Single Photo Resection. It allows image panning within any measurement window for smooth, real-time image movement.

6.5.2 ImageStation Digital Mensuration

ImageStation Digital Mensuration (ISDM) provides a multi-image, multisensor point transfer and measurement environment for a photogrammetric triangulation workflow. The use of auto-correlation and on-line integrity checks (on-line photo triangulation) improves accuracy, increases productivity, and increases reliability. The image point coordinates generated by ISDM can be used in the PhotoT (including bundle adjustment) module or can be formatted for input into one of the Z/I IMAGING supported third-party triangulation packages.

PhotoT provides the user with an interactive interface to a bundle adjustment program and other tools facilitating the photogrammetry adjustment process. These tools are useful for setting up adjustment parameters such as blunder detection and variance-covariance computation, selecting photos/models, quality control analysis for (IO, RO, AO, Bundle), bulk processing, and densification.

ISDM has also an integrated "Map Sheet" capability. This capability allows the operator to collect control points from scanned hardcopy maps or existing pre-registered orthophotos in different coordinate systems. This feature also facilitates finding photo identifiable features on satellite or aerial images using scanned maps or orthophotos.

6.5.3 ImageStation MATCH-AT

ImageStation MATCH-AT (ISAT) is an automated aerotriangulation package combined with editing facilities. The main module of ISAT is MATCH-AT, a fully automated aero-triangulation package provided by INPHO of Germany. The objective of MATCH-AT is to automate point transfer and tie point measurement operations, thereby minimizing manual work and operator intervention. It uses Feature Based Matching (FBM) and Least Squares Matching (LSM) techniques and aims at an operational system leading to very reliable and accurate bundle adjustment results *(Madani, 1997).*

ISAT incorporates editing facilities and an interface with ISDM and combines point selection, point measurement, point transfer, and block adjustment into a single process. ISAT has the capability to use GPS data as initial values for exterior orientation parameters as well as for GPS triangulation.

6.5.4 ImageStation Multisensor Triangulation

ImageStation Multisensor Triangulation (ISMST) is a software package for measuring and triangulating SPOT, LANDSAT, and IRS satellite imagery. The ISDM product is used for measurement, review, and editing operations and TRIFID Corporation provides the mathematical model and the adjustment components.

A particular form of the collinearity equation, which accounts for the time dependent nature of the sensor, is used in this product. The triangulation includes exterior orientation parameters on an orbital "strip" basis. These exterior orientation parameters include the six parameters describing the orbit (position and velocity) and six parameters describing the orientation of the vehicle (roll, pitch, yaw, and their rate of changes).

The primary output from the multisensor triangulation is a three-dimensional object grid files. A set of Rational Function equations are fitted to these grids by a least square adjustment. The estimated rational function coefficients are used for real-time photogrammetric operations (3D-feature/DTM collection) as well as orthophoto generation.

6.6 3-D Feature and DTM Extraction

After triangulation/orientation has been completed, each stereo model is ready for stereo viewing and digitizing. Resampling into epipolar geometry is performed on the fly for each stereo model. 3D feature/DTM extraction is carried out by ImageStation Stereo Display (ISSD), ImageStation Feature Collection (ISFC), ImageStation DTM Collection (ISDC), and ImageStation MATCH-T (ISMT) products.

6.6.1 ImageStation Stereo Display

ImageStation Stereo Display (ISSD) is a complete stereo raster image display and manipulation product that includes Intergraph's exclusive ImagePipe™ core processing software within a MicroStation environment. ISSD provides the operator with multiple stereo views and the ability to display an overview of the stereomodel. This "navigation view" allows the operator to see where he is in the detail or extraction window while also providing a rapid means of windowing in on an area not displayed in the roaming view.

ImageStation ZIII Graphics provides frame sequential stereo. Frame sequential stereo is used to optimum clarity and sharpness of imagery. This translates directly into less operator eye fatigue and greater precision in the "Y" direction. The frame sequential stereo allows the operator not to refocus when interacting with menus, and therefore provides extremely comfortable, flicker free stereo viewing and easy to read texts on the same monitor.

