June 1996

EUROPEAN ORGANIZATION FOR EXPERIMENTAL PHOTOGRAMMETRIC RESEARCH

Proceedings of the

OEEPE - WORKSHOP
on
APPLICATION OF DIGITAL PHOTOGRAMMETRIC WORKSTATIONS

Lausanne, 4–6 March 1996

Editor: O. Kölbl

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Proceedings of the

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(with numerous figures and tables)

Lausanne, 4–5 March 1996

Editor: O. Kölbl

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Preface

Raster technology in conjunction with geographic information systems and digital photogrammetry are creating completely new perspectives and meaning to the world of topography and planning. The techniques, however, are undergoing strong development and it is not easy to obtain thereupon just an overview. With the workshop on the "Application of Digital Photogrammetric Workstations" and the creation of the working group on this topic, OEEPE has tried to create a forum of discussion. The present proceedings of the workshop intend to give an intermediate review on the development and the practical application of digital photogrammetry.

It might be too early to already revise a manual of digital photogrammetry at this stage and these proceedings do not attempt to replace it. The compilation of all the conferences and the transcription of the following discussions might however give a rather good picture of the actual state-of-the-art digital photogrammetry and its practical application. It is understood that such a momentary review of a rapidly changing technology has only a very short lifetime. Consequently, it appeared important to edit these proceedings with the discussions fairly rapidly. Time was of essence and the manuscript had to be prepared within a period of only one month. It is hoped that this book will stimulate and provoke a number of intuitions for the discussions at the Congress of Photogrammetry and Remote Sensing in Vienna. Unfortunately, due to the time pressure, it was not possible to work out all contributions with the necessary care nor was it possible especially, to put the printed discussions at the disposal of the speakers for a review; therefore, the editor takes over the responsibility for it.

On the other side, the discussions especially represent a substantial part of this publication. For example, the necessity of the creation of standards for the exchange of images and the exchange of transformation parameters, or the problematic of the management of some hundreds of Gigabytes of image data are difficult to present in a scientific article. Without any doubt, the activity of the working group is not finished with this publication and it will be of great importance to move forward at a creation of standards as strongly and unanimously suggested.

The editor of the publication is grateful to the working group and to the participating vendors for their excellent collaboration. He would also like to express his thanks to all active participants of the workshop for their valuable and quality feedback. The very open discussions between users and vendors were clearly a very special feature of the workshop and this gives hope to succeed with a much more difficult task of creating more elaborate standards in the future. In addition, the editor extends his thanks and appreciation to the following for their meaningful contributions to the text: the IFAG (Institut für Angewandte Geodäsie) in Frankfurt for the rapid printing; Mrs. Sallie Braun for the transcription of the discussions; and Mr. David Meylan together with Mr. Jean-Claude Lorenzelli for the preparation of the manuscripts.

Lausanne, 15 April 1996 O. Kölbl

Executive Summary
of the
Workshop on the "Application of Digital Photogrammetric Workstations"

The Working Group of OEEPE on the "Application of Digital Photogrammetric Workstations" organized a workshop which was held from March 4–6, 1996, at the Ecole Polytechnique Fédérale in Lausanne. The following principles directed the organization of the workshop :

1. **Digital photogrammetry is used more and more in production work.**
2. **The special working procedure of digital photogrammetry provokes intense modifications in practical work and it opens new perspectives for practical applications.**
3. **The photogrammetrists are confronted with considerable problems when introducing the new techniques.**
4. **An in-depth dialog between manufacturer and system user would be highly desirable.**

The OEEPE Working Group is composed of the following organizations :

- Institut Cartográfic de Catalunya (ICC), Barcelona (J. Colomer, Margarita Torre, J. Romeu)
- National Geographic Institute (IGN), Paris (C. Dekeyne, A. Dupéret, Raphaële Héno)
- National Geographic Institute (IGN), Brussels (J. Vanommeslaeghe)
- Eurosense, Wemmel (J. Loodts)
- Cicade, Namur (Annabelle Honorez)
- Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne (O. Kölbl, President)

In order to give a comprehensive overview on the new techniques, it was decided to concentrate on the following topics :

1. Scanning
2. Aerial triangulation
3. Automatic derivation of a DTM
4. Orthophoto
5. Digital plotting
6. Logistics and integration of the system
7. Financial aspects

Vendors who participated in the workshop:

- Carl Zeiss, Oberkochen (Z. Poth, Gertrud Roth)
- DVP Geomatic Systems, Charny, and Leica Unterentfelden (J.-P. Agnard, J. Coulombe, B. Perini)
- Helava, San Diego and Leica Unterentfelden (A. Dam, A. Chapuis, S Gevrey, A. Meid, B. Taft, U. Tempelmann)
- Intergraph, Huntsville/Hoofddorp (J. Carswell, M. Madani)
- Matra (C. Cruette)

As a brief summary, one can give the following elements:

Techniques of digital photogrammetry are mainly used for the production of orthophotos, for aerial triangulation, for the determination of digital terrain models and to some extent, for mapping and map revision. Digital photogrammetric work stations are replacing more and more analytical plotters, although manufacturers claim that about the same number of analytical plotters are still sold today.

The discussion revealed the efficiency of digital aerial triangulation and also the advantages of incorporating matching techniques for the derivation of digital terrain models. Furthermore, it became evident that costs for orthophotos and also for map printing could be reduced considerably if the user would concentrate on the application of digital data.

Most mapping organizations use different equipment from different vendors in order to meet their specific requirements. The exchange of digital data appears to be very cumbersome in such a multi-platform environment; thus, standards for image formats, transformation parameters and the orientation elements would be necessary; OEEPE was asked to help define such standards. Furthermore, most organizations customize the available software tools. Vendors are asked to open their systems as far as possible and to generalize the intergration of their software tools into user libaries, but again, standards would be desirable.

Part 1. Scanning

(Chairman O. Kölbl, J. Romeu)

Image acquisition is still exclusively done by photographic cameras and scanners have to be used for the conversion of the images in a digital form. The scanning of negatives and colour reproduction still give problems as for the data handling.

Under the scanner session, 4 papers were submitted :

- Preliminary Results of the OEEPE Scanner Test (O. Kölbl)
- PS1 Inserted in a Fully Digital Environment of Image and Restitution Map Production. Work Flows, Fails, Quality and Statistics : Position paper (J. Romeu)

- Desk Top Publishing Scanner (E. Baltsavias)
- Experiences with the Rastermaster RM1 (K. Jacobsen)

During the discussion, it became apparent that scanning is still a very time consuming process, mainly as **each photograph has to be treated individually** and hardly one of the scanners is equipped for roll film.

A problem linked to the management of the scanning process is the **organization of the data.** The repartition of discs in units of 2 Gigabyte or the storing on tape considerably complicates the management of the data and it appears necessary to conceive a special data base for this task.

An important aspect in this context is **data compression**; it seems that JPEG is now accepted as standard; in the near future, however, it will be mainly used as **JPEG software on-the-fly**. Furthermore, it was discussed whether it would be desirable to already include in the scanning process the creation of the image pyramids, the inner orientation, or even elements of exterior orientation.

The **scanning of the original negatives still is not very satisfying** due to the limited dynamic range of the scanner and the rather high image noise in the darker areas. **In addition, when scanning colour and especially false colour photographs, problems arise** due to the lower sensitivity in the blue area. In this context, reflections were made whether the images should be scanned with 12 or 14 bit. The use of desk top scanners seem to be an interesting solution, when the requirements in geometric precision and resolution can be reduced.

According to the discussion, it appeared that **TIFF tiled with JPEG** compression could be a general standard, at least for the exchange of digital photogrammetric images and **OEEPE was asked to prepare a proposal.**

Part 2. Digital Aerial Triangulation

(Chairman : J. Vanommeslaeghe)

Digital aerial triangulation proves to be extremely efficient when compared to the analytical plotters and takes advantages of efficient tools of automatisation.

Conferences to this topic were given by :

- Digital Aerotriangulation in Practice: Position paper (J. Vanommeslaeghe)
- An Overview on Commercial Software Products for Digital Aerial Triangulation (O. Kölbl)
- Digital Aerial Triangulation with the Helava Automated Triangulation System HATS (Th. Kersten)
- Digital Aerial Triangulation in Practical Use on Image Station (M. Beckschäfer)

- Annotations for a Fully Automatical Aerial Triangulation (F. Ackermann)

Currently, the principal commercial software products that are used for production in that field come from Intergraph. **The Intergraph ImageStation allows efficient production**, although the process of automation is quite limited. To some extent, the DCCS software of Helava is still also used in production.

At the workshop, **Zeiss and Helava** demonstrated triangulation software packages as β-version (status March 1996), which allow largely a **fully automated aerial triangulation**. Also, the **Inpho Company (Prof. Ackermann)** in Stuttgart works hard on a fully automatic approach of aerial triangulation. It can be expected that these products will be available and operational within a few months. The Inpho package might be available then on the Intergraph ImageStation.

Currently, a production rate of about 60 models per day can be achieved in triangulation; the preparation of the data by scanning might also require a full work day or a shift of 8 hours. The **handling of the data** for aerial triangulation requires the **use of efficient image servers**, an important prereq-uisite for digital photogrammetry.

The **efficiency** of digital aerial triangulation **justifies the digital approach** even for that operation alone; operational limitations might be the **difficulties to get the operators acquainted** with the new technology and the necessity to dispose on a sufficient volume of work justifying the investments.

Part 3. Automatic Derivation of a DTM

(Chairman: A. Dupéret)

The presentations were focused on experiences with the software packages Match-T and the Helava software. The automatic derivation of a DTM needs precautions as for the choice of the proper filtering technique and the delimitation of the working zones. Nevertheless, it seems that these techniques allow considerable productivity gains compared to the classical measuring methods.

The following papers were given to that topic :

- Overview on Matching Techniques : Position paper (C. Heipke)
- Automatic Derivation of a DTM to Produce Contour Lines (A. Dupéret)
- Experiences with Match-T for Orthophoto Production (M. Torre)
- Some Experiences with Feature Matching (F. Ackermann)
- Automatic Derivation of a DTM with the Helava System (D. Gasior)

The users who were present at this workshop currently concentrate on the use of Match-T and the Helava-Software. Some users also made great efforts to develop their own software to respectively refine the available methods. During the discussion, it was conveyed that experiences are greatly needed to be able to use the DTM software package properly. The ICC in Barcelona uses the Match-T software, but in general, makes 2 runs; in a first run, the area is matched and the results are analyzed and roughly edited. Then in a second run, these results are used as input in order to refine the matching results. Matching is mainly used for orthophoto production. The IGN in Paris also developed a refined strategy to derive contour lines for its 1:25'000 BD-topo with the Helava software.

In an open terrain, a precision between 0.1–0.2‰ of the flying height is obtained; but partially covered terrain needs to be controlled severely and a thorough editing is needed. Nevertheless, the digital matching techniques allow to speed up the production considerably.

In this sense, a severe quality control is vital; several times the "wish" was expressed that the matching program should efficiently support the operator for detecting points with unreliable results.

Also, one heavily discussed issue was the question whether matching should be done in images which were resampled according to epipolar lines or if the original images are preferable.

Part 4. Orthophoto

(Chairman : J. Romeu)

Orthophoto production was mostly the primary reason for many enterprises to engage in the techniques of digital photogrammetry. According to a rough estimate based on a survey of the working group, it showed that about 50–75% of the capacity of digital work stations are used for the production of orthophotos.

The following papers were given to this topic :

- Orthophoto as an Input of Publishing Graphic Art : Position paper (J. Romeu)
- An Introduction to Digital Printing Techniques (D. Meylan)

The presentations and discussions showed that orthophotos are largely accepted by the map user community. Orthophotos could be produced very inexpensively, provided that the clients accept a **digital product** with a minimum cartographic editing and lettering. The pure orthophoto production was estimated to 5% of the total costs; whereas 95% of the costs come from cartographic work and printing. Offset printing and especially, the storage of printed maps cause enormous costs which could be avoided if the **user accommodates to take over the digital data** and then prints the data according to his specific requirements with electronic printers.

It was suggested that **OEEPE should work out standards defining the presentation of orthophotos** either in printed or in digital form.

Part 5. Plotting

(Direction : C. Dekeyne, M. Torre, A. Dupéret)

An advantage of data capture for topographic mapping on digital work stations is the efficient possibility of superimposition of already existing maps for revision or of the map in work. However, it appears that the production is rather expensive, at least on the high end work stations and the image visualisation is less favourable than on the analytical plotters.

The following papers were given to this topic :

- Applications of Digital Photogrammetric Workstations : Digital Plotting : Position paper (C. Dekeyne)
- Experiences with the ImageStation for Data Capture (M. Torre)
- Digital Plotting and Structuring of Data (J.-F. Rolle, O. Kölbl)

National topographic institutions using digital work stations for plotting are the ICC in Barcelona and the IGN in Paris. The IGN in Paris recently started production and currently uses 5 digital work stations of Helava whereas the ICC in Barcelona already started production in 1993 and uses now 8 digital work stations of Intergraph. The ICC earlier used analytical plotters, but shifted the complete production to the ImageStation. The main advantage of digital work stations for plotting is the efficient super imposition of the map in progress; thus, higher productivity results from the cleaner data and savings in post editing. Digital work stations downtime was only 2.3%, as estimated by the ICC Barcelona and does not seem to be higher than with analytical plotters.

The operators seem to accept the new tools very favourably, although the new systems require a radical change of the working methods. This adaptation cannot always be expected from operators who have already worked a long time on analytical plotters. Comfort of operators: no real complaints.

Part 6. Logistics and Integration of the System

(Chairman : Raphaële Héno, J. Colomer, J. Loodts)

This part served to present and share the experiences of the great mapping organizations when introducing the digital working techniques and to initiate a dialogue with the manufacturers.

The following papers were given to this topic :

Logistics and Integration of the System:

- Experience at the IGN France (Raphaéle Héno)
- The ICC experiences (J.L. Colomer)
- The Eurosense experiences (J. Loodts)
- State of the Art of System Components : Position paper (R. Héno, J. Loodts, J. L. Colomer)

The introduction of the new techniques raises a number of problems and a position paper in form of a questionnaire was prepared and vendors were asked to take position. In this way, a large and fruitful discussion between users and vendors was initiated. The main points and recommendations are resumed here :

It proves to be very important to **organize the data files** in an appropriate manner; according to the experiences of ICC, it is advisable to use a **database** for this task; however it is advisable to keep the **working files in ASCII** to have them in a readable form; it is understood that the image files are excepted, and have to remain binary.

For the **data storage**, special **data servers are necessary** to allow a rapid access time. Kirchner and Wolf has used a **"stripe set"** for this task which runs under Windows NT. Such a stripe set allows the creation of a large partition of more then 100 Giga bytes and a very rapid access time. Another recommendation was to use standard servers preferably under UNIX. Closely linked to the data storage is also the archiving of the data and the backups for security reasons.

Hope was also expressed that the processing speed requirements will be met by the recent developments of the computer industry; the use of processors in parallel and the current development of special graphic cards in computer industry should supply the **necessary processing power** for **digital photogrammetry**. However, it became apparent that photogrammetry is only a special application, and it **completely depends on the hardware developments in the computer industry**. Therefore, certain requirements for visualisation like a real time zoom can only be realized with a reasonable effort when the computer industry offers the necessary products.

Although vendors offer a variety of application programs, it was brought up that **users do develop considerable software's on their own** and are asking the vendors to conceive **customizable systems** with an **easy access to user libraries**, as they are offered by Intergraph and Helava. In this context, it was also discussed whether the use of OLE (Object Linking Embedding) or applets as propagated by Microsoft will facilitate the programming for the users.

Closely linked to the development of software by the user and the application of various different systems in parallel is the requirement of **defining standards for the exchange of the images,** including the epipolar resampled images. Standards should also be defined for the exchange of the various **transformation parameters like inner and exterior orientations**. OEEPE was asked to pursue a resolution to this problem and help define such standards. **TIFF tiled with JPEG** compression was considered as a **useful standard for images**; although manufactures might continue to apply their own image formats for internal use.

Part 7. Financial Aspects

(Chairman : C. Dekeyne, J. Colomer)

A great part of the digital photogrammetric work station was acquired in the beginning for orthophoto production. Later on, one realized that they can be used efficiently for digital aerial triangulation and the automatic derivation of DTMs and gradually, mapping organizations also started using them for plotting. Currently, manufacturers indicate that about as many new analytical plotters are sold as digital work stations.

Papers on this topic :

- Maintenance and Amortization: Position Paper (C. Dekeyne, J. Colomer)
- Survey on the 'Application of Digital Photogrammetric Workstations' (O. Kölbl, *not orally presented*)

The introduction of digital systems requires great investments, which are only profitable when a return on investment of 5–7 years can be achieved; its also an investment which depreciates at 15–30% per year.

In addition to the price of the acquisition, it is evident that one has to also take into consideration the maintenance of the system, which should be guaranteed by the manufacturer for at least 5 years. In this context, one should not underestimate the costs for the introduction of the new technology into a mapping organization; the ICC needed about 2 years until they started their actual production. In this context, it is also important to take the human factor into consideration and to think about the difficulties to convert photogrammetry operators with experiences on analytical or even analog plotters to such a different environment.

The discussion made it evident that there is a strong link between the development in the computer industry and in the photogrammetric industry. The rapid development in hardware components leaves only a short time for software development. Additionally, there comes a considerable uncertainty in the economic development, which mainly hits the private enterprises in the first instance, but this is also creating a strong uneasiness at the manufacturer side.

It is evident that **manufacturers and users are finally depending** on each other and it seems important that such a forum also shows the necessity of the collaboration from both sides. It would also be a **topic for OEEPE** to consider this problem.

Part 8. Presentation of the Systems

For the workshop, vendors were invited to present their systems in form of demonstrations for which standardized material was prepared. The proceedings give in part 8 comprehensive presentations :

- Present Status of the DVP System (Coulombe J. et al.)
- Customer Orientation of the Leica Digital Photogrammetric Systems by Helava (Walker A. S.)

- Intergraph Integrated Digital Photogrammetry System (Madani M.)
- The ImageStation Digital Photogrammetry Workflow (Carswell J.)
- PHODIS Innovations (Dörstel C.)

The test materials prepared by the organizers of the workshop comprised 2 blocks for aerial triangulation and photographs for the derivation of DTMs. The material for aerial triangulation was prepared by the EPFL Lausanne and various models for the derivation of DTMs were prepared by the IGN Paris. The material for aerial triangulation consisted of a block of 9 pictures of Echallens (flat and open area, picture scale 1:5'000), and a block of 4 pictures of Chleuwena (mountain area and much forest, 2 pictures flown 2 years later for measurements of terrain movements). The Block Echallens and the test material for image correlation were shown during the demonstrations on the DPW work station of Helava, the ImageStation of Intergraph and the Phodis work station of Zeiss and showed the efficiency of the systems in these applications.

O. Kölbl

Lausanne, April 15, 1996

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Introduction

Direction :

O. Kölbl

An Outlook on the Use of Digital Work Stations in Practice

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Summary

The article tries to give an outlook on the future application of digital photogrammetric work stations. One can conclude that many functionalities of photogrammetric work stations will be integrated in the future into GIS work stations and only view operations will be reserved to specific work stations like aerial triangulation and the derivation of DTMs. An important tool of these future work stations will be the visualization and 3D modeling. However, these applications will also require changes in the current GIS software. A very important role will play already in the near future digital orthophotos and the raster technology.

1. Introduction

All those engaged in digital photogrammetry are certainly enthusiastic on the possibility which offers this new technique. According to the interest or requirements, one will focuse on the automation of aerial triangulation or image matching, the facility of computations or the efficiency of image display. When analyzing various systems one recognizes rapidly that all of them do have number of advantages. One realizes however also that there are considerable differences between the various systems. For example Helava and Matra use polarization screens, whereas most of the other stations work according to the flicker principle; many systems use UNIX as exploitation system, whereas the DVP runs under DOS and Intergraph goes over to Windows NT. Much more important is however the functionality. In the beginning, we had the impression that the digital systems only imitate the analytical plotter, that means image measurements, image orientation and plotting facilities; new was only the possibility for orthophoto production. Later on, operations for automatic height measurements and the automation of aerial triangulation were added. Finally, the digital photogrammetric systems were combined with information systems and with software for visualization. This combination of data acquisition, data analyses with the help of GIS systems and also the data visualization have created a completely new type of photogrammetric systems. It becomes now somewhat obsolete to acquire prior to a planning project all possible data in a preliminary phase, as one we will be able to compliment a set of data according to the specific requirements. Many descriptive elements are even obsolete in a GIS environment when digital orthophotos are available as background information.

From this point of view, the development of digital photogrammetric systems is by far not accomplished and the application will undergo still strong changes. In this sense, a new type of let's say photogrammetric GIS or photogrammetric work stations seems to come up, which will change the practical use still considerably.

2. Functionality and Classification of the Digital Work Stations

2.1 Trial of a Classification

Taking into consideration the ideas developed in the introduction, one can conceive the following ways to classify digital photogrammetric work stations depending whether one has in mind the photogrammetric point of view or a more general aspect. Referring to the photogrammetric view, one could start with a rather classical consideration in establishing the following table :

1. Visualization systems (GIS with raster facilities)
2. Photogrammetric work stations with plotting software and software for the orientation, aerial triangulation and the generation of orthophotos (this type of instrument corresponds largely to the classical analytical plotter).
3. Integrated geographic information systems with photogrammetric functionalities

2.2 Classification According to Functionalities

When looking more into detail into the functionalities of digital photogrammetric work stations and of GIS systems using elements for raster visualization, one will make out the following classification :

1. Visualization of raster data (mostly in conjunction with GIS systems)
   - In mono
   - In stereo (flicker, polarization)
2. Functionalities for image improvement and data compression
3. Geometric transformations of the raster images.
   - Differential rectification of the images. elaboration of orthophotos, draping, generating of synthetic views.
4. Image orientation
   - Single images
   - Stereo images
   - Aerial triangulation
     - Mechanical optical, visual
     - Automation

5. Data extraction

	Drawing of geometric objects in conjunction with CAD or GIS	
		Visual
		Computer-supported
	Extraction of a DTM	Visual
		Automated

6. Generation of raster images and visualization of image sequences

3. Functionality of the Systems

In considering the list of classification of information systems, one realizes that the proper photogrammetric operations as image orientation, aerial triangulation and stereo measurements do not have any more the same place as in the past. Much more importance is now the data extraction from the images and their appropriate integration into a GIS; in addition to these technical operations, the proper visualization with the help of raster data takes more and more space. The visualization makes use on the one hand of real photographs and on the other hand of the means of computer graphics allowing to create more and more realistic scenes. This effort for computer graphics and the creation of realistic synthetic images is not limited to static views and will go more and more in the creation of image sequences and moving scenes. This approach should not only be considered as nice and interesting, but will allow a much more natural planning process and will change the attitude against the classical line maps, standard tool up to now for most of these tasks.

It should be realized that the modelization and the creation of real 3D model views requires another structuring of the data, then was inherited from the classical graphic maps. The modelization of a house, a spatial object, requires some more precautions than all the definitions of a plane surface. The relevant tools are currently in elaboration, but by far not yet completed. Most of the GIS systems are still focused on 2D data and it is rather difficult to include a spatial structure.

The visualization process on a screen is a much more efficient tool than when an image is only printed and than used as planning support. Very often the users require overviews and detailed views. The digital orthophoto has an enormous richness, and even enlargements up to 20 and more from the photograph to the presented image are of great interest. This modularity however is only possible when working with a computer, whereas the use of hardcopies quickly finds its limits when one wants to use such great enlargements. In a similar sense the visualization of oblique images or even motion pictures is much more efficient with the tools of computer graphics than when limited to the classical tools. This means that there is still an enormous potential for further development in visualization and 3D modeling than one was able to put into practice up to now.

4. The Hardware Components

As more or less classical photogrammetrists one realized the importance which played the hardware for our profession. For quite some time, photogrammetry was bound to rather cost-intensive and highly specialized equipment. To some extent this tendency is still maintained with certain digital photogrammetric work stations. As an example, let's mention that for quite some time the Vitec parallel processor was used in the ImageStation and in the Helava station; it was also necessary to rely on hardware components for rapid image compression and decompression. Other digital work stations like the DVP relied completely on the efficiency of standard computers and had to struggle with certain drawbacks in performance. Meanwhile the efficiency of standard computer components has considerably increased and it seems that they reach the performance necessary for an efficient production work.

It appears that only the visualization process in stereo still requires special hardware components. Most probably the development will nevertheless continue in going to more and more standard components. The development of computers has by far not yet reached its limit and the efficiency of processors will continue to increase. Storage capacity has also considerably increased in recent 2 years and it is no more a costly undertaking to store a color aerial photograph with a resolution of 5 - 10 microns with or without data compression. These reflections seem to indicate that the photogrammetric work stations will be more and more a standard computer without specific hardware components for photogrammetric work and the application will be completely integrated into the computer used for data management and the handling of the geographic information.

5. User Interface

Although the requirements in specific hardware components are losing their importance, we realize that the practical use of modern GIS and photogrammetric work stations becomes more and more difficult. At the time of the analog plotters it took an experienced photogrammetrist about 5 minutes to understand a new system and to start to work on it. It was only sufficient to understand where are the trekking components and where to find the handling buttons for orientation in order to start working with these instruments. Already with the analytical plotters the user interface became much more complicated as the system offered to the operator much more functionalities. This tendency accentuated with the coming up of digital plotters and when buying such a system vendors might offer you or even oblige you to follow training courses of a few weeks. Even if one gets used to handle for example digital aerial triangulation on one system, one realizes that one needs considerable training to use another system for the same task.

This complexity of the use of photogrammetric systems should not be underestimated and seems to continue to characterize the profession. However, this complexity is very often also due to an insufficient user interface or even to drawbacks of the software reliability. For quite some time the use of the computer required very specific know-how and informatics was consequently the appanage of highly specialized persons. Meanwhile, the increase in reliability and the higher user friendly interfaces allow to use computers for word processing and have it integrated in the daily work of a secretary. This tendency was introduced by Macintosh and continued with Windows of Microsoft. By sure, this tendency will also continue to be one of the main concern of manufacturers. One of my students told me when he did aerial triangulation on the ImageStation of Intergraph that he has the feeling that he plays a video game, as the menus came up in a logical order and guided the operator reasonably. Nevertheless, it was necessary to accompany the students very closely in the work and to be sure that the aerial triangulation process was set up in an efficient way.

6. Reliability of the Software and the Functionalities

Very closely linked to the question of the efficiency of the user interface is definitely also the reliability of the system. One realizes that in principle aerial triangulation can already be done nearly completely automatically. The same could be said for the derivation of a digital terrain model. Nevertheless, precautions have to be taken in order to allow for strict control of the process of aerial triangulation or to allow for correction of effects on mismatching. Additionally to these deficiencies, which are inherent to the system and the process of automation, one still has to take into account deficiencies of the software and apparent bugs. In production, most concern must be given to the reliability. Automation of a process makes only sense when it really allows to accelerate the overall working time including error corrections and correction for mismatchings. At the time being it seems that the aerial triangulation on the ImageStation, which could be designated as rather conservative, allows a higher productivity than rather sophisticated software tools. The vendors of software are quite aware of this problem and typically the modules coming from industry are much more stable than those offered by universities for example. Furthermore, it should be stressed that a conservative but reliable procedure is of much greater value in production than a rather complex and unstable package. One of the main criteria in software evaluation should therefore be rather the stability of the software than its sophistication and complexity.

7. Conclusions

Many new aspects seem to come up with the new digital technology and it is not very easy to predict the consequences of that development. Most properly it will still take quite some time until 3D modeling and motion pictures are used in planning processes. Even the introduction of digital orthophotos progresses only slowly, although the technique is known and applied since more than 10 years. A complication might also be that most of the new processes like 3D modeling are reserved for large scale applications whereas symbolization and generalization play a key role in smaller scales, techniques which can not be replaced by simple raster views. In this sense one can state that digital photogrammetry seems to give an enrichment to the classical techniques, it will enlarge the available tools for mapping and visualization and will help to come to come to a better planning process, but it will not make obsolete the achievements in mapping and GIS.

Part 1

Scanning

Direction :

O. Kölbl J. Romeu

Preliminary Results of the OEEPE Scanner Test

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Summary

The aims of this study are the analysis of the tone reproduction of photogrammetric scanners and the development of simple test procedures. The most important arguments proposed are the image noise, image resolution, quality of colour reproduction, sensitivity of the scanner and the visual aspect of the images. A good scanner should show an image noise lower than $\pm$ 0.03 D for a pixel size of 10 μm and a resolution up to 10 μm. Furthermore, the dynamic density range should be at least 2D and a good fidelity of color reproduction.

1. Scope of the study

Working methods of digital photogrammetry are more and more applied in practice. However, the aerial camera using photographic films will remain for quite some time superior to all digital imaging techniques. Consequently, scanners play a key role for the conversion of photographic images in a digital form. However, the drawbacks of digital cameras are also present during scanning and it is of great importance to severely control the quality of the scanning process. The main requirements for image quality could be summarized in the following way :

- Geometric quality
- Fidelity of tone and colour reproduction
- Image resolution

Additionally, the user wants instruments that are easy to use and they should operate rapidly.

Photogrammetric manufacturers, but also the printing industry have developed a number of scanners of remarkable quality and for a user it is not always easy to evaluate the different products. However, in practical use, one realizes very quickly that there are considerable differences in image quality between the different scanners. A photographic image generally has a rather wide contrast range and a high resolution. Difficulties are often faced when converting those high-quality images into a digital form. When comparing an image displayed on a digital workstation and on an analytical plotter with a good optical system, one can see that the analytical plotter allows a better detail recognition than on a digital work station even when the scanning was done with a rather small pixel size. High requirements with regards to image quality also stem from automatic image correlation, especially when treating low-contrast areas.

2. OEEPE Working Group on Scanner Test

In order to develop criteria for a systematic analysis of a scanner and to gain experiences on different instruments, OEEPE (European Organization for Experimental Photogrammetric Research) has created a working group. This working group has already organized a first workshop in November 1993 and conceived a comparative test for scanner. Furthermore, a questionnaire was prepared, which should allow to collect technical data on the different systems.

For the experimental test, sets of test materials were compiled:

1. Grid plate, grid spacing 1 cm, dark lines on glass plate, line width 50 µm
   Objective : Analysis of the general precision of the scanner

2. Kodak Photographic Step Tablet no 2 (21 steps), density range ~ 0.05 - 3.05 D (CAT 152 3398)
   Objective : Analysis of the dynamic density range and of the noise of the scanner

3. Kodak Ektachrome colour table (from Kodak Colour Reproduction Guides Q60A) (CAT 815 5822)
   Objective : Analysis of the quality of the colour reproduction and of the noise in the different spectral regions

4. Fresnel pattern (black-and-white)
   Objective : Analysis of irregularities in geometry

5. Black-and-white diapositive copy of aerial photograph no 101012 taken with camera Wild RC20 30/4 NATA-F no. 17027 on Agfa Pan 150 film (density range of the diapositive 0.1 - 1.1 D, copied on film Agfa Avitone P3p, aerial flight Penthaz of 15.4.1987)
   Objective : Analysis of the reproduction of a low-contrast image, computation of the MTF and of the image noise

6. Original black-and-white negative of aerial photograph no 5266 taken with camera Wild RC20 15/4 UAGA-F no. 13129 on Kodak Panatomic-X film (density range 0.1- 2.0 D, aerial flight Dübendorf of 8.6.1994)
   Objective : Analysis of the reproduction of a high-contrast original negative, computation of the MTF and of the image noise

7. Colour aerial photograph no 0439 taken with Wild RC20 30/4 NATA-F no. 17027 on Kodak MS2448 colour film
   (density range 0.2 - 2.5 D, aerial flight Nyon of 15.8.1994)
   Objective : Optimal reproduction of a colour aerial photograph. It would be desirable that the signalized points can be properly recognized and easily measured on a digital working station. Furthermore, it would be important that details in the shadows remain recognizable

3. Participants in the OEEPE Test

In order to attain the scope of the working group, it appeared most appropriate to invite in a first phase the manufacturer to scan the test material and to proceed on an analysis of the scanned images. The members of the working group intended to run different test on the material and should be rather free to develop their proper strategy. The synthesis of these analysis should then allow to develop standard procedures for testing of scanners. However, the scanning of the material took much longer time than planned. As only one test set was available composed of originals, the delay within one only organization seriously extended the scanning phase. Therefore, the analysis of the test material remained very limited and only the results of the pilot centre (Technical University of Lausanne) can be presented up to now.

The following firms have participated up to now in the scanner test, which is highly appreciated :

Agfa, Mortsel, Belgium with the Agfa Horizon Plus

Intergraph, Huntsville USA with the PS1

Wehrli & Assoc, Valhalla USA, with the RM1

Helava, San Diego USA with the DSW200

Complementary scanning have been made by the following organizations :

ICC Barcelona with the PS1

Cetop, Lausanne with the PS1

Institute of Photogrammetry of the ETH-Zürich with the Agfa Horizon

Institute of Photogrammetry of the EPF-Lausanne with the DSW200

4. Analysis of the Test Material

Although the invitation for the test scanning was sent out in spring 1995, we disposed only in the beginning of February 1996 of some representative test material. The time for the analysis was therefore very short and is by far not finished. Earlier publications concentrated on the analysis of black and white photographs and showed how to determine the image noise, image resolution and the dynamic range (cf. [1],[2]). The current tests included resolution patterns, photographed with aerial cameras on high resolution film (test 6) and colour test patterns (test 3). It appeared of great interest to accelerate the analysis of the image resolution and of the colour reproduction, as these criterias have not been treated earlier too intensively.

4.1 Image Resolution

A lot was already discussed on image resolution and very often the pixel resolution is considered as limiting factor. However, when analyzing the reproduction of small objects in photographs, like signalized points, one realizes that the cut off frequency is not at all decisive, much more important is the loss of contrast for larger frequencies. This loss of contrast is given by the modulation transfer function (MTF). In order to determine the modulation transfer function, one should know the object function and of course the image function, but which is anyhow given by the digitized 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 1 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 of Intergraph. One recognizes that the contrast diminishes with the increasing frequencies and the signal vanishes with frequencies of about 50 lines/mm.

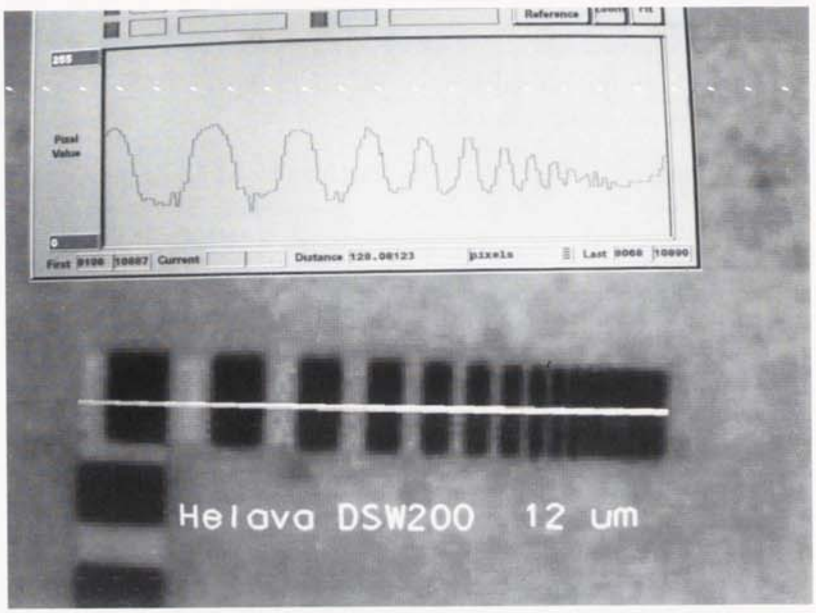

Fig. 1 Resolution pattern (test 6) and density profile scanned on the DSW 200.

Figure 2 gives an overview of the determined transfer functions for the different scanners tested and different image configurations. The best curve was obtained for a simulated pixel size of 2.5 µm for 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, corresponding now to 10µm with respect to the original. The effective transfer function for 12 µm is about 10% lower. It is however astonishing that a very similar transfer function was obtained with the PS1 with a pixel size of 15 µm as with the enlarged photographs. Another scan on the PS1 with a pixel size of 7.5 µm at a private firm gave a much more unfavorable result. The result of the Rastermaster RM1 of Wehrli (12µm pixel size) and the

Agfa Horizon Plus (20 µm pixel size) are very similar.

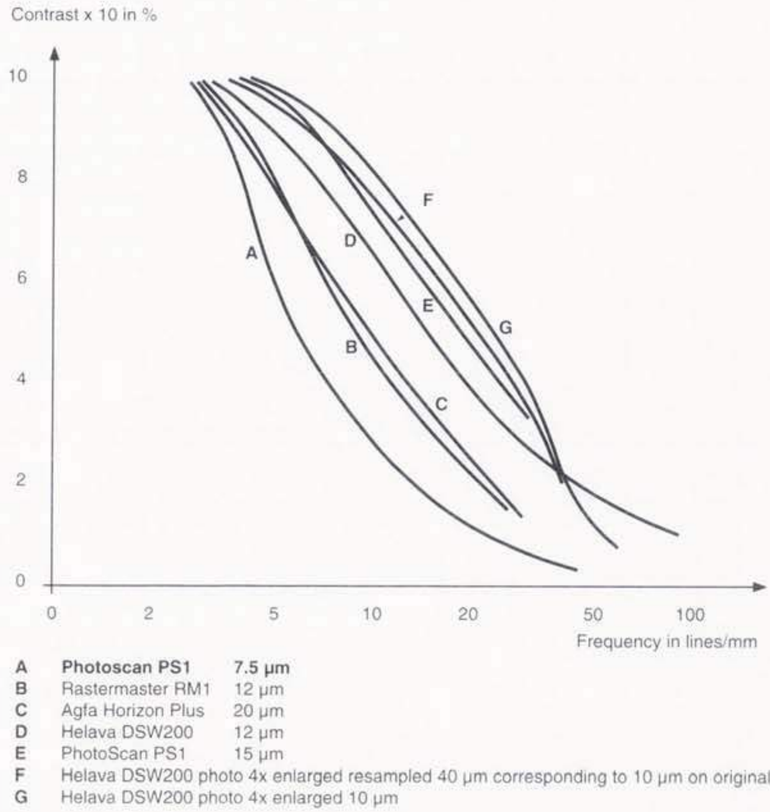

Fig. 2 Modulation transfer function for different scanners.

The results do not show the importance of the pixel size as one would expect; but it must also be stated that these results are very preliminary and have still to be verified. It will also be interesting to compare these results from the MTF determined earlier form the graininess of the photographic emulsion (cf. paper 'Tone Reproduction of Photographic Scanners').

4.2 Analysis of the Colour Reproduction

When working with colour photographs, in general one is not too strict as for colour fidelity like in printing industry. Furthermore, one is aware that haze considerably degrades the colour reproduction; even worth, very often one prefers false colour photographs instead of true colours as they give more information. All this might explain why the colour reproduction was not really analyzed up to now.

The Kodak Ektachrome colour table Q60 gives an efficient tool for the testing of the colour reproduction. The table includes batches which are only transparent in the 3 bands (red, green, blue) and transparency in the other bands is below 1%. When controlling the pixel values after scanning one has the impression that the Agfa Horizon scanner gives a very adequate response whereas the Helava DSW200 and also the PS1 are not too sensitive in the blue band and one misses about 30% of light intensity. This seems to be compensated by a smearing effect of the green band. That means that the transparency of the blue filter is too wide and is affected by light from the green band.

This is often not noticed as our eyes are not very sensitive to the blue light and in aerial photographs only few objects are blue. The situation is different when one wants to derive an image with more or less natural colours from a infrared false colour film. Then it is disturbing when the measured blue band, which corresponds to the green band in nature corresponds largely to the neighbouring band. It must be admitted that these measurements are also very new and will need confirmation, however, that they can contribute for a discussion.

5. Conclusions

Although a lot of studies have already been made with scanners it seems that many aspects still have to be analyzed. 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 of the OEEPE will initiate a wider discussion and that finally recommendations can be given for an overall scanner test.

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Discussion after the Conference:

Preliminary Results of the OEEPE Scanner Test, by O. Kölbl

Becker:
As for the resolution tests you showed, we also analyzed various scanners and apparently, other patterns appear when you look at the resolution targets. The higher frequencies especially, seems to be affected by special patterns and I feel some correlation might exist between the higher resolution and the special scanner patterns.

Kölbl:
It seemed to me that the results of my resolution analysis was not affected in a noticeable manner by this phenomenon. When specifying the conditions for the test scanning, we have asked not to apply any image enhancement. However, we observed this effect on scanners of the printing industry, for example, on the Screen scanner, which applies a strong edge enhancement. Finally, it should not be forgotten that the photographic film by the Schwarzschild effect also shows a similar phenomenon, leading to an edge enhancement.

Baltsavias:
I would like to draw your attention that various desktop scanners like the Afga Horizon have a different behavior in both vertical and horizontal directions due to the scanning process and other various reasons. We analyzed this phenomenon in detail and found very specific values. There might also be some effects interfering with aerial triangulation and image matching.

Dam:
I think that the power frequency and maybe the MTF are more of an issue for image correlation.

Ackermann:
For correlation and image matching, it is quite a problem when the scanner has a repetitive pattern, unless an appropriate filter is applied. It is important that this effect is corrected. It should not go into the correlation process.

Tone Reproduction of Photographic Scanners

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This article, written in 1993, gives number of fundamental considerations on the requirements of photogrammetric scanners and shows comparative test results of different instruments. Therefore, the article was included in these proceedings, however it was not specially prepared for that workshop and already published in 'Geodezja i Kartografia' (Poland) and submitted to PE&RS but there not yet published. It would otherwise be difficult to be obtained by the interested reader.