6.6.2 Map Feature Collection

ImageStation Feature Collection (ISFC) provides a low-cost, easy-to-use, map feature digitizing system for use with stereo aerial, SPOT, and other satellite imagery. ISFC provides an efficient map feature digitizing system that extends MicroStation capabilities. It furnishes numerous commands to collect and edit feature data. ISFC utilizes screen-based, icon-driven menus to provide a user interface designed for map production. A feature-based table is utilized, allowing the user to define a series of map symbologies and manage them on a job-by-job basis.

6.6.3 DTM Collection

ImageStation DTM Collection (ISDC) provides an interactive method for collecting digital terrain model (DTM) data, elevation points, breaklines, and other geomorphic features. ISDC can also be used to edit existing DTM data. Real-time dynamic editing allows the user to see what effect the edits have on the contours or TIN surface immediately. ISDC uses a feature table to define geomorphic features and acts as a front-end for ImageStation MATCH-T, automatic DTM collection.

ISDC provides different modes of semi automatic DTM collection utilizing a Cursor-On-Surface (COS) module. It overlays ISMT batch DTM extraction on the stereo model for editing and detection of trouble areas. It also imports and exports various DTM file types.

6.6.4 ImageStation MATCH-T (ISMT)

ImageStation MATCH-T (ISMT) provides automatic extraction of DTM elevation points from digital aerial and satellite stereo images. A high degree of automation is achieved through the use of hierarchical image data structures and image processing methods. This product works in conjunction with the ISDC software.

ISMT generates DTM points in a model, ground, or user-defined coordinate system. ISMT creates separate class definitions and symbologies for points of different statistical qualities. Matching and terrain parameters and DTM grid spacing can be tuned within the ISMT environment.

6.7 Orthophoto Generation

Orthorectification is a process of removing the effects of tilt, relief, and other lens aberrations from perspective imageries. Orthophotos can be created using the following Z/I IMAGING products (Figure 5).

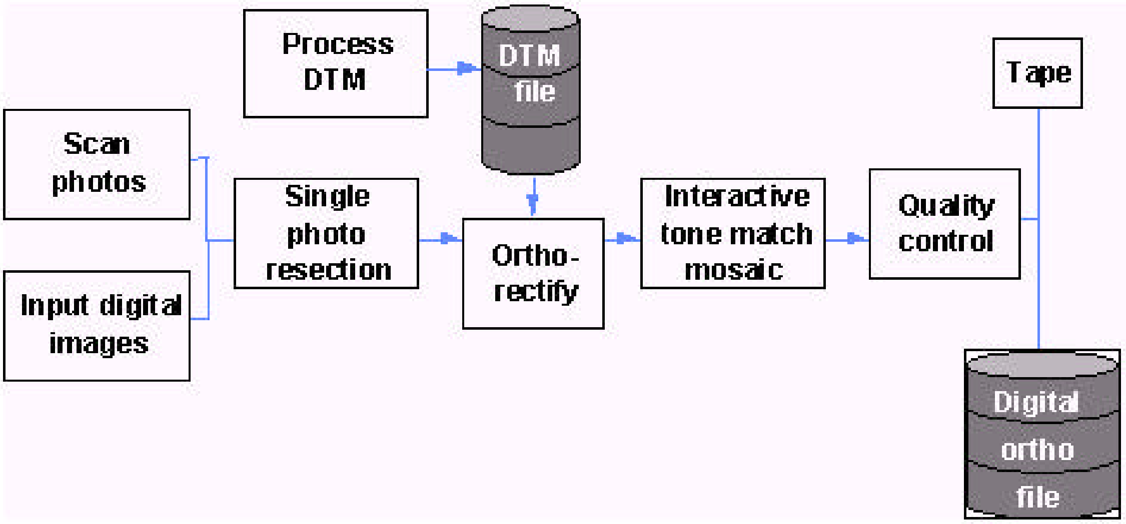

Figure 5 – Orthophoto Rectification and Mosaicking Workflow

6.7.1 ImageStation Base Rectifier

ImageStation Base Rectifier (ISBR) is an interactive and batch program for ortho-rectification of aerial and satellite imagery. Orthorectified imagery produced by ISBR can be used as input for softcopy and hardcopy image map and orthophoto map production. The orthorectified image can be used as a backdrop for a GIS or for heads-up digitizing. Any ground features collected in stereo 3-D extraction can be displayed in their true orthographic positions directly on top of the newly generated orthophoto. ISBR has the capability to choose output pixel size in ground units or by defining the number of rows and columns in the output image. The user can define the type of resampling method, the pixel spacing for the anchor points, different tile sizes, the number of overviews and how they are processed, and the coordinates and rotation of the output image. ISBR uses DTM files in either grid or TTN formats and it also supports different raster formats.