Summary

The aims of this study are the analysis of the tone reproduction of photographic scanners and the development of simple test procedures. The most important arguments proposed are the image noise, image resolution, sensitivity of the scanner and the visual aspect of the images. A good scanner should show an image noise lower than ± 0.03 D for a pixel size of 10 µm and a resolution up to 10 µm. Furthermore, the dynamic density range and the fidelity of tone reproduction should be controlled. The study includes tests on the scanners most commonly used in photogrammetry and in the printing industry but shows that their efficiency does not allow to fully exploit the high image quality of modern aerial photographs.

1. Scope of the Study

The primary condition for the use of digital procedures in photogrammetry is the conversion of photographic images into a computer-compatible form. This conversion is commonly done with a scanner. Various tools coming from the photogrammetric or printing industry have been developed for this task. In the printing industry, desktop publishing in particular provoked a great demand for scanners of various qualities and performances.

In practical use, one realizes very quickly that there are considerable differences in image quality between the different scanners. A photographic image generally has a rather wide contrast range and a high resolution. Very often difficulties must be faced when converting those high-quality images into a digital form. When comparing an image displayed on a digital workstation and on an analytical plotter with a good optical system, one can see that the analytical plotter allows a much better detail recognition, even when the scanning on the workstation is done with a small pixel size. The difference is even more decisive when producing orthophotos. Practical work has shown that orthophotos made from aerial photographs by applying analogue techniques as, for example, by using the Leica orthoprojector OR1, can be enlarged until 10 times. Similar tests with digital orthophotos give the impression that the limits are already reached with an enlargement of about 5 times. High requirements with regard to image quality also stem from automatic image correlation, especially when treating low-contrast areas.

Without a doubt, the best known scanner in the past was the Optronics which was developed some 20 years ago. It was a drum-scanner, in which the light density was measured by a photomultiplier. Since then, flat-bed scanners have been developed in addition to the drum-scanners and the photo-multipliers have been replaced by CCD-photodetectors as line or matrix sensors. The illumination can be met in a variety of ways thereby also allowing the scanning of color images.

The scope of this study is to analyze the tone reproduction of different photographic scanners. This evaluation was done with a view to the acquisition of such an instrument by the Institute of photogrammetry, which has been already engaged for quite a long time in image correlation using CCD-cameras integrated into an analytical plotter for image digitizing. However, the noise and the dynamic range considerably limit the possibilities of image correlation. Consequently, the idea was to purchase a scanner with a higher performance. Investigations showed, however, that the radiometric quality of scanners is rather limited and does not cope well with the high quality of aerial photographs. Due to the topicality of the subject, it seemed appropriate to make this study available to a larger audience.

2. Requirements in Photographic Scanners

The most important criteria for the quality analysis of scanners can be summarized as follows :

Geometry : With current aerial photographs, a level of precision of the order of $\pm$ 2 µm can be reached in aerial triangulation. This precision is also usually obtained with analytical plotters. Consequently, it is useful to also require such precision for photographic scanners.

Image resolution : This parameter is decisively determined by the quality of the film and by the aerial camera. As will be shown later on, it seems appropriate to require a pixel size of 10x10 µm for black-and-white images whereas a pixel size of 15-20 µm might be sufficient for color photographs.

Image noise : The noise of photographic film is mainly defined by its granularity. If considering the values given by the producers, the sensor noise should not exceed $\pm$ 0.03 D for a pixel size of 10 x 10 µm and an image noise of only 0.02 D could even be reached with the Kodak Panatomic-X film. This presumes that the modulation transfer function of the scanners also allows a resolution corresponding to the pixel size.

Dynamic range : This should correspond to the contrast of aerial photographs which might range from 0.1 to 2.0 D for black-and-white pictures and from 0.2 to 3.5 D for color photographs.

Color reproduction : With the increasing use of color photographs, it is important to be able to also scan color photographs.

Data compression : The great mass of data produced when digitizing images can be effectively reduced by data compression techniques.

Instruments handling : The handling of the instruments as well as the management of the considerable amount of data are important criteria; however, this aspect is not going to be discussed in more detail here.

2.1 Image Resolution of Aerial Photographs

The image resolution of aerial photographs is generally characterized by the resolution of lines per millimeter. This is however a rather subjective criterion, depending heavily on the object contrast, and the use of the modulation transfer function (MTF) is much more suitable. The MTF indicates the contrast reduction of a sine wave with a given frequency. The Fourier transform of the MTF indicates the spread function which is the image function of an ideal point image in the object space. This spread function can be easily related to the pixel size. Different MTF functions characteristic of aerial photographs have been determined in a recent study of OEEPE (Jaakkola, 1985; cf. also fig. 1 and 2). According to this study, the spread function has a size of 20-25 µm, which is the distance between the two inflexion points of the Gauss function for an intensity of 50% for black-and-white films and of 30-35 µm for color films. Similar investigations with the Panatomic-X film and high-quality lenses gave values between 8-15 µm (Kölbl, 1986).

If one is to ensure that the original image quality of aerial photographs is not degraded by the scanning process, one should work with pixel sizes of approximately only a half of the spread of the Gauss function; furthermore, the quality of the optical system of the scanner should not reduce this performance. That means that the spread function of the scanner itself should not exceed the pixel size. Consequently, for conventional black-and-white films, a pixel size of 10x10 µm might be appropriate, whereas, for color films, values between 15-20 µm might be sufficient. An even smaller pixel size would be useful for the Kodak Panatomic-X or other high-definition films.

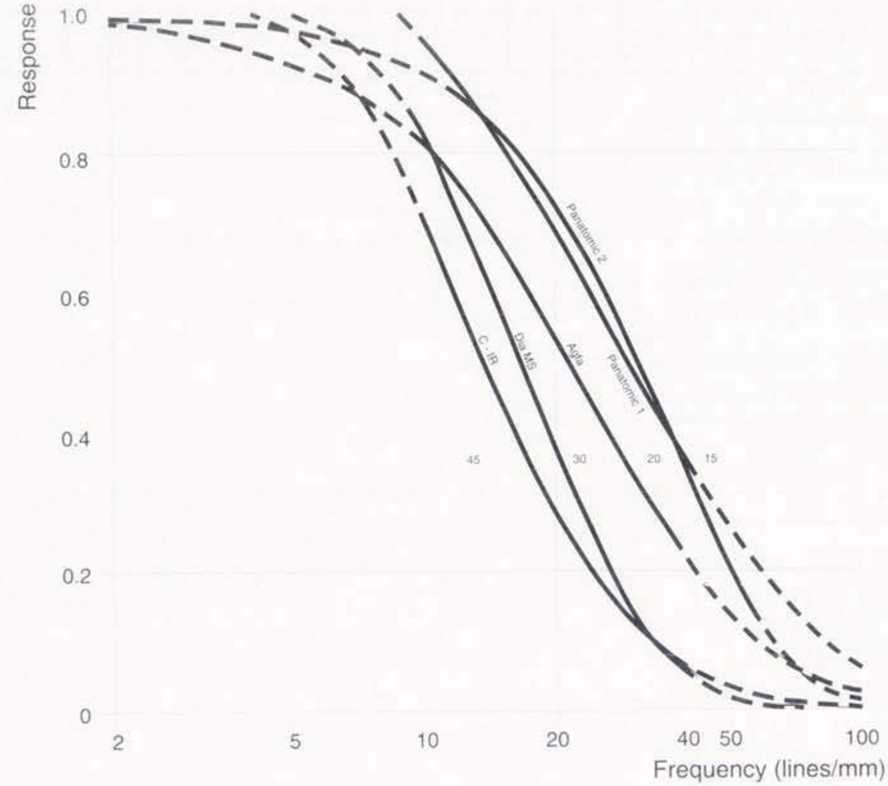

Fig. 1
Modulation transfer functions of different films (thick lines) and corresponding Fourier transforms of Gauss functions with their spread (thin lines). The curves were taken from Jaakkola (1985) fig. 17 and Kölbl (1986) fig. 6 with some modifications.

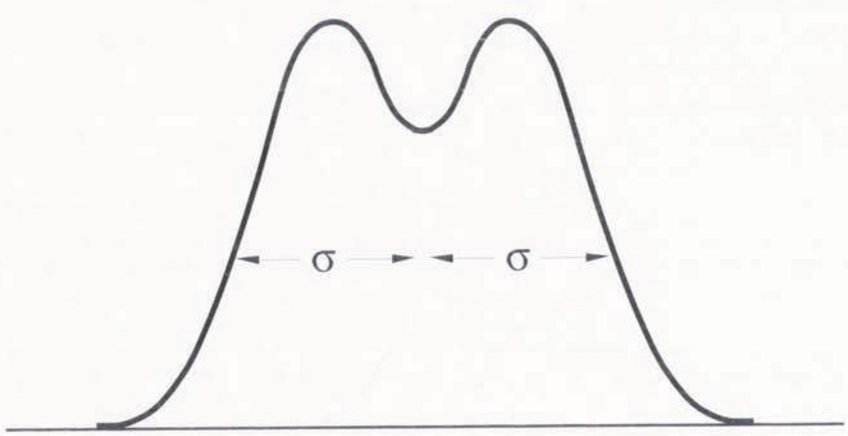

Fig. 2
Gauss curves with the spread s as used in this paper. The figure illustrates that it should be possible to distinguish two bares with a distance of σ when the spread of the point spread function is σ, cf. Kölbl (1986).

2.2 Granularity of the Photographic Emulsion

The granularity of aerial films is rather closely related to the image resolution. The 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 analyzed by manufacturers. The Kodak Data Book of Aerial Films indicates the 'Diffuse Root Mean Square Granularity'. This granularity is measured on a microdensitometre with diffused illumination. A homogeneously exposed film probe is scanned with a 12x optical enlargement and a circular window of 48 µm. The standard deviation of the density value multiplied by 1000 is given (cf. Kodak, Agfa and also table 1). For example, the granularity for the Kodak Plus-X film is 26 res. 28, and 9 for the Panatomic-X for a photographic density of 1. For the Agfa Pan 150PE, the corresponding values for the granularity lie between 17-25 for a circular aperture of 50 µm. Consequently, an image noise of ± 0.017 - 0.025 D is to be expected when working with a quadratic pixel size of 45x45 µm (conversion from a circular aperture to a quadratic one). For a pixel size of 10x10 µm, one should expect primarily an image noise of ± 0.075 - 0.1 D, meaning values 4.5 times larger than the initial ones. In this case, one supposes that the gray values of neighboring pixels are not correlated. However, it will be shown later that neighboring pixels are generally heavily correlated, which provokes a smoothing of the image noise. 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, the image noise should amount only to ± 0.035 - 0.05 D; the corresponding tolerance values for the Panatomic X would amount to only ± 0.02 D.

2.3 Dynamic Range of Aerial Photographs

According to the above-mentioned OEEPE publication (Jaakkola, 1985), one can also get an overview of the current density range of aerial photographs. In general, black-and-white films have less contrast than color films. In this study, the signalized points have been observed with a density of the background varying between 0.2 and 2.0 D using the Kodak Panatomic-X film, whereas a range of 0.3-3.5 D was obtained for the IR color film. Consequently, one has to require from scanners a density range of about 0.1 - 2.5 D for black-and-white films, whereas a density range of 0.1 - 3.5 D is needed for color films.

3. Constructive Elements of Scanners

3.1 General Set-Up

The set-up of a scanner is heavily influenced by the photodetector used. 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 photodetec tors are generally mounted outside of the drum and scan the image image line by line. The transparencies are illuminated by a light

Type of film	RMS Granularity
KODAK Plus-X Aerocon, Film 3411	26-28
KODAK Panatomic-X Aerographic, Film 2412	9
KODAK Tri-X Aerographic, Film 2403	30-40
KODAK Double-X Aerographic, Film 2405	26
KODAK Aerochrome Infrared, Film 2443	17
KODAK Aerochrome MS, Film 2448	12
AGFA Aviphot Pan 150 PE	25
AGFA Aviphot Pan 200PE	27

Table 1.

Overview of the granularity (Diffuse Root Mean Square Granuiarity) of a selection of films Kodak and Agfa. The granularity refers to a circular window of 48 µm, given is the standard deviation of density multiplied by 1000 (taken from Kodak, 1982 and Agfa).

source mounted within 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 makes it possible to obtain a high performance with regard to resolution and dynamic range. The disadvantage is, however, that the film must be mounted on a drum.

A mounting between glass plates is much more protective for the film, but this is only possible with flat-bed scanners. In this case, the film is mounted on a motor-driven cross carriage. An alternative is, of course, the moving of the illumination and of the photo detector. The illumination can be diffused or directed; as a detector, one generally uses line sensors or matrix sensors.

3.2 Photodetectors

The most important photodetectors are currently the photomultiplier and the line or matrix sensor. The **photomultiplier** is based on the exterior light electric effect. If light touches a cathode, then electrons are detached which are attracted by the anode. The current produced in such a way is then measured.

In order to obtain greater sensitivity, the flow of photoelectrons produced on the photo cathode is amplified by the introduction of auxiliary cathodes, the so-called dynodes. These photosensors are then designated as photomultipliers. They have a very high sensitivity and also a high dynamic range. The sensitivity of a photomultiplier can be raised to the detection of individual photos. Moreover, they have a very low response time. From the beginning, there was therefore a great interest to also use these sensors in scanners. However, the photomultipliers cannot be combined to form a sensor line or sensor matrices. Nevertheless, the high response time makes it possible to pass the film of a scanner very rapidly over the measuring device. It was therefore logical to use the photomultipliers mainly in drum-scanners.

For quite some time, **photo diodes and photo transistors** have been used for light measurements in addition to the photocells. The photo elements are based on the so-called interior light electrical effect or semi-conductor photo effect. In this case, the photo electrons produced by the incident light remain within the semi-conductor and serve as conducting electrons for the photo current. These solid-state image sensors can be mounted on a silicon chip as line or matrix elements. However, these elements of the photo detector matrix have to be coupled with electronic means for the read-out of the current produced. Such a connection is not easily applicable for each individual element of a matrix. A practical solution is the transfer of the charges from one element to the next. The electronic charge produced by the radiation can be transferred without nearly any loss over a whole line of matrix elements and will then be read out, whence, the designation **charged coupled detectors** (CCD).

According to this principle, it is understandable that matrix sensors offer less sensitivity than line arrays. According to the literature (Murphy, 1989), the dynamic range of a line detector is about 5 times higher than that of a matrix detector.

3.3 The Illumination System

An important role for image reproduction is also played by the illumination system. It is useful to distinguish between directed and diffused illumination (see also fig. 3).

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 light energy, as only lamps with a rather modest heat radiation are necessary. In order to reduce even further this heat radiation, one can use fiber optics for the transmission of the light to the remote light source. A strongly directed light provokes a very small optical opening angle and increases considerably the depth of field of view. An optical system with directed illumination might also be less sensitive to small effects of defocusing. On the other hand, light is rather coherent and can provoke diffraction effects.

A **diffused** light is obtained when using milk glass for diffusion. This can be done by placing a milk glass or even better a opalescent glass plate directly on to the photographic film or by using fluorescent light which has a strong diffusing effect. More refined possibilities are the use of the "Ulbrichtkugel" or a light channel. The "Ulbrichtkugel" is an empty sphere, the inside of which is coated with magnesium dioxide. Light is introduced laterally and comes out via a very small opening. This opening should not exceed 1/50 of the sphere diameter (Vieth, 1974 p. 126).

It is remarkable that optical enlargers of today generally use only diffused illumination, whereas older instruments such as the famous rectifiers were generally equipped with Fresnel lenses as condensers. Many of the photo enlargers constructed today are equipped with a light channel. Photogrammetric instruments also very often use diffused light in order to get a more pleasant image quality.

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

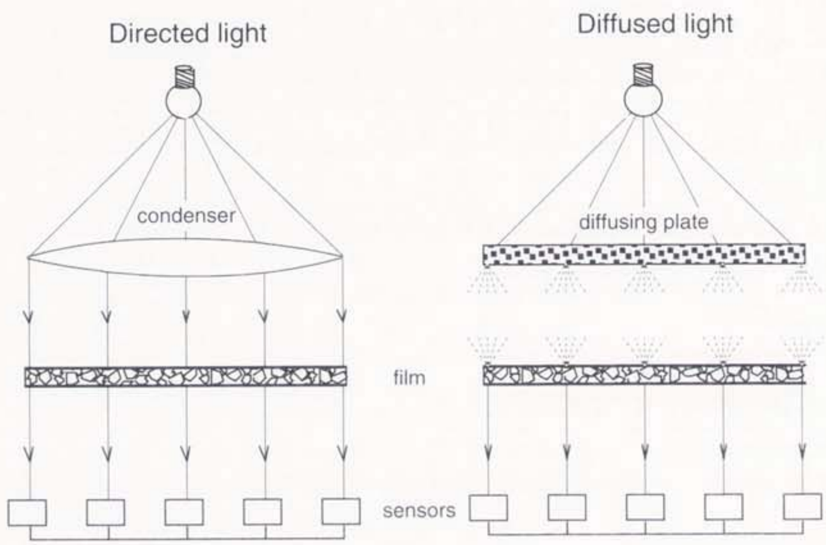

Fig. 3

Illustration of an illumination system with directed light by a condensor (left) and diffused light by a diffusing plate (right).

4. Experimental Investigations

As already mentioned, the practical investigations concentrated on the analysis of scanners with view to purchasing a system. Consequently, the tests were limited and consisted in the digitizing of a few typical aerial photographs (a medium-contrast black-and-white photograph, a high-contrast Panatomic-X photograph of a snow-covered area and a false color photograph). A more detailed analysis then concentrated on the medium-contrast image only. After testing one or the other scanner considered as interesting for the tasks of the Institute, an attempt was later made to extend this series of tests in order to get an overview of the tone reproduction of the different scanners. Table 2 gives an overview of the different scanners incorporated in this study. The investigations included 2 drum-scanners, mainly used in the printing industry and 9 flatbed-scanners, only one of which (DSR 15 analytical plotter) must be considered as experimental; in total 3 of the tested scanners come from the printing industry. Figure 4 shows a comparison of image sections resulting from the different scanners. This comparison shows that images can differ considerably with regard to noise and sharpness. However, the visualization also makes it possible to detect other image errors such as strips or blurring effects.

Sensor	Type of construction	Trademark	Illumination system	Min. pixel size	Max. Bit/pixel	Variability of pixel size
Photo-multiplier	Drum-Scanner	Screen DT-S1030AI	directed	13 μm	10 b/w	Software
	Drum-Scanner	Crosfield	directed	14 μm	10 b/w	Software
	Flatbed-Scanner	Perkin Elmer 20 x 20 G	directed	22 μm		Exchangeable optic
Line-CCD	Flatbed-Scanner	Du Pont High_Light 1850/1875	diffused	10 μm	12	Software
		PhotoScan PS1 (Zeiss)	directed	7.5 μm	11/color	Software
		Wehrli RM1	directed	12 μm		Zoom-lens
		Agfa ACS100	diffused	10 μm	12	Zoom-lens
		Agfa Horizon	directed	21 μm		Software
Matrix-CCD	Flatbed-Scanner	Vexcel VX 3000	diffused	10 μm		Zoom-lens
		DSWI00 (Helava)	diffused	13 μm	12	2 cameras
		Philips CCD in the DSR15	directed or diffused	8*12 μm	8	Software

Table 2. Overview of the different scanners used for the practical tests.

The numerical analysis focused on the determination of the image noise, the resolution of the digital images and the sensitivity of the scanner. In parallel, the general aspects of the scanned photographs have been evaluated. The medium-contrast photograph can be considered as a typical aerial photograph with a built-up area and a zone of very poor contrast. This photograph was taken on Agfa PAN 150 film with a Leica RC20 camera equipped with an Aviogon lens. As it appeared too risky to scan the original negative, a positive copy was made on Agfa duplicating film. Care was taken that a new copy free of scratches or other damage be available for every test.

The main objective of the test was to find a scanner with rather low noise and good tone reproduction. When analyzing the graininess or noise of an image, one quickly realizes that the image noise is closely related to the pixel size and also to the resolution. Images scanned with a small pixel size generally have a larger image noise than images with larger pixels, as the larger pixels can be obtained by computing the mean of the smaller pixels; the computation of the mean naturally causes a smoothing approximately proportional to the square root of the number of pixels. Consequently, it can be expected that the image noise increases in an inversely proportional way to the dimension of the pixels. In parallel, the imaging system can have a important smoothing effect, as the optics or other factors might cause a strong smearing effect. It was consequently of great importance to determine the MTF of the imaging system prior to any other analysis.

4.1 Determining the MTF of a Digital Image

As for the evaluation of the performance of lenses, one can also determine the modulation transfer function (MTF) for a scanner. The point spread function corresponds to the autocorrelation function of an image, provided that the image content can be considered as random (white noise). This type of computation can be easily done with digital images, preferably for rather homogenous areas.

The autocorrelation function was determined for pixel matrices of 20 x 20 elements. The correlation values for neighboring pixels were then approximated by a Gauss function; the parameters obtained for the spread are given in table 3, column 7. The inverse of this value, multiplied by 1000, is a rough measure of the resolution in lines per millimeter. The same table gives the correlation between neighboring pixels (columns 8, 9). Rather large values of nearly 50% or even more are obtained to the next neighbor, but then the correlation coefficient decreases rapidly. Very similar results for the spread functions have been obtained when computing the autocorrelation function across a very distinct line.

When analyzing the image resolution one is astonished that the Agfa-Horizon scanner seems to have an image resolution of only 0.1 mm or about 10 lines per millimeter. Other scanners have a resolution much closer to the pixel size but the size of the spread is in general 2-3 pixels. It was only for the Perkin Elmer scanner that practically no correlation was obtained between neighboring pixels. This is not astonishing if one considers that the system operates with a photomultiplier, a low measuring rate and microscope optics scanning sequentially pixel by pixel.

It is most probable that not all factors influencing the resolution were properly located. For example, the DSR15 shows a strong increase of the spread with increasing light intensity (decreasing resolution with increasing light intensity, cf. table 3, column 7). Nevertheless, an interesting value is determined by the autocorrelation function characterizing the resolution of digital images much better than the pixel size only.

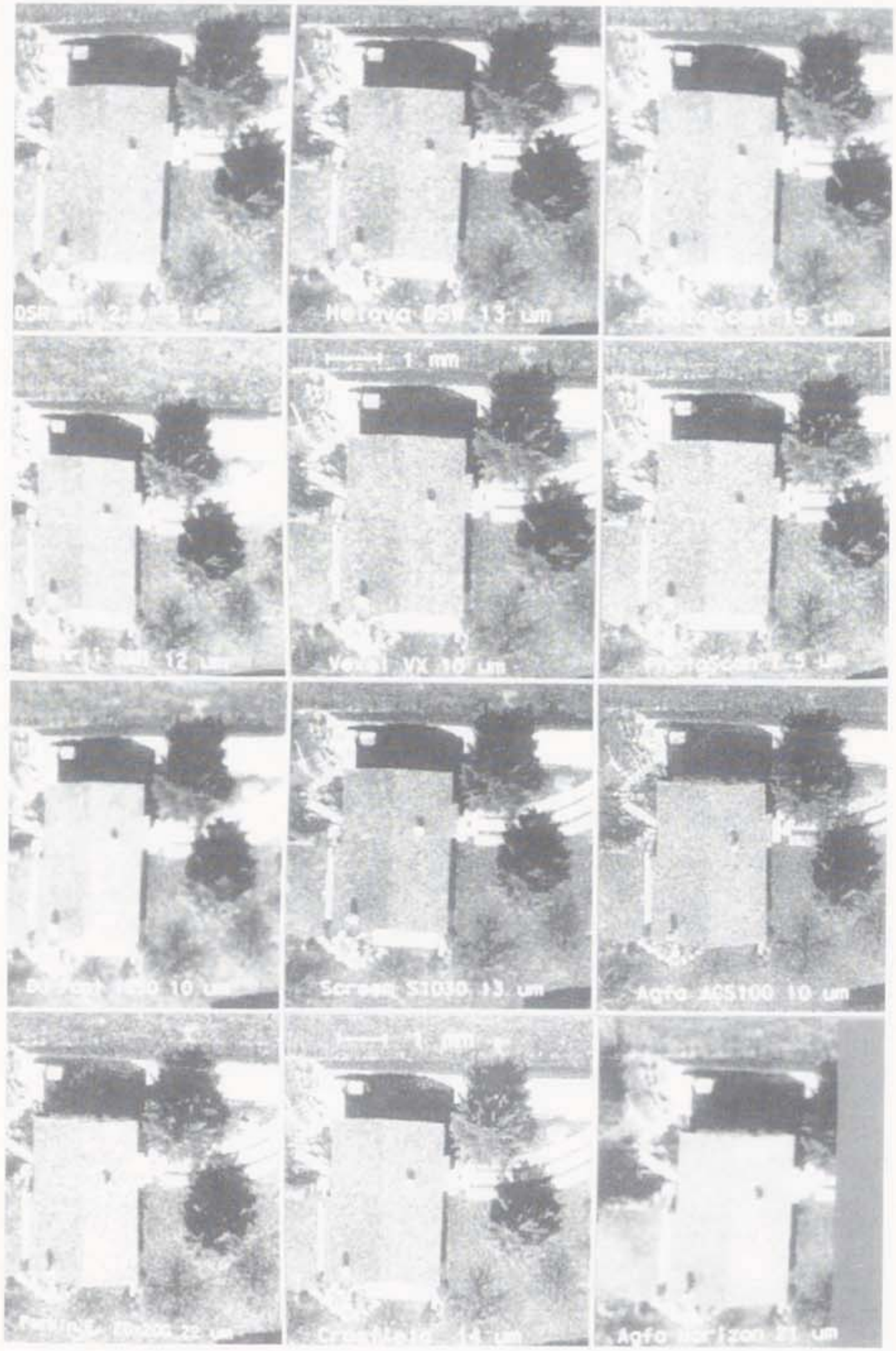

Fig. 4

Comparison of an image section scanned on different instruments, displayed on a CRT screen.

Scanner	Measured image noise in [D]				Pixel size	Spread	Corr. 1.Pix	Corr. 2.Pix	Image noise reduced to a spread of 10μm in [D]				Light type
	0.4 D	0.5 D	0.6 D	0.7 D	in [μm]	in [μm]	in [%]	in [%]	0.4 D	0.5 D	0.6 D	0.7 D	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Du Pont High_Light 1850 2540dpi	0.011	0.014	0.017	0.021	10	40*46	72.3	53.3	0.044	0.060	0.073	0.090	diffused
1875 2540dpi off	0.008	0.009	0.009	0.008	10	62*56	88.1	68.4	0.047	0.053	0.053	0.047	
1875 1132dpi soft	0.013	0.018	0.023	0.028	22	40*44	48 6	16.8	0.055	0.076	0.097	0.118	
1875 1132dpi off	0.009	0.011	0.013	0.014	22	60*64	64.0	35.8	0.056	0.068	0.081	0.087	
Helava DSW100	0.024	0.023	0.024	0.028	13	25*34	58.3	25.0	0.072	0.069	0.072	0.084	
Vexcel VX3000 10μm	0.036	0.038	0.044	0.051	10	18*18	40.9	16.0	0.065	0.068	0.079	0.092	
24μm	0.021	0.019	0.019	0.020	24	58*52	54.0	27.7	0.116	0.105	0.105	0.110	
Philips - CCD in the DSR15- **diffused**													
- dark (GV 90 ~ 0.4D)	0.017	0.018	0.017	0.019	8•12	36*40	62.6	49.4	0.065	0.068	0.065	0.072	
- medium (GV 130 ~ 0.4D)	0.013	0.012	0.013	0.013		38*48	69.6	54.6	0.056	0.052	0.056	0.056	
- bright (GV 230 ~ 0.4D)	0.017	0.015	0.013	0.017		43*66	79.7	64.4	0.095	0.083	0.072	0.095	
Philips - CCD in the DSR15- **directed**													directed
- dark (GV 80 ~ 0.4D)	0.024	0.022	0.018	0.018	8•12	36*36	68.5	48.6	0.086	0.079	0.065	0.065	
- medium (GV125 ~ 0.4D)	0.025	0.022	0.025	0.020		40*50	78.7	57.6	0.113	0.099	0.113	0.090	
- bright (GV 240 ~ 0.4D)	0.026	0.022	0.017	0.016		42*52	82.7	59.0	0.122	0.103	0.080	0.075	
Agfa ACS100 - 2400dpi (EPFL)	0.025	0.026	0.027	0.029	10	35*38	74.2	37.9	0.093	0.096	0.100	0.107	
- 1800dpi (firm)	0.044	0.045	0.044	0.049	14	34*34	59.8	13.6	0.150	0.153	0.150	0.167	
- 900dpi (firm)	0.088	0.089	0.134	0.121	28	30*30	12.4	6.4	0.264	0.267	0.402	0.363	
- 300dpi (firm)	0.190	0.142	0.103	0.061	85	250*145	62.3	14.4	3.8	2.8	2.1	1.2	
Agfa Horizon - 1200dpi	0.010	0.011	0.011	0.011	21	114*120	87.5	65.5	0.117	0.129	0.129	0.129	
Screen DT-S1030AI 2000dpi	0.038	0.037	0.026	0.026	13	26*36	58.4	15.9	0.123	0.115	0.079	0.079	
Crosfield - 900dpi	0.062	0.058	0.054	0.050	28	34*52	27.3	9.5	0.267	0.249	0.232	0.215	
1800dpi	0.060	0.059	0.059	0.058	14	19*33	37.4	14.7	0.156	0.153	0.253	0.151	
Perkin Elmer 20 x 20 G	0.042	0.047	0.053	0.064	22	22*22	8.6	1.9	0.092	0.103	0.117	0.141	
Wehrli RM1	0.027	0.024	0.026	0.026	12	29*32	61.8	20.3	0.084	0.074	0.081	0.081	
Zeiss PhotoScan PS1 7.5μm	0.058	0.060	0.071	0.080	8	12*14	46.6	9.1	0.075	0.078	0.092	0.104	
15μm	0.024	0.026	0.029	0.029	15	27*36	50.9	19.4	0.074	0.081	0.090	0.090	

Table 3.
Overview of the image noise and of the size of the spread function determined for the different scanner. Columns(C) 2-5 give the root mean square deviation of gray values computed for an image matrix of 20 x 20 pixels of homogeneous areas expressed in density, C 8 and 9 give the correlation coefficients to the neighboring pixels and the second neighbor and C 10-13 represent the standardized image noise for a point spread funtion of 10μm (f.e. C10=C2*C7/10)

4.2 Analysis of the Image Noise

The image noise was computed again from pixel matrices of 20 x 20 elements of homogenous areas. For each image, some 20 different matrices have been used with different densities. In the first line, a scanner gives gray values mostly without clear relation to the density of the photograph. For a proper comparison of the measurements, it was necessary to establish therefore a clear relation; density was chosen as reference. The Fig. 5 shows the relation between the gray values measured on the PS1 and the corresponding density of the test patches as measured on a Macbeth densitometre (diaphragm 0.1 mm).

Table 3 gives an overview of the computed image noise reduced to density values. The image noise is given for densities between 0.4 and 0.7 D (columns 2-5), which occurred frequently in the photograph used. The same table also gives the pixel size used for scanning (column 6) and the size of the point spread function (column 7). The point spread function was then used to standardize the image noise for a uniform point spread function of 10 µm (columns 10-13). This corresponds to a scan with a pixel size of 10 µm, provided that the correlation to the neighboring pixel is not higher than ~ 10% (exact value 6.7%!).

After the conversion of the image noise to a standardized pixel spread function of 10 µm, one gets a rather uniform result with an image noise of ± 0.1 D. Somewhat higher values are obtained with scanners from the printing industry like

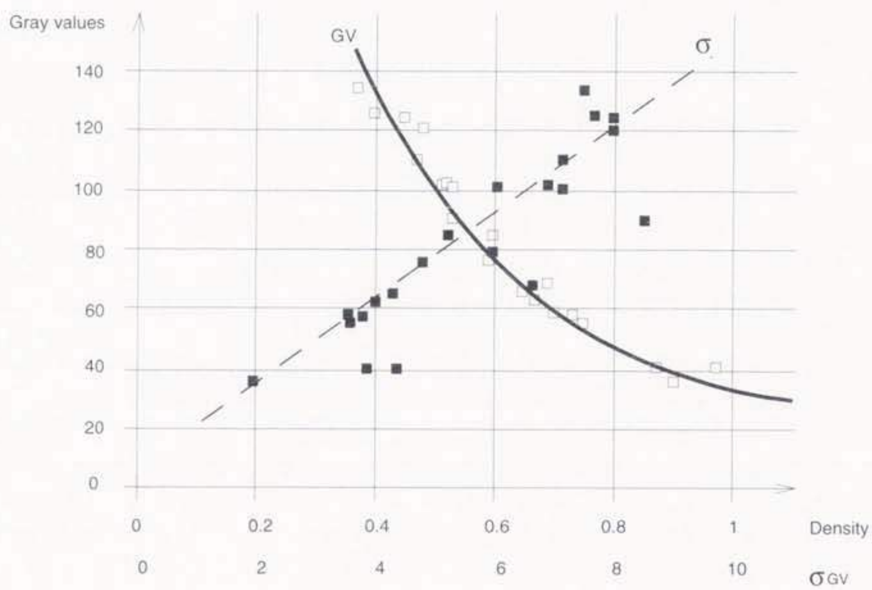

Fig. 5

Relation between gray values obtained by scanning and the density of the corresponding batches for the PS1. The same diagram gives the image noise in gray values and the density values.

Screen, Crosfield or Agfa Horizon. The lowest image noise was also obtained from a scanner of the printing industry, the Du Pont High Light 1850. The experimental results confirm that scanners with diffused light give about 20% less image noise than scanners with directed light. This is also shown very clearly by the comparative test on the DSR15. The same equipment was used in this case, only the illumination system was changed. For the test with the directed light, the original light source was used, whereas a diffuser plate and a stronger light source were used in the other case.

However, this tests do not reveal the source of the image noise. According to the prior computations, one should expect an image noise of ± 0.03 - 0.05 D for the film used. Only the Du Pont High Light is close to the expected values, whereas all other scanners seem to generate additional noise within the electronic system. Specific tests on the DSR15 using films with different graininess (Kodak Double-X, and Kodak Plus-X) did not give the expected results. The image noise did not increase with the graininess of the film; it seems that the effect of the graininess is much smaller and does not influence significantly the image noise, apart from the above-mentioned effect of the illumination.

4.3 Sensitivity of the Scanners

The resulting measurements from the photographic material used give little information on the dynamic range of the scanners tested. The photographs used have a low contrast and most of the picture information is limited to a density between 0.4 and 1.0 D. This rather poor image contrast appeared ideal in the beginning, as the dynamic range of a CCD-camera used earlier by the Institute of photogrammetry had a very limited density range and a brightness saturation of one pixel resulted in a blurring of the whole scan line. Meanwhile, the scanners have been mainly equipped with array sensors with an internal measuring range of 10 -12 bits or even more. The usual 8 bits values are obtained after conversion allowing for much greater internal sensitivity. Consequently, the results presented can only give an indication of the tendency, but no concrete values on the dynamic range.

Table 4 gives an overview of the reduction of sensitivity with an increase of density. One may note that many scanners have a constant relation between gray values and the density of the photographs and clearly have a rather high dynamic range far beyond a density of 1 D such Crosfield or Screen. These scanners use photomultipliers which generally show very high levels of sensitivity. On the other hand, a much smaller dynamic range must be expected from scanners with CCD-matrix sensors. This is extremely well demonstrated on the DSR15; however, the dynamic range of this instrument is also considerably reduced by parasite light, which is difficult to control, due to the open construction of the plotter. The values in Table 4 show that parasite light is much more important when working with diffused light than with the original illumination source of the instrument (directed light). The measurements on this instrument also show that an increase of the light intensity does not allow a better observation of the dark areas

Scanner	Max. sensit.	Sensitivity in Density			Corresponding grey value				Look-up-table (LUT)/
	in [D/10GV] in 0.4 D	Sensit. reduced to 1/2	Sensit. reduced to 1/4	Estim. Minim.	Max. sensit. in GV in 0.4 D	Sensit. reduced to 1/2	Sensit. reduced to 1/4	Estim. Minim.	Change of Light intensity (ChLI)
1	2	3	4	5	6	7	8	9	10
Du Pont High_Light 1850 2540dpi 1875 2540dpi off 1875 1132dpi soft 1875 1132dpi off	0.025 0.025 0.025 0.025	const const const const	const const const const	>> >> >> >>	210 220 220 230	- - - -	- - - -	<< << << <<	Lut/ChLI
Helava DSW100	0.035	0.7	0.9	1.0	120	60	40	~30	Lut
Vexcel VX3000 10μm 24μm	0.045 0.035	0.8 0.7	1.0 0.9	1.2 1.2	130 110	40 40	30 20	~20 ~10	
Philips - CCD in the DSR15- **diffused** - dark (GV 90 ~ 0.4D) - medium (GV 130 ~ 0.4D) - bright (GV 230 ~ 0.4D)	0.078 0.050 0.025	0.9 0.8 0.7	1.0 0.9 0.9	1.3 1.1 1.2	90 130 240	40 60 120	30 50 100	~20 ~40 ~80	Lut/ChLI
Philips - CCD in the DSR15- **directed** - dark (GV 80 ~ 0.4D) - medium (GV125 ~ 0.4D - bright (GV 240 ~ 0.4D)	0.050 0.035 0.025	0.7 0.8 0.8	0.8 0.9 0.9	1.2 1.0 1.2	80 130 240	30 50 70	20 30 50	~10 ~20 ~40	Lut/ChLI
Agfa ACS100 - 2400dpi (EPFL) - 1800dpi (firm) - 900dpi (firm) - 300dpi (firm)	0.038 0.035 0.045 0.040	const 0.7 0.8 0.7	const 0.9 1.0 1.0	>> 1.2 1.2 1.1	190 140 130 140	- 70 60 60	- 50 50 50	<< ~40 ~40 ~40	Lut
Agfa Horizon - 1200dpi	0.030	0.8	-	>>	120	20	-	<<	Lut
Screen DT-S1030AI 2000dpi	0.020	0.7	0.9	>>	180	40	10	<<	Lut
Crosfield - 900dpi 1800dpi	0.050 0.045	const const	const const	>> >>	190 200	- -	- -	<< <<	Lut
Perkin Elmer	0.045	0.9	1.1	1.3	190	100	90	~70	
Wehrli	0.045	0.7	0.9	1.2	80	40	20	~10	Lut
Zeiss PhotoScan PS1 7.5μm 15μm	0.015 0.028	0.6 0.6	0.7 0.8	1.1 1.1	220 130	100 80	70 50	~20 ~20	Lut

Table 4. Analysis of the sensitivity of the scanners.

of the photographs. This might appear to be a paradox and could be explained by the diffusion of light from the surrounding brighter parts of the image.

This diffusion probably also explains most why many of the other scanners lose their sensitivity in darker areas which finally indicates the determined values (cf. columns 5 and 9 of table 4). This means that the measured density of small dark areas is reduced by the scanning process and the detail recognition in dark areas might also be reduced in comparison to the original photographs. In this sense it is understandable that the Zeiss PhotoScan also shows in this example a density limit of 1.1 D, although photographs with a much higher density can be scanned on that instrument. Nevertheless, the dynamic range of this instrument showed also clear limitations when we tried to scan a Panatomic-X image of a snowy scene with extended areas of a density up to 3.0 D.

4.4 Visual Analysis of Image Disturbances

A numerical analysis of the scanned images might appear very objective due to the clearly defined computation process. Such a process also clearly provides comparable results, as long as all images are obtained under the same conditions. However, the scanning process is very often combined with procedures for image correction and image improvement. For example, the images from the Crosfield scanner had undergone a rather strong edge enhancement (cf. fig. 6); the image scanned on the Screen scanner shows a different image resolution in the scanning direction and perpendicular to it (cf. fig. 7 and Table 3, column 7) and the Vexcel scanner gave a repeating pattern in low-contrast areas (cf. fig. 8). On a great number of scanners it was also possible to observe remaining errors due to the limited scan width and to the necessary tone adoption. This type of tone adoption is of course very important for matrix scanners, but is also often applied for array scanners.

This brief review of image disturbances shows that a visual image inspection is very important beside the various numerical analyses and might reveal very fundamental problems in a scanner. It is not our intention here to provide a complete overview of the image disturbances detected and the few aspects mentioned only serve as examples.

5. Conclusions

The main objective of this paper was to present a number of testing procedures concerning tone reproduction, which can be easily applied by a photogrammetrist interested in the use of digital images. The most important arguments concerned the image noise, the image resolution, the sensitivity of the scanner and the visual appearance of the images. A good scanner should show an image noise lower than ± 0.03 D for a pixel size of 10µm, although only one scanner came rather close to these values. Depending on the purpose of the image, one can also fairly state that a good scanner should allow a resolution up to 10µm (pixel size and size of the point spread function). The greatest difficulty might be presented by a thorough control of the dynamic range and the fidelity of tone reproduction. It is possible that the sensitivity of a scanner is considerably reduced in dark areas, affecting the detail recognition in these zones. Nevertheless, it seems that all scanners reach their limits in dark areas and reasonable tolerances should be applied corresponding to the effective requirements of production.

We had the feeling that such a study did not make sense without showing the practical application to various products of the arguments put forward. It is, however, clear that the results of these tests allow only a very limited comparison of the products. As already mentioned, the results are heavily influenced by the current calibration of the instrument, the skill of the operator and other exterior factors, which have practically nothing to do with the effective quality of an instrument. Many of the tests are already older than a year and many elements might have changed meanwhile. For example, earlier tests on the Vexcel scanner gave a rather low image resolution; when discussing the results with the manufacturer, it became evident that these results are no longer representative of the instruments and a new scan gave the results shown in the tables and corresponding to the performance of a good scanner of that type.