6.7.2 ImageStation OrthoPro

ImageStation OrthPro (ISOP) provides a more complete system in support of orthophoto generation workflow. ISOP assumes that the user has performed an adjustment on all input images and now wishes to generate a mosaicked, tonally balanced orthophotos.

ISOP combines the functionalities of existing Photogrammetry and Imaging products. It uses ISPM for project information (camera, control, photo), translators for import/export data and file management, ISBR for image rectification, GeoMedia for product planning, mosaic line definition, basic image display and the user interface for tonal correction and graphical image selection.

Elevation data may be selected as a grid, TTN, USGS DEM, USGS SDTS DEM format or as any combination of these. The DTMs are selected from a list or graphically. Graphic selection allows the user to see areas where DTM data may be missing for the coverage area. Multiple DTM files of different format and coordinate systems can be combined into a new coordinate system on the fly. Other ISOP main features are:

- Tone matching and balancing the radiometry of all images both black & white or color
- Mosaicking along user-defined seam lines
- Feathering seams based on user-defined parameters
- Digital dodging for "hot spot" removal – improves the output image during the mosaic process
- Displaying input image footprints, output boundaries, and elevation data boundaries
- Specifying clipping areas – eliminates fiducial areas from the final output product
- Quality control - control points may be automatically placed in the GeoMedia display for QC/QA.
- Multi-threaded orthorectification – takes advantage of multiple process machines for fast processing and handling of large image loads.

7 UNIX based systems

7.1 Introduction

PHODIS is the UNIX based digital photogrammetric system from Z/I IMAGING which has been very successful since its launch on the market in 1991. PHODIS initially comprised an orthophoto module and was very rapidly extended by a stereo- and monoplotter, TopoSurf and finally by the automatic aerotriangulation system and a roll film scanner. These PHODIS components will be dealt with in the following chapters, with special emphasis on the degree of automation already achieved.

7.2 PHODIS Base

PHODIS Base forms the basis of the dedicated PHODIS components. It provides all functions jointly required by the PHODIS components and, in addition, offers each user a software interface to permit the control of PHODIS components or the processing of PHODIS data files via user-specific software. PHODIS usually receives its digital images from the Z/I IMAGING SCAI or PS1 scanner, but it also processes images from other scanners in different formats which are converted into PHODIS image files by PHODIS Base. One of the largely automated modules of PHODIS Base is the interior orientation feature (AIO) which permits fully automatic measurement of the interior orientation for all common types of aerial survey cameras. AIO determines the position of the fiducials and the image rotation, and is able to recognize whether the image is a positive or negative and whether a "right reading" or "wrong reading" image is involved.

7.3 PHODIS AT (Automated Aerotriangulation)

PHODIS AT makes full use of the benefits of digital photogrammetry and speeds up the aerotriangulation process many times over. Starting out from rough information on the block structure, a combined "feature based" and "intensity based" matching method is used for the fully automatic measurement of all tie points in the block. In this process, the points are simultaneously measured in all overlapping images. Automation in PHODIS AT has advanced to such a degree that the operator only needs to monitor the process and perform the semi-automatic measurement of the control points. PHODIS AT offers the following outstanding features:

- Block information can be imported from the flight management reports. If no reports are available, the block information can also be specified in a local system.
- The block can be divided into subblocks to solve the problem of limited disk capacity.
- Simultaneous "multi-image" processing, i.e. the simultaneous matching of images with multiple overlaps.
- Semi-automatic control point measurement
- Fully automatic tie point measurement
- Convenient user guidance
- Processing of any type of block configuration combining longitudinal and crossing strips
- Connection to standard block adjustment programs such as PAT-B, BINGO, BLUH, ALBANY, CLIC
- Fully automatic generation of control point sketches.
- No need for GPS or DTM data

The extraordinary cost-effectiveness of the system and, in particular, the high attainable accuracy have been verified in intensive tests (*Hartfiel P., 1997; Braun* et al. *1996).*

PHODIS AT was recently changed and provides now an enhanced correlation between strips and between the photos in the strips, thus increasing the stability of the overall block.