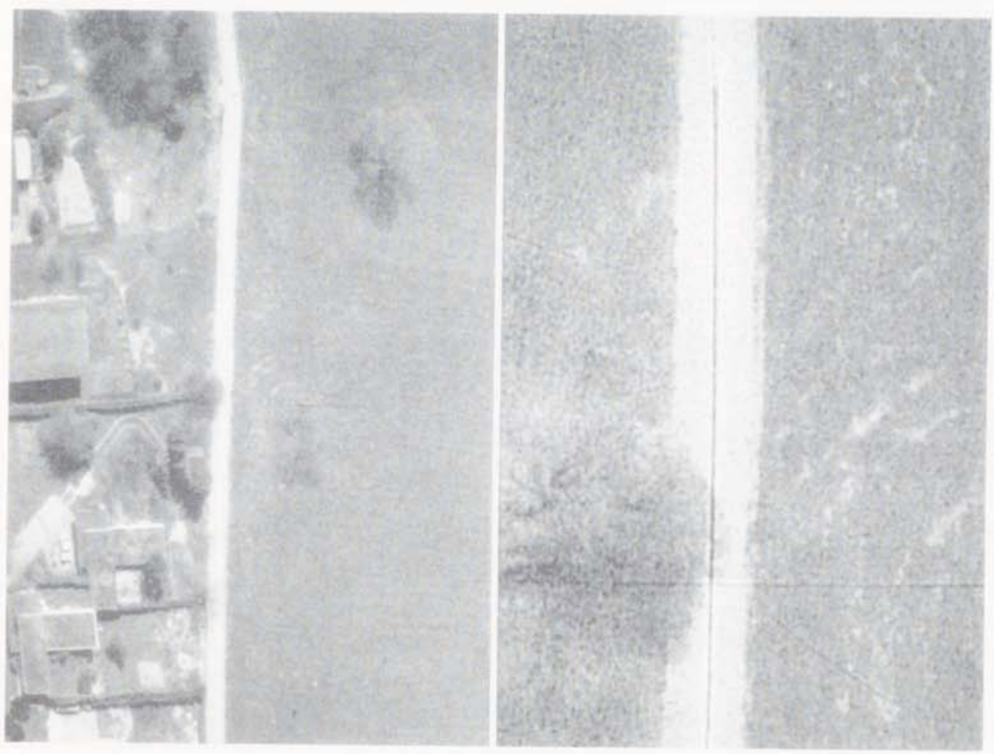

Fig. 6

Section of the image scanned on the Crosfield scanner, showing the effect of edge enhancement.

Although many restrictions have to be made concerning this study, one nevertheless gets the impression that the development of scanners is still in progress and that no final stage has yet been reached. At a congress on Infography in Zurich in 1993, one could observe the rapid developments in the printing industry. Most of the scanners shown in the 1992 congress had already been replaced a year later by new or improved models. The development in the photogrammetric industry might be different, but will also be influenced by the progress in electronics and by the requirements of the practice. Digital photogrammetry and digital image processing have considerable advantages compared to analog techniques. However, it seems that it is not yet possible to take full advantage of these new promising techniques due to limitations in the scanning process. The photogrammetric industry has always played a key role with regard to image quality and it is difficult, in photography, to find lenses with similar standards to those produced for aerial cameras. Consequently, a substantial increase in scanning quality might also require special developments.

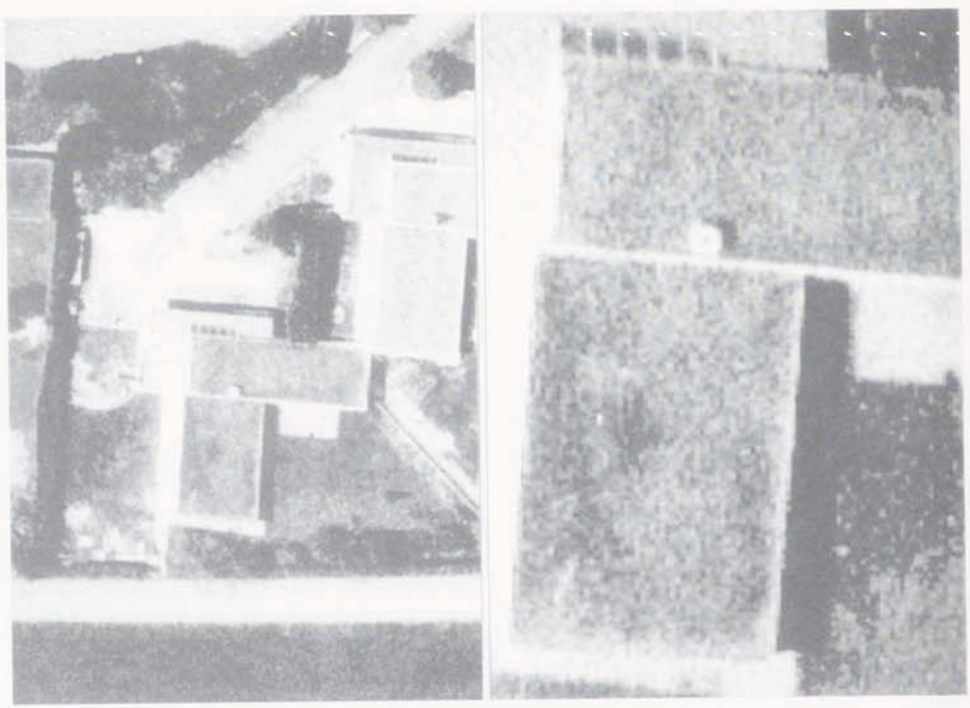

Fig. 7
Section of the image scanned on the Screen scanner, showing the different levels of image resolution, in the scanning direction (vertically) and perpendicular to it.

The authors are grateful to all firms having contributed to this study by scanning photographs on their products. All the scanners included in this test certainly have a number of special advantages which were not brought out within this study, which concentrated only on rather limited aspects.

Consequently, we would like to encourage all firms to continue in their line of research.

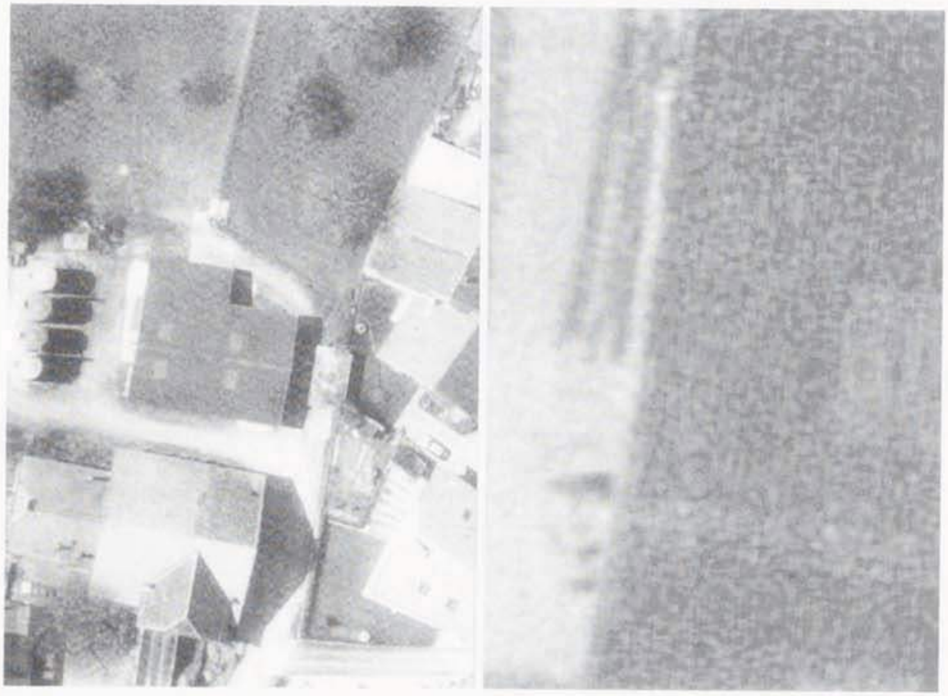

Fig. 8

Section of the image scanned on the Vexcel scanner showing a repeating patern due to image processing, most probably to the adaptation of the individual batches of the matrix camera.

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PS1 in a Digital Environment of Image and Restitution Map Production. Workflow, Failures & Quality.

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1. Introduction

The first productive photogrammetric scanner at the ICC was a Gestalt scanner, used to do altimetry and orthophoto image generation, until 1990.Then, to improve the quality of the images we started working with a drum scanner, the Joyce Loebl and it was only used for orthophoto purpose.That scanner only had a density/transmissivity range and one image format.

In 1991 the ICC bought a PS1, but it had not started working in production line until 1993 for the orthophoto images generation. Since 1994, PS1 has been the only scanner used at the ICC.

Actually, there are different production lines served by this device: digital aero-triangulation, stereo compilation (altimetry, planimetry, close range photogrammetry, ...) and orthophoto image generation. That means that each different goal has different needs and we try to standardize the demands as much as we can.

Digital Aerotriangulation works with compressed files but requires all the overviews.
Stereo compilation uses compressed files and a screen size overview. And the software for orthophoto works with images without compression. Also, the same project could have different necessities if the purposes are different. For example (see tabl. 1) it was necessary to scan at 15 microns of resolution compressed files to run Match T, but for orthophoto 30 microns was enoughth, although the files should be without compression.

Workflow appears sligthly different when the digital photogrammetry becomes more popular in a full productive environment. PS1 has been using for stereo compilation since 1994 and this year we started to scan for digital aerotriangulation.

The workflow has been modified during the several approaches to the current one.

Table 1: 1995 PRODUCTION OF SCANNED IMAGES

scale	fil	color	resolution	size	use	number	project name
1:32.000	neg	B/N	15 M.C.	250	ortho	438	1:5000 Catalunya
1:60.000	pos.	RGB	30 M.C.	90	ortho	150	1:25000 Catalunya
1:60.000	neg	clear	15 mic.	JPEG 65	Match T	540	1:20.000 MEDEA
1:60.000	neg	B/N	30 M.C.	70	ortho	202	1:20.000 MEDEA
1:20.000	pos	RGB	22.5mic	140	ortho	354	1:5.000 Barcelona
1:60.000	pos	clear	15 mic	JPEG 65	Match T	163	1:25.000 Asturias
1:5.000	pos	RGB	30 mic	JPEG 35	resti	933	1.2.000 AMB
1:5.000	pos	B/N	15 M.C.	JPEG 65	resti	1300	1:2.000 REGSA
1:15.000	neg	B/N	15 M.C.	JPEG 65	resti Upd	50	1:5.000 MTN

Total equivalent B/N 1995 production = 4581 scans

2. Goals for 1996

Some considerations from 1996 ICC's point of view: One of the main purposes for the ICC is to substitute some parts of photographic LAB for the scanner. That means that the scanner has to be as robust as it is the photographic LAB. The LAB needs 30 seconds to transform a negative into a diapositive and the PS1 needs 12 min (on average) to transform the negative into a digital diapositive to start in AERO, 3D-COMPILATION and ORTHOPHOTO.

Although digital process is more expensive than LAB process (about factor 10), in the ICC the use of scanned images is out of discussion, also for the 3D compilation, because we are updating existing digital maps and benefit from digital data. For Aerotriangulation the advantages are coming.

And without additional cost: Orientation is just once. It can be used to do digital enlargements in the map shop. Digital database of images as a Backup. And... thinking in future.

Internal demands to PS1

Actually the PS1 is serving 3 different customers (scanning purposes):

A. Compilation (Planimetry and altimetry) in DPWS
B. Match_T for DTM to produce Orthophoto out of Catalunya.
C. Orthophoto Production

And the main demands are: No so much contrast, precision in orientation, no artifacts (swathing, strips), good control of color (and specifications of aerial films in the software, color balance), scanning of color negatives (0.D to 3.5 D)

As it has been said at the beginning , we have a new customer in 1996:

D. Digital Aerotriangulation

Features demanded:

Negative
JPEG - Compression
Full set of overviews
15 microns or less
High speed, precision, large number of files to start their job.

3. Failures of PS1 scanner

In 1995 it was the first year to support scanning pressure by photogrammetrists. 1996 is going to be more productive because aerotriangulators are starting to work with digital images and need the scanner. This pressure is converted in a demand of services that can be achieved in a photo-Lab domain but not in digital .Due to the different projects listed before and due to the failures occurred in the daily operation, we need a backup storage of different projects that take at least 15 days.

We are using the 2.5 exabyte as transport media.

In the last 2 years we have an average of 8% of downtime, 1995's production was 4581 scans. Main failures are due to mechanical movement of axis, radiometric calibration and digital transfer of information from scanner to aplications.

List of 1995 failures

- Cleaning and calibration of the axis.
- Calibration of the illumination parameters due to the lamp exchange.
- Calibration: lamp, integration time and speed parameters.
- Motor exchange and global calibration.

Discussion after the Conference:

PS1 Inserted in a Fully Digital Environment of Image and Restitution Map Production. Workflow, Failures, Quality and Statistics, by J. Romeu

Beckschäfer:
We also work with the PhotoScan PS1 and Intergraph work station equipment. My questions to you are: how did you set up your workflow from the scanner to the triangulation? How did you fix the problem with the Intergraph system since it is not able to set up a "stripe set" and that you only have 2 Gigabytes at your disposal. I agree with you when you say that you should handle some 200-400 images in order to ensure an efficient workflow. With the system you have, it is impossible to have 15 µm scans because it will require some 10 different disks to organize it. Just think, if you have 2 operators on the system, working on two different projects as we do in our enterprise, then it is very difficult to solve this problem. So how do you organize the data in your organization?

Torre:
I must admit that we have yet to solve this problem. We hoped that the "Project Manager" of Intergraph's ISDM software implemented could assist in this task, but it seems that this tool is not available in the current version. The ICC is a big organization and currently, we mainly use Exabyte Tapes for data storage. It is not possible to store each image file on a separate tape therefore, a supplementary software would be necessary for the management of the files. It is understood that the image files are scanned first then the data has to be sent to the work station for aerial triangulation and finally sent to another station for plotting. So to answer your question, the management of the data gives us considerable problems and we have not found a satisfying solution yet.

DeskTop Publishing Scanner

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Summary

Scanners have been used as input devices in photogrammetric and cartographic applications mainly for digitisation of aerial images and maps. This paper deals with the use and applicability of DeskTop Publishing (DTP) scanners for photogrammetric/cartographic applications. The motivation of the paper is the investigation as to what extent low-priced DTP scanners, which are rapidly improving during the few last years, can be used for such applications. The paper will mainly concentrate on flatbed scanners with aim the scanning of films. However, many of the topics mentioned in the paper are also valid for drum scanners. The paper gives a review of recent technological developments with respect to these scanners, describes advantages and disadvantages, presents characteristics, tests and problems of such scanners, and investigations on their geometric and radiometric accuracy. Test patterns for calibration of such scanners and results using five different scanners will be presented.

1. Introduction

Scanners are an essential component in photogrammetric and cartographic applications. They have been used for scanning of aerial and satellite images, as well as digitisation of topographic and thematic maps, plans, charts and atlases. Aerial and satellite imagery has been used to derive Digital Terrain Models, orthoimages, and for digital mapping (new generation or update of existing map data). A trend is the use of digital orthoimages for generation and update of databases, generation of orthoimage maps, integration with other raster and vector data and visualisation. Although the developments in direct digital data acquisition have been enormous in the last decade, film-based systems are used in all fields of photogrammetry. In aerial photogrammetry film-based systems will provide the main data input for many years to come. Film-based satellite images are provided by many Russian sensors. Scanned topographic maps have been used as a central base layer within GIS, as a backdrop in different applications, e.g. navigation systems, for visualisation, or for subsequent vectorisation of digital map data.

The scanning requirements of aerial images and maps differ. Aerial images are scanned in grey levels or colour, require a format of 25 x 25 cm, a geometric resolution of at least 600 - 1200 dpi, a geometric accuracy of 2 - 5 μm (for high accuracy applications), a radiometric resolution of 10 - 12 bit and a density range of 2.5 D (panchromatic images) to 3.5 D (colour images). Satellite images have the same scanning requirements as aerial images with the exception of the scan format (up to 30 x 45 cm). Maps/plans are black and white or colour, can be transparent or opaque, require a large scanning format (e.g. A1), a geometric resolution of 400 - 1000 dpi, a geometric accuracy that is higher than the map accuracy (usually 0.2 - 0.3 mm), and generally a radiometric resolution of 1 - 4 bit (scanning in 256 grey levels or in full colour is rather rare). There is no single scanner, as far as the author knows, that can fulfil all these requirements. The scanners that come closer to fulfilling these requirements are: (i) high-end DeskTop Publishing scanners, which have up to A3 format and a geometric accuracy of more than 20 - 100 μm, and (ii) scanner/plotters of large documents (e.g. Intergraph's Mapsetter Series, Ektron Model 6447, Kirstol ZED HRC-1000). The main problems of the first group are geometric accuracy and resolution, and scan format. Scanners of the second group cannot scan in transmissive mode, mostly can not scan images without dot screening, have a geometric accuracy that does not suffice for high accuracy photogrammetric applications and are very expensive.

A classification of scanners is given in [1]. DTP scanners can be divided in flatbed and drum scanners, or low (1,000 - 20,000 SFr. with few exceptions) and high cost (> 50,000 SFr.). Although drum scanners (Howtek D4000, Optronics ColorGetter Plus, Kirstol/Dainippon ISC-2010, ScanView's ScanMate magic) have a high geometric resolution (2000 - 4000 dpi), and high density range (3D - 4D), they are generally more expensive than their flatbed counterparts, and most importantly they have low geometric accuracy due to drum inaccuracies, unflatness of film on drum etc. and because of the same problems and the inability to scan glass plates an accurate geometric calibration is not feasible. Here, mainly only lost cost flatbed scanners will be treated.

2. Overview of DTP Scanners

DTP scanners have been developed for applications totally different than the photogrammetric/cartographic ones. However, since they constitute the largest sector in the scanner market, they are subject to rapid developments and improvements. The consultancy BIS Strategic Decisions (Norwell, MA) forecasted in 1993 that the colour flatbed DTP scanner market will grow 39 % annually over the next five years. Flatbed scanners typically employ one or more linear CCDs, and move in direction vertical to the CCD to scan a document in one swath. Usually the stage is stationary, and the sensor/optics/illumination move. They can scan binary, halftone, grey level and colour data (with one or three passes), may have good and cheap software for setting the scanner parameters, image processing and editing, and can be connected to many computer platforms (mainly Macs and PCs, but also Unix workstations) via standard interfaces. They can usually scan A4 format, but some can scan up to A3 or even more. Some do not scan transparencies, others do so but only of smaller format (for A4 scanners the maximum transparency scan width is 8´´- 8.5´´). Such a width suffices to scan aerial films with 8 fiducials (5 fiducials are visible).

Flatbed scanners have a resolution of up to 1200 dpi (21 µm pixel size) over the whole scan width. Few scanners offer the option to increase the resolution by projecting a document portion (smaller than the full width) on the CCD. Their price range, with few exceptions, is 1,000 - 20,000 SFr. The big price jump occurs when going from A4 to A3 format. The transition from 600 dpi to 1200 dpi costs less. A3 scanners with 600 x 1200 dpi start at ca. 19,000 SFr. A4 scanners with 600 x 1200 dpi and transparency options cost much less (2,000 - 5,000 SFr.). Their radiometric resolution and quality, and scanning speed can be comparable to or even exceed that of the more expensive photogrammetric film scanners. DTP scanners with automatic density control and user definable tone curves that can be applied during scanning need for the setting of the scan parameters a few minutes as compared to much more time required by most photogrammetric scanners. In particular, the sensor chip and the electronics of DTP scanners are updated faster and are in most cases more modern that the respective parts of photogrammetric scanners. New generation DTP scanners employ 10 - 12 bit digitisation and have a density range of up to 3.4D. Some employ modern 3-colour linear CCDs and scan colour documents in one pass. Functions that can be encountered in DTP scanners include sharpening, noise removal, automatic brightness and contrast adjustment, manual and automatic thresholding, white and colour balancing, black/white point setting, negative scanning, automatic colour calibration, self-defined screens for scanning halftone documents and printing images, multiple self-defined thresholding for each colour channel to scan multi-colour documents, preview (sometimes with variable zoom) and scan area selection, CMYK scanning, colour correction, integrated JPEG compression, and batch processing. The scanners can be bundled with other packages for image processing, editing, and retouching, colour management and calibration, image management etc. Their quality is rising while their price drops (especially for the A4 format scanners). The main disadvantage of DTP scanners are the small format and the insufficient geometric accuracy and stability, caused mainly by mechanical positioning errors and instabilities, large lens distortions, and lack of geometric calibration software. For scanning maps the geometric accuracy may be sufficient but the format is limited to A3.

Table 1. Specifications of some DTP scanners

Model	Agfa Horizon Plus	Agfa Arcus II	UMAX Mirage D-16L	UMAX PowerLook II	Sharp JX-610	Scitex Smart 340 L
Mechanical movement	stationary stage	stationary stage	stationary stage	stationary stage	moving stage	stationary stage
Sensor type	3 butted CCDs 3 x 5,000 pels	trilinear CCD 5000 pels	colour CCD[1] 5000 pels	trilinear CCD 5000 pels	linear CCD 7500 pels	linear CCD
Scanning format (mm)	A3 (refl.) 240 x 340 (tran.)	210x355 (refl.) 203x254 (tran.)	305x452	212x297 (refl.) 212x254 (tran.)	305 x 432	A3 (refl.) 262x420 (tran.)
Geometric resolution (μm) vert. x hor.[2]	21.2x21.2	21.2x42.3	31.75x63.5 (A3) 15.9x31.75 (half width)	21.2x42.3	21.2x42.3	21.2x21.2
Density range/max.	3.2/3.4	3.1/3.2	3.0/3.2	3.3/	3.3/	
Rad. resolution (bits) internal /output	12/12 or 8	12/12 or 8	10/10 or 8	12/12 or 8	12/8	/8
Illumination	halogen 400 W	fluorescent 8 W	halogen	cold cathode 3 W	3 RGB strobing fluorescent	
Colour passes	3	1	1	1	1	
Geometric accuracy[3] (μm) x/y	92/47	61/37	18/19	52/43	56/28	

[1] The manufacturer does not specify whether colour is achieved by a trilinear CCD or colour filter multiplexing on the elements of one CCD. Patterns occurring in colour images scanned with Mirage indicate that the scanner uses colour filter multiplexing.

[2] Horizontal is in CCD direction, vertical in scanning direction.

[3] Values estimated by using 525-625 grid crosses as control points and an affine transformation (see Table 2). Higher order transformations lead for some scanners in smaller geometric errors.

Scanning throughput[4] and/or speed (ms/line)	0.35 Mb/s (1200 dpi) 1.7 (B/W)	4 - 15	5.4 (B/W) 9.9 (colour)	ca. 5 (B/W) 9.4 (colour)	0.62 Mb/s (A3) 12 (B/W) 35 (colour)	0.48 Mb/s (A4) 0.68 Mb/s (A3)
Internal image buffer	8 Mb (32 Mb option)	1 Mb (2 Mb option)	2 Mb	2 Mb		
Host computer/ interface	Mac, PC, Unix/ SCSI-2	Mac, PC/ SCSI-2	Mac, PC, Unix/ SCSI-2	Mac, PC/ SCSI-2	Mac, PC, Unix/ GPIB, SCSI-2	Mac
Software[5]	FotoLook FotoTune Light Photoshop	FotoLook FotoTune Light Photoshop	MagicScan MagicMatch Photoshop Binuscan Color-Pro Live Picture	MagicScan MagicMatch Photoshop Binuscan ColorPro Live Picture	Scan JX Photoshop ColorSync	
Approximate price (SFr.)	40,000	4,500	12,000	4,500	19,000	65,000

[4] Scanning throughput depends mainly on data transfer rate to host, and speed of writing data on disk.

[5] Other optional packages and third party software also available.

Table 1 shows the major features of scanners, that can scan 23 cm x 23 cm aerial films, and some A4 scanners that were tested. Other A4 scanners with resolution of 600 x 1200 dpi and transparency options include among others: Agfa DuoScan (1000x2000 dpi), Epson ES1200C, HP Scanjet 4c, LaCie Silverscanner III, Linotype-Hell Saphir, Mustek Paragon 1200, Nikon Scantouch AX1200, Tamarack's Artiscan 12000C, Ricoh FS2, Microtek ScanMaker III, Sharp JX-330M, Relisys 9624, Mirror Color Scanner 1200, Spectrum Scan III. Other A3 scanners include: Linotype-Hell Topaz (variable resolution/500 dpi over 30.5 cm width, 203 x 457 mm transparencies), Scitex Smart 320 (variable resolution/500 dpi over A3 width, 260 x 434 mm transparencies), Pixelcraft's ProImager 8000 (400 x 1400 dpi, transparency option in preparation), and the older models Imapro QCS-2400 (600 x 1200 dpi, 5´´ x 7´´ transparencies), Howtek Scanmaster 3+ (400 x 1200 dpi, A3 transparencies), Anatech Eagle 1760 (600 dpi, 419 x 610 mm format).

3. Scanner aspects and requirements

Different scanner aspects and necessary requirements will be discussed below. Knowledge on these topics allows users to better understand and evaluate scanners or appropriately set the scanning parameters. Details on these aspects and different implementation options and technological alternatives are presented in [1]. Here only a summary of some important requirements will be given.

- Illumination

  Uniform, stable, diffused, white illumination, no heating of the scanner sensitive parts. The whole system should be designed such that the power of the illumination is the minimum possible. Avoidance of flare light particularly when scanning transparencies.

- Dynamic range and quantisation bits

  10 to 12-bit quantisation with freely definable reduction to 8-bit, density range greater than 2.5D (preferably ca. 3.5D). Linear sensor response (nonlinearities occur particularly in the dark areas). Radiometric noise of ca. 1 grey level (for 8-bit output).

- Colour scanning

  Colour scanning preferably in one pass (the best option is using trilinear CCDs). Registration of colour channels with an accuracy better than the positional accuracy of the scanner. Colour balancing (especially enhancement of the blue channel) by varying the integration time and/or the light intensity.

- Scanning speed

  Mechanical scanning (movement) speed user-definable, very low speeds should be possible ; variable, user-selectable integration time.

- Calibration

  Calibration (radiometric and if necessary geometric for each scanning stage for which calibration is required, i.e. for each scan and each colour channel), corrections implemented in hardware as much as possible, calibration software and test patterns provided, geometric errors constant over a long time period.

4. Geometric and radiometric problems and tests

Geometric and radiometric calibration procedures are usually applied by all DTP scanner vendors but in all cases they are incomplete, or not accurate enough. In DTP scanners geometric calibration is not implemented, or if it is, patterns and procedures of low geometric accuracy are used. Calibration and test procedures can and should also be applied by the user periodically. For such calibration procedures software and test patterns should ideally be supplied by the scanner vendors but this is unfortunately a rare case. In addition, the scanner vendors rarely provide the users with all relevant technical specifications of the scanner and with error specifications, e.g. tolerances for the RMS and maximum error that can occur in different cases.

Error types can be classified according to different criteria, e.g. geometric and radiometric errors, or slowly and frequently varying errors. In the following the second classification will be used. The main slow varying or constant errors are lens distortions, defect pixels, CCD misalignment errors, subsampling errors, smearing due to defocussing and high speed, colour channel misregistration etc. The main frequently varying errors are mechanical positioning, illumination instabilities, stripes, vibrations, electronic noise, dust etc. As it can be seen from the above, the frequently varying errors mainly refer to the radiometry, whereby frequently geometric errors refer to mechanical positioning and vibrations. For a detailed description of possible errors see [3] and the description of a high-end DTP scanner (Agfa Horizon) and the errors it exhibits see [2].

The major errors are geometric positioning inaccuracies, lens distortions, electronic noise and small dynamic range, colour balance and colour misregistration. Other errors can occur depending on the design, construction, and parts of each individual scanner. Whether some errors are slowly or frequently varying depends on the quality and stability of the scanner, e.g. in DTP scanners the positioning errors vary from scan to scan or even within one scan. In DTP scanners the geometric errors in CCD direction considerably increase towards the borders of the scanner stage, and in scanning direction they may increase slightly towards the end of the scan.

5. Test patterns

Different test patterns, test and calibration procedures are given in [3]. The most important test patterns are grid plates for the geometry, resolution charts for determination of the MTF, grey scale wedges for determination of the density range, grey level linearity and noise level, and colour charts for colour reproduction and purity. The test patterns that were used in our tests were the following:

1. Resolution chart

   A USAF resolution 3-bar chart on glass plate produced by Heidenhain.

2. Gray scale wedges

   A transparent Kodak grey scale wedge with 2.5 x 14 cm size. The grey scale was measured repeatedly with a Gretag D200 densitometer and the 21 densities with an approximate step of 0.15 D were found to cover the range 0.05 - 3.09 D.

3. Grid plates

   Two plates were used (see Figure 1). The left one (off-line) is used to model the slow varying errors (lens distortion). The right one (on-line) is scanned together with the film and is used to model the frequently varying errors (mechanical positioning). The left plate has 25 x 25 grid crosses with a grid spacing of 1 cm, the right one 237 crosses at each border (left and right) with a spacing of ca. 1 mm. The plates were custom-made with thick lines (ca. 190 μm) and a small white square at the center of each cross. The squares were measured repeatedly at a Wild AC1 analytical plotter with an estimated accuracy of 2 - 3 μm. Films of the plates with Estar thick base were produced at an Optronics 5040 scanner/plotter and copied on high quality glass by a company specialising in fine optics. The cost of each plate was ca. 850 Sfr.

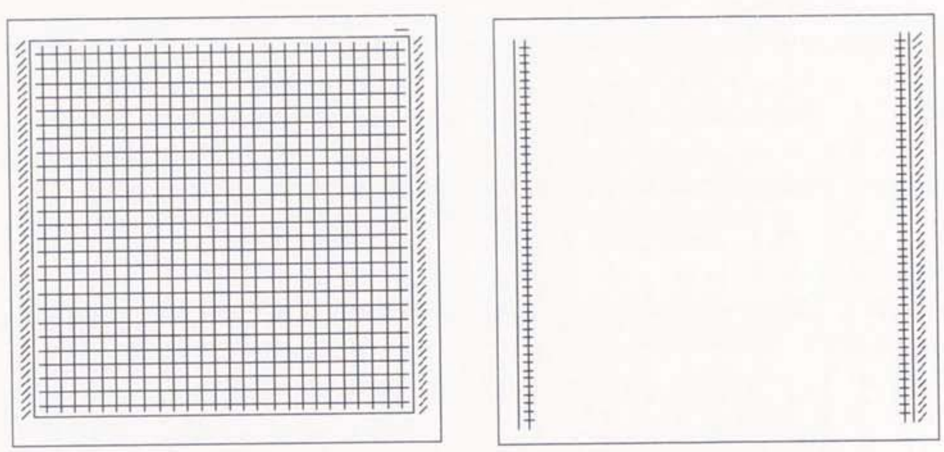

Figure 1. Grid plates for geometric tests and calibration.

6. Tests of DTP scanners

Using the above test patterns the following five scanners were tested: Agfa Horizon, Agfa Arcus II, UMAX Mirage D-16L, UMAX PowerLook, Sharp JX-610. The first scanner belongs to our Institute and was tested over a few years, the remaining ones were tested at companies or were lent. In all tests a resolution of 600 dpi was used (exception: 400 dpi for Mirage). The same test patterns, data analysis, data measurement and calibration procedures were used for all scanners. A difference exists for the grid plates. The 25.4 cm wide plates could not be put flat on the A4 scanners (Arcus II and PowerLook) and a part of the plates could not be imaged. Latter is important for the on-line plate because one of the border lines was totally missing. This plate positioning (one side of the plates was lying on the scanner frame around the scanner glass plate, less than 1 mm higher than the scanner glass plate) caused imaging displacements which could not be modelled by an affine transformation (as used in the interior orientation).

For all geometric tests Least Squares Template Matching (LSTM) was used to measure the grid crosses. The standard deviation of the matched positions was 0.03 - 0.04 pixels, i.e. 1.3 - 2.6 µm, for the 600 dpi and the 400 dpi scans respectively. In the following x-direction is the direction of the CCD line (horizontal), y-direction is the direction of the scanning movement (vertical).

6.1. Geometric accuracy without calibration

Table 2 shows the geometric accuracy of the scanners. For all scanners, except the Arcus, two scans were made. The results were similar for both scans, however here the worst of the two results is shown. For this test all grid lines were measured by LSTM and an affine transformation was computed between these values and the reference values (as measured at the analytical plotter). As control points either all points were used, or four corner or eight points. In the last two cases the remaining points were serving as check points and their errors are shown in Table 2. The versions with all points as control show the global geometric accuracy of the scanners. Only for Horizon the accuracy is worse than 60 µm, for the Mirage it is even close to 20 µm! The maximum errors are bounded and correspond to ca. 2.5 - 3.5 RMS. The errors are generally larger in x, indicating large lens distortions. Using only 4 control points the errors of the check points increase. This is natural because the corner points have larger errors than points let's say in the middle of the scanner stage, and thus the estimated affine parameters have larger errors. The big systematic errors introduced by the errors of the corner points are also indicated by the large mean errors, which ideally should be zero. A version with 8 control points (4 corners and 4 points at the middle of the outer borderlines) was also tested. The results were better, in some cases significantly.

The above mentioned scanner accuracy may be sufficient for some applications. Consider for example a scanner with 100 microns geometric error, used to generate hardcopies of digital orthoimages in scales 1:24,000 and 1:12,000, using 1:40,000 scale input imagery scanned with 25 microns, and an orthoimage pixel size of 1 m (equal to the footprint of the scan pixel size). The scanner error translates to a planimetric error of 4 m in the digital orthoimage, and 0.17 mm and 0.34 mm in the 1:24,000 and 1:12,000 hardcopies. This approximates the measuring accuracy in topographic maps, and may be acceptable for many users.

Table 2. Geometric scanner accuracy without calibration. Errors (residuals) after an affine transformation.

Scanner	Control/ check points	RMS (μm)		Mean (μm)		Max absolute (μm)	
		x	y	x	y	x	y
Horizon	4/621	146	71	-5	-26	224	151
	8/617	147	67	-4	-13	223	139
	625/0	92	54	0	0	220	159
JX-610	4/621	106	51	67	-39	214	117
	8/617	91	42	45	-26	182	105
	625/0	56	29	0	0	182	91
Mirage D-16L	4/621	35	20	24	-4	73	56
	8/617	32	20	20	-7	67	54
	625/0	18	19	0	0	56	51
Arcus II	4/521	85	81	51	-69	199	151
	8/517	76	62	36	-46	180	129
	525/0	63	41	0	0	216	122
Power Look	4/546	101	112	-66	103	181	177
	8/542	87	77	-45	65	158	138
	550/0	52	43	0	0	185	114

6.2. The geometric calibration procedure

The calibration consisted of two stages. In the first stage the effects of the lens distortion were modelled. Radial lens distortion caused large displacements in x-direction, and the tangential lens distortion smaller but significant displacements in y-direction. The off-line plate was scanned, all points were measured by LSTM and an affine transformation between these values and the reference values using all points as control points was computed. The residuals of this transformation were indicating the occurring errors. These errors were transferred from the pixel to the scanner coordinate system. There an x-correction regular grid was interpolated based on the residuals. The same procedure was repeated many times and the correction grids were averaged to reduce temporal noise, especially due to vibrations. For the Horizon four scans were averaged, for the other scanners two, except for the Arcus where only one scan was available. For the y-correction grid (modelling of tangential distortion) a similar procedure was used. In this case once an affine transformation and once a 7 parameter transformation (affine plus an x^2 term in y) was used. The x^2 term in y corresponds to the second order tangential distortion. By subtracting the residuals from the two transformations, we were left with the errors modelled by the x^2 term in y, and subsequently a y-correction grid in the scanner system was computed as for x. The x-grid was always used, the y-grid (called y-precorrection) is optional. Errors due to lens distortion are stable, so these correction grids do not need to be computed often (for the Horizon we applied the calibration using correction grids that were computed one year in advance).

For the second stage of the calibration the crosses of the two border lines of the on-line plate were measured by LSTM and an affine transformation between these values and the reference values using all points as control points was computed. The y-residuals of this transformation were indicating the occurring errors at the two border lines. For the A4 scanners only one border line was imaged, so a similarity instead of an affine transformation was used. Since scanning is performed in one swath by one linear CCD we assume that no errors can suddenly occur in the interior of the CCD. Thus, the error at any point in the interior of the image can be bilinearly interpolated using the errors at the border. This calibration stage is used to model the y-errors. They are mainly due to mechanical positioning. The part coming due to the tangential lens distortion can either be excluded by using the y-precorrection grid, or it can be modelled by using a transformation higher than the affine in the interior orientation. We used just a 7 parameter transformation (affine plus an x^2 term in y). This was sufficient for all scanners. The seventh parameter can be only determined, if 8 control points (fiducials) can be used.

6.3. Geometric accuracy after calibration

To check the validity of the calibration procedure we scanned the two plates simultaneously, i.e. the off-line plate was placed on top of the on-line and were fixed by tape to the scanner stage. This could be avoided, if we had designed the off-line plate such that it included the two border lines of the on-line plate with the dense crosses. Due to this procedure the crosses of the upper plate were naturally radially displaced, but this effect could be accommodated by the affine transformation. However, this could not happen with the two A4 scanners since the glass plates were not lying on the scanner stage and the radial x-displacement was asymmetric. The same problem occurred with the Mirage. This scanner has a dual lens system employing many mirrors (unfortunately the scanner representative did not want to or could not provide us with technical details). The x-residuals of the off-line plate revealed an asymmetry with respect to the centre of the scanner stage, thus indicating that the lens had an asymmetric position with respect to the CCD line. These x-errors for the three scanners could be reduced by using additional transformation terms (x^2 or xy) in the x-direction (see version 3 in Table 3). The scan of both plates was done twice except for the Arcus. The results of the two scans were similar and the average is shown in Table 3. Table 3 shows statistics of the residuals of the check points of the off-line plate after calibration.

Version 1 includes an affine transformation and y-precorrection. Version 2 includes the aforementioned 7 parameter transformation and no y-precorrection. Version 3 for the last three scanners is like version 2 but with an additional term (x^2 or xy) in the x-direction. The results of the three last scanners are not optimal due to the aforementioned problem with the positioning of the glass plate and the dual lens system of the Mirage. Still with version 3 we get an accuracy of 6 - 10 µm. This is remarkable especially for the Mirage, which had a scan pixel size of 63.5 µm. The results of the first two A3 scanners is more representative and show an accuracy of 4 - 7 µm. The JX-610 reaches an accuracy similar to that of many photogrammetric scanners. Version 2 is slightly better than version 1 and does not require y-precorrection, so it is faster. The errors in x- are slightly larger than in y-direction, and have a remaining systematic part. The maximum errors are equal to 2.5 - 3.5 RMS. The achieved geometric accuracy corresponds to 0.1 - 0.2 pixels. If 8 fiducials and a 7 parameter transformation can be used, then no y-precorrection is necessary, while in all other cases the y-precorrection brings substantial improvement.

Thus, calibration paves the way for use of DTP scanners in practically all photogrammetric applications, but at a cost: grid plates, development of calibration software, more computations for calibration and, if necessary, image resampling.

Table 3. Geometric scanner accuracy after calibration indicated by the residuals of the check points.

Scanner	Version[1]	Control points	RMS (μm)		Mean (μm)		Max absolute (μm)	
			x	y	x	y	x	y
Horizon	1	4	8	8	4	6	22	27
	2	8	7	6	3	0	20	20
JX-610	1	4	7	6	5	5	14	16
	2	8	5	4	4	1	14	15
Mirage D-16L	1	4	19	10	-15	2	40	23
	2	8	14	8	-9	1	30	22
	3	8	8	9	1	1	21	22
Arcus II	1	4	18	11	8	-5	45	25
	2	8	16	9	4	3	39	28
	3	8	10	9	4	3	22	28
Power-Look	1	4	12	6	-6	-1	32	15
	2	8	12	6	-5	1	33	16
	3	8	10	6	0	1	26	16

[11] See explanation in text.

6.4. Colour misregistration

It was tested by scanning the resolution chart in colour and separating the R, G, B channels. Well defined points (e.g. corners) were selected in the R channel and the same points were found by LSTM in the G and B channels. The difference of the pixel coordinates of corresponding points gives the channel misregistration. A better criterion would have been to use the maximum distance between any two of the three channels.

Table 4. Misalignment of colour channels

Scanner	Colour channels	RMS difference (μm)		Mean difference (μm)		Max absolute difference (μm)	
		x	y	x	y	x	y
Horizon	R - G	18	29	17	28	33	41
	R - B	4	20	1	19	17	32
JX-610	B - G	7	4	-7	-3	14	7
	B - R	10	2	-9	2	14	4
Mirage D-16L	R - G	5	19	4	15	18	47
	R - B	10	16	9	-9	26	43
Arcus II	R - G	2	9	0	7	6	22
	R - B	4	10	-1	-6	13	23

These errors are mainly due to the mechanical positioning inaccuracies (for 3 pass scanners), chromatic properties of the optical system (all scanners) and errors in the calibrated offset between the 3 colour CCDs (for trilinear CCDs). Table 4 gives some statistics of the misregistration errors. The mean difference shows that a large part of these errors is systematic. One pass scanners generally exhibit smaller errors than three pass scanners, although, as the case of Mirage shows, the errors can be large even for one pass scanners. The errors are larger in y-direction, influenced by mechanical positioning or offsets between the 3 colour CCDs. Figure 2 shows the differences between R and G channels for the Mirage D-16L. It must be noted that this test covers a small area (ca. 1 x 1 cm) at the centre of the scanner stage. Ideally the whole stage should be covered. It should be expected that the misregistration errors increase towards the left and right borders due to the chromatic properties of the lens.

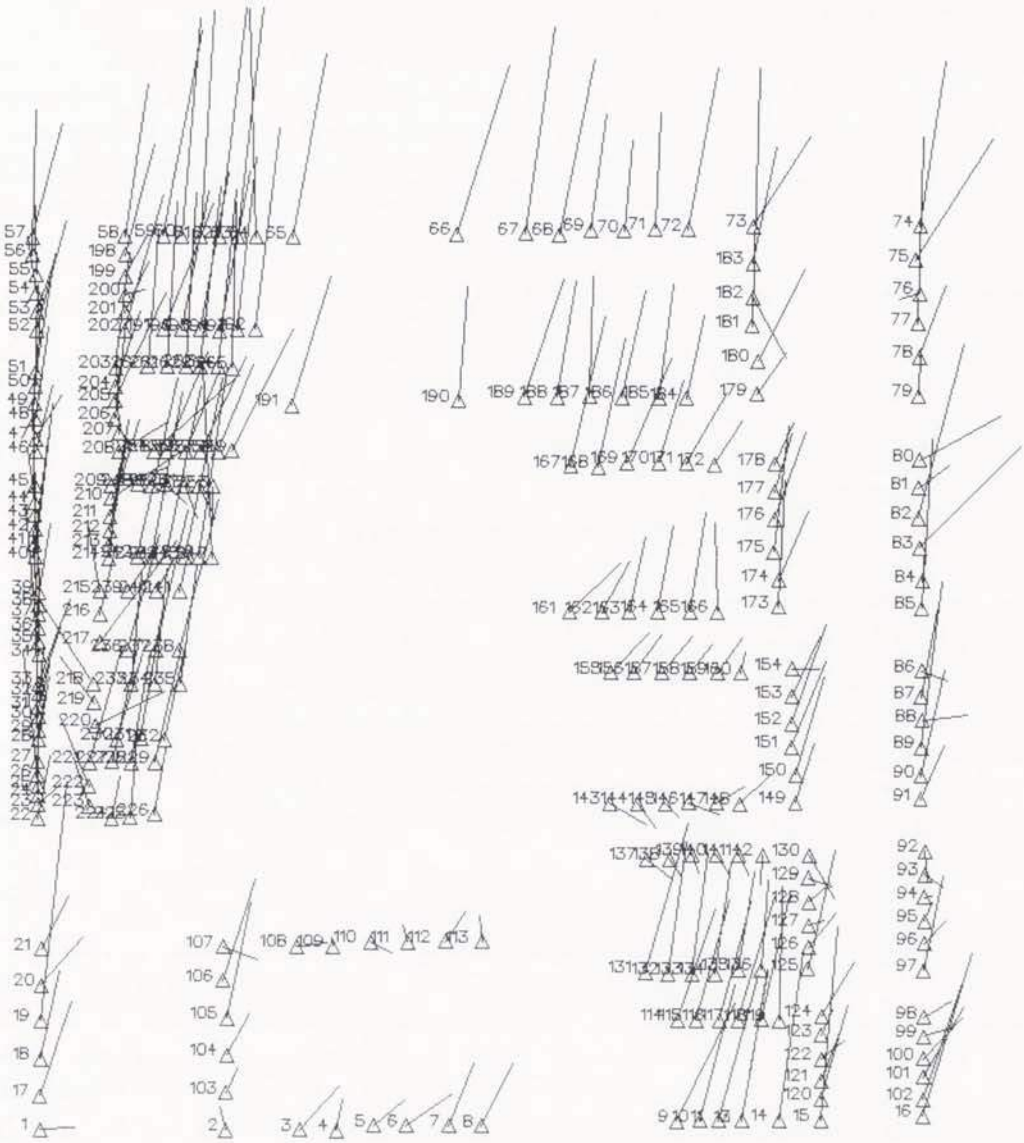

Figure 2. Differences between the R and G channels (Mirage D-16L).

6.5. Dynamic range, grey level linearity and noise

The grey scale wedge was scanned for this test. In all cases the scanning parameters (e.g. min and max D) were set automatically by the scanners. A rectangle at the centre of each grey scale was cut out to avoid border effects. Each rectangle included ca. 40,000 pixels (for 600 dpi) or 22,000 pixels (for the Mirage). The influence of dust and similar noise was reduced by excluding all pixels outside the range [mean ± 3 standard deviation]. Thus, for each grey scale a mean and standard deviation was computed (see Table 5). Arcus II, Mirage and PowerLook are saturated for D = 0.05, as indicated by the very small standard deviation. The smallest density they can scan is 0.08 to 0.1 D. The Horizon shows the least noise for low densities but the highest noise for high ones. The newer generation sensors employed in Mirage, PowerLook and Arcus shows another behaviour with low noise for high densities, and higher noise for low densities. Sharp' s noise level is quite independent of the densities. The bold numbers in Table 5 show the highest density D_i for which (mean + standard deviation) > mean of density D_{i-1}. As it can be seen, in all cases densities greater than 2.5 D can not be meaningfully resolved. For the high densities, the differences between the means of neighbouring grey scales are larger for the Horizon and Arcus (7 grey levels range for the densities 1.9 - 3.09 D), while for the other scanners they are smaller (3 grey levels range for the densities 1.9 - 3.09 D). The big differences between the means of the five scanners for the same density (for D=0.2 the maximum difference is 60 grey levels!) show that the grey levels have only a relative value.

It must be noted that for medium and high densities variations within the grey levels of each grey scale were noted. The grey values were for all scanners higher towards the borders of the grey scale that were next to the scanner glass plate. The grey level differences between borders and centre reached ca. 20 grey values for the highest densities. Only ca. the central half of the grey scale wedge was not influenced by this effect. Unfortunately, the rectangular region was cut out from each grey scale for further analysis was larger than half the width and not exactly the same for all scanners. Thus, some scanners may have exhibited higher grey level standard deviation (noise) due to this effect. We did a second test with the Horizon, by analysing only the central half of the grey scale wedge and the mean grey level standard deviation and maximum standard deviation for the high densities were 1.2 and 1.4 respectively, as compared to 2.5 and 3.7 in Table 5.

Table 5. Radiometric test with grey scale wedge[1]

Density	Agfa Horizon[2]		Agfa Arcus II		UMAX Mirage D-16L		UMAX PowerLook[3]		Sharp JX-610	
	Mean	St.D.	Mean	St.D.	Mean	St.D.	Mean	St.D.	Mean	St.D.
0.05	248.6	1.1	255.0	0.1	255.0	0.0	255.0	0.0	219.8	1.7
0.2	177.2	1.7	199.1	1.6	221.6	2.6	209.7	2.5	161.9	2.0
0.35	128.9	1.2	151.5	1.6	150.6	2.1	140.2	1.9	117.9	1.9
0.51	95.5	1.1	113.9	1.5	100.4	1.8	92.9	1.4	84.5	2.0
0.66	74.8	1.2	87.6	1.3	68.9	1.4	63.7	1.2	61.8	2.0
0.8	60.7	1.1	68.5	1.1	48.2	1.2	44.8	0.9	46.4	2.1
0.96	49.0	1.3	52.5	1.0	32.8	1.0	30.6	0.8	34.1	2.1
1.12	39.2	1.4	40.0	0.9	22.3	0.9	20.8	0.6	25.2	2.1
1.28	30.5	1.9	30.9	0.8	15.4	0.7	14.2	0.5	19.0	2.2
1.44	23.6	2.4	24.0	0.8	10.9	0.7	9.9	0.5	15.0	2.3
1.59	18.0	2.8	18.9	0.7	7.9	0.6	7.1	0.4	12.2	2.3
1.75	13.7	2.8	15.1	0.7	5.9	0.6	5.2	0.4	**10.3**	**2.3**
1.9	**10.9**	**3.0**	11.5	1.0	4.5	0.6	3.9	0.4	9.0	2.4
2.05	8.6	3.5	9.9	0.8	3.6	0.6	3.0	0.4	8.1	2.3
2.22	6.7	3.7	8.2	0.9	3.1	0.5	2.3	0.5	7.4	2.3
2.37	5.7	3.7	6.8	0.9	2.5	0.6	1.9	0.4	7.0	2.4
2.52	5.0	3.7	**6.0**	**0.9**	**2.2**	**0.6**	**1.6**	**0.5**	6.7	2.4
2.67	4.4	3.6	5.4	0.9	2.1	0.6	1.3	0.5	6.4	2.3
2.82	4.1	3.6	4.9	0.9	1.9	0.6	1.2	0.4	6.3	2.3
2.95	3.8	3.5	4.7	0.9	1.9	0.6	1.1	0.4	6.2	2.3
3.09	3.7	3.5	4.5	1.0	1.8	0.6	1.1	0.4	6.1	2.4
Mean[4] St. D.		2.5		1.0		1.0		0.8		2.2

[1] Scanning resolution 600 dpi (Mirage 400 dpi), transparency, all scan parameters set automatically.

[2] Density range = 3.0 D, maximum density = 3.3 D

[3] Density range = 3.0 D, maximum density = 3.2 D

[4] Excluding lowest and highest density which are partly affected by saturation.

The grey level linearity is checked by plotting the logarithm of the grey values versus density (see Figure 3). Ideally, these plots should be straight lines with equal distances between the means of neighbouring grey scales. The two models of UMAX and of Agfa respectively show as expected a similar curve. The curve of JX-610 is the one with the largest deviation from a line. The two UMAX scanner curves can be approximated by a line with an inclination of much less than 45 degrees. This implies a tone curve with a gamma of less than 1, i.e. the bright areas are stretched, while the dark ones are compressed. The results of all scanners (especially for high densities) depend on the form of the tone curve (LUT) that is used to reduce the 12 or 10 bits to 8, but the form of this LUT is unknown. A gamma larger than 1 will increase the noise for high densities and decrease it for low ones, while a gamma of less than 1 has the opposite effect. Given that the LUTs of the scanners are unknown the most objective comparison between the scanners is for the medium densities between 0.7 and 1D. All in all, Arcus II seems to have the best performance. In all cases the density range and maximum densities given by the manufacturers do not make much sense for high densities, as long as the noise level is too high to permit a meaningful discrimination between neighbouring densities.

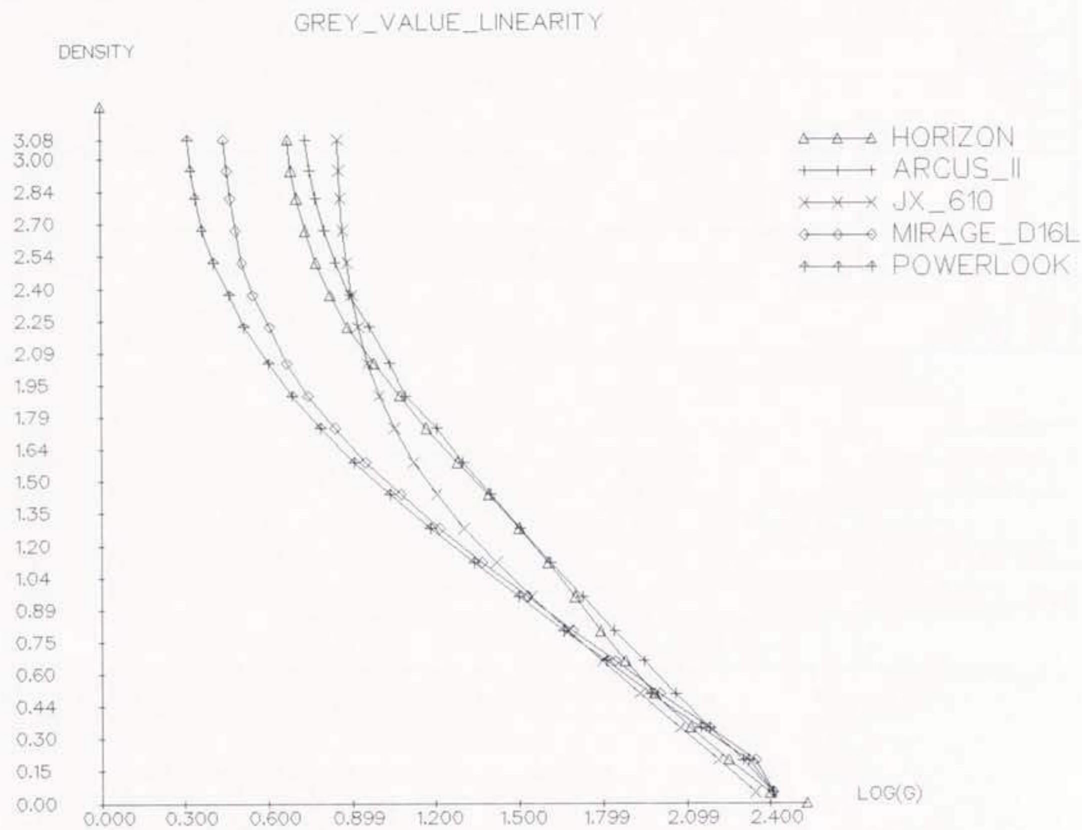

Figure 3. Grey level linearity for various scanners. Logarithm of grey values versus density.

7. Conclusions

DTP scanners are the fastest growing segment in the scanner market. Improvements in their overall quality, scan format, geometric and radiometric resolution and lower prices should be expected. Most companies that produce DTP scanners have an expertise in optoelectronics and mechanics and could certainly improve the positional stage and the optics of the scanners to achieve a high geometric accuracy. However, DTP scanner vendors either are not familiar with scanner requirements for photogrammetric/cartographic applications, or they simply ignore this market and concentrate on much bigger ones like desktop publishing etc. Thus, realistically an improvement in the geometric accuracy of the DTP scanners (this would make them more expensive and unattractive for customers in the big markets), or the production by DTP scanner manufacturers of new scanners specifically for photogrammetric/cartographic applications should not be expected. What could be done however, is the optional provision of customers with calibration patterns and software at an extra cost which could be around 4,000 to 6,000 SFr. Some companies could even use hardware processing that is present in their scanners to perform very fast certain operations needed in calibration (e.g. interpolation). The software development could be even made by a third party (e.g. a university), if the scanner vendor does not want to invest into it. Here we presented a general and simple geometric calibration procedure that has been used with various scanners and led to an accuracy of 5 - 7 μm.

In their current state, DTP scanners can be used in some photogrammetric tasks. The important point is that the user must clearly define the application requirements and examine himself whether they (particularly the geometric accuracy) can be fulfilled by a given DTP scanner. The main problem of DTP scanners regarding image scanning is that they lack high geometric accuracy. Improvements on this topic will drastically increase the range of their application. Regarding scanning of maps, plans etc. DTP scanners provide sufficient functionality and in many cases their geometric accuracy, even without calibration, is sufficient. Since, however, the format of DTP scanners is not expected to increase, their use for scanning of cartographic documents is limited to A3. For the above explained reasons the developments in the DTP scanners should be closely monitored.

Acknowledgements

The major part of the here presented scanner tests was performed by Mrs. Barbara Waegli within her diploma thesis at our Institute. The contribution of Mr. Marc Troller is also acknowledged.

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Discussion after the Conference:
DeskTop Publishing Scanners, by E. Baltsavias

Kölbl:
I have pointed out this morning that we have problems in the blue spectral band and the sensors of the DSW200 Scanner are not sensitive enough to reproduce this range properly. Therefore, my question to the manufacturers is whether they are aware of these problems and are there any visible solutions?

Jacobsen:
In my opinion, this is a typical problem of the CCD sensors, which is a physical limitation.

Kölbl:
It is true that there is no real solution if one only considers the limited sensitivity. In colour photography, you use colour correction filters in order to get a satisfying tone reproduction which could also be applied for scanners. I would like to pretend that you can easily get 100 times more light on the Helava DSW200 Scanner than is currently needed. This means that colour correction filters could be introduced with higher transparency in the blue area in order to correct for differences in sensitivity.

Dam:
Currently, the blue filters of the DSW200 Scanner are almost as translucent as the red and the green filters. There is not much that can be done here, but I think it is a function of the media, meaning the photographic material which is limited. We reproduce the colours as sharp as possible.

Kölbl:
Nevertheless, I think we can state that different scanners behave very differently and it is not only a question on technology. For example, I pointed out that the Agfa Horizon scanner reproduce the blue spectra rather well, whereas other scanners are quite insensitive in this part of the spectra.

Heipke:
If we sufficiently keep in mind our task, I was wondering whether the blue channel is really the most important one. For the correlation, for instance, we know that the green, and the red band especially, will give you much more information due to the physical conditions. Therefore, I wonder if it is useful to push the blue channel for photogrammetric applications.

Kölbl:
I have tried to explain this morning that the question is of real importance when you use false colour photographs. For a flight mission, you very often hesitate to use colour or infrared colour films. False colour photographs give much more details for vegetation and environmental studies. However, for making good orthophotos, colour photographs are very often preferred as they reproduce a more natural appearance of our environment, whereas false colour photographs very often shock the general mind when one sees our wonderful trees in purple. In order to derive from false colour photographs, orthophotos in real colour, it is necessary to extract the blue and the green band. This is only possible if the scanner has enough sensitivity in the narrow blue band corresponding to the colour dyes of the film, otherwise, this information is mixed with the information of the green band and will not lead to an acceptable colour image.

Jacobsen:
We have similar experiences. It is true that in colour diapositives, the blue information is very poor. This situation is different in false colour photographs; but also in colour photographs, it is nevertheless, important to reproduce this band in order to get a high quality product.

Baltsavias:
I would like to add to this discussion on colour reproduction that the Agfa Horizon scanner is especially adapted for this task. It scans the blue bands with a much longer integration time than the other bands, which then results in a much better product. It is evident that this scanner also presents technological limitations.

Kölbl:
I am thankful for this explanation and I think it is very important to properly understand the process of colour reproduction. When discussing with scanning specialists of the printing industry, one is very often asked about the control of colour according to CIE standard. It is true that we do not have a full control, from taking photographs to the printing of the orthophotos, as very often haze already reduces the reproduction of colours severely, but nevertheless, we must assure that we get all the information available on the film, and that we make optimal use of it.

Colomer:
On a desktop scanner, we usually have a software that is very flexible for colour balancing and adjustment. It allows to define and modulate the transfer functions step wise. You definitely have much more tools and flexibility. However, this software is not organized like on the PS1, which is limited to the gamma function. This is a great disadvantage because in mass production, it is hard to spend time adjusting every image. So for me, the solution for colour would be to use the latest technology applied in desktop scanners and to use better CCDs. A relevant question in this context is the use of 12 to 14 bit images. Our photo production line spends more time, actually in image processing than in the field of geometric corrections and it is very important that the scanning is done in a satisfactory way. Therefore, my recommendation to the manufacturers would be to supply us with good

scan data which would allow us to make the necessary image processing. In any case, photographs with peaks in the dark and bright areas are very difficult to scan and will continue to be problematic.

Becker:
We work with a lot of orthophotos and the problems of scanning is obviously in the dark areas. Has anyone tried scanning negatives to obtain optimal images or orthophotos? It might be that the use of positives could be an answer, but nevertheless, you will have problems in shadow areas.

Ackermann:
I would like to come back to the practical question of digitizing negatives. We heard that it is hard or not possible at all to scan negatives directly. Some vendors are using "second generation sensors," which seem to offer scanning possibilities for negatives even in the automatic mode. Is this procedure operational or will it continue to give problems? What is the situation now? Another question I would like to add was already brought up in a workshop on scanners two years ago whether 8 bit dynamic range is enough for scanning images which contain very dark and extremely bright areas. We were told then that 8 bit should be sufficient, provided non-linear scales for gray values are applied otherwise 8 but are definitely not sufficient. Has anything happened in this respect since then? Are "the second generation sensors" able to handle larger dynamic range?

Kölbl:
I think this is a very important question and I still feel responsible when I pretended that 8 bit should be enough for image processing provided that you transform the image in a way that you suppress the gray tone scale according to the observed noise. Therefore, it is not necessary to use 12 bit for the final presentation of the image. 8 bit should be sufficient for image representation for a density range from 0 to 2 or 2.5 D.

Dam:
We are scanning more and more negatives, and of course, more people wants to go with the original material. The results for normal contrast negatives have been fairly good. Though sometimes, we still recommend scanning in 10 bit output primarily because we are not often sure what the proper presentation in 8 bit output would be. What would give the optimum results is not always easy to create on the fly for the operators, and there are situations where the larger range is used and maintained until the product is used in the appropriate media for printing or for soft visualization. I think for black and white negatives, we are just about there. As for colour negatives, this might still be the question that Dr. Kölbl was commenting on, we still need to look at that. But in spite of that, I think we now have the sensitivity to do black and white negatives.

Ackermann:
From a practical point of view, it is absolutely mandatory to scan negatives. It seems ridiculous that first a photographic reversal has to be made. There may be technical problems involved but from a system's point of view it is impossible to produce a diapositive just for easier scanning.

Experiences with the Rastermaster RM1

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Summary

The Rastermaster RM1 of the Institute for Photogrammetry and Engineering Surveys of the University of Hannover has been tested for it's geometric and radiometric quality. The geometric quality is corresponding to an analytical plotter. The dynamic range of the TDI sensor included in the scanner is limited to 1.5D, this value is often exceeded by aerial photos. The relation between the gray values and the optical density of the image is not linear, causing problems with photo negatives. The radiometric limitation is not special for the RM1, it is caused by the silicon-technique of CCD-lines and arrays.

The time consuming procedure for the determination of the optimal scanner settings could be replaced by a fast and simple procedure by means of a desktop scanner.

1. Introduction

The amount of information included in an aerial photo cannot be transferred with the today technique into any type of storage within the time period available from exposure to exposure. By this reason also in the next future photos have to be scanned for getting digital images with sufficient resolution. Line scanners do not have the number of pixels corresponding to a photo (~18 400 pixels would be required) and the geometry cannot be compared.

It has been shown that only image scanners designed for photogrammetric purposes do have a sufficient accuracy. Drum scanners with diodes do have a better radiometric characteristics than CCD-lines and arrays but the geometric quality is limited to the use for orthophotos. Image correlation, data acquisition for aerial triangulation and photogrammetric stereo measurements have to be based on digital images with position accuracy's not less than ±5µm.

Because of the limited budget of the Institute the photogrammetric image scanner Rastermaster RM1 from Wehrli & Associate Inc. has been chosen. During the decision phase the amount of images which have to be scanned was underestimated, so that the lower speed in relation to more expensive scanners has been tolerated. In the period of now 12 month the scanner was intensively used. If a scanner is available, the request for digital images automatically is raised.

2. Technical Elements of the RM1

The RM1 of the Institute has been designed in December 1994. Meanwhile it is changed by the company. The main changes are in the radiometric characteristics - the light source is now different and a color sensor is available. The geometric behavior is the same, only some parts are reconstructed for improving the life time and reducing the required service.

The general geometric design is corresponding to an analytical plotter. The movement of the photo carrier is controlled by servos based on linear encoders. The plate is moved by a friction drive. With a working space of 245mm•245mm no problems for handling standard size aerial images are existing.

The time delay and integration sensor (TDI) DALSA CL-E1-2048A has a length of 2048 elements and integrates over 96 pixels, that means, it is not a line, it is an array with 2048•96 elements. The integration of the TDI-sensor over 96 elements reduces the noise and systematic line errors by the factor of 96 and raises the sensitivity 80 times against an individual CCD-element. This sensor is also used in another photogrammetric image scanner.

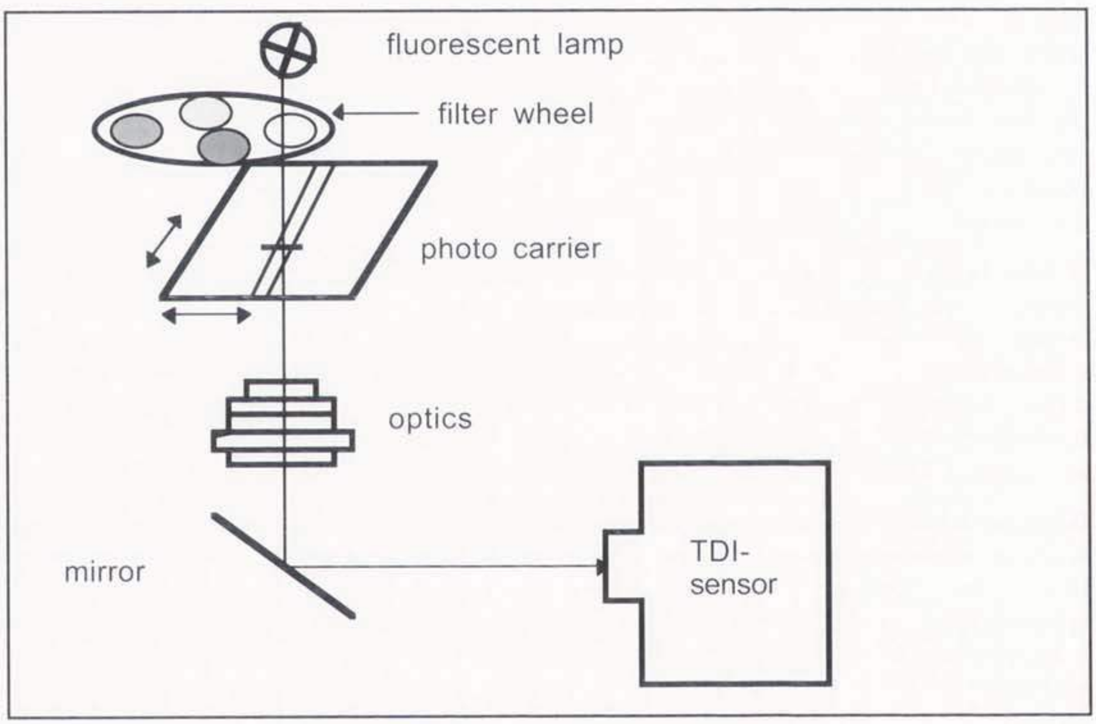


figure 1: configuration of the RM1

The RM1 is using only 1024 of the 2048 rows. The active part can be selected by the scanner control data, usually the center part is used. The sensor has no possibility for a selection of the spectral range, this only can be done by a computer controlled filter wheel with the standard red/green/blue selection. The transmitted light from the fluorescent lamp is passing through an APO-RADOGON-D lens system from Rodenstock over a mirror to the sensor. By the projection the original pixel size of 13µm in the sensor is changed to 12µm in the scanned image.

3. Radiometric Characteristics

The scanner is using a depth of 8 bit corresponding to 256 gray values. This is usually sufficient. The relation between the gray values and the optical density of the film has been determined by means of a calibrated Kodak gray scale. The whole range of the scanner settings, that means speed and diaphragm, has been checked. Figure 2 gives an overview over some of the results. Caused by the different settings the relation between the gray values and the optical density is primarily shifted. The dynamic range of approximately 1.5D is not changed by this.

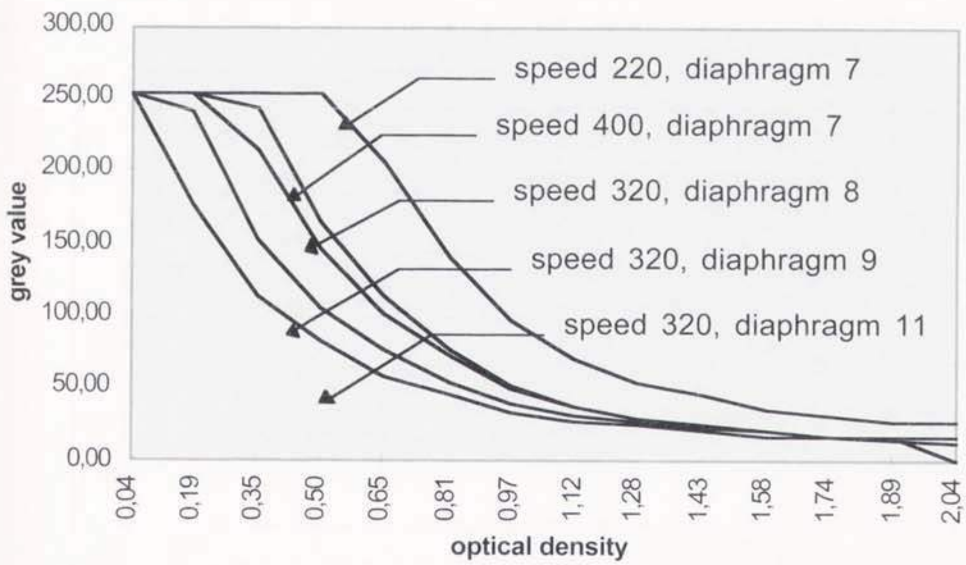


figure 2: relation gray value - optical density

With a look up table (LUT) the relation between the gray values and the optical density can be linearized, but this is only changing the visual impression. The poor information in the dark parts will stay poor, that means, the noise is enlarged and reverse in the more bright parts information is lost by a LUT-transformation. Corresponding to this, the correlation of images stretched by a LUT was not so good like with the original information. By this reason we do not use a LUT during the scanning process, this can be done later together with the production of orthophotos.

Due to the fact of a limited density range, the optimal selection of the scanner settings is important. An over-saturation of the CCD-elements has to be avoided because is can cause a very strong blooming effect. In the extreme case the whole sensor line can get blind, that means a larger area will have the gray value 255. By this reason we cover the area around the scanned photo with cardboard. The optimal results are achieved if the bright parts of the photos are just getting the gray values 255, that means there is a loss of information in the dark parts of the images. Usually this is not causing problems in the case of film positives or color diapositives. Also the visual impression is based more on the bright parts. The dominating information is included in the more bright parts of the images. This is causing problems in scanning film negatives, where the main information is in the dark parts and as it can be seen in figure 2, this information is compressed and finally lost. After digital change of the scanned images from negative to positive this fact is obvious. Only film negatives with poor contrast can be accepted.

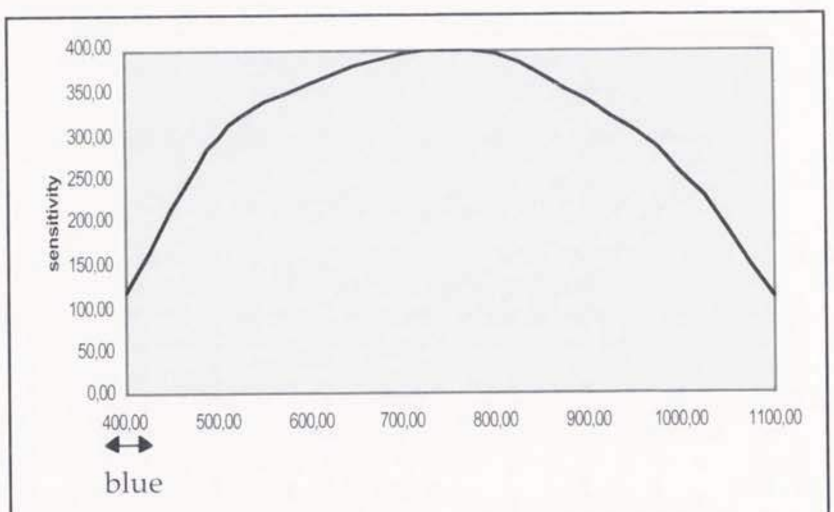


figure 3: spectral sensitivity of the CCD-sensor

If color images have to be scanned in color, this only can be made with our RM1 in scanning three times with the computer controlled filter wheel. Poor results have been achieved with the blue color. Even with the lowest speed and the largest opening of the diaphragm the blue channel has had only very poor results. Of course also aerial photos do have only limited information in the blue channel, in addition reduced a little by filters, but the main problem is caused by the low sensitivity of the CCD-sensor in this spectral range, which can be seen in figure 3 (blue ~ 400 - 490 nm). Now a more strong light source is available for the RM1 which can be installed also in existing scanners with the old light source and the new scanners can be equipped with a color TDI-sensor which can scan in the three spectral bands in one operation.

The empirical determination of the optimal scanner settings is very time consuming. It takes approximately 30 minutes with the RM1 and it has to be done at least for every photo flight. Within a photo flight the settings only have to be changed if a general change of the landscape is within the area. As mentioned before, the optimal settings are shifting the bright parts of the photos just to the gray values of 255 to avoid an over-saturation. It is much more fast to scan the photo tránsparencies with a desktop scanner like the HP Scanjet IICX. In the Institute of Photogrammetry and Engineering surveys we only do have the possibility to use the desktop scanner with reflected light, that means the scanned transparencies are not looking very nice. The density range of the HP Scanjet is also smaller in relation to the RM1 (see figure 4) and the gray values cannot be compared directly, but the density of the bright parts can be measured and with an empirically developed table the optimal RM1-settings are available within one minute.

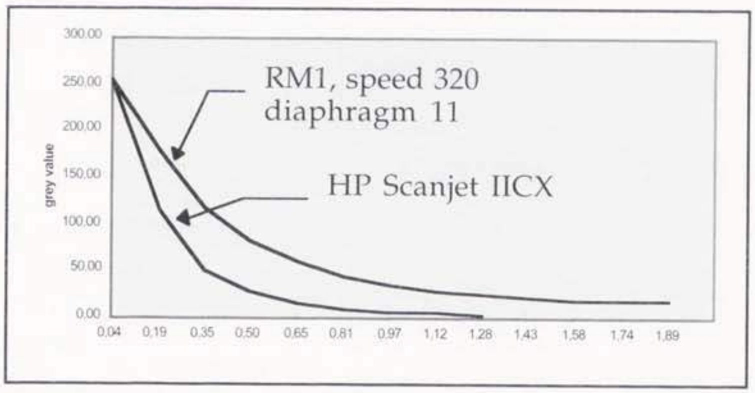


figure 4: relation gray value - optical density for the HP Scanjet IICX compared with the RM1

The general limitation of CCD-lines and arrays with the color and the density range are only allowing a limited quality of generated orthophotos. By this reason in some sensitive projects, the photos have been scanned twice - at first with the RM1 for the image correlation and then with a drum scanner for getting the optimal color information.

4. Geometric Characteristics

For geometric purposes no essential loss of accuracy of the original image precision should occur by the scanning process. The geometric accuracy should not be mixed with the pixel size because sub-pixel accuracy is possible. In the extreme case of close range photogrammetry with large targets up to ±0.02 pixels have been reached based on CCD-arrays (Bösemann, Jacobsen 1995). The basic construction of the RM1 is corresponding to an analytical plotter, but there are few additional error sources because opposite to the analytical plotter the image coordinates are not just determined for a point, a line of pixels is scanned at the same time.

At first the optical system can cause a deformation of the sensor line, but the used Rodenstock optics shall not have an essential radial symmetric lens distortion and tests have not shown any effect. Then the projected location of the sensor line in the image is important - this is a question of the instrument calibration and remaining effects may be available. As it can be seen in figure 5, the sensor line should fit to the distance between neighbored scans and the line should be perpendicular to the scan direction.

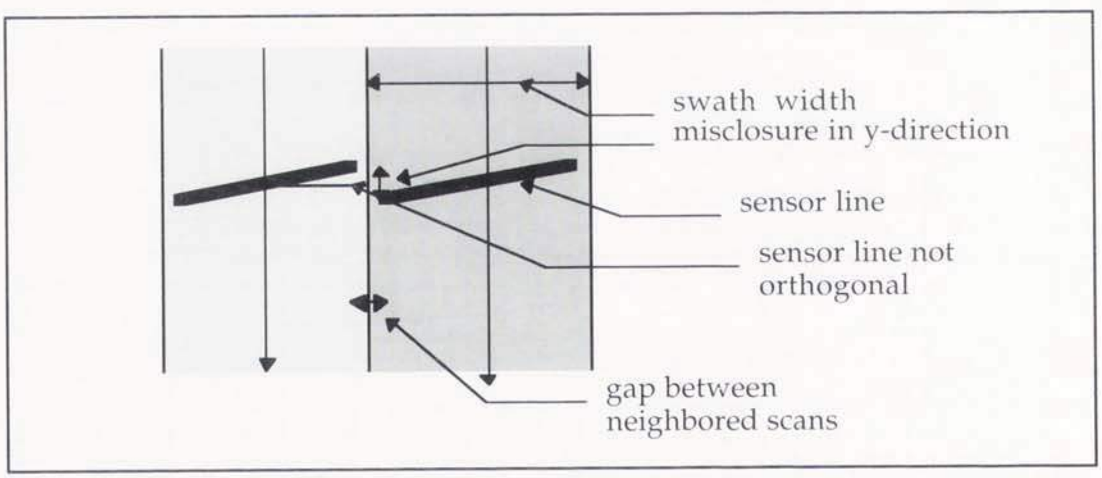


figure 5: location of neighbored CD-lines

The RM1 has been checked by means of 2 different reseau platen, one from the Rollei Reseau Scanner with 121•121 reseau crosses with a spacing of 2mm and one with 11•11 lines with a grid spacing of 12.5mm. For both platen the calibrated grid coordinates are available with an accuracy < ± 1μm. The platen have been rotated slightly against the instrument axis to avoid the check of only few rows and columns. The discrepancy between the measured and transformed grid coordinates to the calibrated values have been analyzed for random and systematic errors. The separation of the systematic errors can be made in the same way like the self calibration in bundle block adjustment. Additional unknowns which are able to compensate the typical geometric problems have to be introduced.

The formulas shown in table 1 are originally developed for the calibration of analytical plotters (Jacobsen 1982 and 1984). It was only necessary to add the additional unknown 14 for the line scale and rotation. The additional unknowns are checked for correlation, total correlation and significance like usual additional parameters in block adjustments (Jacobsen 1980).

x' = x - P1 x' = x - P1	y' = y - P1 x' = x - P1
x' = x - P2 • X • Y • 1.0E-6	y' = x - P2 • X • Y • 1.0E-6
x' = x - P3 • X • Y • Y • 1.0E-6	y' = y - P3 • X • Y • Y • 1.0E-6
x' = x - P4 • SIN(X • π/90.)	y' = y - P4 • SIN(X • π/90.)
x' = x - P5 • SIN(Y • π/90.)	y' = y - P5 • SIN(Y • π/90.)
x' = x - P6 • COS(X • π/90.)	y' = y - P6 • COS(X • π/90.)
x' = x - P7 • SIN(Y • π/90.)	y' = y - P7 • SIN(Y • π/90.)
x' = x - P8 • COS(X • π/45.)	y' = y - P8 • COS(X • π/45.)
x' = x - P9 • SIN(Y • π/45.)	y' = y - P9 • SIN(Y • π/45.)
x' = x - P10 • SIN(X • π/45.)	y' = y - P10 • SIN(X • π/45.)
x' = x - P11 • SIN(Y • π/45.)	y' = y - P11 • SIN(Y • π/45.)
x' = x - P12 • COS(X • π/22.5)	y' = y - P12 • COS(X • π/22.5)
x' = x - P13 • COS(Y • π/22.5)	y' = y - P13 • COS(Y • π/22.5)
x' = x - P14 • (X - INT(X/12.288) - 6.144)	y' = y - P14 • (X - INT(X/12.288) - 6.144)

table 1: used formulas for the separation of systematic scanner errors

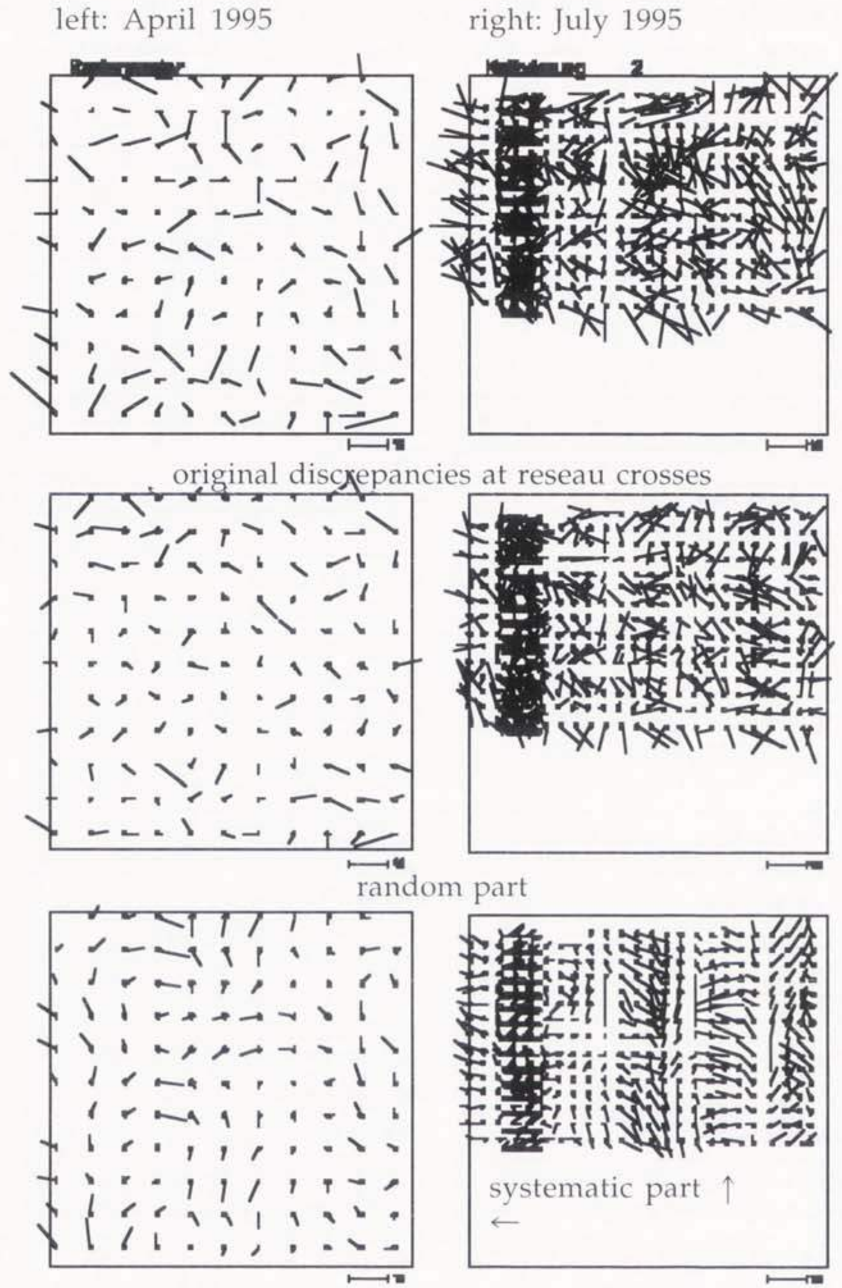
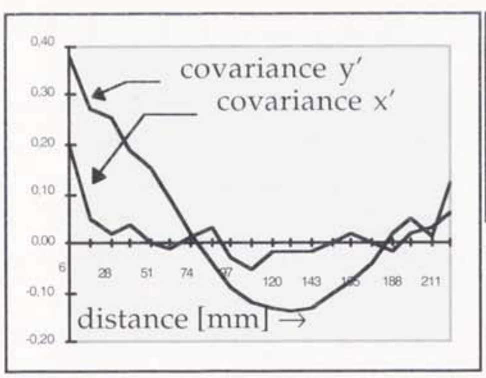


figure 6: results of the RM1-calibration

The scanner was calibrated by means of the reseau platen several times over a longer time period. The scanned reseau platen have been measured at first manually, later automatically. The difference between the reseau crosses measured in the digital images have been compared with the calibrated reseau coordinates after affinity transformation. Affinity errors of the scanner are unimportant because it will be compensated by the inner orientation of the scanned images, what have to be done with an affinity transformation. The systematic errors and the random errors are in the same range. The root mean square error of the original discrepancy at the reseau crosses after affine transformation was +/- 4.7µm as mean for x and y and as mean of 4 calibrations. If the influence of the pointing is respected, the mean square discrepancies are +/- 4.2µm. This total effect can be separated into the random part with +/-3.5µm and without the influence of the pointing +/- 2.9µm and the systematic part of +/-3.0µm. For precise applications the results of the calibration can be respected or determined as systematic image errors in a bundle block adjustment and so finally the scanner has a random influence of +/-2.9µm. The systematic errors have been astonishing constant, no significant change could be detected.