The major new feature of the PHODIS AT is the increased number of multiple points within the block.

During automatic block generation in PHODIS AT, significant points are first extracted at the top image level in all images. These points are then traced through all pyramid levels down to the original images. In this process, the assignment of the points to individual images may be lost. A 6-fold point, for example, may be reduced to a dual point.

In the new version, the program searches the multiple overlap areas for such multiple points and transfers them to the adjacent images using least squares matching. This ensures that a point really correlates with all images in which it occurs.

The new version also checks closely adjacent points. If two points are found to be identical or virtually identical, one of them is eliminated.

The following table compares the results obtained with the former and new versions in different blocks:

Example	**Former Version**							**New Version**				
	9x	*8x*	*7x*	*6x*	*5x*	*4x*	*9x*	*8x*	*7x*	*6x*	*5x*	*4x*
atdemo				5	8	21				40	21	32
kapellen				1	5	64				36	26	160
kunrau 1				0	0	4				1	8	54
kunrau 2				0	0	3				8	51	71
montserrat			3	40	43	153	68	18	14	146	62	100

7.4 PHODIS TS (Automated DTM generation)

DTM generation was one of the first applications in Digital Photogrammetry to become highly automated for operational production-oriented photogrammetry. As the generated DTMs require some means of quality control, interactive tools have been developed to check, re-measure, and substitute the automatically derived elevations by interactive measurements. Tools of this type have been implemented in PHODIS TS which incorporates the functionality of a digital stereoplotter (see below). In preparation for an automated DTM run, morphological information such as breaklines, cutout areas and singular points can be collected in the stereo model. This additional information helps to further increase the quality of the automatically measured, derived, and modeled DTM which is optimally generated for the stereo model. Stereoscopic color superimposition of the resulting DTM and secondary data, e.g. contour lines, is possible. Thus, DTM generation is partly an interactive and partly an automated processing stage in the photogrammetric production flow.

7.5 PHODIS OP (Orthoimage Generation)

Orthoimages are digital orthophotos. Their generation, in the way implemented by PHODIS OP, is often the main purpose of a photogrammetric application flow. Aerotriangulation and DTM generation are then considered as necessary, but only intermediate steps. Fortunately enough, all three applications – aerotriangulation, DTM generation and orthoimage generation – are extremely suitable for automation. Geometrically ideal orthoimages can be obtained by digital orthoprojection if artificial objects such as houses, bridges etc. can be modeled *(Mayr 1994)*. Such objects can then be correctly positioned within the orthoimage. In this way, the orthoimage achieves a level of quality that can never be reached in an orthophoto produced, for example, on an analytical orthoprojector. Also of importance is the possibility of generating radiometrically homogeneous, seamless orthoimage mosaics. Both, orthoimages and mosaics, often serve as an image backdrop for the vector information stored in the GIS database.

7.6 PHODIS ST (Digital Stereoplotting)

Digital stereoplotting has to compete with analytical stereoplotting. To achieve the same performance, it must be possible to move large image windows smoothly in a continuous stereo mode over the stereo monitor. All implementations used an intermediate preprocessing step and generated pairs of epipolar images. This reduced the display task to a simple translation of the image windows. The drawback, however, was the preprocessing step which required disk space and extra time. With PHODIS ST10, Carl Zeiss for the first time introduced the stereoscopic display of a pair of oriented images without the need to generate epipolar images in an off-line preprocessing step. This is possible through an algorithm which acts as a kind of *digital real-time dove prism* and also allows continuous zooming, real-time image rotation, and arbitrary image positioning with subpixel accuracy and with on-line resampling in real-time. The equivalent of the real-time loop known from analytical stereoplotters is open, e.g. for the implementation of different imaging geometries. This feature has been incorporated to integrate the imaging models of the SPOT and MOMS cameras in a mathematically correct way *(Dörstel 1996).* An application programmer's interface enables PHODIS ST to be hooked up to different data capture systems. This is of particular interest for GIS which in this way can consider the digital stereo plotter as a 3D-digitizer and directly record 3D coordinates and topology. Such automated orientation procedures as automatic interior and relative orientation have successfully simplified the stereo model setup and made it attractive, for example, for GIS users.