At first equally distributed reseau points have been used, later a densification was made in some parts to get better information about the sensor-line-scale and rotation. In the upper part of figure 6 the original discrepancies are shown. It is obvious that neighbored points are correlated. That means systematic errors are present. The correlation is strongly reduced in the center part of figure 6 where the random component is shown.

The covariance analysis (figure 7) demonstrates the effect of the separation of the systematic errors. There is still a remaining part of the covariance after selfcalibration with the set of formulas shown in table 1, but this is typically - the very local effects of systematic cannot be eliminated with just 14 unknowns.



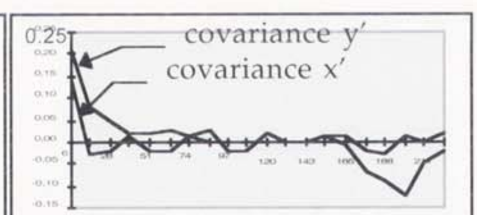


figure 7: covariance analysis of the discrepancies at reseau crosses

left: original results right: „random part"

It was not possible to determine a rotation of the sensor line, only a remaining mechanical calibration error of the fitting of the sensor length to the swath width in the range of 3µm could be seen.

5. Operational Problems

The RM1 is controlled by a PC Pentium 90. This PC is only used for the scanning, further processing of the digital images usually happens on workstations, that means the data have to be transferred. The data transfer takes not much less time than the scanning and during this time the scanner is blocked. By this reason the PC was equipped in total with 8Gb disc space to store all images of a day. The data transfer then can be made by batch process over night. In addition a CD-writer is connected to the PC to allow also the output on CD.

The scanning of one image including the handling takes approximately 30 minutes, this is sufficient under the conditions of a University.

Once in a group of digital images a shift of a scan-line by 1 up to 2 pixel could be detected. This may be caused by abrading material from the friction drive of the photo carrier. After cleaning the wheel, the problem has not been seen again. A loss of reference has been seen also in digital images scanned with other scanner types and also in analytical plotters. The abrading of the friction drive made it necessary to replace the friction drive after one year of operation. The material has now been changed from aluminum to stainless steel, so the problem may be solved.
As mentioned above it is necessary to cover the area around the photos on the photo carrier by cardboard to avoid an over-saturation of the sensor.

6. Conclusion

The CCD-lines and arrays do have a limited dynamic range in relation to aerial images, by this reason it is necessary to use the optimal settings of the scanner. The time consuming empirical determination can be replaced by a pre-scan with a desktop scanner. Based on the pre-scan with a developed table the settings can be found within one minute. Nevertheless a loss of information will happen in the dark parts. By this reasons problems are existing in scanning photo negatives. With photo positives and color images which shall be scanned only black and white, no real radiometric problems are existing.
The geometric accuracy of the RM1 corresponds to an analytical plotter, that means, it is sufficient also for jobs where precision is required like image correlation and aerial triangulation.

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Wehrmann, H. 1995, Kalibrierung des Photoscanners RM1 Rastermaster, Diploma Thesis, University of Hannover

Discussion after the Conference:
Experiences with the Rastermaster RM1, by K. Jacobsen

Baltsavias:
I have two questions, one concerning the radiometry and the other regarding the geometry. As for radiometry, I would like to know whether you used all 96 cells of the CCD camera, and what about the noise in the dark areas? I especially wonder why you stopped at 1.5 D density?

Jacobsen:
Well, that is the situation we have with the scanner, which means that we have a maximum dynamic range of 1.5 D and in the dark area, we have a very poor resolution. Furthermore, I have to state that we effectively used all 96 pixels. The noise is not included, which amounts to about 3 to 5 gray values over the whole range. Here, I would prefer to talk about the noise in the range of gray values and not refer to the optical density because this is rather a constant value.

Kölbl:
I think it is not useful to express the noise only in gray values as a change of the light intensity will already change the result. I prefer density values for the noise as they are independent of the set up of the system. That is also important in dark areas where you have a very weak response and a rather large noise which finally means that you do not have any image information in dark areas, a phenomenon which gets evident if the noise is expressed in density values; whereas a statement that the noise is in the order of three gray values seriously hides the real effect.

Jacobsen:
Yes, it is a problem to scan dark areas. In reality, we effectively have more or less the same noise over the whole range of gray values, and we should transform these values into optical density. We also know that we have limitations in the dark areas; that is also one of the reasons why we mainly scan positives and not negatives.

Baltsavias:
Mr. Jacobsen, you stated in your conference that the geometric precision over the total area of the scanner was 4.6 µm. Is this the average over several calibrations? If so, then it would make the random part considerably smaller or does it only come from one scan?

Jacobsen:
This should be seen as a question of definition. In my paper, I gave the results of 4 individual scans over a longer period of time, but we did not average the results. That means that the error only refers to one individual scan.

General Discussion on Scanning

Dowman:
I have two questions for Mr. Baltsavias, the first question concerns the geometric accuracy and the second question concerns the stability of the desktop. Are the repeated calibrations really improving the same geometric property? And if you are calibrating, then how often would you recommend using the grid points to update your calibration?

Baltsavias:
First of all, I would like to state that I cannot make a comparison between the 600 and 610 model because it was only recently developed. Generally, I would expect improvements in technology and the whole system to be more stable. Currently, even the system is rather stable and a series of errors will not change like lens distortion. As for the other errors that vary frequently, you should do the calibration after each scan; the border information should already give most of the elements needed. There is one component in the scanning direction that you can figure, but the mechanical positioning is limited, but to a good part constant.

Beckschäfer:
Since we are talking about scanning and you ask for topics, another topic that we should also talk about is data compression because if you are working on projects with, let's say 1000 or 2000 images, then from my point of view, data compression is extremely necessary. When I came to this Congress, I thought I would hear new things about data compression. So my questions are: Where will data compression go from here? Will there be new techniques? Would it be possible to scan and compress data with the Helava system and then work with the Intergraph system and so on? Who can give an answer to this topic?

Dam:
I do not know of any new techniques other than JPEG. JPEG is now a real standard. and it is so standardized. Certainly, if it becomes faster and more off the shelves, its use will generalize even more.

Kölbl:
I have to admit that I did not want to put too many topics into the discussions. I wanted to discuss what is available today from the manufacturers and what the practical experiences are. I think the Congress in Vienna will cover the scientific aspects much better.

Agnard:
I just want to say a few words on the stability of desktop scanner used in connection with the DVP. As for what we found after calibration, we did not see much difference from scan to scan and our software calibrates rather efficiently.

Kölbl:
I think there is still one topic that has not been discussed yet which concerns the MTF. I do not know what your experiences are in this field, but I would pretend that the scanners still do not cope with the quality of aerial cameras. We do not get the complete image information and we should rather adapt the pixel size according to the effective MTF. Too often, one uses the cut-off frequency to determine the required pixel size, but one seldom realizes that for 5 or 10 lines per millimeter, one already looses 10% - 20% of contrast. But this fact is much more important for the image forming than the cut-off frequency.

Ackermann:
I want to make a statement from a system's point of view. We have heard that scanning has many technical problems, that we are trying to solve. The results are quite encouraging, but we are not really through yet. Also, we have talked about data compression and the whole storage problem, becoming particularly important now that automatic aerial triangulation is coming up. Mr. Romeu made a very interesting remark by saying that the scanner or the scanning department in a big organization substitutes the photolab. From a system's point of view, I would like to put that one step further. We should look beyond the scanning process and think about the output. Why not combine the scanning with interior orientation, since all data are there? We could deliver a product, ready for the user to go on. So, deliver corrected, transformed and re-sampled digital image data. Then the data can be used immediately for plotting, matching, orthophoto production, etc.

Carswell:
You have to be careful with re-sampling because everything you re-sample also causes a loss of information. So I think it is better that you keep all your original image data until the final re-sampling stage.

Beckschäfer:
That is absolutely right, in our company, we have profit centers in both photogrammetry and laboratory. There is a very big discussion about where the scanning process should reside. Our photogrammetrists say that it is their job to do the scanning, however, when they send the scanned photos to the laboratory, the lab crew says that they cannot print the orthophotos because the image has been poorly scanned. So from this perspective, I think scanning has to be done in the laboratory where photogrammetric duties such as interior orientation and supplementary corrections also have to be done; when the photogrammetrists get the image, they can then just measure image coordinates, and will not have to apply any additional transformation.

Part 2

Aerial Triangulation

Direction :

J. Vanommeslaeghe

Digital Aerotriangulation in Practice

J. Vanommeslaeghe

N.G.I. – Belgium

Summary

Digital aerotriangulation is used at the N.G.I. of Belgium in projects where other applications of digital photogrammetry are also involved. The different operations in aerotriangulation are compared with those in analytical photogrammetry. Digital systems are fast and accurate but can still be improved, among other points by some standardization.

Introduction

Nowadays, nearly all organizations involved in photogrammetric applications make use of aerotriangulation techniques. In this field, each organization has developed its own habits and techniques according to

- the available equipment;
- the landscape,the possibilities to prepare control points, the nature of the control points, the scale of the images;
- the experience of the operators;
- the intended purpose, the required accuracy, the required output (if necessary, a good description of the tie points ...).

Although there is not so much variation in software for block adjustment, there are many ways to organize aerotriangulation itself. In a lot of studies the achieved accuracy is considered to be most important, but in practice the method is determined by the intended efficiency and the available means.

It is difficult to compare software because it is changing rapidly.

The advantages of aerotriangulation play a major part in the choice of a digital instrument. Analytical instruments already disposed of such tools as the transfer to tie points in the previous model, automatic numbering, graphic display of the positions of the points, control through an estimation of the position of the model. In spite of some imperfections, digital instruments offer much more possibilities. Among these we should, of course, mention the software for automatic aerotriangulation, that is now being commercialised. This development was one of the most important issues during the Photogrammetric Week in Stuttgart.

Maybe aerotriangulation shall become superfluous as systems fór direct calculation of camera coordinates and angles using GPS and inertial surveying systems are developing also.

We however think that we should still pay attention to the normal procedures of the various aerotriangulation instruments. In the following survey we will also stress the differences between the method using digital instruments and the method using analytical instruments.

Operations

PREPARATION

There are three aspects in the preparation:

1. Definition of the project, input of the camera data, etc.: these operations are much alike for both techniques analytical and digital.

2. Preparation of the points to be surveyed.
   The modes of preparation are very different, ranging from very detailed (all points are marked on the slide or negative) to very brief (more unprepared surveys) preparations. The more possibilities there are to survey tie points in and between strips and the better the control of the results is, the more we will be inclined to carry out a detailed preparation. With analytical instruments the preparation was also often reduced to a minimum, namely to the preparation of the control points only. In the case of a fully automatic aerotriangulation, there are of course no tie points to be prepared, but approximate coordinates of the photograph centres and values of the angle K must be input, so that the topology of the photographs can be calculated.

3. Loading of the images and possible conversion into the requested raster format: this is a typical problem of digital photogrammetry.

INNER ORIENTATION

The transfer to the fiducial marks and their surveying are carried out on digital instruments. Now these operations are generally automatic. It is however sometimes useful to check the results. In future , when digital cameras will be used, this operation will become superfluous.

SURVEY OF TIE POINTS

This can be carried out during or after the relative orientation, or even without any relative orientation. The use of a relative orientation gives more certainty about the results.

We can spare a lot of time by using a more precise and reliable correlator of images. Several studies dealing with this subject have already been published. We refer to V. TSINGAS, T. SCHENK, F. ACKERMANN and W. FÖRSTNER.

The direct correlation of more than two images, which can never be achieved with analytical instruments, is possible with many digital instruments.

A comparative study of BC1, DCCS, Image Station and DPW has been carried out by O. KÖLBL and M. CROSETTO.

At NGI in Brussels we sometimes use a method, according to which only relative orientations are performed for all ties in and between the strips. With one photograph we can, in theory, perform 10 relative orientations, although 4, 5 or 6 can be sufficient (left, right, up, down). All accepted points of the relative orientation come into the block adjustment. So, with this technique the points never appear more than twice in the block. Special attention should be payed on how the block is being constructed. This can be done in this way (where each line is a relative orientation):

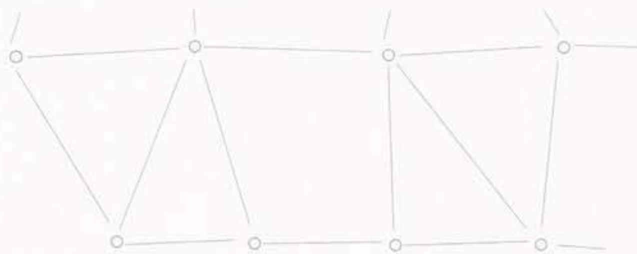


fig. 1

or :

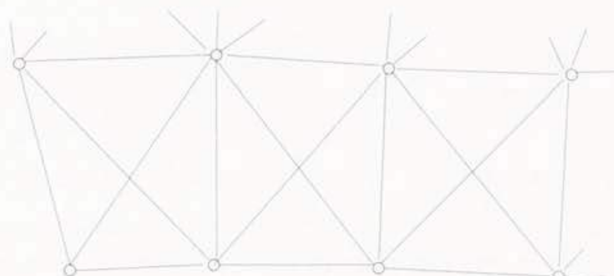


fig.2

If you have lots of control points in the block, you can work with less relative orientations.

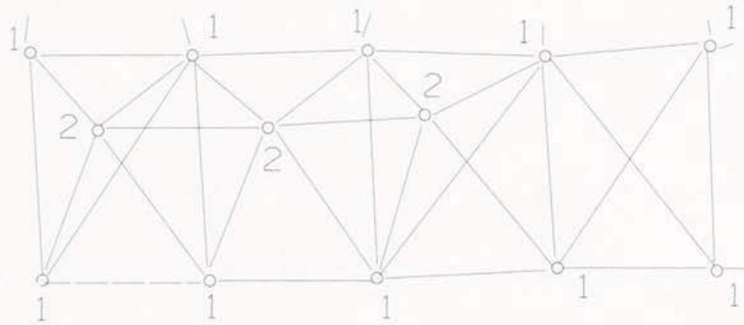
Some loss of accuracy is compensated by

- the larger number of points
- the reliability of the points (control through relative orientation)
- a better selection of the points (they should not be identified on more than 2 photographs)
- a good spreading of the points over the photograph.

Therefore, automatic point numbering and image matching are used for all points, except for the control points.

Very interesting new possibilities are also offered to attach a new flight to an old block: We can use point transfer between two images in the new flight with two or more images in the old one.

But we can also use only relative orientations in the new strip and between the new strip and the old strips:



(1= old images, 2= new images)

fig.3

Of course we need some software and a logic point numbering to integrate the new observations in the old block.

SURVEY OF CONTROL POINTS

For both analytical and digital systems, the definition of the photo centres by GPS can replace the survey of control points either in part or in whole. The combination of GPS with an inertial surveying system yields very good results.

However, this techniques are not yet applied generally, because it requires the acquisition of some new equipment, or because of required precision for large scale applications. Even the values obtained by kinematic positioning are very useful for a fully automatic aerotriangulation, because approximate values of the photograph centres must be given for this technique. Without GPS the survey of control points often remains a time-consuming activity, surely when there is no special terrain preparation and a lot of natural points must be selected and surveyed.

Automatic identification of points for absolute orientation has already been developed by W. SCHICKLER for the AMOR software. During the Photogrammetric Week in Stuttgart, E. GÜLCH assessed various methods making use of image matching and feature extraction. Manual measurements are still most reliable, but automatic measurements yield an equally high accuracy. For automatic measurements GPS can also provide some help by defining the approximate values of the orientation of the images.

For the interactive survey of both control points and tie points, digital instruments should be practical for image motion (by roaming or by marking in a scheme) and for in and out zooming, which is more difficult than with an analytical instrument equipped with zoom lenses.

We hope that in the future some new tools could be developed for on-line control point definition and registration, using oriented digital images.

The first system uses digital orthophotos and DTMs :

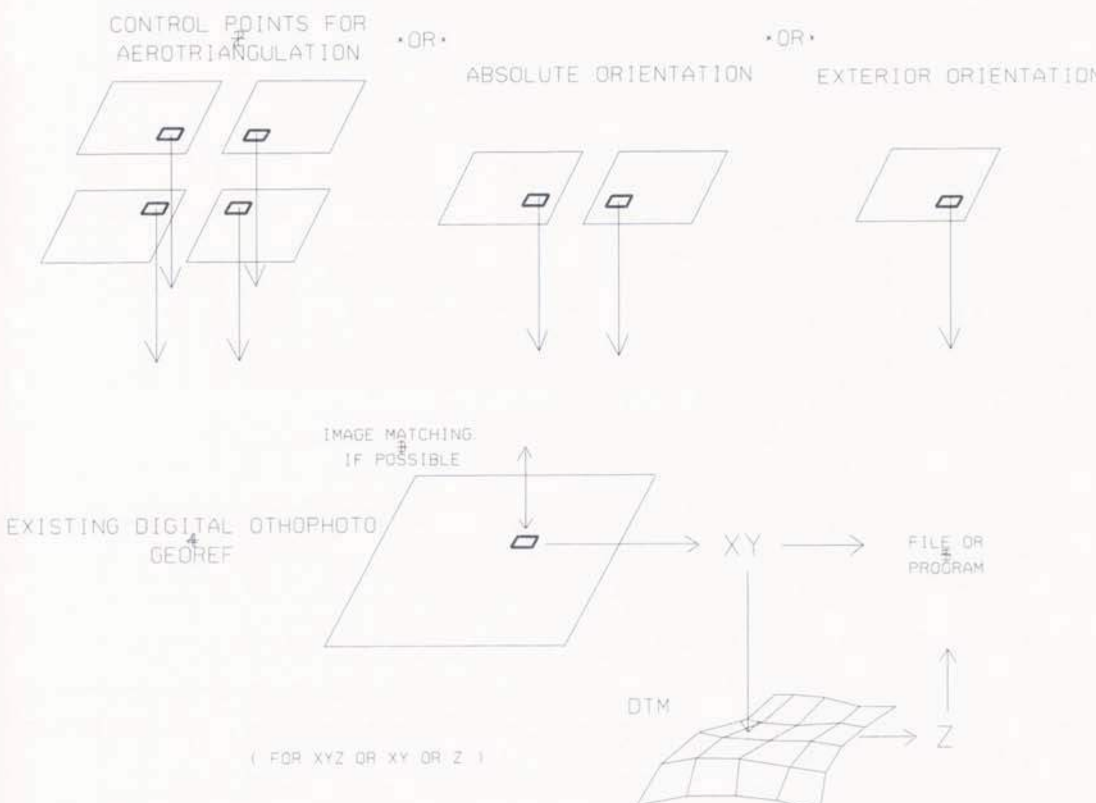


fig. 4

The second system, that is of more practical profit and more accurate, uses the data of oriented models:

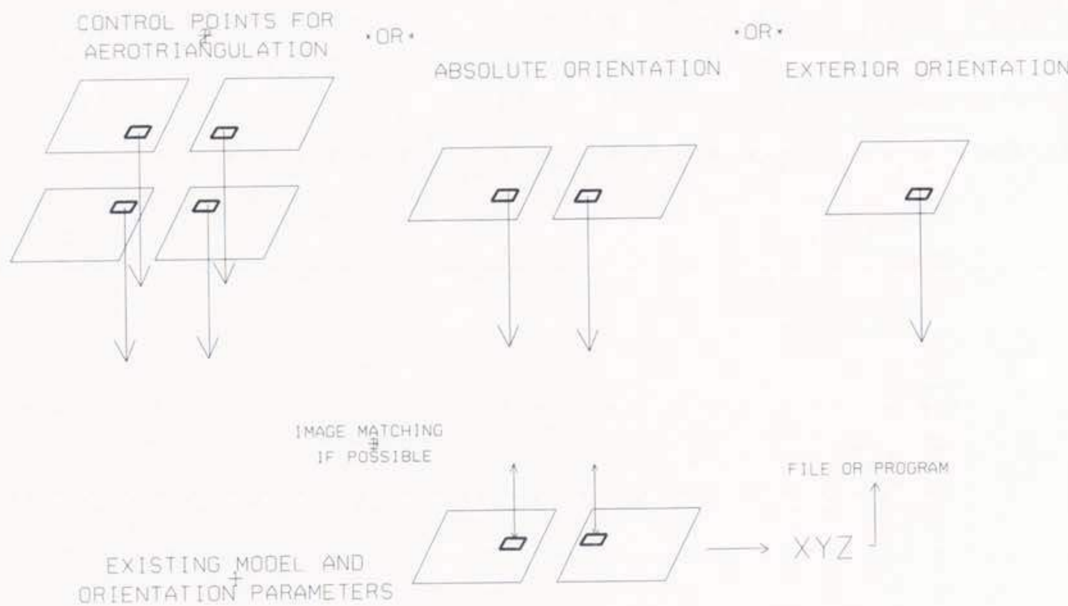


fig. 5

Both systems are also suitable for absolute and exterior orientation and both could use image matching if the images are not too different.

CORRECTIONS

Sometimes, after a provisional block adjustment, some points have to be remeasured. Because of such corrections, it is very practical when all images of the block can be kept on external disks.

Practical Problems

1. If your instruments use different raster formats, more images must be stored and a lot of time is wasted in formatting.
2. Scanning
   When a block must be created with images originating from different scanners, there can be some differences between those images.
3. Transfer of images
   Copying from and onto a magnetic tape remains a time-consuming, not thoroughly reliable, but inevitable operation.
4. Measurement of control points

5. Lack of uniformity of the image coordinates (or: of the inner orientation).

All systems give an output of photo coordinates, reduced to the centre, oriented according to the fiducial marks and corrected for the film distortions and for the radial lens distortion. But in practice this results in lightly different coordinates. Analytical instruments give different results, but so do digital instruments using the same raster images. On some instruments the direction of the X–Y coordinate system is reversed.

At NGI in Brussels we want to create some aerotriangulation blocks with measurements performed on four different plotters. In such a case we must create more groups for self-calibration. Also in some blocks we want to group systematically for each photograph all measurements carried out on different instruments. The present lack of homogeneity in internal orientation diminishes the accuracy.

The same problem occurs if you want to integrate new observations in an old block.

6. Not only the input of a block adjustment is not homogeneous, but also the way to input the results to the stereoplotter is not standardized. For an organization using several types of instruments it is very important that the results of an aerotriangulation performed with one instrument can be used directly by another.

There are four ways to use the results:

- inner, relative and absolute orientation are repeated: this should be avoided.
- the provisional relative and (possibly also) absolute orientation, performed during the aerotriangulation, is recalculated using the coordinates from the block adjustment: this method exists on all stereoplotters, but can only be implemented when input and output of the aerotriangulation are done on identical instruments.
- the coordinates of the projection centres and the rotation matrices, results of the block adjustment, are input and used for the external orientation of both images: this is the most practical solution, but it is offered only by a few manufacturers.
- both the photograph coordinates (input for the block adjustment) and the terrain coordinates (output) of the points are input and used for an external orientation: this solution is possible, but requires also a homogeneous definition of photo coordinates.

7. One of the products of aerotriangulation is often, besides the terrain coordinates, the definition or description of the tie points for use later on during the absolute orientation on analogue or other instruments. If these points are natural points, sketches are sometimes made of them. At NGI in Brussels we use Polaroid photographs taken from the display or from the contact photo, with enlargement. For the manufacturers it is perhaps possible to include this in their standard software, so that we can extract some details from images in a generally used raster format, directly edit them for notes and possibly print them out with a good quality.

8. Many operators prefer the optical systems of analytical plotters to the displays of digital instruments for the elimination of parallaxes and for stereoscopic measurements, especially for height measurements. A good image matching is then generally (whenever possible) to be chosen above a bad interactive measurement.

   In and out zooming is not always easy.

9. Aerotriangulation is the step in the photogrammetric production process that requires the highest resolution for scanning.

This places the operator in a dilemma: to use

- either all images with a high resolution
- or all images with an average resolution
- or to use two sets of images.

Scanning with a high resolution would not be a problem, if storage and transfer were cheaper and quicker and if the size of the images would have no influence on the performance of the instruments.

Conclusions

From our experience at the N.G.I. we think we may draw the following conclusions:

For the time being, digital aerotriangulation

- means, on some instruments with easy point transfer, a considerable gain of time;
- offers new possibilities;
- is easy to learn and to use;
- can give an accuracy of the same order as the analytical aerotriangulation;
- entails additional costs (scanner, data storage) that, for high precision projects, can only be justified when the raster images are also used for other digital applications (orthophotos, plotting, ...);
- can still be improved as far as hardware and software are concerned;
- should be standardized in many respects (the users should urge the manufacturers to do this).

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Discussion after the Conference:

Digital Aerotriangulation in Practice, by J. Vanommeslaeghe

Colomer:

I only have one question regarding the use of the PS1 scanner. Did you also have problems when using 22.5 µm as a resolution? Because we had several complaints and an improvement only happened when the software was re-installed.

Vanommeslaeghe:

It is true that we also use the PS1 scanner, but we do not have one in-house so we subcontract the job to private companies. I think we just recently had a resolution of 22.5 µm, but I cannot give a more direct answer to your question.

An Overview on Commercial Software Products for Digital Aerial Triangulation

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Summary

The article gives an overview on currently available commercial software products for digital aerial triangulation. This overview concerns the DCCS software of Helava, integrated in the DSW 100 scanner, the DPW aerial triangulation software package HATS and the aerial triangulation software of the ImageStation of Intergraph. The article tries to show the typical work flow of operations and reflects the impression during practical work.

1. Introduction

In the last 2–3 years, digital aerial triangulation became an operational tool, allowing a considerable increase in productivity. Meanwhile, several firms have offered largely automated tools for aerial triangulation.

In 1993, OEEPE initiated a comparative test on digital aerial triangulation. This test was directed by Juha Jaakkola of the Finnish Geodetic Institute (cf. [1] and OEEPE-Publication in preparation). At this time, most of the used software packages were developed by universities and many of the digital photogrammetric work stations had only tools for relative and absolute orientation. The only system especially conceived for aerial triangulation was at that time the DCCS (Digital Correlator Comparator System) of Helava. The Institut of Photogrammetry of the EPFL has participated in the test of OEEPE with commercial aerial triangulation package integrated in photogrammetric workstations:

- DCCS software integrated in the Helava scanner DSW100
- Photogrammetric workstation DPW by Helava
- ImageStation by Intergraph

Additionally, the block was measured on the analytical plotter BC1 for comparison. As a contribution to this test, the Institute has revised an article describing aerial triangulation on these different systems. Meanwhile, a considerable development of the tools for aerial triangulation has taken place and it seemed interesting to show again the different systems with the techniques currently in use. The following article endeavors to present the 3 most state-of-the-art systems in a more or less comparative way. This comparison should be the strength of the article, whereas other contributions to this workshop go much deeper into the technical aspects, limiting themselves however to a specific system.

2. DCCS, the Digital Correlator Comparator System by Helava

One of the first instruments that became available on the market was definitely the DCCS (Digital Correlator Comparator System), presented for the first time in 1987 in Baltimore at the congress of the American Society of Photogrammetry (cf. [2]). At that time, it was hardly possible to store several aerial photographs; consequently, the DCCS does not store a whole aerial photographs but small image segments centered around the measuring points. However, the software enables an automatic point transfer to the neighbouring pictures with the help of correlation procedures. This instrument brought a tremendous increase in efficiency for practical work. It met with a certain degree of success in Europe; however, only few institutions have a sufficient quantity of models for triangulation to justify the acquisition of such a special instrument. Later on, the DCCS software was integrated into the DSW100 scanner.

2.1 Short Presentation of the Instrument

The DSW100 digital scanner consists of a scanning unit (fig. 1 right), a control monitor (right screen), a monitor for the dispiay of images (left screen) and a digitizing tablet. The system is driven by a 486 PC in Unix.

Fig. 1 – General view of the Helava-Leica scanner DSW100 with the scanning unit (right), the control monitor and the monitor for the display of images.

The proper scanning unit consists of an image carriage for the format 23 x 23 cm (cf. fig. 2). For the illumination, a halogen lamp is used, the light of which is transmitted by fibre optic into the illumination system. The illumination system has been changed several times. At one time, great efforts were made to get diffused light by using an Ulbricht sphere. Later on, the use of colour filters required modifications and a filter wheel was mounted directly above the aerial photographs. As these filters absorb considerable light, the Ulbricht sphere had to be eliminated.

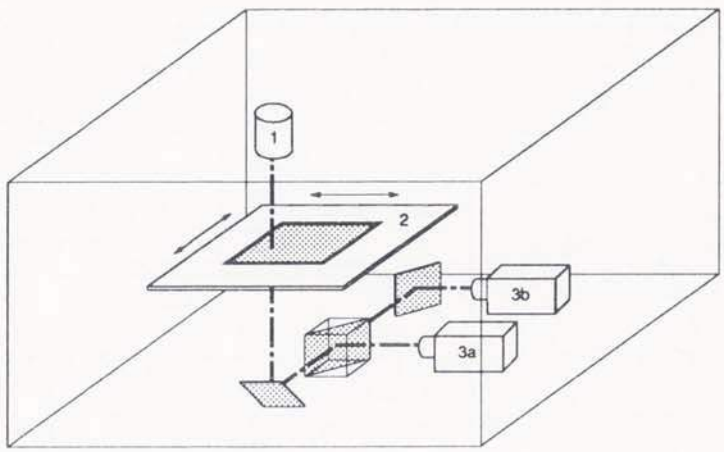

Fig. 2 – Schematic view of the scanning unit of the DSW100 Helava-Leica with the illumination unit (1), the plate carrier (2) and the 2 digital cameras (3a,b).

When doing an aerial triangulation, one is limited to black-and-white reproductions of the aerial photographs. For the image scanning itself, one uses 2 digital cameras with matrix sensors of 480 x 480 pixels of the type Pulnix. The 2 cameras have different lenses (f = 135 and f= 105 mm) which allow a scanning with pixel sizes of 12.5 x 12.5 or 25 x 25 μm.

2.2 Principle of Aerial Triangulation on the DCCS

Aerial triangulation on the DCCS is characterized by storage of image segments and automatic transfer of points. The aerial photograph to be treated is introduced into the scanner. This instrument is directed by the digitizing tablet on which one normally places a paper copy of the aerial photograph in order to guide the operator.

With the help of this digitizing tablet, the operator selects regions which will be measured subsequently. The corresponding image segments are digitized and displayed on the monitor. A floating mark also displayed on the monitor makes it possible to exactly pin-point the measuring point. For the first image this work is limited to the selection of points. It is only for the next image that the points are transferred and that the relative orientation is calculated.

An interest operator can be used for the selection of the measuring points. The process of image correlation itself is not described in detail in the literature, but it is based on the 'relaxation' method developed by Helava (cf. [1]). One stores only one image segment for one measuring point; this segment will be conserved and will always be available for the measurements in connection with the subsequent images. Consequently, points can be transferred without any limitations to neighbouring strips or even to cross strips.

2.3 *Detailed Working Procedure on the DCCS*

The image triangulation runs essentially according to the following procedure:

1) Introduction of the aerial photograph onto the image carrier of the scanner

2) Measurement of the fiducial marks for inner orientation; the film carriage is automatically driven to the fiducial marks, but the measurements have to be done visually.

3a) First image of a strip only: selection and measurement of the tie points and control points and storage of the corresponding image sections. When selecting the tie points, it is possible to use an interest operator in order to determine the exact position of the points.

3b) Following images :

- automatic positioning of the points in the overlapping zone to the previous pictures
- monitoring of the segments of homologous images (segment of the image currently in work and previously stored segment; cf. fig. 3)
- automatic image correlation and determination of the position of the tie points with possibility of control by the operator.
- computation of the relative orientation to the preceding image and display of the residual parallaxes after the measurement of 5 points.
- selection and storage of new image segments presenting the tie points to the next images and eventual additional control points. This work is done with one image only, as under point 3a.

2.4 *Experiences with the DCCS*

The Institute has the DCCS software package integrated into a DSW100 scanner, instead of the original instrument; the advantage is that it is not necessary to acquire a special instrument only for aerial triangulation. Handling of the instrument is relatively simple and enables the user to obtain a satisfying production after a short introduction (cf. also [3]).

For the practical work, the original colour photographs were used. The block shows a very regular structure with a strong side lap. Consequently, it was possible to choose the tie points directly on the instrument. However, it appeared appropriate to choose 4 tie points at the position of the schema points (Gruber points) in order to ensure that a sufficient number of points would finally be available. By definition, the selection of the points is limited to one image only; therefore, the operator cannot judge whether a point chosen to be measured is effectively on the ground or may be visible on the neighbouring image, as it might only be a scratch or any other defect of the emulsion.

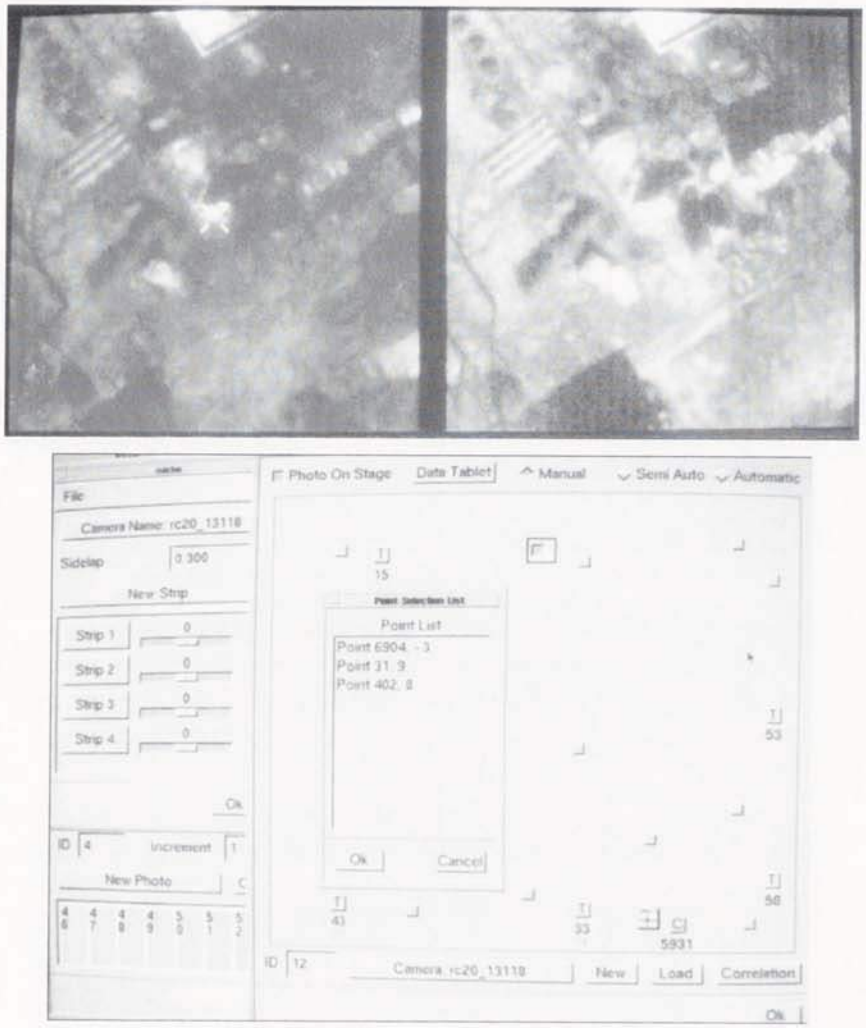

Fig. 3 – Presentation of the working environment for aerial triangulation on the scanner DSW100 with the software package DCCS. Above, the display monitor with 2 corresponding image sections serving for measurements and below the control monitor with the information on residual parallaxes (right window) and a sketch of the block configuration (left window).

This difficulty is amplified by the rather mediocre image reproduction on the monitor; the segment shown corresponds to an image size of 5 x 5 mm on the original film.

Nevertheless, the DSW100 also has considerable advantages; it proved that one can work fairly efficiently in regions which are not too difficult. The Rijkswaterstaat in Delft has published figures according to which about 40 models can be handled per day (8 hours) (cf. [2]). This is also due to the fact that the transfer of points to neighbouring strips can be done very efficiently. However, there is a lack of quality control for this point transfer as it is not controlled numerically. Within a model, the relative orientation is computed from the 5th measuring point onwards and the residual parallaxes are displayed. This function is very satisfying as long as the points are sufficiently wide apart. When they are too close, they are summarized within a group of points and the residual parallaxes can only be visualized by opening a special menu field. One might also regret that no absolute orientation can be done, as this would considerably simplify the location of points given by their coordinates.

It can also be considered as an advantage that the aerial photographs not be digitized as a whole; however, it is not easy to know whether the results of the aerial triangulation can be transferred without any special precautions onto digital or analytical stereo plotters for a further use. If one continues to work with digitized photographs, uncertainties might result concerning the inner orientation. Similar questions arise when transferring the orientation elements directly onto an analytical plotter. It would certainly not be wise to completely leave out the use of control points for the individual models. This, however, requires either that points be marked onto the aerial photographs or the elaboration of sketches. These precautions are not required if all operations are done with digital images, which means that the aerial triangulation is also performed with photographs which have been first digitized.

Another disadvantage is the relatively slow motion of the image carriage. Displacing the image by 20 cm requires about 10 sec. Queries in the image menu during the measuring procedure also require considerable response times. The re-measurement of points in a previously measured image is also rather cumbersome, as the photograph has to be re-introduced in the instrument and the whole measuring procedure has to be re-run from the beginning.

3. Aerial Triangulation on the DPW (Digital Photogrammetric Workstation) by Helava-Leica

3.1 Short Description of the System

The photogrammetric workstation DPW by Helava-Leica is based on a general-purpose computer. Partially, this has been a PC with an Intel 480 processor or a Silicon Graphics Computer. However, most of the workstations use Sun Spark computers. The software 'Socet Set', which represents a universal program system, includes all photogrammetric operations such as image orientation, stereoplotting, automatic derivation of digital terrain models, computation of orthophotos and mosaiking. The basic computer is sufficient for all these operations, without any additional processor. Only the possibility of stereo observation requires additional means. In the most simple case, adding a stereo viewer can be sufficient; the homologous images are then displayed side by side. The complete stereo station uses a Tektronix screen for stereo observation based on the polarization principle. This screen needs a special processor card. Earlier models used the Vitec board; today, the Dupont-Pixel-Card is mostly used. If desired, it is also possible to use the flicker principle with an interlaced monitor. It should be mentioned in this context that aerial triangulation does not strictly require stereo observation.

The Institute of photogrammetry disposes on a Sun Spark 10/41 computer on which the Socet Set software was loaded. When the OEEPE test was conducted in 1994, this computer had only a very limited local disk capacity and was exploited within a network. For image storage, it was necessary at that time to use an external disk server controlled by a Cray computer (Nestor); this processor is operated by the Computer Center of the University.

The efficiency of data access was not optimal, due to the special configuration of the network. Later on, the computer was equipped with a local disc of 9 Gigabyte (Seagate-Hammilton) and disconnected from the central server, a Spark 2000 computer. These measures allowed to increase up to 10–50 times number of image manipulations. Meanwhile, also the Tektronix screen was acquired so that the Institute disposes now on a complete photogrammetric workstation. A trackball is used for image displacement, in addition to the 3-button mouse of the computer for data manipulation and the computer commands.

3.2 Principle of Aerial Triangulation on the DPW

Originally, the DPW software for aerial triangulation was limited to relative and absolute orientation of a stereo couple. Later on the "HATS" (Helava aerial triangulation software package) was added. This software package is intended to accomplish an aerial triangulation completely automatically. It locates automatically the tie points and transfers them to all overlapping photographs. Additionally, one can locate the control points or other points of interest, which are then also transferred to the neighbouring images. Points which seems to be mismatched according to the verification algorithm are indicated by the program and shown up for visual inspection and re-measurement.

Additionally, the operator can freely measure points in a stereo model and also perform absolute orientation. A powerful correlation algorithm can be used for point transfer.

3.3 Working Procedure for Aerial Triangulation on the DPW

Essentially, the operations for a block triangulation are the following :

1. Loading of the digital images on the work station, and generation of the image pyramid.
2. Measuring of inner orientation, automatically from the 3rd fiducial mark on.
3. Selection of the tie point pattern and eventually preparation of a file with predefined point coordinates.
4. Initiation of HATS. The HATS process runs completely independent and takes about 2–3 minutes per photograph.
5. Remeasurement of points which were not properly determined by HATS.
6. Measurement of additional tie points and of the control points, provided these points were not predefined; the parallaxes can be automatically eliminated.

   The selection of the tie points can be supported by the use of an interest operator.

   Points already measured in a previous model can be located with the help of their point number.
7. Closing of the measuring mode, computation and monitoring of the residual parallaxes.

3.4 Experience with the DPW

When used to working with classical photogrammetric instruments, one is surprised that aerial triangulation can be performed on a mere general-purpose computer. The speed of the operations depends essentially on the efficiency of the computer system, although one has the feeling that the image display could be accelerated when doing control measurements after automatic point transfer by HATS. The correlation algorithm proved to be very reliable, and mismatching is detected correctly in most of the cases.

The optical quality of the image display is rather good and also the possibility of subpixel enlargements are satisfying.

The Helava system uses Motiv as user surface. The windows for the display of data and the presentation of images were designed on that basis (cf. Fig. 4). In this way, however, one obtains a rather unsatisfying user interface; numerous windows contain comparatively little information; stronger compacting would make it possible to have much more information available. For example, the operator does not have access to the residual parallaxes during image measurements. That is rather cumbersome if re-measurements are necessary. The absolute orientation, which would facilitate the search of control points or check points according to predetermined values, is rather complex and in certain cases the absolute orientation did not converge, meaning that no orientation was computed. In general, one gets the impression that the user interface could be considerably improved.

The HATS software was added only recently and has very interesting features; however it appears to be a β–version and is not too reliable. Most of the cases, the software only uses a minimal tie point configuration which does not allow for automatic blunder detection. Furthermore it is not possible to restart the transfer of tie points when have reached a first approximation as all previous results would be overwritten and the computation starts from the beginning. However, these seems to be problems of the very first release corrected later.

Fig. 4 – Screen copy from the DPW working environment for point measurements. One remarks the 2 corresponding stereo photographs and in the right window the command field for the introduction of point numbers, possible terrain coordinates, etc.

4. Aerial Triangulation on the ImageStation by Intergraph

4.1 Short Description of the Instrument

The photogrammetric workstation of Intergraph represents a special development by Intergraph based on the processor Clipper 6487 or the new version with the processor 6887. The 6487 has a processing capacity of about 30 Mips. Additionally, one has the parallel processor Vitec 50 for image operations and a hardware board for the compression and decompression of images. The mass storage of the work station used at the Institute has a disk capacity of 5 Giga-bytes. The work station is equipped with a high-quality image screen of 1200 x 1800 pixels and allows the monitoring of 24-bit colour images. For stereo viewing, one uses 'Crystal Liquid Eye Shutter' glasses; the corresponding stereo images are monitored in an interlaced mode.

The system operates under UNIX with a special Clipper processing system. The software package of photogrammetry available at the Institute of photogrammetry represents a pre-release with automatic image correlation.

4.2 Principle of Aerial Triangulation on the ImageStation

Originally, aerial triangulation on the image station was limited to the measurements of stereo couples like on an analytical plotter. Later on, the number of possible images to be displayed on the screen was extended to up to 6 photographs; furthermore colour images can now be displayed. When working with two or 3 photographs, one can display up to 3 different enlargements; a maximum of 12 different image windows can be opened. In this way, it is possible to display the whole photograph, a section with full pixel resolution and a subpixel enlargement. Additionally a window for stereo display can be opened. The simultaneous display of several windows allows a very efficient work; in addition, the operator is supported by the computer for point transfer by matching techniques.

In principle, it is also possible to proceed on a completely automatic point transfer after the measurements of 2 or 3 points for relative orientation. A program for elimination of blunders controls the quality of the parallax measurements and eliminates mismatching and maybe in 50% of the cases, a correct relative orientation is already obtained in less than 1–2 min. Further transfer points can be added, an operation which can be supported by automatic image matching and by using an interest operator for point selection. If the model was not properly orientated by the automatic matching algorithm, it is necessary either to pin-point the blunders and measure these points visually or to reject the whole automatic measurements and transfer all points visually.

When measuring in the mode of multi-images, it is necessary to measure at least 3 control points within the 3–6 photographs treated as first group in order to obtain a solution for the orientation. After the measurement of 2 points, the program already assists the operator in the point location.

The ImageStation has a special processor for data compression. Image data are only decompressed for displaying. The data compressions enable data reduction by a factor of about 4–5 which means that a rather large block digitized with a small pixel size (e.g. 15 µm) does not require an excessive disk space. About 30 picture scanned with a pixel size of 15 µm can be stored on a disk of 2 Giga-bytes. Using a Seagate disc of 9 Giga-bytes is possible, but requires a partitioning; a partition cannot be larger than 2 Giga-bytes.

4.3 Detailed Working Procedure on the ImageStation

1. Loading of the digital images on the workstation, possible conversion of the images into the internal format and generation of the image pyramid.

2. Measuring of the inner orientation; this procedure runs automatically from the 2nd image on, provided that an inner orientation was done during scanning, otherwise 2 fiducials have to be measured manually.

3. Mode "relative orientation" (RO), display of only 2 photographs : Selection of 2 to 3 tie points and visual elimination of the parallaxes; subsequently, full automatic relative orientation which permits a completely automated transfer of image points already localized in one of the two images. Afterwards, additional tie points and control points can be measured.

4. Mode "point transfer" (PT) : 2–6 images can be displayed. In general one prefers to work with 3 images for the transfer of points within a strip in order to have greater image windows with a reasonable enlargement; only for the point transfer to the neighbouring strips it is useful to display the 6 images. Point transfer is sustained by image matching techniques. The residuals are displayed after the measurement of each point, provided that a solution was found (minimum 3 points).

4.4 Experiences with the ImageStation

After a relatively short introduction, one obtains the impression that digital aerial triangulation on the ImageStation is very efficient. One of our students remarked that this type of work is like a video game. Effectively, the opening of various windows of image sections systematically after the previous measuring very clearly defines the measuring process and drives the operator without giving too much constraints. The arrangement of the menus on the screen can be organized very freely and allows a thorough control of the measuring operations (cf. Fig. 5). Furthermore, several operations are performed largely automatically. The production rate in practice rises to about 60 models a day. Data compression also appears as a great advantage.

However, image correlation for points transfer did not prove to be very reliable and led to several miscorrelations. Consequently, it proved more efficient to use the interactive image matching supporting the operator in point measurements.

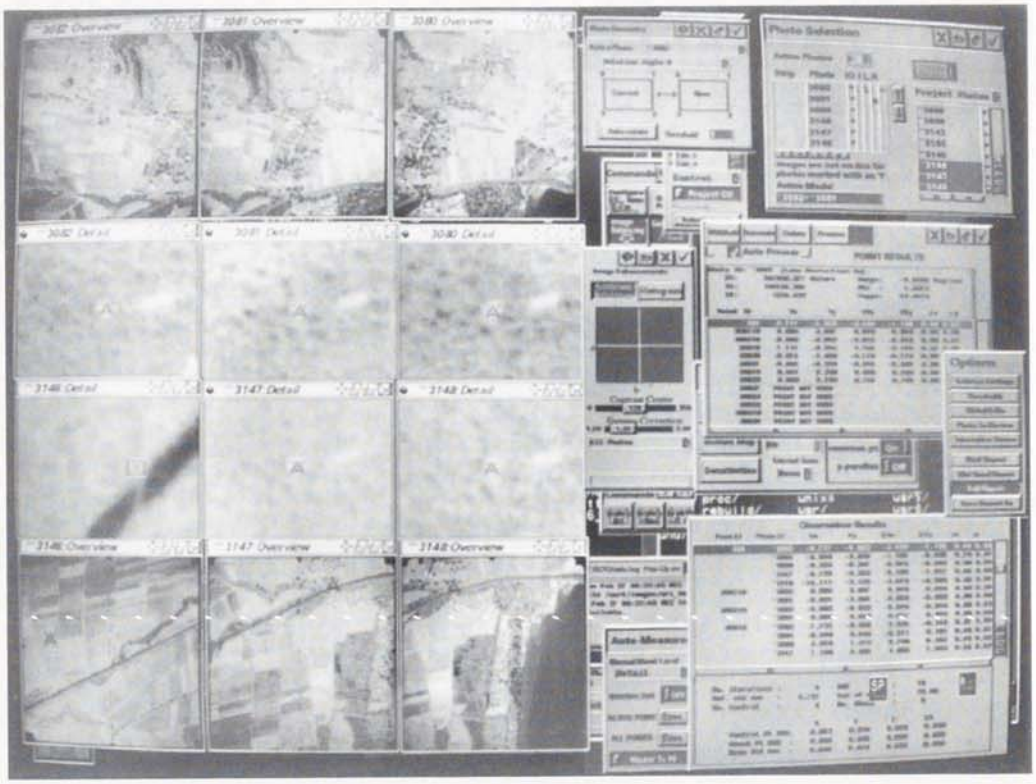

Fig. 5 – Screen copy showing the working environment on the Intergraph ImageStation for aerial triangulation. The left part shows 6 photographs simultaneously treated. Upper row and lowest row show an overview of the images and the central part shows the measuring points strongly enlarged; the right windows serve for the control of the measuring process.

When placing a tie point, the system tries to transfer the point automatically to the neighbouring photographs. Mismatching is controlled immediately and can be corrected.

The 10 button control cursor running on a digitizing table appears efficient; only the necessary double click for image enlargements or reductions leads to mistakes from time to time.

Although the screen of the ImageStation is of high quality, one often struggles with the contrast of the images displayed in the orientation mode. When scanning photographs normally they are controled on the ImageStation with the software package "ISI". In this mode, the photograph might appear quite satisfying. When doing orientation, however, the same images are less satisfying and seem to have poorer contrast.

5. Conclusions

Digital aerial triangulation is developing quite rapidly and already today it seems that this technique is more efficient than triangulation on analytical plotters. The tendency is clearly to more and more automation. However, the advantage of automation is rapidly lost if the system is not reliable or the correction of mismatching takes too much time. Of great importance is also the efficient presentation of intermediate results. When measuring a point it is quite favourable when the operator can immediately control the quality of the measurements.

When comparing the approach of Helava and Intergraph one is fascinated by the great automation offering the DPW, however the cumbersome error correction seems to eliminate the advantages rapidly. The Intergraph approach appears much more primitive, but is at the moment much more efficient. The DCCS approach was fascinating at a time when storing photographs in a digital form was expensive and difficult. Helava does not offer any more this facility on its new scanner DSW200 and seems to put all its efforts in the development on the DPW.

For technical reasons it was not possible to include other systems beside the three into these considerations and it is hoped that other contributions to this workshop will fill that gap.

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Discussion after the Conference:

An Overview on Commercial Software Products for Digital Aerial Triangulation, by O. Kölbl

Loodts:

You can use a considerable number of images when you do image compression as it is necessary for aerial triangulation, but did you notice any miss-correlation due to image compression?

Kölbl:

To be honest, we had considerable problems with image correlation on the ImageStation. When I measured the OEEPE test block, I no longer used image correlation after half of the block because I thought I already obtained too many miss-correlations and error corrections becomes too tedious. Currently, we only use image correlation for interactive point transfer so that the operator can control each point after the automatic point transfer. But we did not realize any link between data compression and failures in matching.

Carswell:

I think that as far as your questions go, as long as you do not compress too much you should not have any problems with image correlation. I have never found any problems, let's say if you compress 3 to 4 times. However, if you compress more than 10 times, you will probably run into some problems. Now, as far as the measuring procedure is concerned, I think if you run the bundle adjustment on each strip before you tie the strips together then you will get better correlation when you use the point transfer. You can take a point from strip one and transfer into the other strips. Your parameters for each photo will be close to their real results and then the point gets transferred easier.

Digital Aerial Triangulation with the Helava Automated Triangulation System

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Abstract

In this paper, we present our investigations and results on a digital aerial triangulation of two Swiss test blocks using the Helava Automated Triangulation System (HATS). In a pilot study, digital image data scanned with a resolution of 25 μm, from the block St. Gallen/Appenzell including 109 b/w images and from block Zug (82 b/w images), both at a photo scale of ca. 1: 27'000, was triangulated. The measurements were carried out on the Helava/Leica Digital Photogrammetric Workstation DPW770 each using a different tie point pattern. All observations were later adjusted in the GPS supported bundle adjustment program BLUH using self-calibration. The empirical accuracy from check points, which had not a very good quality due to their various sources, was better than 1 m in planimetry and about 1.3 m in height using GPS photo centre coordinates and sparse ground control information in the combined adjustment. The RMS values of the GPS station coordinates were about 0.6 m in planimetry and 0.3 m in height.

1. Introduction

With the development of higher-resolution scanners, high quality digital imagery is increasingly available. Additionally, with the progress in high performance computer hardware and software, e.g. higher-resolution screens and faster image-handling capabilities, automation of photogrammetric processes becomes presently possible. 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 Häring, 1995), relative orientation (Schenk et al., 1990), point transfer in photogrammetric block triangulation (Tsingas, 1992), and the generation of Digital Terrain Models (Krzystek, 1991).

The first digital photogrammetric system has been commercially available on the market since 1987. Today, with each new release, systems provide an increasing degree of automation in implemented photogrammetric procedures. In the past five years these systems are increasingly used in photogrammetric production to significantly improve the efficiency of the production processes. Specially in aerial triangulation, digital photogrammetric stations are surpassing conventional analytical plotters in accuracy and functionality, i.e.

in the degree of automation in data capture and processing. Currently several commercial digital photogrammetric systems, e.g. Intergraph ImageStation, Leica DVP, DIAP from ISM, Helava/Leica DPW670 and DPW770 among others are available for photogrammetric production. To produce digital orthophotos for the entire area of Switzerland, swissair Photo+Surveys Ltd. purchased digital photogrammetric equipment from Helava/Leica. For the project SWISSPHOTO blocks including in total 7800 colour resp. infrared photos must be processed within the next couple of years to meet the requirements of many customers in providing digital orthophotos as up-to-date basic data for various GIS applications. Consequentely this requires 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.

In this paper we present our investigations and results of a digital Aerial Triangulation (AT) of two blocks using the Helava Automated Triangulation System (HATS). The goal of a pilot study was to test the performance and the functionality of HATS. The object was to provide sufficient ground control to perform a traditional AT and compare the results with a GPS supported AT using GPS coordinates of the photo centres with a minimum amount of ground control points. Results of the GPS supported bundle adjustment and experiences with the functionality of HATS are presented. Advantages and drawbacks of HATS for automated digital triangulation under production conditions are also discussed in this paper.

2. Test data and photogrammetric systems used

2.1. Test data

Two test blocks were selected comprising of ca. 2% of the large block covering the entire area of Switzerland. For the project SWISSPHOTO, Switzerland was flown in two phases using colour and infra-red films simultaneously. In phase 1, the urban areas and the northern part was flown from June to August, while in phase 2 the Alps and all valleys in the southern part were flown from August until October 1995.

The photo scale was approximately between 1: 24'000 and 1: 28'000 in the non-mountainous areas including the separate flights in the southern valleys and between 1: 34'000 and 1: 45'000 in the alps. During the flights camera stations were recorded by DGPS using a Leica GPS receiver in the airplane 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 signalized as control points. Flight and block data are summarized in Table 1.

For this pilot study 109 images (St. Gallen) resp. 82 images (Zug) at a scale of about 1:27'000 spread over 6 parallel flight lines for each block were selected covering the major part of the Cantons of St. Gallen and Appenzell in the north-eastern region of Switzerland and the whole Canton Zug. The flight lines were flown from east to west and in the opposite direction with an azimut of ~20 resp. 200 degrees. The dates and times of the flight lines varied from the 30.06.95 to 20.07.95 and from 7.25 AM to 12.44 PM (UTC).

	Block 1	Block 2
Area:	St. Gallen, Appenzell	Zug
Area covered:	~1000 km^2	670 km^2
Ground height:	400 - 1700 m	400 - 1900 m
Flying height a. s. l.:	~ 4800 m	~ 4800 m
Camera:	Wild RC30, 15/4 UAGA-F	Wild RC30, 15/4 UAGA-F
Photo scale:	~1: 27000	~1: 27000
Forward/side overlap:	70%/30%	70%/30%
Number of strips:	6	6
Number of images:	109	82
Date of flight:	30.6.95/20.7.95	30.6.95/20.7.95
Film/digital imagery:	colour diapositive/greyscale	

Table 1: Flight and block data of the test blocks St. Gallen and Zug

2.2. *Hardware*

The aerial triangulation was performed on a Helava/Leica digital photogrammetric workstation DPW770. All images were scanned on a Helava/Leica Digital Scanning Workstation DSW200 in RGB mode. The turn around time for scanning for each photo was about 30 min. For triangulation the digitized colour images were converted in greyscale images in order to reduce disc space usage. The resolution of the images was 25 µm (1016 dpi), which corresponds to a footprint of approximately 0.7 m on the ground, and the size of each greyscale image was about 80 MByte. Large portions of the approximately 75 GByte available disc storage capacity were used for the triangulation data.

2.3. *Software*

For the test block St. Gallen the software release SOCET 3.1.6b (beta version) was used, while the test block Zug was measured with the latest SOCET 3.1.1.2. version. HATS is a fully digital system 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 remeasure these unacceptable points by moving the floating mark to their proper locations.

3. Digital aerial triangulation

The triangulation was divided into several processing steps, which included the preparation, measurements and the final bundle adjustment.

3.1. Preparation

Before starting the measurements, the image import and the minification of the images (building-up image pyramids) was performed in a batch mode. The GPS photo centre coordinates of each image were also imported to provide approximate values for the overlapping of the images in the blocks. In the block St. Gallen (Zug) only 4 (2) signalized LV'95 points were available. Their distribution was not ideal, but the points were visible. To obtain sufficient ground control points without establishing an additional GPS campaign four different sources were used for this pilot study:

- 1 signalized points from the new Swiss GPS primary network LV'95
- 1 3-D control points from previous photogrammetric in-house projects measured on the SD2000
- 1 planimetric control points from cadastre maps at 1:500 - 1:2,000 scale
- 1 height control from LK25 maps (Swiss 1: 25'000 map series)

The preparation of the ground control was a very time consuming effort. In total, for block St. Gallen 54 h and for block Zug 42 h were used.

3.2. AT measurements

The processes of AT measurements in HATS are divided into several steps which includes Automatic Points Measurements (APM), Interactive Point Measurements (IPM), and Blunder Detection and Simultaneous Solve (Remeasurements).

Before starting HATS the Interior Orientation must be performed. For the interior orientation the first two fiducial marks were measured in a semiautomatic mode, while the rest of the eight fiducials was measured fully automatically. A fully operational automatic interior orientation for the DPW770 is introduced by Kersten and Häring (1995), which can be performed in batch mode without any operator's intervention. 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. The tie point pattern consisted of 16 points for block St. Gallen. For block Zug the standard 3x3 tie point pattern was used. After APM 75% of all points were measured successfully for block St. Gallen, while in total 266 points required an interactive measurement. For APM block Zug was devided into two subblocks, where in the first subblock 78% and in the second subblock 71% were measured successfully, while in total 70 resp. 142 points required an interactive measurement. Blunder detection could be used after each measurement mode and gross errors were eliminated. The blunder detection was a very useful tool for „online" checking of model and strip connections as all 109 (82) images could be displayed, and all connections re-checked and re-observed if necessary.

Ground control points and additional points were measured with IPM. If the datum is fixed by measurement of three control points, the program drives the operator to the approximate position of the subsequent ground control points automatically. The correct identification of natural points was not as easy as using an analytical instrument, and using points on houses for example was not really a good idea due to problems from height differences for the correlation algorithm. If natural points are to be used, we propose that only points on relatively flat surfaces be used in the future. The AT observations were adjusted using HATS and the resulting RMS was 0.34 pixel, X=0.6 m, Y=0.5 m and Z=1.5 m for block St. Gallen and 0.35 pixel, X=0.5 m, Y=0.5 m and Z=0.3 m for block Zug.

3.3. Bundle adjustment

All observations (image coordinates, control point coordinates and GPS photo centres) were adjusted in a combined bundle adjustment with self-calibration for each block separately. For this GPS supported bundle adjustment the data was adjusted at the University of Hannover using program BLUH. As a reference the results of an adjustment without using the GPS station coordinates (see table 2) were compared to results of a GPS supported adjustment (see table 3) in order to see the accuracy potential of GPS supported aerial triangulation for SWISSPHOTO data. For the adjustment without GPS 43 (45) horizontal and 64 (66) vertical control points were used for block St. Gallen (Zug). In the combined bundle adjustment only 3 resp. 4 horizontal and 13 vertical control points were used, while as a measure of accuracy all other control points were used as check points (see table 3).

For the St. Gallen and Zug data the root mean square values of differences at control points is about 0.6-0.7 m in planimetry and about 1m in height (see table 2). Theoretically is should be possible to obtain a precision of 1/3 of a pixel, which corresponds to 8.5 µm and 0.25 m in planimetry and 0.5 m in height at a photo scale of 1: 27'000. Thus, compared to what is achivable the RMS values in table 2 are worse by a factor of 2. Also, there were slight differences of the results compared to the adjustments with HATS (see above) which could be attributed to different weighting of control points.

block	Control H/V	obs	red	σ_0 [μm]	RMSE X [m]	RMSE Y [m]	RMSE Z [m]
1	43/64	3456	1289	12.4	0.70	0.68	1.16
2	45/66	2242	795	9.7	0.59	0.61	1.02

Table 2: Bundle adjustments without GPS

block	adj	Control H/V	Check H/V	σ_0 [μm]	RMS X_0 [m]	RMS Y_0 [m]	RMS Z_0 [m]	μ_X [m]	μ_Y [m]	μ_Z [m]
1	GPS	3/13	43/64	13.0	0.53	0.52	0.11	1.02	1.03	1.24
2	GPS	4/13	45/66	9.9	0.63	0.53	0.26	0.83	0.81	1.46

Table 3: Combined adjustments

In the combined adjustment 10 resp. 5 station coordinates observations from the St. Gallen resp. Zug block were eliminated from the adjustment due to gross errors. The RMS value of the GPS photo centres are about 0.5 m in X_0 and Y_0, and better than 0.3 m in height. When using all control points as check points the combined adjustment yields an empirical accuracy (μ_{XYZ}) which is by a factor 1.5 worse than the RMS values from the reference adjustment.

These results show that the quality of the ground control points is not very good. Specially, many of the ground control points taken from the cadastre maps were not of sufficient quality as well as the fact that the cadastre was partially out of date. Here, correct weighting of control points was very important for the adjustments. This demonstrates clearly that it is necessary to perform the GPS supported triangulation using only signalized points, GPS photo centres and additional height control at overlapping strip ends. Thus, further subblocks which are to be processed of block Switzerland must be defined in an area of at least four available signalized control points. To test the quality of height points in LK25 maps, 83 well distributed points were measured in the block St. Gallen, which were triangulated with HATS, and used as height check points. As a result the average difference of all points was 1.4 m, which fits very good to μ_Z = 1.24 m from the comparison of the control points used as check points, with the maximum difference being 4.1 m.

3.4. Time required

The following time was required to process the below summarized AT processing steps:

No	AT processing step	mode	block 1	block 2
1	*Preparation for AT (data files)*	*manual*	2.0 h	4.0 h
2	*Interior Orientation*	*manual*	2.0 h	2.0 h
3	Automatic Point Measurement	batch	2.3 h	1.3 h
4	Interactive Point Measurement	manual	10 h	5.0 h
5	Blunder Detect & Solve	manual	15 h	2.0 h
6	*Measurement of ground control points*	*manual*	8.0 h	2.0 h
7	*Simultaneous Solve and Re-measurements*	*manual*	8.0 h	7.0 h
8	Final GPS supported_block adjustment	manual	3.0 h	3.0 h
		Total	50.3 h	26.3 h

Table 4: Processing steps for AT and elapsed time

The total elapsed time which was required excluding scanning, ground control preparation and data transfer for triangulation of block St. Gallen was 51 h. This corresponds to 28 min per image. Benefitting from the experiences of the first triangulation block all 82 images of block Zug were processed in 27 h, which corresponds to 20 min per image resp. 24 images per day (8 h). In comparison the large differences in the time used for blunder detection and manual measurement of ground control as indicated in table 4 can be attributed to the better knowledge of the user interfaces and to the improved interface of version 3.1.1.2 while processing the second block. But the reduced elapsed time for block Zug compared to block St. Gallen must also be partially attributed to the use of a sparse tie point pattern, which causes less interactive point measurements. Compared to conventional triangulation on analytical plotters this is only a slight speed-up, but, in general, there is still potential for improvements in digital triangulation using HATS. In table 4 all lines in *italics* indicates processes, which could be automated or where the elapsed time could be reduced significantly from our point of view.

4. Assessment of HATS

The quality of the results and the efficiency of the whole triangulation process are dependent on the algorithm used for the measurements. In our investigations the following aspects caused problems for the correlation algorithm:

2 Extreme height differences in the images resp. block

2 Strips with different flight dates (vegetation changes in summer)

2 Shadows from early morning flights (bad quality terrain representation)

2 Densily forested areas and lakes

To improve HATS with respect to speed, precision, robustness and user friendliness we suggest the following software improvements which are summarized below:

(1) The superimposition of the tie point pattern in any image/model of the whole block with the possibility of interactive placement of tie points in anticipation of problem areas which will occur in APM will improve the success rate of measured points.

(2) The use of an existing DTM in APM speeds up the APM process and increases the robustness significantely, so that less IPM will be required afterwards. We have in Switzerland for example a hectare-raster DTM covering the whole country, which could be used.

(3) The use of GPS camera station data in HATS should be supported more efficiently.

(4) An ideal improvement of increasing speed after APM would be to measure the tie points only in their two nadir images across strip direction and the program then is capable of measuring all other related combinations of this point automatically.

(5) The implementation of an image matching technique (Gruen, 1985), which uses besides two shift parameters also two shears and scales, improves the precision of the measurements slightly. A small drawback of a slightly reduced speed should be neglected.

Comparing the latest HATS with an earlier version of the orientation tool in SOCET Set it must be stated that the graphical user interface and the additional implementated options increased the userfriendliness significantly. In Kersten and Stallmann (1995) the SOCET Set version 2.4 was compared to an experimental software package and no significant differences were found between software packages. Both systems used a semi-automatic measurement mode, but the image matching algorithm in the experimental system performed 10% more accuratly than the correlation algorithm of SOCET Set. Today, the system from Helava provides much more automation in data processing and the advantages of HATS are:

2 Automatic measurement mode using an user defined tie point pattern

2 Quasi online blunder detection for eliminating gross errors

2 Point remeasurement capability after residual checking

As a drawback of the overall system it must be noted that the build-up of a graphical user interface or the redisplay of images on the extraction monitor is often too slow (up to 20 seconds during the measurement mode). In general, the zoom capability should be improved as well.

5. Conclusions and outlook

Digital aerial triangulation was performed with two test blocks, St. Gallen and Zug, using HATS. It was found, that HATS including the highly automated measurement procedure is a powerful triangulation tool, which can be recommended for use in production. To increase the efficiency of the digital triangulation, HATS has still potential for improvements as mentioned above. During processing the AT using beta version of HATS 3.1. problems occured, which could be solved in cooperation with experts from Helava. In experience, it can be summarized that for such a complex and highly tuned software package like HATS extensive training and well documented user manuals are absolutely necessary to be capable of driving through problem situations with the software.

The achieved results of approximately 1m in planimetry and 1.3 m in height is not satisfactorily using images with a photo scale of 1: 27'000. But we have to be aware that the ground control was not of a very good quality, which influences the results significantly. Although the results are approximately the same using different tie point patterns, we recommend the use of the dense tie point pattern for more reliable connecting of the block. AT using the conventional amount of ground control is time consuming and requires a lot of resources. Using only the minimum ground control of 4 points with additional height control and the GPS photo centre coordinates can speed up and automate the process significantly. Thus, the goal for using the recorded GPS photo centre coordinates is to avoid time consuming efforts for providing sufficient control points from various resources in a optimal configuration and distribution, and in sufficient accuracies.

However, we think, that we can reduce the time needed and the manual intervention of the operator significantly for GPS supported aerial triangulation in the future to produce much more efficiently. We hope that we can triangulate more than 30 images per shift using HATS in the near future.

6. Acknowledgements

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Discussion after the Conference:

Digital Aerial Triangulation with the Helava Triangulation System HATS, by Th. Kersten

Agnard:

You only use black and white reproduction of the photographs for your block. Do you think your results would be any better if you scan in black and white?

Kersten:

We scanned the colour images in RGB and then we converted them into gray tone.

Agnard:

I would like to formulate my question in a different way. Do you think your results would have been better if the photographs were taken in black and white instead of colour?

Kersten:

Yes, this could have improved the result.

Loodts:

Do you think you could get a higher precision with a smaller pixel size, let us say 25 µm?

Kersten:

In order to get a higher precision, you should use a higher resolution for the scanning.

The new version of the Helava program is now also able to use JPEG data compression and decompression on the fly, but we did not compress the data in this investigation.

Agnard:

I think we have the same kind of experiences; we also fly in colour and then use black and white images for measurements. It might be more favorable to use colour reproductions. Another problem concerns the scanning of colour negatives; we experienced difficulties when scanning the negatives and prefer to use positive prints.

Kersten:

We now dispose on the whole block of Switzerland in colour and in infrared. We chose a large pixel size of 25 µm as we wanted to reduce the amount of data; that was also the reason why we converted to gray tone images. I have the opinion that the information of black and white images is much better for triangulation, for correlation and also for DTM generation.

Meid:

You mentioned that you achieved a precision of 1 meter on the control points which corresponds to a value of some 30 µm in the photo scale. What is the reason for this rather low precision?

Kersten:

The quality of the control points was not very good. We used control points from the cadastral maps and I think there were some serious problems due to discrepancies. I think we can only improve the precision when using GPS data and ensure having more reliable control points.

Meid:

Could you analyze the reasons for these discrepancies?

Kersten:

The accuracy of the topographical and of the cadastral maps are not very homogeneous. A real improvement would require signalized points and the use of GPS data for the projection centers of the photographs.

Everaerts:

Did you try to find out which of the control points were reliable? Up to what extent did you use the GPS data to improve the precision?

Kersten:

Yes, we did find out which control points were reliable. We only used 4 horizontal and 13 vertical controls points, and in our opinion, this block was very good. However, when we introduced the check points, we could not overcome the problem of imprecision in the control points even when we introduced the GPS data. If we could have better control points, then we could expect better results.

Practical Experiences with Digital Aerotriangulation based on INTERGRAPH ImageStations

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1. Introduction

The company KIRCHNER & WOLF Consult GmbH (KWC) has been working for more than ten years with the hardware and software equipment of INTERGRAPH. So it was consistent that when digital aerotriangulation software became available it was implemented in the production line of KWC and has been further developed continuously. Today KWC has practical experience with more than 10,000 digital images and in the meanwhile has changed the production process so that digital aerotriangulation is carried out exclusively. In order to increase the acceptance of the systems by the corresponding employees, the analytical devices were sold in order to replace them with digital components. Above all this process resulted in a very high productivity increase after a familiarization phase.

As a result of numerous specific developments in the hardware and software area, today it is possible to triangulate more than 60 aerial image models in an eight hour shift. The components necessary for this are to be discussed in more detail below and the necessary workflows will be described.

2. System prerequisites

A precision-flat bed-scanner of the company of ZEISS / INTERGRAPH (PS1) is used for scanning the images

2.1 Scanner.

The PS1 has a very high geometric accuracy of better than 2 microns and resolutions of 7,5, 15, 30, 60 and 120 microns, so that it is excellently suited for the concerns of digital aerotriangulation. The connected computer of the type INTERGRAPH-Interpro 6850 (IP6850) has a 64 MB Memory, a 27" monitor and 2 x 9 GB disk capacity. The connected Exabyte-drive serves for saving and archiving the scanned data.

An integrated JPEG-Board compresses the data according to adjustable JPEG-factors. The data can be compressed by factors of 5 (black and white images) to more than 20. The degree of compression depends on the project to be processed. However, in the author's opinion in the case of the preparation of large projects, it is indispensable to compress the data, since otherwise the necessary file management takes too much time and causes correspondingly high costs. An economical performance of a digital aerotriangulation in comparison with an analytical then is no longer guaranteed. The scanned data are scanned offline from the actual triangulation measurement. Synchronization with the triangulation was tried, but it led to numerous problems so it was abandoned.

2.2 Aerotriangulation systems

The actual measurement of the aerotriangulation is carried out at two ImageStations of the Interpro 6887 (IP6887) type. The stations have 64 MB Memory, a 27"Monitor, an additional VITEC-processor, and only 2 GB-Hard disk-Space. The ISDM (Imagestation Digital Mensuration) program package is used as the software. The essential advantage of this digital software vis-à-vis analytical packages is the possibility of digital auto correlation of measurement points. However, the integration of this possibility into operative business activity requires a considerable rethinking of the corresponding operators so that a long acclimatization phase is required.

While in case of analytical procedures roof ridges and similar points are objects well suited for the determination of connection points, surface structures (for example a freshly plowed field) are very satisfactory measurement objects in digital triangulation. Converting to this new way of thinking took quite a while. Even operators, who have worked with the system for several years, today speak about a certain "Instinct" that must be developed in order to master the "way of thinking" of the machine. An employee who possesses this "Instinct" is able to triangulate 60 images in an eight hour shift (best output obtained up to now: 66 images). Others - above all beginners- reach production rates of only around 20 models. However, the very high productions are influenced by the fact, that the operators are released from any file management.

2.3 Imageserver

The storage of the digital images is not carried out locally at the workstations, but on an Imageserver set up exclusively for that. The computer of the Intel Pentium type has 128 MB of Memory, an internal 2 GB-hard disk and fourteen 9 GB hard disks, which are connected to the systems via a special triple-SCSI-2-Controller. The special feature of the data drive consists in the fact that the hard disks are connected together in one Stripeset with parity to only one volume.

This functionality of the Windows-NT-server operating system allows the connection of a logic hard disk to the INTERGRAPH UNIX-machines. The parity formatting of this drive makes it possible to continue working without restriction in the case of a failure of a hard disk. The system recognizes the hard disk and reconstructs the data saved on it out of the redundancies of the remaining 13 hard disks. Therefore to be sure a free capacity of only 13 hard disks is available; however, the defective system can be replaced while the system is operating. It was necessary to make use of this possibility at KWC twice during recent months. In contrast to the options which are indicated in the corresponding manuals and then do not work as described there, the exchange of a defective disk in a Stripeset with parity works exactly as simply as was described here - in this report.

The experienced reader now will ask himself how it is possible to read several GB of data over a 10 MB network so quickly that the transfer of the data to an external computer is not a drag on the system. The technical realization was made by means of a 100 to 10 MBit Netswitch. A 100 MBit network card was incorporated into the Imageserver . This is connected to a Netswitch, which connects a 100 MBit input channel with ten 10 MBit output channels.

Therefore it is possible to connect up to ten workstations via twisted-pair cables to make the full speed of 10 MBit available to each station. In addition a semiautomatic digital Aerotriangulation program never requires the whole data of a digital image.

Because the images are saved in image pyramids, an "overview" is sufficient for a general quicklook of a total image. The detailed measurement of the points will be done with tiles, that also constitute only a small volume of data. Therefore it is possible to work on a network computer without any problems and not to have to put up with any loss in production. KWC does not make a data back-up of the very large amounts of data, and also it does not appear to be necessary. The scanned images are saved on Exabytes, in the case of an unintended deletion of the data these can always be restored. This is realized with a special Windows NT based TAR (Tape archive) program. This UNIX- compatible program can restore the data without any problems. In practice it even occurred that older sets, which could not be restored on UNIX-stations (tape media error) could be read with Windows NT operating system without any problems!

2.4 Digital Orthophotosystems

In addition to the possibility of a considerable increase in productivity by means of digital aerotriangulation, this procedure pays for itself especially in the manufacturing of digital orthophotos. Two further workstations, INTERGRAPH-Interpro 6885 (IP6885) and technical desktop 4 (TD4), are used at KWC in order to be able to produce in this very productive way.

The digital Orthophotos are resampled on these stations, which are connected to the Netswitch, and then they are combined into mosaics. The corresponding software modules are:

- Imagestation Image Rectifier (ISI-R)
- Imagestation Imager 2 (ISI-2)
- Modular GIS Environment Base Imager (MGE Base Imager).

Both workstations also have a JPEG-Board. Although very different hardware- architectures are involved here, the compressed data is binary-compatible to the systems. So the images corrected at the UNIX station can be processed on the Intel -based workstation without any problems. Numerous additional developments were made at KWC for controlling and improving the individual program modules. Thus the batch-based calculation of the orthophotos is controlled with the help of Excel sheets. This very efficient Spreadsheet program of Microsoft has very efficient calculation algorithms which calculate the command lines completely automatically. Thus, for example, with the aid of Excel from the map name of a German base map, the corner point coordinates of this map can be derived automatically and transferred into the calculation procedure. In this way input errors are excluded, and therefore incorrect calculations are avoided. Numerous further modules serve for the visualization of the calculation results which are also integrated into the production process of the orthophoto calculation. By means of this integrated total concept, KWC is in the position to calculate 100 and more digital Orthophotos in 24 hours. At the present time the bottleneck is to be found in the INTERGRAPH CLIX- hardware, which is not state of the art today. It remains to be seen to what extent the capacity can be increased further through the integration of Intel-based multiprocessor systems. Today KWC is proceeding from the basis that in the foreseeable future 200 to 500 digital orthophotos can be produced in 24 hours. The corresponding hardware (16 Intel Pentium Pro Processors on one Motherboard) is already available. It is up to the software developers to adapt its programs by means of the multiprocessor- and multithreading- functionality of the current hardware systems.

3. Summary and outlook

Semiautomatic digital aerotriangulation works very productively and is to be preferred to analytical triangulation today. It has a higher productivity, and -because more than 20 tie points are measured- it has a higher absolute accuracy. Moreover, this advantage can be used in order to derive an approximated digital height model. This model is sufficiently for numerous orthophoto projects and therefore can be calculated from the triangulation results without significant extra expenditure. It was possible to achieve an optimal workflow, which has largely automated digital orthoprojection, by means of the integration of numerous additional tools. For the future it remains to be hoped that the institutions which need current data material concerning the topographical state of the surface of the earth, will become better attuned to modern technology and use increasingly more digital image material for their processes. A digital orthophoto can be produced for a fraction of the price of a digital map. This is sufficient for very many planning and documentation purposes. Even the considerably larger amounts of data are no problem for modern computer systems.

Discussion after the Conference:

Practical Experiences with Digital Aerotriangulation based on INTERGRAPH ImageStations,

by M. Beckschäfer

Colomer:

Have you tested the link of the Intergraph software with the relational database which can do import and export only on the base of the ISDM package?

Beckschäfer:

We have not tested it yet, but it is an option. The problem is not only whether you can use the hardware, but you would also have to use 20 different disks and it is not very easy to get a straight work flow in this way. It is much easier and more efficient to only have one disk and to have a project number for each project which refers to the respective directory. We developed a directory structure upon this concept to manage the whole data so that if someone becomes ill and another person has to take over, he will not have to figure out how the data are really organized. In my opinion, this is really important, especially when you deal with thousands of files. If you do not have a strict data structure then you will become bankrupt.

Kölbl:

You informed us that one of your operators makes 60 models a day, but do these figures only include the measuring activities? How much time does it take to scan the images and are the post-treatment of the data and the proper block adjustment included in these figures?

Beckschäfer:

If I say 60 images per day then that definitely means 60 images without doing anything else, but it also depends on the project. This amount of data was produced with black and white images and 30 µm scanning with a JPEG factor of 5. We successfully produce on our scanner 40 images per shift, so in one working day, we produce 80 images and sometimes 120 depending on whether we find the people to cover the night shift. The triangulation depends upon the size of the block, these 900 or something model block calculates for about 8 hours on a PC 486 with 60 MB Memory.

Some Considerations about Automatic Digital Aerial Triangulation

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ABSTRACT

Digital aerial triangulation is a primary process in digital photogrammetry. After the previous progress in computational block adjustment now point transfer and point measurement can be automated by digital image processing techniques.

The paper displays a straight forward strategy for almost full automation, referring to the MATCH–AT program. Essential items are feature extraction and feature matching in highly redundant point clusters. Also, block adjustment is integrated part of the process. The redundancy principle gives the necessary robustness for automation and will regularly provide high accuracy results which are, as is shown, equivalent to the best results obtainable by conventional analytical aerial triangulation.

1. INTRODUCTION

This paper is not intended to give a comprehensive review of digital aerial triangulation. Instead, some **general considerations** are submitted concerning aspects of scope, of approach, and of system performance. Nevertheless, the deliberations refer in particular to the system approach of the **MATCH–AT** program for automatic aerial triangulation which is being developed by Inpho Company, at present.

1.1 Automatic digital aerial triangulation stands in the line of the direct **automation** efforts which are presently undertaken in **digital photogrammetry**, on the basis of low level digital image processing techniques. Especially the generation of DTMs, the production of orthophotos, and the execution of aerial triangulation can be largely automated with digital methods, by applying **low level image processing methods** which do not take recourse to intelligent knowledge based methods. It is my conviction that the successful automation of such processes and products is the key to the immediate acceptance of digital photogrammetry in practice. Their application provides the necessary direct advantage over analytical photogrammetry. The long term added value aspects of digital photogrammetry, by multi–data techniques, will take effect very much later and will not be sufficient for the immediate transition to digital photogrammetry.