7.7 PHODIS M (Digital Monoplotting)

The combination of orthoimages or mosaics with a DTM and their use for coordinate measurement is the classical task of monoplotting. PHODIS M implements this combination and the connection to either PHOCUS or MicroStation. Map revision, map updating, and change detection are examples of applications for which this tool can be used.

8 Solutions for Mapping and Geoengineering

Depending on your discipline – engineering, government, transportation, forestry, or a related geographic field – you have many different sources of data. To meet your needs, Z/I IMAGING offers solutions for integrating raster and vector data across the spectrum of mapping and geoengineering. Our imaging solutions provide the tools to handle image mapping, GIS, civil engineering, and data conversion projects that require large images, – whether from satellite or aircraft platforms, scanned maps, radar, or any other type of imagery.

These products allow you to integrate disparate data – native read of industry-standard format, including TIFF, GeoTIFF, TIFF World, BMP, PCX, JFIF (JPEG), GIF, MrSID, BIL, USGS DOQ, NITF, and others – into your existing workflows. Whether you are simply placing an image backdrop to your design or doing complex feature extraction, our integrated solutions will make your task easier. You will benefit from our special features, such as rapid display and manipulation of very large raster data sets, fast dynamic zoom, pan, fit, window area, and hybrid (raster and vector) plotting. Our solutions offer complete vector graphics and raster integration on MicroStation, providing a seamless environment with other MDL-based mapping, civil engineering, and GIS applications.

8.1 Image Viewer

Image Viewer is a low-cost, high-powered solution for displaying map-registered binary, gray scale, or color raster images. Image Viewer provides a host of easy-to-use image viewing and management tools for users who require economical and efficient image backdrop display for screen-based digitizing and vector/map update.

8.2 I/RAS C

I/RAS C is a powerful toolkit for the display and manipulation of grayscale and color raster images and maps. I/RAS C provides a full set of commands to import, display, warp, mosaic, and enhance raster images. I/RAS C is a complete solution for cartographic updates, aerial image mapping, and GIS applications that do not require multispectral analysis.

8.3 Image Analyst

Image Analyst offers all the features of I/RAS C, plus advanced processing and analysis tools for your specialized satellite and aerial images. Added features, like radiometric and atmospheric correction, spatial filtering, color transforms, and multispectral classification, make Image Analyst the clear choice for advanced users.

8.4 I/GeoVec

I/GeoVec is used to interactively convert scanned maps into GIS-intelligent vector features. I/GeoVec utilizes advanced semi-automatic line-following techniques, automatic cell and symbol placement, and automatic feature capture and assignment. I/GeoVec's tools are optimized for the unique requirements of map data conversion and handle both line work and text.

8.5 I/Parcel Vec

I/ParcelVec accelerates parcel data capture by providing a set of semi-automated, customizable raster-to-vector conversion tools tailored for parcel management applications. It takes any scanned parcel drawings or other digital parcel data in raster form and converts them to vector features for use in cadastral workflows in a variety of GIS, LIS, and AM/FM applications. For parcel-related data, I/ParcelVec's powerful, easy-to-use customization tools offer significant increases in performance and accuracy over table and heads-up digitizing and other raster-to-vector conversion methods.

8.6 Terrain Analyst

Terrain Analyst provides capabilities to create, manipulate, display, and analyze digital terrain models that can be represented as triangulated irregular networks (TIN) or regularly spaced matrices (grid). Terrain models can be built from MicroStation design file elements, ASCII formatted files, DMA DTED files, USGS DEM files, SDTS DEM data, or existing .ttn, .grd, and .xyz files. Output representations of the surface models include contours, color-coded elevation displays, wireframe displays, grid surface displays, shaded relief displays, image draping, and drainage networks. Output file formats include TIN, grid, ASCII, DEM a DTED. MGE Terrain Analyst also provides a method for tagging contours, and for reading elevation values directly from a database.

References

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