1.2 Digital aerial triangulation stays within the general scope of conventional aerial triangulation. (The potential future development towards general matching of different sensor data remains outside the present considerations.) However, digital aerial triangulation is expected to give a **great push** concerning accuracy, economy and cost reduction. The distinction against analytical aerial triangulation lies in the **image processing techniques** resp. in the potential for automation of low level image processing methods. All previous progress in aerial triangulation, during the last 30 years, was achieved by the computational development for **block adjustment**. Now, the operations of **point transfer** and **point measurement** come into the reach of automation. Those operations have been the task of the human operator, up to now, requiring human intelligence and insight. This holds in particular for the selection and the transfer of tie–points. Thus, when tackling such tasks by automation an algorithmic substitute for the human **intelligence performance** has to be found, unless the essential parts would remain reserved for interactive operations.

1.3 Digital aerial triangulation is distinguished, at present, by automation on 2 different levels. The first level concerns the **semi–automated aerial triangulation** which more precisely may be called operator guided point selection and automatic point transfer. The actual point transfer is executed by digital image matching. Digital aerial triangulation on the semi–automated level is becoming common, at present. It is highly successful, effective, and economic, leaving space for interactive interference, if necessary. Each image workstation will have such a system, in near future. Nevertheless, those systems only go half the way, still following the customary conventional steps. As complete automation is possible the semi–automation of aerial triangulation only represents a **transitory** stage, in my opinion. Operator guided digital aerial triangulation is not the topic of this presentation. Instead, we concentrate here on the possibility and the potential of fully automated digital aerial triangulation.

2. AUTOMATIC DIGITAL AERIAL TRIANGULATION – THE MATCH–AT SYSTEM

2.1 We consider here the potentially **complete automation** of the total aerial triangulation process and refer to the system approach of the **MATCH–AT** program of INPHO Company as an example. Automation does not mean that operator support would not be allowed at all. But interactive support should be restricted to some initialisation at the beginning and, if necessary, to quality control, acceptance, and perhaps some editing at the end. The main part of the process is designed to run as **batch process**, without any operator attendance nor on–line control. That structure is the main reason why automated aerial triangulation can run still faster and less costly than a semi–automated system. That the results can be more accurate, too, relates to the implied redundancy principle which will be referred to below.

There is only one sub–process which is not yet suited for automation, unless special targetting is applied, namely the identification and image measurement of **ground control** points. Hence, image observations of ground control points belong, for the time being, to the interactive part of the MATCH–AT system at the beginning of the process. It is, by the way, the only part which requires high image resolution.

2.2 The actual MATCH–AT system is strictly subdivided in 2 parts, distinguished as initial approximation and the actual kernel system of the method. The requirements for the **initial approximation** (also called initialisation, but not to be confused with the interactive initialisation of paragraph 2.1) depend somewhat on the system chosen. The MATCH–AT system, for instance, only looks for tie–points in **predefined conjugate image patches** which are located at the 9 standard image positions, known as von Gruber positions, see Fig. 1. Tie– points are most effective for the aerial triangulation at these locations. The size of the pre– chosen patches is normally 3 cm x 3 cm in the image. Conjugate tie–points are to be selected and matched within those conjugate patches. If the linear overlap between conjugate image patches is at least 15 – 20 mm (or about 30 – 40 pixels on the highest image pyramid level of, say, 480 μm pixel size), then feature matching is successful, normally. Clusters of conjugate points are then expected to be found.

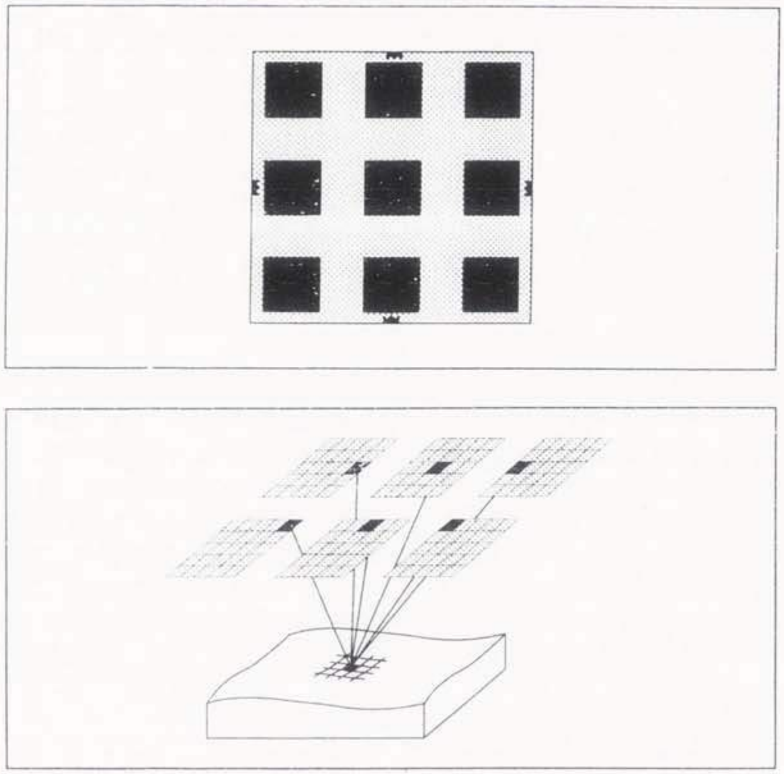

Fig. 1 – Conjugate image patches for point transfer

In order to obtain such **initial overlap** of the patches, the absolute positions of the photographs must be known to better than 1 cm in image scale (by GPS flight navigation data, for instance), attitude values to better than 2 degrees, and the terrain DTM (relief displacement) to better than 10 % of the flying height. How these approximations can be provided, or derived automatically, is not discussed here. In the worst case some operator support may be called in at the beginning of the process, as part of the interactive initialisation. The actual kernel part of the program assumes that the conjugate patches are given with sufficient relative overlap.

2.3 The **kernel part** of the MATCH–AT system comprises the actual automatic aerial triangulation which is approached in a quite straight forward manner. It is based on digital feature extraction and feature matching. The **feature extraction**, by the 2 D Förstner operator, is done separately for each image patch, throughout the whole block. Here, it is a basic point of philosophy that no single tie–points are aimed at, as in the conventional analytical aerial triangulation. Instead, always **clusters of tie–points** are extracted. That **redundancy principle** has an effect on the resulting accuracy of aerial triangulation. Moreover, it represents the essential condition for substituting intelligent point selection by an algorithmic process. It is the basic philosophy of low level automation to replace intelligence functions by redundancy, resp. of obtaining equivalent results through algorithmic methods and data analysis, based on redundancy.

The feature extraction, having been done separately in all individual patches, through all patches of the block on the first level of the image pyramid, is followed by the next step, concerning the identification of conjugate points in conjugate patches, known as **feature matching**. This is first done pairwise in all combinations (which was not so in conventional point transfer). Then multiple matches are identified through heuristic search routines and checked for mismatches. That check for mismatches is not done locally but simultaneously over the whole block by applying a **complete bundle block adjustment**, of which especially the blunder detection capability is essential, at this stage.

The described procedure is iterated through all levels of the image pyramid. The method is quite robust, hence 3 or 4 pyramid levels are sufficient. When the process has gone through the image pyramid, the final iteration represents the **final blockadjustment** which in this way is included in the total process. For that reason the block adjustment uses all available information, right from the beginning (ground control, GPS camera position data, interior orientation). As a side remark it may be observed that the described method only operates on the digitized image patches throughout the process. The volume of image data to be directly accessed may be reduced accordingly.

3. SOME ADDITIONAL REMARKS

3.1 The process iterates through the image pyramid (3 or 4 levels only), starting normally at about 480 µm pixel size. The feature points of a pyramid level are not projected through onto the next level, because initial feature points may lose their identity in the higher resolution. Each projection only determines the center of a new subpatch on the next lower pyramid level, see Fig.2. The feature extraction takes place independently on each level.

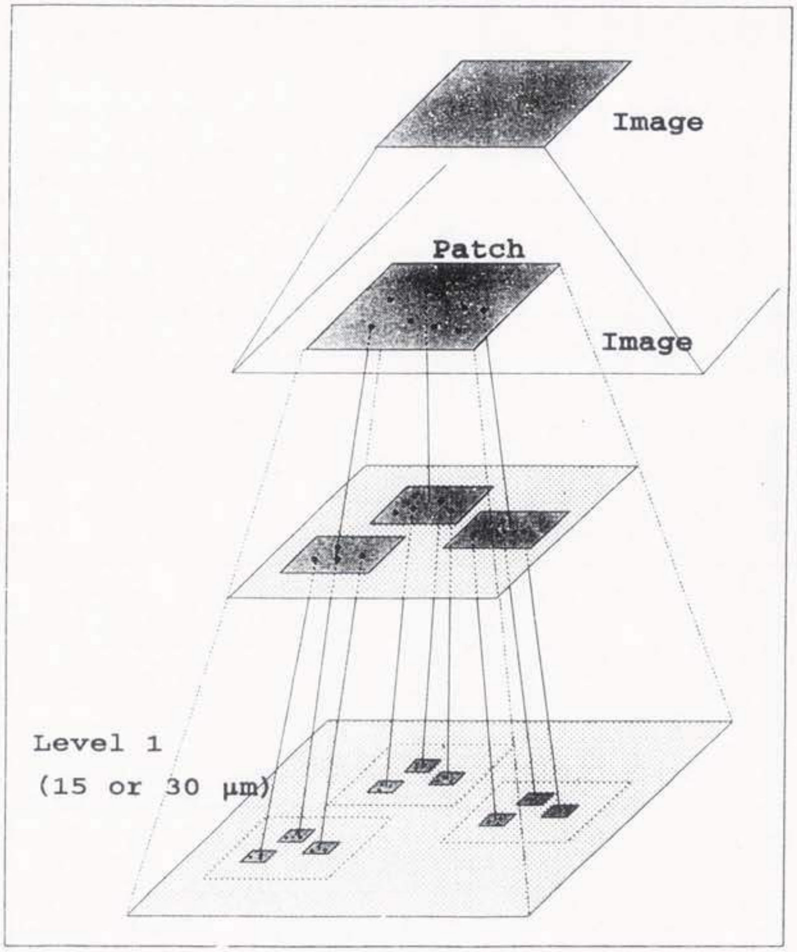

Fig. 2 – Strategy for sub-patch selection through the image pyramid

There are several strategies possible how to project feature points through the image pyramid. Within the original patch several points and hence subpatches at the next level may be chosen in each of which new tie points will be extracted and matched. As a rule of thumb at the end perhaps 25 tie-points per original image patch are matched and made available for the final block adjustment. They give altogether perhaps **200 to 300 tie points per image**. That redundancy will have an influence on the stability and the final accuracy of the block.

3.2 The MATCH–AT method of automatic aerial triangulation is based on feature extraction and **feature matching**, motivated by the robustness of the method and its high accuracy which is obtainable in connection with high redundancy. Other systems work with **area matching** methods, like cross–correlation or least squares matching. Each method has its own conditions of application and system consequences. However, there is no point in putting up an antagonistic polarisation as a program can easily have several matching methods implemented. The MATCH–AT program will have least squares matching implemented, for optional use, especially on the final pyramid level.

A basic difference between feature matching and least squares matching is the final **precision**. With feature matching the standard deviation of image coordinates is 0.3 – 0.4 pixel, whilst least squares matching can reach 0.1 pixel. On the other hand there are differences with regard to the kind of points captured. Feature points can be any points, also points on buildings, on roof tops, even on trees, while area matching requires locally flat or even horizontal areas, a condition which has to be verified at each point.

3.3 The redundancy principle which is essential for the Match–AT approach is applicable on condition only that the whole process is fast enough. From initial experience it is expected that the net **processing time** is in the order of 5 min/image or less (on a Silicon Graphics R 4000 processor, somewhat longer on an Intergraph image workstation, for the time being). Even if the data storage, the initialisation, and the editing may altogether add a few minutes per image it is expected that the automatic aerial triangulation is quite fast and therefore highly economic, especially as a large part of the total processing runs in batch mode, and as the final block adjustment is included. Actual results will be published very soon.

4. ACCURACY CONSIDERATIONS

4.1 When judging the accuracy results of aerial triangulation there are 2 separate parameters to be distinguished. We have first the precision of image coordinates which act as observations of weight 1 in the least squares bundle blockadjustment. It is (together with other weighted observations) estimated and expressed in the σ_0 value of the bundle block adjustment. It has been pointed out often enough that the magnitude of the σ_0 value is normally determined by the precision of the point transfer, compared with which the actual measurement precision of the image points is nearly negligible. σ_0 values for non–signalized image points or for pugged points have been, for a long time, in the range of 7 – 10 (15) µm. More recently values of 5 µm or better are being reached in analytical aerial triangulation, possibly because of the improved image quality of modern air survey cameras. If, in special applications, all tie–points are signalized (like in cadastral photogrammetry), the empirical σ_0 estimates reach 3 µm or slightly better. This precision level is obtained because signalized points have no transfer error. Still better values, as suggested by the measuring precision of image coordinates of 1 or 2 µm, are prevented by inherent systematic image deformation.

The **precision** level of **digital aerial triangulation** with automatic digital point transfer depends on the matching method applied and on the pixel size of the digitized images. If we take, for instance, 20 µm pixel size and assume a matching (transfer) precision of 0.3 – 0.4 pixel for feature based matching resp. of 0.1 – 0.2 pixel for least squares matching, then the equivalent σ_0 values would be about 7 µm resp. about 3 µm. These values would directly represent, in conventional terms, a **high quality** resp. an excellent aerial triangulation result.

4.2 The **absolute accuracy** of an adjusted aerial triangulation block depends on the precision level of the observations (σ_0) and on the geometry of the block (as given by photography, overlap, ground control, number and distribution of tie-points, GPS data). This is expressed by the general relationship

$$\sigma_i = \sqrt{q_{ii}}\,\sigma_0 \tag{1}$$

Here, i is the index for any unknown of the adjustment problem, in particular the terrain coordinates of the adjusted tie-points and the image orientation parameters; q_{ii} stands for the diagonal elements of the inverted normal eqation matrix $Q = N^{-1}$. If the geometry of different blockadjustments (ground control, overlap, number and distribution of tie-points, auxiliary data) is identical, or sufficiently comparable, then the resulting absolute accuracy goes proportional with the precision (σ_0) of the image coordinates (and of other observations properly weighted). In particular, under equal external conditions the results of digital aerial triangulation can directly be compared with conventional aerial triangulation, the decisive parameter being σ_0.

4.3 If, however, like in the case of the MATCH-AT system, a large number of tie-points is measured, then the geometry of a block is changed. We would have to replace in (1) the geometry factor q by a different q* which would represent the changed geometry. In the case of tie-point clusters we can, however, reduce the case to the original geometry, because a local cluster of points could be considered, if reduced to its arithmetic mean, to be equivalent to 1 point with a reduced standard deviation of $\sigma^* = \sigma / \sqrt{n^*}$, where n* represents the size of the cluster. Hence, for the case of tie-point clusters, we can substitute equation (1) approximately by

$$\sigma_i^* = \sqrt{q_{ii}^*}\,\sigma_0 = \sqrt{q_{ii}}\,\sigma_0^* = \sqrt{q_{ii}}\,\frac{\sigma_0}{\sqrt{n^*}} = \frac{\sigma_i}{\sqrt{n^*}} \tag{2}$$

(In this general form the relation (2) is not valid for individual points, but only for the orientation parameters i of the images). If clusters of about 25 tie-points are used then the expected reduction $\sqrt{n^*}$ amounts to about the factor 5. Thus, in this case, we can expect that with feature based matching of **tie-point clusters** the adjusted block is – under otherwise equal conditions – about 5 times more accurate than if only 1 tie point would be used per patch. In case of reference to pairs or triples of tie points the accuracy gain is modified, respectively, to factors of 3.6 and 2.9. Thus, to go back to the above example, the block adjustment would reach an equivalent σ_0 of about 1.4 µm. This would compare very well with the theoretical result of least squares matching (with pairs or triples of tie points), keeping in mind that σ_0 magnitudes of < 2 µm or 2,5 µm cannot be realized in practice because of systematic image deformation.

These are, of course, **preliminary** general **considerations**. It remains to be seen whether and how close practical results will agree with such considerations. It can be concluded, in any case, that digital aerial triangulation is capable of obtaining results which are as good or better than the best conventional aerial triangulation results with non-signalized tie-points. Even, the results are expected to compare very well with the best analytical results which are obtained with signalized tie–points. **High precision** results will be the **standard** case in future digital aerial triangulation.

4.4 The **improved accuracy** of digital aerial triangulation is directly effective at the adjusted unknown **orientation parameters**. The accuracy of the individual points of a point cluster, however, does not benefit much from the improved overall accuracy of the block, as long as the measuring resp. transfer precision of the actual point remains the main error effect. In other words, the individual point does not benefit from the cluster principle, contrary to the image orientation parameters. These parameters directly represent the increased absolute accuracy of the adjusted blocks.

Digital photogrammetry can directly exploit the increased accuracy of the orientation parameters in the subsequent absolute orientation of stereo–pairs, for mapping purposes for instance, as digital systems allow **direct setting** of the **orientation parameters**. Adjusted tie– points lose their conventional function as minor control points for absolute orientation, having served their purpose in the block adjustment. It may be concluded that digital aerial triangulation aims at the image orientation parameters in first instance. It must be noted, however, that direct setting of orientation parameters requires identical maintenance of the interior orientation as used in the block adjustment. Otherwise appropriate corrections must be taken into account.

4.5 In conclusion it can be expected that automated digital aerial triangulation is faster, less expensive, and more accurate than conventional analytical aerial triangulation. It can push aerial triangulation to a new level of performance.

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Discussion after the Conference:

Some Considerations about Automatic Digital Aerial Triangulation, by F. Ackermann

Carswell:
When do you expect this automatic aerial triangulation program to be ready?

Ackermann:
It should be ready by the Congress in Vienna. The development is in the final stage. We still have the problem of initilization, how far to go back. Can we always assume that GPS position data are given? Furthermore, for mountainous terrain, the system has to automatically produce a rough DTM. This idea could then be pursued to make a completely automatic system for orthophotos which would include the DTM and aerial triangulation part.

Beckschäfer:
I wanted to ask if this triangulation package is developed by the Inpho Company. Will it be integrated in a photogrammetric work station like the one of Zeiss or will it be available as batch program?

Ackermann:
It is an independent development by INPHO Company and will be made available as batch programm. There are negotiations with other companies. It is hoped that the system might soon be taken over by Intergraph like MATCH-T.

Beckschäfer:
Your program is based on which hardware?

Ackermann:
Currently, the Silicon Graphic's R4000 processor is the platform for development. We also have the programme running on Intergraph's work-station. Transfer to any other Unix platform should be no problem.

Beckman:
Do you have any statistics on large blocks?

Ackermann:
No, no yet, but empirical results will soon be available. Perhaps, in this context, I come back to another point which has been raised. I would like to draw the attention to an important change of attitude. In digital aerial tri-

angulation we are not interested any more to utilize adjusted tie-points as minor control points for subsequent absolute orientation of stereo pairs. All you need is the orientation parameters which can be directly set at any digital station, especially if the interior orientation of the image data is not changed. In this way the accuracy effect of redundant tie-point clusters can be fully transmitted.

Kölbl:
I never realized that your approach is so similar to HATS. Can you help me understand the difference?

Ackermann:
Well, the developments were independent. The main difference is perhaps that we operate, so far, with feature matching, that we go for high redundancy with clusters of tie-points. The checks on mismatches are different and the final block adjustment is included, on-line. Also, the system essentially runs in batch, with interactive interference only at the beginning and at the end, in principle.

Kölbl:
I think it can be stated that HATS operates quite similar to yours as the part for relative orientation runs completely automatically nearly like in a batch mode and the program prompts you afterwards on the points which have been miss-matched.

Ackermann:
Yes, but we want to avoid re-measuring of great numbers of points. I have great applications for the many functionalities of HATS. Perhaps our approach is still more radical. Whether this pays off remains to be seen.

Jacobsen:
I think you have to be careful when speaking of accuracy in aerial triangulation because it will also be influenced by systematic errors like image deformations. A great number of measuring points produce high accuracy provided that the image deformations can be neglected and the pointing errors are absolutely random; then a great number of points really improve the precision.

Ackermann:
Well, I agree with you. Of course, digital aerial triangulation faces the same basic situation as conventional aerial triangulation. But the precision of the digital approach is superior, because of high matching precision and/or higher redundancy except for the case of signalized points. For the same reasons also the chances are improved for capturing systematic image deformation by self-calibration.

Kersten:
I have a feeling that your system works well in open area, but what happens to areas with forest covers and great height differences?

Ackermann:
I think, that case is one important advantage of feature points. They are almost independent of the surrounding terrain. Points on trees or on roof tops, for instance, can be perfect triangulation points for feature matching. Great height differences should not cause special problems, especially if modelled with a local DTM. Even poor features may remain applicable, if clusters of points can be captured.

Heipke:
What I foresee you would have as one of the major problem is checking for blunders. I wonder if the sequential approach would be more efficient. This is a more general question, would it not be useful to increase the side lap? What is your position on this?

Ackermann:
It is a matter of basic philosophy, where I maintain a hard attitude. If you consider greater overlap, especially 60 % side overlap, you apply it because you need it and not because your computations get easier. It is a wrong philosophy. Like in former times, when aerial surveys had to be planned to fit the Kelsh plotter restitution. Digital aerial triangulation must be able to handle all standard cases and must cope with the pertinent practical conditions. It should not formulate special requirements.

Heipke:
I wonder why you chose the sequential approach for blunder detection?

Ackermann:
The blunders in digital point transfer are small, right from the beginning. They cannot be larger than a patch, and do not seriously distort a block. Hence, we have an ease case as far as blunder detection is concerned. Also, we have many points. Even if complete clusters of points would be eliminated, the overall block would not fail, being stable enough. In all, there is no sufficient reason to approach the blunder detection especially. By the way, the internal blunder detection algorithm does not work sequentially.

General Discussion on Aerotriangulation

Kölbl:
A lot was discussed on the efficiency of digital aerial triangulation and this aspect seems to be well proven, but one wonders why so few firms do choose this approach?

Adam-Guillaume:
There are still many analytical photogrammetric instruments out there which cost zero dollars an hour because the machines are paid off so the only expense to the company is the salary of the operators.

Beckschäfer:
I would like to answer this question. We still have several analytical instruments and they are still in use. My point is that we do not do triangulation with analytical systems. Every image produced in the company is scanned first, triangulated and then we print the orientation and photogrammetric exchange files, followed by data capturing which is done on the analytical plotter. So from my point of view, triangulation is only digital triangulation, but data capturing with ImageStation, for example, in my opinion is too expensive for our company. We cannot buy additional ImageStations for data capturing because they are too expensive for what they can do since this job can be done even with a personal computer or those analytical machines.

Adam-Guillaume:
To invest millions of Francs to buy a new equipment is a very hard decision to make especially when your company has to work hard and you have a very small market share of the business. Furthermore, if you can still work on a purely mechanical instrument, why make that big investment? The transition period of converting to digital triangulation maybe easy for the younger operators, but it is not easy for those who are used to working on the old machines for many years.

Beckschäfer:
You are absolutely right. We had to change our staff for triangulation. There is only one operator who came from the analytical triangulation side who is now triangulating digitally and the others are not. It is very difficult for the operators to adapt. When I talk about "instinct," I mean that they have to have the feeling for this and that, for instance, the operators would know when not to touch the cursor because they know the system would crash. So you have to have the instinct, you have to have the feel for it when it is not right or it will not work.

Meid:
I still feel many customers today invest in analytical instruments for one or two reasons providing that the triangulation quality is there.

Kersten:
I would agree in the point of matching. If we have to produce orthophotos or work out a DTM then digital aerial triangulation is a very good approach and that is why we bought a digital equipment.

Adam-Guillaume:
That is why I think new products like ortho image requiring digital image give a good background to introduce new products. The production will be cool in the market.

Gevrey:
Another important aspect is the stereo superimposition. In my opinion, it is more productive when you go for digital stereo plotting and editing.

Kölbl:
It think it is evident that digital triangulation is extremely efficient. I am not so much in the production side, but I realized after the OEEPE test from the Finnish Geodetic Institute, that it is much quicker to do digital aerial triangulation than to continue on the analytical plotter; the instruments are very expensive though. If we would be free to invest, it is apparent that aerial triangulation should be done digitally. However, it is not quite clear yet if the precision is also the same. The Helsinki tests showed that the analytical plotter gave a somewhat higher precision than when we worked purely on the digital equipment. But it is also not yet clear whether a better technology or better scanning could provide even a higher precision for digital techniques than on analytical.

Vanommeslaeghe:
About digital photogrammetry, it is a very important investment, and the price has to be considered, but this factor might be changing very rapidly.

Part 3

Automatic Derivation of a DTM

Direction :

A. Dupéret M. Torre O. Kölbl

Overview of Image Matching Techniques

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Summary

This paper gives an overview of image matching techniques. Some of the fundamental problems which have to be dealt with are discussed. It is shown that image matching is inherently an ill-posed problem, and additional assumptions and constraints have to be introduced to make it well-posed. The individual modules of some existing matching algorithms are described and analyzed in detail. It is shown that the matching strategy plays a decisive role for the success of any particular algorithm. A hierarchical approach combined with epipolar geometry and a highly redundant set of conjugate primitives is found to be very important in order to control the computational complexity and to ensure a high reliability for the results.

1 Introduction

According to the 1993 Webster's New Encyclopedic Dictionary the term *match* has many different meanings including those of a *tennis match* and a *prospective marriage partner*. The most relevant definition in our context reads: a match is *a person or thing equal or similar to another*. Matching is defined as *to make or find the equal or the like of*. Thus, the range of uses for *matching* is rather large, perhaps surprisingly so.

In photogrammetry and remote sensing, matching can be defined as *the establishment of the correspondence between various data sets*. The *matching problem* is also referred to as the *correspondence problem*. The data sets can represent images, but also maps, or object models and GIS data. Many steps of the photogrammetric processing chain are linked to matching in one way or another. Examples include the reconstruction of the interior orientation: the image of a fiducial is matched with a two-dimensional model of the fiducial; relative orientation and point transfer in aerial triangulation: parts of one image are matched with parts of other images in order to generate tie points; absolute orientation: parts of the image are matched with a description of control features, mostly ground control points; generation of digital terrain models (DTM): parts of an image are matched with parts of another image in order to generate three-dimensional object points; and finally the interpretation step: parts of the image are matched with object models in order to identify and localize the depicted scene objects.

Looking at this large variety of tasks it comes as no surprise that matching has long been and still is one of the most challenging tasks in photogrammetric research and development. In this paper an overview is given of a more specific class of matching algorithms usually called *digital image matching*. Digital image matching *automatically establishes the correspondence between primitives extracted from two or more digital images depicting at least partly the same scene*. In the remainder of this paper digital images are assumed to be available, and the term *digital* is omitted. The primitives can be gray level windows or features extracted from the images. Thus, all input data sets are images or parts thereof. Objects as such need not be modelled explicitly. It should be kept in mind, however, that each algorithm uses at least an implicit model of the object surface, since it is the object surface which is depicted in the images.

In photogrammetry and remote sensing, image matching is employed for relative orientation, point transfer in aerial triangulation, scene registration and DTM generation. Also, the reconstruction of the interior orientation falls within the category of image matching, since the model of a fiducial is usually represented as a gray value image.

The next chapter gives a further insight into image matching, explains cross correlation as the most simple algorithm for image matching, and points out some of the obstacles one faces when matching images. This discussion is followed by a detailed analysis of the different components of a matching algorithm and some conclusions.

2 Image matching background

First solutions for image matching have been suggested already in the late fifties (Hobrough 1959, he still used analogue images and procedures). Since then a steady increase in the interest for image matching has occurred, and the question may be asked, why image matching has not been solved long ago. A first answer can be given by considering the information content of the most elementary primitive in the input data set, namely a pixel. An aerial image scanned with 15 µm contains approximately 235.000.000 pixels, and each gray value usually lies in the range of 0 to 255. Assuming an equal distribution of the gray values the image contains roughly 920.000 pixels of each gray value. This little computation demonstrates that matching on the basis of single pixels is certainly impossible. It also exemplifies two fundamental problems of image matching:

- ambiguous solutions may occur, if image matching is tackled using local information, and
- computational costs are high and have to be controlled.

A more realistic approach is that of cross correlation. In order to compute the cross correlation function of two windows, a template window is shifted pixel by pixel across a larger search window (see figure 1), and in each position the cross correlation coefficient ρ between the template window and the corresponding part of the search window is computed according to equation (1). The maximum of the resulting cross correlation function defines the position of the best match between the template and the search window.

$$\rho = \frac{\sum_{r=1}^{R}\sum_{c=1}^{C}(g_1(r,c)-\mu_1)(g_2(r,c)-\mu_2)}{\sqrt{\sum_{r=1}^{R}\sum_{c=1}^{C}(g_1(r,c)-\mu_1)^2\sum_{r=1}^{R}\sum_{c=1}^{C}(g_2(r,c)-\mu_2)^2}} \quad ; \quad -1 \le \rho \le 1 \qquad (1)$$

$g_1(r,c)$ individual gray values of template matrix
μ_1 average gray value of template matrix
$g_2(r,c)$ individual gray values of corresponding part of search matrix
μ_2 average gray value of corresponding part of search matrix
R, C number of rows and columns of template matrix

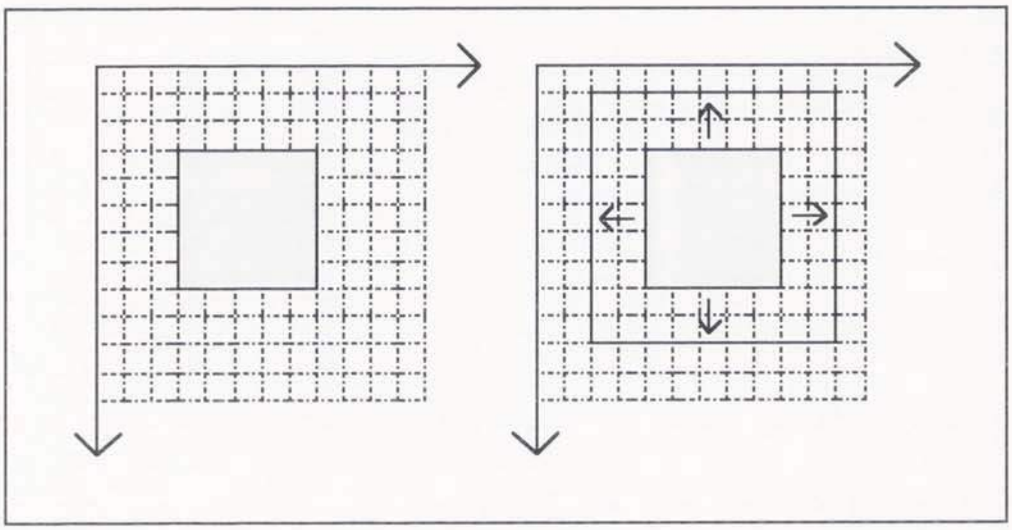

Fig 1: Principle of cross correlation

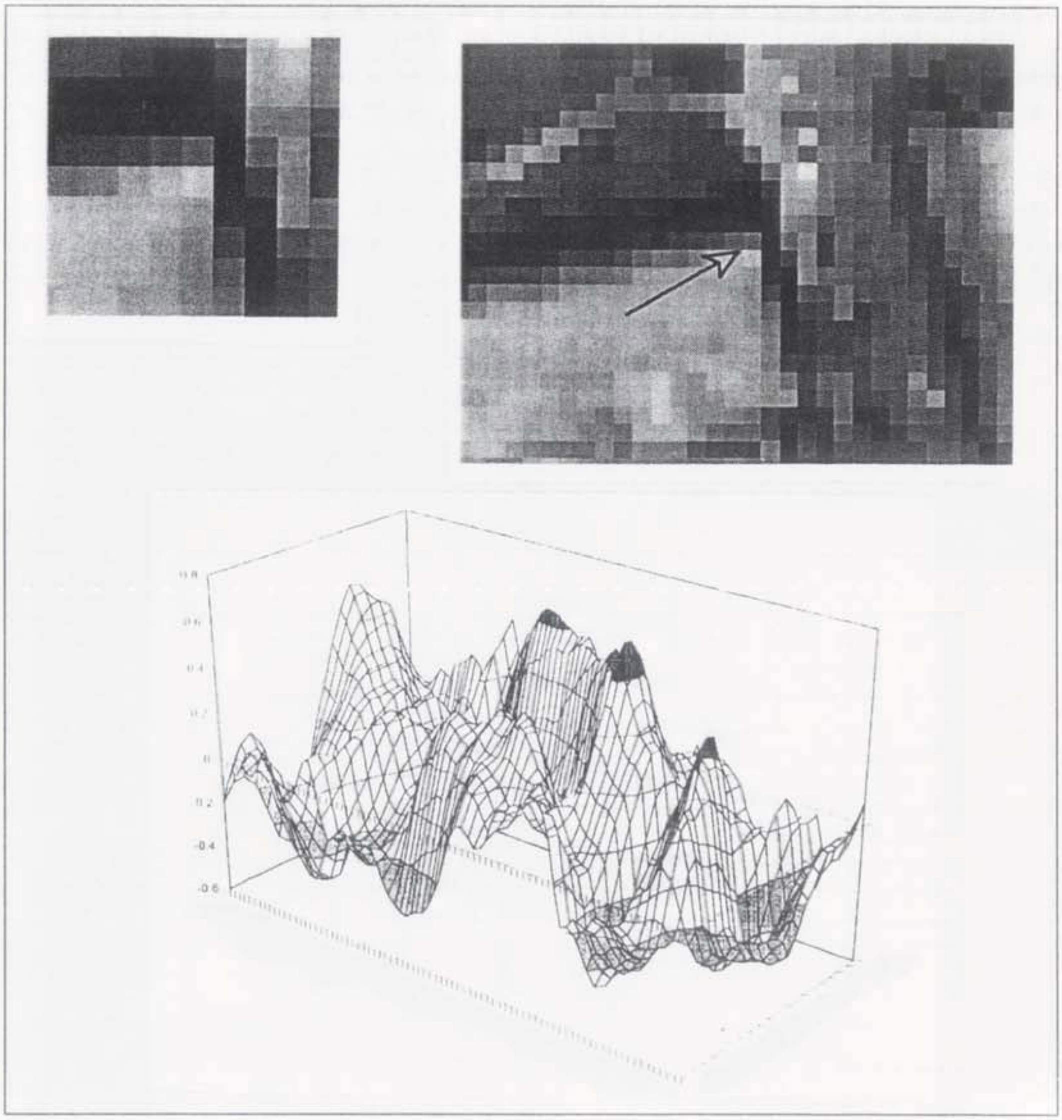

Fig. 2: a (top left) left image; b (top right) right image; c (bottom) cross correlation function

A typical result of cross correlation is shown in figure 2. Figure 2a shows a typical small *template window* of the left image of an aerial stereo pair, figure 2b depicts the corresponding larger *search window* in the right image. In figure 2c a plot of the cross correlation function of the two windows is shown. The cross correlation coefficient is a simple but widely used measure for the similarity of different image windows (see e.g. Sharp et al. 1965; Kreiling 1976; Hannah 1989). As can be seen in figure 2c the spatial variation of the cross correlation coefficient can be extensive making it a difficult task to find its maximum. We are again faced with the same problem: ambiguous solutions may arise.

Using image matching we try to reconstruct the three-dimensional object surface (or parts thereof) from two-dimensional projections. During this projection information is lost. This is most evident in the case of occlusions. Image matching belongs to the class of so called inverse problems, which are known to be ill-posed. A problem is ill-posed, if no guarantee can be given that a solution exists, is unique, and is stable with respect to small variation in the input data. Image matching is ill-posed, because for a given point in one image, a corresponding point may not exist due to occlusion, there may be more than one possible match due to repetitive patterns or a semi-transparent object surface, and the solution may be unstable with respect to noise due to poor texture (see e.g. Zheng 1993 for a more detailed discussion on ill-posed problems).

In order to find the solution of an ill-posed problem one usually has to deal with an optimisation function exhibiting many local extrema (as can be seen in figure 2c), and thus a small pull-in range. Therefore, stringent requirements may exist for initial values for unknown parameters to be determined. Moreover, usually there is a large search space for these parameters, and numerical unstabilities may arise during the computations.

Ill-posed problems can be converted to well-posed problems by introducing additional knowledge about the problem. Fortunately, a whole range of assumptions usually holds true when dealing with photogrammetric imagery:

- the gray values of the various images have been acquired using one and the same or at least similar spectral band(s),
- the illumination together with possible atmospheric effects are constant throughout the time interval for image acquisition,
  [note that both assumptions might not be valid in remote sensing applications]
- the scene depicted in the images is rigid, i.e. it is not deformable; this implies that objects in the scene are rigid, too, and do not move,
- the object surface is piecewise smooth,
- the object surface is opaque,
- the object surface exhibits a more or less diffuse reflection function,
- initial values such as the approximate overlap between the images or an average object height are known.

Depending on the actual problem at hand additional assumptions may be introduced, and some points of the list may be violated. It is this mixture of necessary assumptions which makes the design of a good image matching algorithm difficult, and has lead to the development of different algorithms in the past.

3 Analysis of image matching algorithms

Most matching algorithms proposed in the literature implicity or explicitly contain a combination of assumptions about the depicted scene and the image acquisition. Rather than trying to describe these algorithms as a whole it seems more appropriate to decompose them into smaller modules and discuss those (see Gülch 1994 for a similar approach).

The questions to be answered are:
- which primitives are selected for matching?
- which models are used for defining the geometric and radiometric mapping between the primitives of the various images?
- how is the similarity between primitives from different images measured, and how is the optimal match computed?
- which strategy is employed in order to control the matching algorithm?

The remainder of this chapter looks at each of these questions. As will be shown they are useful as a suitable base for analyzing the algorithms, although some of the questions are not entirely independent.

3.1 Different matching primitives

The distinction between different matching primitives is probably the most prominent difference between the various matching algorithms. One of the reasons is that this selection influences in part the answers to the other questions. The primitives fall into two broad categories: either windows composed of gray values or features extracted in each image a priori are used in the actual matching step. The resulting algorithms are usually called *area based matching (ABM)*, and *feature based matching (FBM)*, respectively. Note that when talking about ABM or FBM not only the selection of the primitives, but the whole matching process is referred to.

In both cases there is a choice between local and global support for the primitives. The terms *local* and *global* are not sharply defined. *Local* refers to an area seldom larger than about 50 * 50 pixels in image space, *global* means a larger area and can comprise the whole image.

3.1.1 Gray value windows as primitives

As mentioned above in ABM small windows composed of gray values serve as matching primitives. The window centre, possibly weighted e.g. with respect to the gray value gradient can be used for the definition of the location of a point to be matched. The gray values are regarded as quantised samples of the continuous brightness function in image space, and concepts of signal processing can be employed for further computations.

The windows can be extracted very fast, and the actual matching methods are rather straightforward. Also, ABM has a high accuracy potential in well-textured image regions, and in some cases the resulting accuracy can be quantified in terms of metric units. Disadvantages of ABM are the sensitivity of the gray values to changes in radiometry e.g. due to illumination changes, the large search space for matching including various local extrema (see again figure 2), and the large data volume which must be handled. Blunders can occur in areas of occlusions, and poor or repetitive texture.

ABM is usually based on local windows. One example is cross correlation (see chapter 2), another one is the original least squares matching approach (Förstner 1982). ABM can also be carried out globally using connected windows (e.g. Rosenholm 1987). In this case poor and repetitive texture can be successfully dealt with to a certain extend.

3.1.2 Features as primitives

In FBM features are extracted in each image individually prior to matching them. Local features are points, edge elements, short edges or lines, and small regions. Global features comprise polygons and more complex descriptions of the image content called structures. Features should be distinct with respect to their neighbourhood, invariant with respect to geometric and radiometric influences, stable with respect to noise, and seldom with respect to other features (Förstner 1986).

Each feature is characterised by a set of attributes. The position in terms of its image coordinates is always present. Further examples for attributes are the edge orientation and strength (gradient across the edge) for edge elements, the length and curvature of edges and lines, the size and the average brightness for regions.

Global features are usually composed of different local features. Besides the attributes of the local features, relations between these local features are introduced to characterise global features. These relations can be geometric such as the angle between two adjacent polygon sides or the minimum distance between two edges, radiometric such as the difference in gray value or gray value variance between two adjacent regions or topologic, such as the notion that one feature is contained in another. Matching with global features is also referred to as *relational matching* (Shapiro, Haralick 1987).

The result of feature extraction is a list containing the features and their descriptions for each image. Only these lists are processed further. It should be noted that the features are discrete functions of position: after feature extraction a feature either exists at a given position or it doesn't.

Features are more abstract descriptions of the image content. As compared to gray value windows features are in general more invariant with respect to geometric and radiometric influences. Feature extraction schemes are often computationally expensive and require a number of free parameters and thresholds which must be chosen a priori. In some cases a shift in the feature position is introduced during the extraction. If this shift is corrected for local features have a high accuracy potential. It is, however, difficult to quantify this accuracy in metric units. In areas of low texture the density of extracted features is usually sparse. For local features, seldomness is difficult to achieve, and a large data volume must be handled. Global features are more seldom and thus provide a better basis for a reliable matching. However, it is difficult to define and extract global features, and they tend to be more application dependent then local features.

Local features have been used for matching e.g. by Barnard, Thompson (1980); Förstner (1986) and Hannah (1989). In each case points were selected as features. Vosselman (1992); Vosselman, Haala (1992); Cho (1995) and Wang (1995) dealt with relational matching involving global features. Schenk et al. (1991) used a combination of global and local features.

3.2 Models for the mapping of primitives

The mapping between the primitives of the various images is defined via two models: a sensor model, and a model for the object surface. Simple two-dimensional transformations from one image to the next such as a two-dimensional translation or an affine transformation implicitly contain a combination of these two models. They are rough approximations of the situation during image acquisition and should only be used, if the selected matching primitives have local support. If, on the other hand, primitives with global support are used, the mapping between the images must be modelled more rigorously. Usually, the sensor and the object surface model are specified separately. As shown in figure 3 any two-dimensional transformation can be constructed from a sequence of two three-dimensional transformations: one from image space into object space, and a second one into the image space of the other image.

There is an advantage if the mapping between the primitives - local or global - is formulated in terms of object space parameters which are common for more than two images: multiple images can be matched simultaneously. This results in a higher redundancy for the matching problem and thus a greater reliability is achieved for the results. Multi image matching using ABM has been shown to be superior to matching of two images (Heipke 1990; Baltsavias 1991).

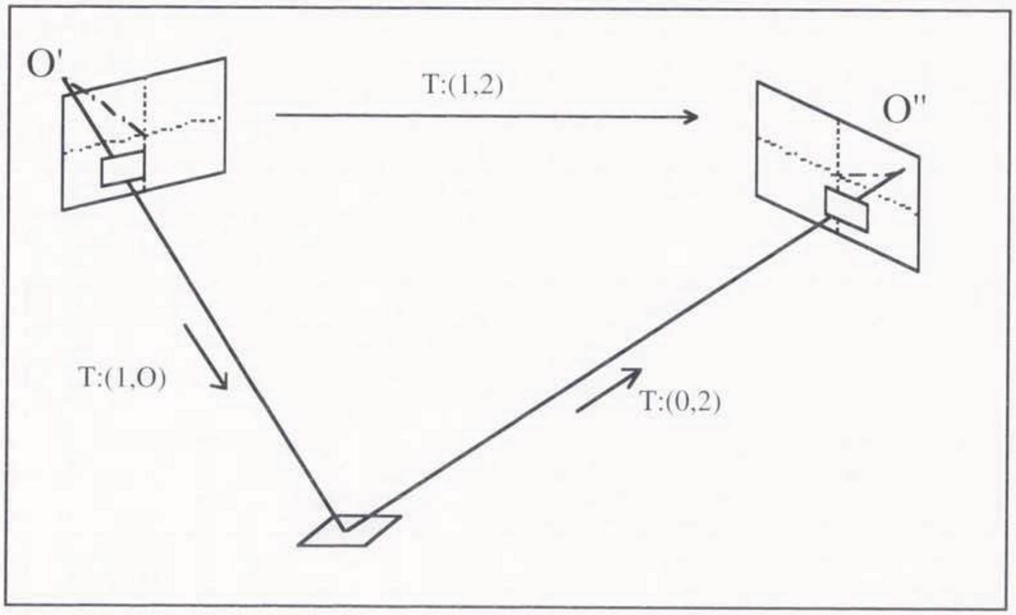

Fig. 3: A 2D transformation can be expressed as a combination of two 3D transformations

3.2.1 Sensor model and epipolar constraint

In many cases a central perspective projection can be assumed when dealing with photogrammetric imagery. Central perspective projection provides for a very powerful constraint, namely that of *epipolar geometry*, see figure 4. Given two images the so called *epipolar plane* for a point in 3D space (model or object space) is defined as the plane containing this point and the two projection centres of both images. This plane intersects both image planes in straight lines, the so called *epipolar lines*. If the relative orientation of two images is known, for a given point in one image the epipolar line in the other image can be computed, and the corresponding point must lie on this epipolar lines. Thus the image matching problem is reduced from a two- to a one-dimensional task.

In order to facilitate matching along epipolar lines the two images can be transformed into the normal case in a preprocessing step, eliminating the vertical or y-parallaxes in the complete stereo model. Subsequently, matching only needs to be carried out along the (horizontal) direction of the base line. Note, that this preprocessing step is not required as such in order to take advantage of the epipolar constraint: for a given point in one image the epipolar line in the other image can be computed using the parameters of relative orientation, and matching can then be carried out along this epipolar line.

The epipolar constraint is vital in reducing ambiguity problems and computational cost. Even if only approximate values for the parameters of relative orientation are known, the epipolar constraint should be used in order to restrict the search space for conjugate primitives in the direction perpendicular to the base line. Note that the epipolar constraint can only be formulated for pairs of images.

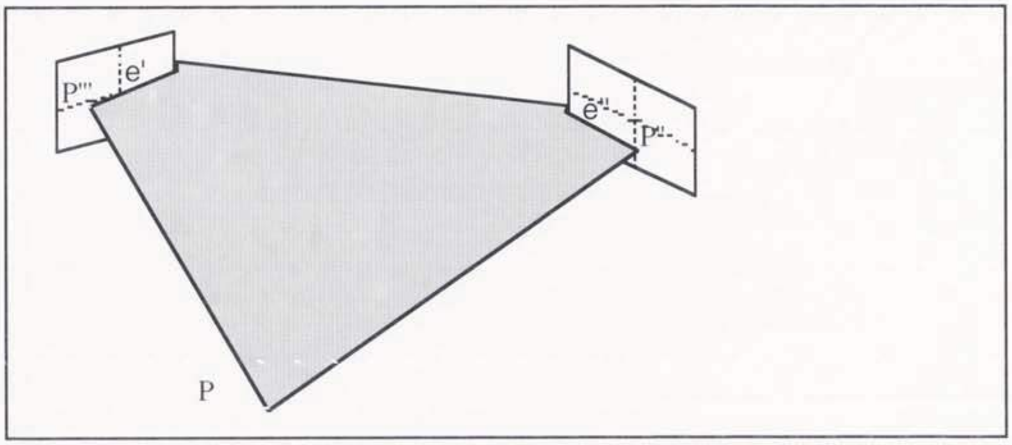

Fig. 4: The epipolar constraint: the epipolar plane (P, P', P'') and the epipolar lines e' and e''

3.2.2 Object surface models

Geometric models for the object surface used in image matching range from horizontal and tilted planes to piecewise smooth surfaces exhibiting discontinuities in the surface slope or the surface itself. Also, models borrowed from DTM generation such as finite element representations (Ebner et al. 1980) are used. As mentioned above the object surface is assumed to be rigid, i.e. it does not change during the time interval between image acquisition.

Radiometric surface models describe the brightness of a pixel in object space, also called *groundel*. Due to deviations from the Lambertian (diffuse) reflection function, relief influences (shading), and other factors such as noise a groundel usually has a different brightness when viewed from different directions. In image matching these differences are usually modelled by means of a local linear radiometric transformation. Thus, changes in overall brightness and contrast between different image patches are taken into account.

Another assumption of the object surface model is that it is opaque. This assumption guarantees that for a given primitive in one image there exists at most one corresponding primitive in each other image. In the case of occlusions, no corresponding primitive may exist.

3.2.3 Examples for sensor and object surface models in image matching algorithms

For cross correlation the two images are assumed to be of identical scale and azimuth, and to have parallel optical axes. In addition, the object surface is implicitly modeled as a local plane parallel to the image planes. This set up is equivalent to the so called *normal case* of photogrammetric image acquisition. In the most simple case the epipolar constraint is not used, however, it can be easily introduced by shifting the template matrix across the search matrix in a predefined direction only. The object surface is assumed to be opaque, and linear differences between the gray values of the two windows are allowed.

In least squares matching the rather strict geometric assumptions for cross correlation are relaxed: rather than only shifting the template matrix across the search matrix an affine transformation is used for the geometric mapping between the windows. As a result small deviations from the normal case can be tolerated, and the object surface is modeled as a local tilted plane. Again, the epipolar constraint can be easily introduced. The radiometric model is the same as for cross correlation.

For ABM in object space the collinearity equations are explicitly set up. If local primitives are used the object surface model is implicitly given by a tilted plane (Grün 1985). For global primitives a separate object surface model, often represented as connected bilinear surface patches, is introduced (Ebner et al. 1987; Wrobel 1987; Helava 1988; see figure 5). This general model allows for the introduction of all orientation parameters (thus, the epipolar constraint is implicitly observed), and constraints for the geometric shape of the object surface such as parameters minimising the surface curvature can be directly introduced.

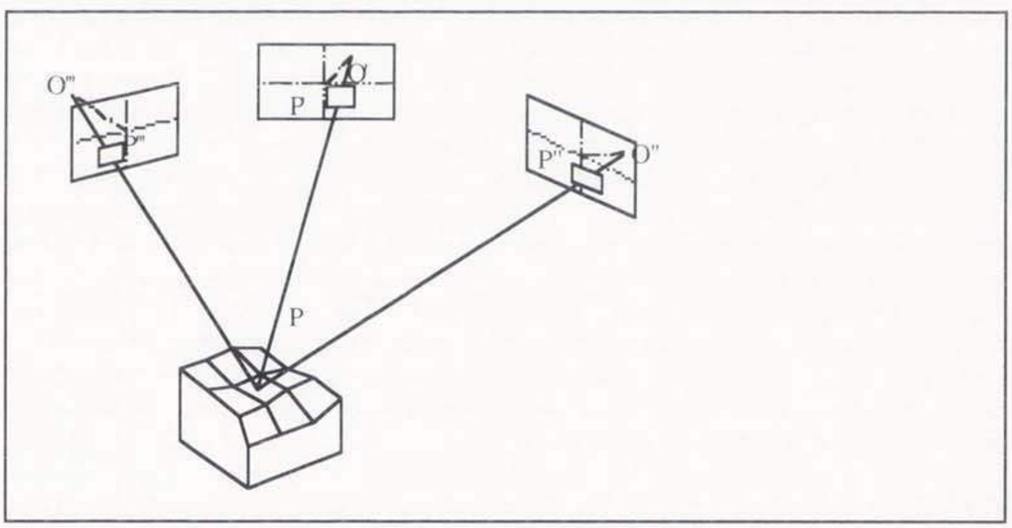

Fig. 5: Sensor and object surface model for object space least squares matching

curvature can be directly introduced. Within this model simultaneous multiple image matching can be carried out as discussed before. Again, the radiometric model is the same as for cross correlation.

In FBM sensor and object surface models are usually represented implicitly in order to reduce the search space. The epipolar constraint is used in most approaches. Due to the higher radiometric invariance of features as compared to gray value windows, radiometric models play a secondary role in FBM. They are, however, contained in the radiometric feature attributes.

3.3 Similarity measures and optimisation procedures

The definition of criteria for a good match obviously plays an important part in each matching algorithm. For ABM the similarity between gray value windows is defined as a function of the differences between the corresponding gray values. This function can be the covariance or the cross correlation coefficient between the windows, the sum of the absolute differences between corresponding pixels, or - as is the case in least squares matching - the sum of the squares of the differences. These measures have their background in statistics and are theoretically well understood.

Defining a similarity measure for feature based matching is more complicated. The definition must be based on the attributes of the features. In most FBM algorithms the differences in the geometric and radiometric attribute values are combined using heuristics and thresholds in order to compute the similarity measure, called a *cost function* or *benefit function*. Whereas a cost function is to be minimised, a benefit function must be maximised in order to achieve a good match.

The optimisation procedure which can be applied depends on the choice of the matching primitives. In local ABM an exhaustive search can be carried out as is the case in cross correlation. Alternatively, gradient based iterative schemes such as ordinary or robust least squares adjustment are available. As already indicated in chapter 2 the pull-in range for these approaches is rather small and lies in the range a few pixels only. Therefore, good initial values for the unknowns must be at hand. In order to subsequently achieve global consistency conjugate points are usually transformed into object space, e.g. via forward intersection. In this step the orientation parameters of the images may also be improved, leading to a bundle adjustment. The resulting 3D points are subsequently filtered, and blunders are detected and eliminated. In global ABM the optimisation procedure, the generation of tree-dimensional information and the estimation of parameters describing the object surface are integrated into one model.

FBM starts with discrete features. Therefore, gradient based methods can not be employed for optimisation. In local FBM for each given feature in one image a small search area is defined in the other image(s) using the selected mapping transformation. Subsequently, an exhaustive search is usually carried out in this search area. At this stage multiple matches may still be allowed. After all features of a certain region have been processed, blunders are detected through global consistency checks similar to local ABM. Alternative schemes for global consistency shall only be mentioned here. They include relaxation labelling (Banard, Thompson 1980), simulated annealing (Banard 1987), and dynamic programming (Kölbl et al. 1992). For relational matching tree search methods (Vosselman 1994) are employed.

3.4 The matching strategy

As has been explained is the previous paragraphs an image matching algorithm consists of a number of steps. Each of the individual modules which can be employed for each step has advantages and disadvantages. Thus, potentially something is to be gained from suitably combining these modules. Moreover, some parameters such as the approximate overlap or an average terrain height must often be provided a priori in order to reduce the search space, and values for free parameters and thresholds (window sizes, criteria for stopping the optimisation etc.) must be initialized. Finally, internal quality checks should be carried out in order to guarantee a correct result.

In the matching strategy the individual steps carried out within the algorithm are determined. This includes the input of prior information from a human operator, and the presentation of the results for final visual verification. In a comprehensive comparison between different image matching algorithms for photogrammetric applications Gülch (1994) showed that while under good condition accurate matching results can be achieved with a large variety of algorithms, a good matching strategy is decisive for a successful solution in more complicated situations. Faugeras et al. (1992) obtained a similar result for algorithms popular in computer vision. Some of the aspects of a good strategy are discussed in the following.

3.4.1 Hierarchy

Hierarchical methods are used in many matching algorithms in order to reduce the ambiguity problem and to extend the pull-in range. They are employed from coarse to fine, and results achieved on one resolution are considered as approximations for the next finer level. For this task images are represented in a variety of resolutions, leading to so called *image pyramids*. A typical image pyramid in which the resolution from one level to the next is reduced by a factor of 2, is depicted in figure 6. A coarser resolution is equivalent to a smaller

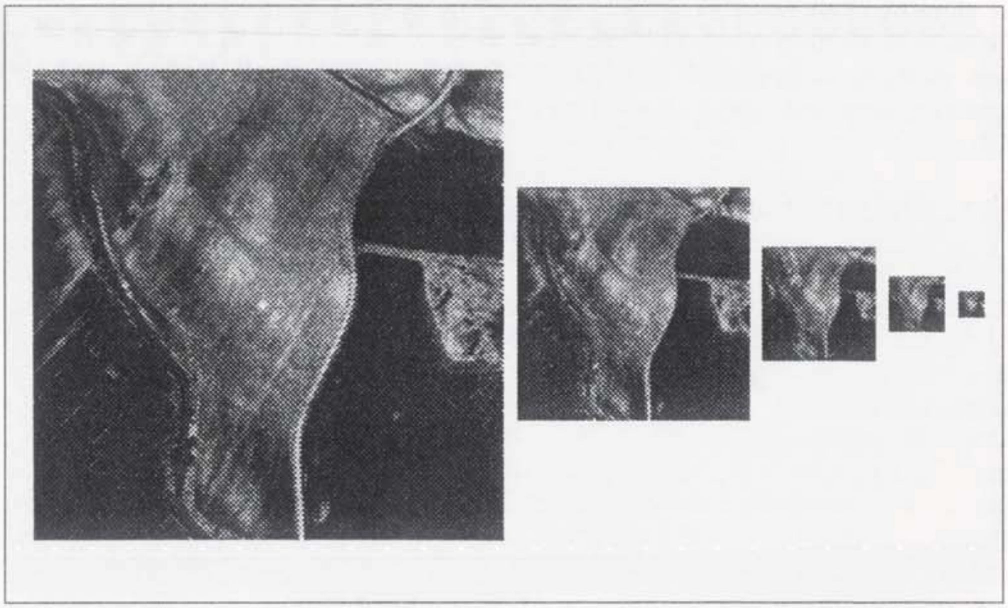

Fig. 6: Example of an image pyramid

image scale, and a larger pixel size. Thus, the ratio between the (fictitious) flying height and the terrain height increases as the resolution decreases, and local disturbances such as occlusions become less of a problem. Besides image pyramids, usually also a hierarchical representation of the object surface model is used.

When FBM is used, feature extraction should be carried out on each resolution level separately, since features can vanish or be displaced from one level to the next due to the low pass filtering which is inherently present when decreasing the resolution.

3.4.2 Redundancy

It is not known how the human operator measures points stereoscopically, but he or she is certainly still more capable to set the measuring mark on the ground than any developed matching algorithm. In other words, the blunder rate for individually matched points can be rather high. Efficient blunder detection is only possible if there is a large redundancy in the system.

Therefore, it is prudent to determine many more points when using an automatic matching algorithm than a human operator would measure. It is also possible to do so, because the number of points to be measured is a secondary issue in an automatic procedure, as long as enough computational speed is available. A high point density can for instance be used to implicitly represent breaklines in a DTM. Also, single obstacle on top of a DTM such as houses or trees can be filtered out, if enough nearby points on the ground are given.

Another issue related to redundancy is that of multi image matching, and thus of object space matching, see also discussion in chapter 3.2. As pointed out by Schenk, Krupnik (1996) in a conventional photogrammetric block with 60 % end overlap and 20 % side overlap only 24 % of an image in the interior of the block is covered by two images, and the same area is covered by six images. Thus, multi image matching can be of advantage for DTM generation without having to acquire more images. Besides, it is a prerequisite for applications in aerial triangulation.

4 Conclusions

This paper gave an overview of image matching techniques. Some of the fundamental problems which have to be dealt with were discussed. It was shown that image matching is inherently an ill-posed problem, and additional assumptions and constraints have to be introduced to make it well-posed. Subsequently, existing matching algorithms were decomposed into smaller modules, and these modules were described and analyzed in detail. It was shown that the matching strategy plays a decisive role for the success of any particular algorithm. A hierarchical approach combined with epipolar geometry and a highly redundant set of conjugate primitives was found to be very important in order to control the computational complexity and to ensure a high reliability for the results.

A well designed matching algorithm, i.e. the proper combination of various of the mentioned assumptions together with internal self diagnosis and a minimum of human interaction, provides a powerful solution to image matching in photogrammetry, especially when integrated into digital photogrammetric workstations (Heipke 1995). Examples for commercially successful software packages include MatchT for automatic DTM generation (Ackermann, Krzystek 1991) and PHODIS ARO for automatic relative orientation (Tang, Heipke 1996) among others. At the moment strategies and software packages for automatic aerial triangulation are being developed (Ackermann 1995; Mayr 1995; Schenk 1995). For this task but also for DTM generation multi image matching in object space is likely to become a powerful tool.

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Discussion after the Conference:
Overview on Image Matching Techniques, by C. Heipke

Ackermann:
Just a few remarks. First, my congratulation, this has been a very good review of what we are dealing with and what the assumptions and the problems are. You listed the properties of area matching. They are very precise, but have some weak points, operationally. The pull-in range, resp. the convergence radius of least squares matching is very small. I recall that the inventor of least squares matching, Helava, had abandoned its application in an early stage, for that reason. You mentioned the Newton interpolation curve. The property of continuity is not sufficient. The local curvature is also required for a solution not to converge to another maximum. With regard to the linguistic implication of the word matching, there is a subtle difference between area matching and feature matching. Feature matching is not really an active matching process like matching. In feature matching, features have been independently extracted. The matching of features is, strictly speaking, only an identification process, by which the correspondence ("Zuordnung") of features is established.

Heipke:
To give an answer to your comment, if you take a cloud of points in one image and a cloud of points in the other image, you are matching those two clouds. If you are looking at a specific feature, you are searching for which one could be the corresponding one. A feature can have attributes, a position is an attribute, even of a point feature. If you look at let's say a person, you have additional values which can be used as attributes. But I agree that points are the simplest and the most stable case as far as geometry is concerned too because if you are matching lines, you never know where you are on the line.

Loodts:
I believe that you are really optimistic about matching because at the moment, what is commercially available does not work at all in large scales. I have the impression that at the moment, we never use features in any algorithms, we just use correlation techniques and correlation gives a lot of problems in large scales. Features also give us problem in large scales because if, for example, you extracted one line in one image and two or three lines in the other image you match these features, you cannot really make an association of these lines even with the epipolar constraints or other constraints. What is your opinion on this problem?

Heipke:
It is important to first define what is large scale, let us say 1:3000 images. My report concerns matching and structural matching for different scales. Effectively, feature matching and area correlation are used not only in research work, but also in commercial products. Therefore, I cannot quite agree with your comment. You are right in saying that in large scales we

have more problems. Obviously, one of the major problems are occlusions. Feature matching is used and it certainly gives more height information than area correlation. It is true that in large scales we have more problems, but correlation techniques do work. You have to do more editing of the_DTM then in small and medium scales, but it is also a question of what you really want. Do you want to just push a button and then leave? and take your result out? or are you satisfied with having half of the job done automatically and still have to do some editing? It depends on what you consider a success. Post editing is needed, but it is still better than without matching. I personally like to work with matching, but I never like to work on the analytical plotter P1 just to do point measuring. I do not think I am the only one in that respect. So there is a progress, and it does work, however, it does not work in each and every case, but I do not think anybody claims that.

Automatic derivation of a DTM to produce contour lines

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Summary

This paper gives an overview about the classical approach of correlation in Digital Photogrammetry. Then ,with the production organisation point of view, an evaluation process is proposed, similar to the work done by IGN France in 1995 with the SOCET SET® software of HELAVA. This shows what kind of differences occur between various algorithms and helps to evaluate the technical reliability of the softwares. The next chapter shows what kind of transformation can be applied to a correlated DTM (Digital Terrain Model) to make it suitable for cartographic contour lines production. If the first task mainly requires computer resources, the DTM's transformation needs a human operator and becomes a critical task as far as the economical aspect is concerned. At the end, conclusions are made, based on IGN's experience. For the Lausanne workshop, a couple of images and control data were proposed to all manufacturers to help for comparison.

1. Correlation in photogrammetry

This first chapter tries to give a quick idea on various aspects of the use of correlation in photogrammetry. This does not refer to any specific software.

A number of applications now require to find correspondences with a pair of pictures of the same scene. Sometimes, it occurs that a pixel of the first image can not be associated with a pixel in the second image, because of hidden or shaded parts, disappeared objects...

Correlation is now also generalised to sets of n pictures, where the correspondence can be seen as a research of a trajectory if the pictures are ordered, or a combinatorial problem within a set of C pairs if they are not ordered. Various domains require correspondence finding :

- stereovision (in photogrammetry or not),
- movement modelling,
- multi-sensor fusion in remote sensing,
- medical imaging,
- robot vision,
- character recognition.

Many methods have been implemented to find correspondences between two images. If correlation is one of them, there is also mean squares methods, dynamic programming... Stereovision in photogrammetry gives a complete knowledge of the scene geometry : position, orientation and calibration of the cameras, geographical location.

1.1 Digital images

The performances of a correlation process will first depend on the quality of the images and the quantity of information carried out by them. For image processing, many criteria have been studied and should probably be evaluated for the aerial photogrammetry :

- entropy of the images,
- auto-correlation function,
- histogram of variations of radiometry,
- transfer function after scanning...

An image may give access to various types of primitives. The choice might be related to the type of application :

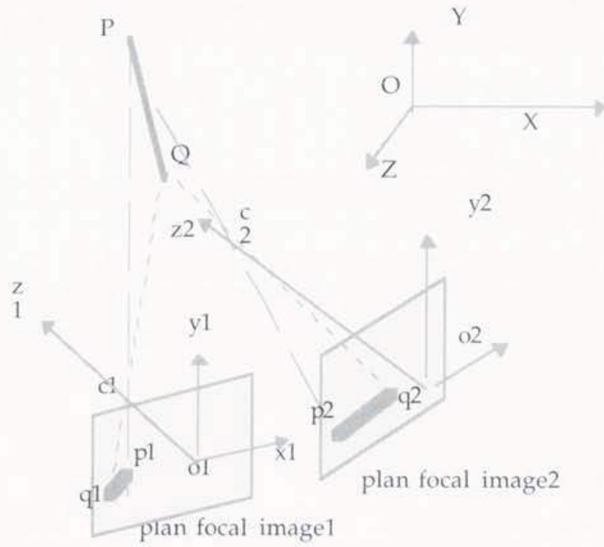
1. **The pixel** is the lowest level to deal with in the image. It can be used with all types of images because of its periodic structure. Alone, it is not sufficient to find the correspondences.
2. **The set of pixel** is the most frequently used and is a centred window with a variable size.
3. **The particular pixels** such as contour pixels, contrasted or high curved pixels...
4. **The edgels** (edge elements) are sets of joined contour pixels that have common properties.
5. **The areas** are contiguous pixels that verify a homogeneity property (shape factor, statistical values...).

Presently, there is no pre-established rule to define what primitives must be used. Commonly, it is the second one, *set of pixel*, in photogrammetry ; in fact, aerial photography often contains radiometric noise that prevents the user from building some of the upper primitives reliable enough. It seems that the correspondences finding is more efficient when the geometrical constraints are lower.

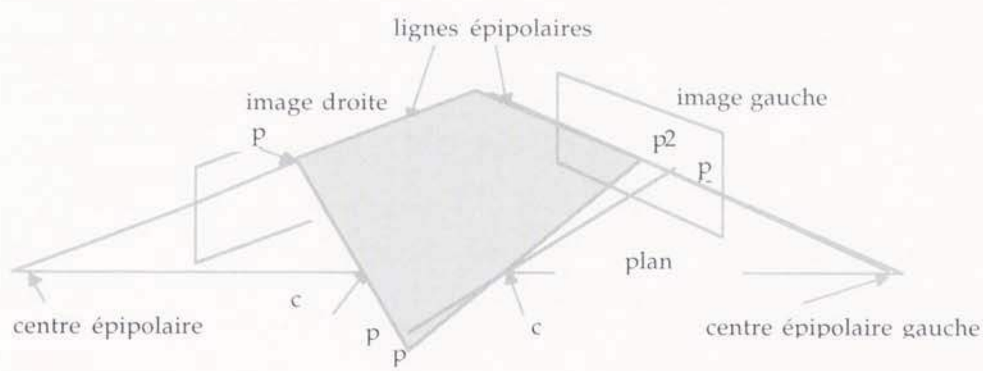
1.2. Correlation

1.2.1. Correlation principle

The geometrical aspect of the stereovision works on the disparities between the two photographs where an object is seen from different angles of view. The human brain interprets the differences like a distance.



Basically, the correlation methods compare the grey levels within two windows centred, for the first one on the current pixel p1 of the first image taken as a reference, and on the candidate p2 for correspondence with p1 in the second image. The research can be done with windows of various sizes. The farther an object is, the smaller the difference look between the two images of this object and less shape is felt. In photogrammetry, the correspondence finding might take advantage of the epipolar geometry. This is a special conformation of the picture space due to the stereovision when metric cameras are used. In epipolar geometry, the correspondence finding becomes a 1D problem. One epipolar line in the first image has one single correspondent line in the second image. So, the research of the correspondent of the current pixel is limited to the exploration of the epipolar line correspondent of the line which the current pixel belongs to.



Some methods also use Interest Operators that are standard procedures in image processing such as contour extraction. Characteristics details (buildings, roads) are located in both images and the correlation algorithm will then try to associate them by pair of points of left and right images. This method is called the Feature Based Matching.

In aerial photography, the following difficulties are met :

- difference of visibility between the two images,
- dependence of the variations of the scene photometry,
- particularities in the ground occupation : secular reflectance, presence of objects with regular and periodic structures, object motions (wind, clouds, vehicles...)

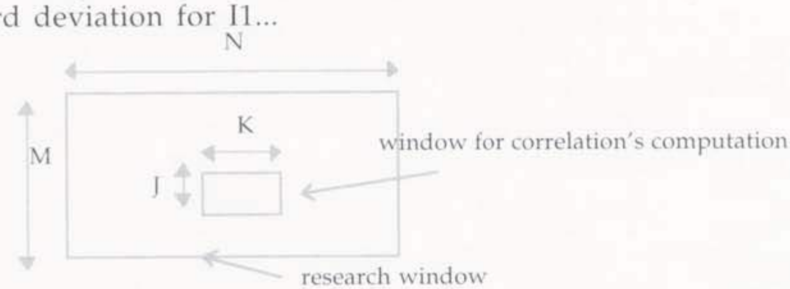
1.2.2. THE CROSS CORRELATION METHOD

a. Principle

The most common correspondence finding function of a pixel centred in the window I2 (part of the second image) with the current pixel centred in a reference window I1 (part of the first image) is characterised by the following expression ,

$$C_{I1I2}(k,l) = \frac{\sum_{i=1}^{K}\sum_{j=1}^{J}\left(I1(i,j)-\overline{I1}\right)\left(I2(i+k,j+l)-\overline{I2}\right)}{\sum_{i=1}^{K}\sum_{j=1}^{J}\left(I1(i,j)-\overline{I1}\right)^2 . \sum_{i=1}^{K}\sum_{j=1}^{J}\left(I2(i+k,j+l)-\overline{I2}\right)} = \frac{cov(I1,I2)}{\sigma_{I1}\sigma_{I2}}$$

where $\overline{I1}$ represents the mean value of the radiometry inside I1, σ_{I1} the standard deviation for I1...



Major properties of C_{I1I2} :

1. $-1 \leq C_{I1I2}(k,l) \leq 1$
2. $C_{I1I2}(k,l) = \pm 1$ ssi $I2(i+k,i+l) = aI1(i,k) + b$
3. $C_{I1I2}(k,l) = 1$ et $C_{I1I2}(k',l') = 1$ then I1 (or I2) is periodic i.e. $I1(i-P.(k-k'), j+Q(l-l')) = I1(i,j)$
4. if I1 has real values (i.e. non complex) then $C_{I1I1(k,l)} \leq C_{I1I1}(0,0)$ and $C_{I1I1}(k,l) = C_{I1I1}(0,0)$ only if I1 is periodic

b. Add-on constraints

Algorithms now frequently use constraints on the primitives in order to find an optimal solution. The most common ones are :

- the epipolar constraint : *two homologous points must respectively be located on two homologous lines.* This constraint depends on the geometry of the aerial survey and is independent of the scene's content.
- the unicity constraint : *the primitive of an image cannot have more than one homologous primitive in the other image.* This rule often has exceptions, such as hidden parts, transparent surfaces or lineaments supported by the axis camera.
- the surface's continuity constraint
- the order constraint : *if p1 is on the right of q1 in image1, then p2 is also on the right of q2 in the second image.* An inversion of points occurs only for objects that present a high perspective deformation on the image.
- the photometry constraint : based on Lambert's hypothesis, the reflected light intensity should be the same for two homologous points. For aerial survey, many reasons may cause radiometric variations between two adjacent images.

c. Direct approach

The following description is a generic overview of the basic treatments needed to compute a correct DTM. Prior to running a correlation algorithm, an epipolar resampling is sometimes needed, especially when images present a rotation exceeding a few degrees.

With a single pass, the correspondence finding is done with a neighbourhood research that does not take into account break lines or any external information.

- for every pixel, the mean value and the standard deviation of the window are computed. If they do not fit, the current position is abandoned and the research continues with the following pixel.
- the parallax (X-shift) is computed from the nearest good and preceding points so as to give an approximate position of the homologous point in the second image. The research is limited along the epipolar line supported by this point and within a limit that depends on slope limits or distances given by the operator. This reduces the amount of calculation.
- the correlation function is computed. If the value is too low, it will not be used subsequently.
- based on the surrounding points, a morphological criteria is applied. If it is not verified, the point is not accepted and the research continues with the next point.
- at the end of the current line, holes corresponding to undetermined points are interpolated from the correct ones. This can also be performed after the end of the image is reached.

If necessary, the high frequencies of the DTM (i.e. the small shapes with high slopes) are removed.

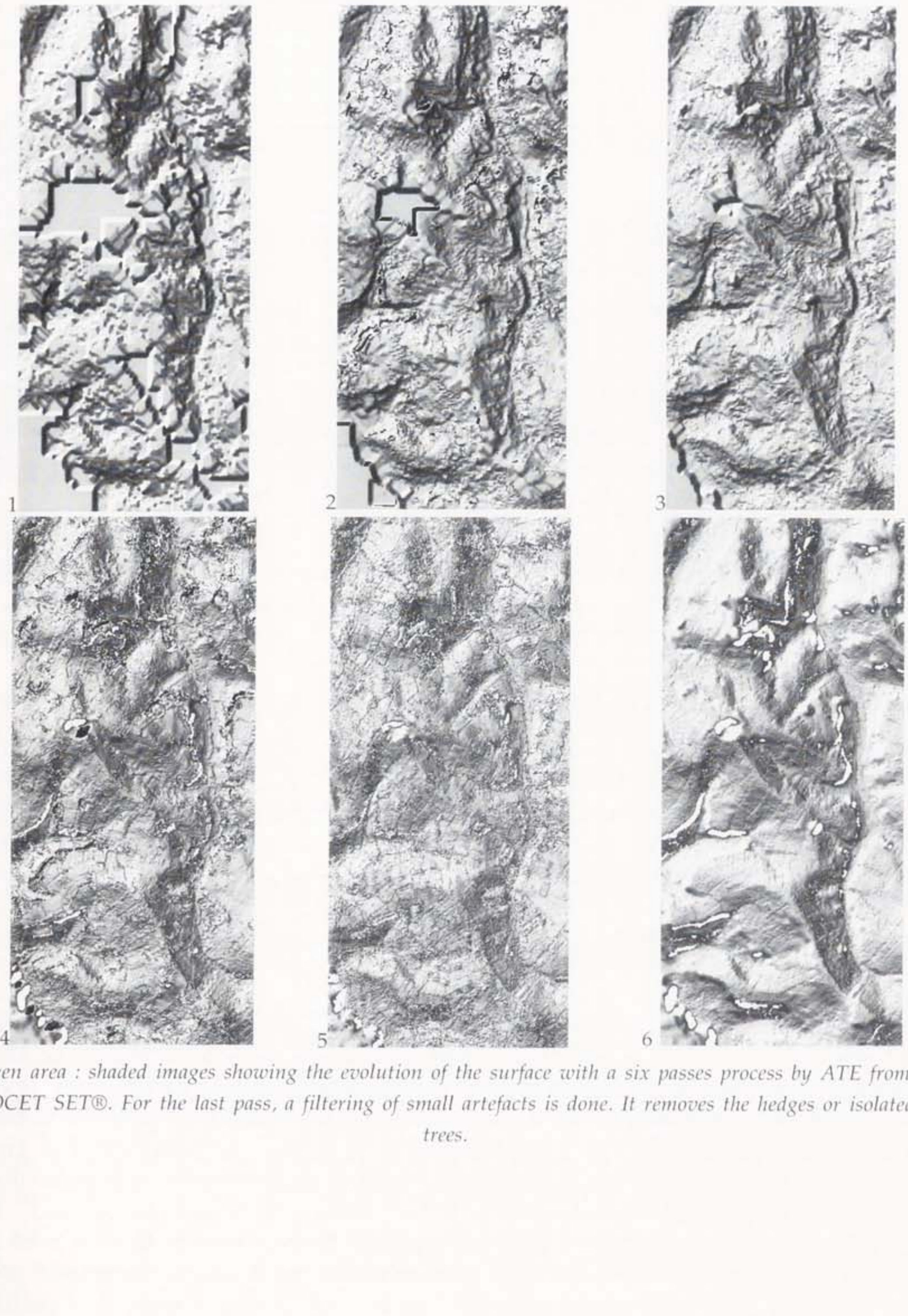
For a medium scale such as 1:20 000 and for a mean landscape, the following values look powerful:

- image size : 7x7 pixels,
- slope limit : from 20 up to 100% for flat to steep landscapes.
- spike limit : from 20 up to 100 metres for flat to steep landscapes.

Agen area ; shading of DTM correlated by the IGN's algorithm

d. Recursive approach

The recursive approach determines the parallax between the two images. It works first on small scale images, under-sampled. At every step, the post density is doubled until the full resolution is reached. For one single step, parameters can be set up independently. At the beginning, a sparse post spacing is used for the DTM completion ; afterwards, it is progressively densified. This confines the time of computation. The main danger is the propagation of the errors that occurs during the first steps. Therefore, one has to be careful with the values of the parameters when starting to work with new images.



Agen area : shaded images showing the evolution of the surface with a six passes process by ATE from SOCET SET®. For the last pass, a filtering of small artefacts is done. It removes the hedges or isolated trees.

A quick overview of the algorithms that have been developed is now given. One can refer to the bibliography for more details.

1.2.3. Least squares method

The least squares method can also be used for a correlation algorithm. One window is extracted from each image. The first one being the reference, the second one is modified by an affinity transform to take into account the geometrical distortions. The mean squares equation works on the difference between the grey levels inside the two windows

After linearisation, an equation for each pixel is made. The system is solved by the least squares method to estimate the parameters of the affinity transform. For each pass of the algorithm ;

1. both positions windows are modified,
2. the second window is modified by an affinity transform that takes into account the geometrical distortions (differences between angles of sight, terrain slope...)
3. the first window is not modified.

until the convergence can be achieved. In case of convergence, the two window's centres will become homologous. An overview of this method is done with <GRUN86> and <ACKERMANN83>.

1.2.4. Multi-point matching

The Multi Point Matching method also works with mean squares methods and is developed in <ROSENHOLM87>. There, the method consists in an estimation of the X-parallax of a grid of finite elements by minimising the difference in grey level for the two current windows. A continuity constraint for the parallax between adjacent elements is also used.

1.2.5. Dynamic programming

With this method, for grey levels of two epipolar lines, a graph of cost is built for the pairs composed of one point on the reference line and another point one the research line. The cost function represents the accuracy of their possible correspondence ; it might be the difference between the grey levels of the two points or also a more complex function. A 2D array of costs is built, with the points of the left epipolar line in abscissa and points of the right epipolar line in ordinate. Then, the algorithm computes the sequence of all best corresponding pairs, according to the costs previously calculated. For each path of this graph, a total cost is given by the sum of the costs of all the involved pairs. The path with the minimal total cost is computed using a dynamic programming method such as the Viterbi algorithm <FORNEY73>. At first, it was used in digital communication for messages recognition in a terminal, statistics...

Recently, applications extended to image processing, specially in stereomatching. Instead of comparing pixels of conjugate epipolar lines, more complex primitives can be used such as edges or blocks. A comparison with the least squares methods is with <BENARD86>.

1.2.6. Multi templet matching

The multi-templet matching has been developed in the Institute of Photogrammetry of EPF Lausanne. Initially this method was conceived for large scale photographs. This matching algorithm encompasses the determination of break lines, the approximation of the terrain by finite elements and the filtering of obstacles.

The first pass determines the characteristic image lines with a Sobel operator. As far as this detects also the edges of roof, roads or outlines of trees, an analysis is performed to select only the break lines in elevation. With image correlation, the creation of a DTM requires a mathematical function to be used as the interpolation surface that allows a rigorous control of the automatically derived height parallaxes. There, the use of finite elements is effective. The obtained lines are incorporated into an irregular grid composed of plane triangles. With the multi-templet matching, the parallaxes are determined for overlapping zones with a hierarchical approach, where the templates have a size that varies from 12x12 up to 400x400 pixels.

1.3. Specificity of the photogrammetrical applications

Photogrammetry is needful to compute epipolar lines or DTM but it is not necessary for all the applications that use correlation : robotics vision, character recognition...

Because of the need of accuracy in the determination of location, the resolution needs a high accuracy. The best photographic emulsions require longer exposure and this reduces the resolution because of the camera movement. Therefore it is useful to work at greater scale even if more images are required. The camera used is important <KOLBL86>.

From the beginning, photogrammetrists have been accustomed to a human operator and everything was set-up for that. Now that algorithms working on digital images are available, it seems that the required intrinsic properties of the images are not the same :

- the correlation works well along the limit of shaded areas where a human does not like to,
- noise or small periodic textures trouble the algorithms more than the operators...

The scanning is also an important stage for the digital images. The quality of the scanner itself and the pertinence of the way the calibration has been done for the scanning are fundamental elements that have been studied in many publications ; one can refers to <KOLBL94> and <SAUR95>.

2. Proposal for an evaluation process

2.1. Objectives of the evaluation

In a production context, a complete comparison of several algorithms should deal with the following aspects :

- time of computation,
- ease of use,
- quality of the results.

Considering the **time of computation**, only a real benchmark with the same images on one computer could give an idea of the time needed by the algorithms available. The Lausanne workshop should give some elements on this aspect even though the performances are often linked with the parameters given to the algorithms ; e.g. choice of the full resolution image or a lower level one, pre-processing such as epipolar resampling, post processing such as filtering artefacts... Besides this, the correlation process is sometimes organised to be batch-processed, so to optimise the CPU occupation during the day.

The **ease of use** is related to various things : quality of the user's manual, creation and storage of strategy for managing the correlation, limitation in the number of user's tasks, possibility of working and managing huge quantity of data... All these aspects basically deal with the relation between the client and the manufacturer, the reliability of the hardware and the software.

The **quality of the results** must be evaluated in regard to different types of landscapes to give a precise idea of the changes to be applied to the parameters.

☞ **Here, the choices of the areas and of the evaluation process are those made by IGN France in 1995. The aim is the contour lines production at 1: 25000 scale. They are described in <DUPERET95>. This preliminary study was made to evaluate correlation in the production environment ; both technical and economical aspects were evaluated.**

2.2. The evaluation process

The best method is to verify if the generated DTM allows the production of contour lines corresponding to the specifications of the database. From that point of view, the DTM is just a temporary set of data. The result is visually evaluated after the altitudes have been converted into contour lines and for a 3D check or compared to other sets of data. This approach is absolutely necessary for a local investigation of the work done.

In order to make a pre-evaluation, automatic tools may be very useful. The altitudes computed in the DTM are statistically compared to various sets of control points : TIN, DTM, manual measurements...

The following steps were used to organise the evaluation :

1. Scanning of the image : for the purpose of this benchmark, two different scanners were used ; the DSW200 of HELAVA (pixel size of 12,5µm) and the PS1 of ZEISS/INTERGRAPH. (pixel size of 15µm).
2. Inner and exterior orientations were computed by the specific module available in the photogrammetric software used (the ground coordinates are given from the IGN's triangulation program).
3. DTM computation by every software available ; the only constraint is a step of 5 meters for the DTM. Every kind of treatment is allowed : epipolar resampling, choice of level of imagery...
4. Statistical comparison of the DTM with files of control points. The control points are given in the DXF format and correspond to a BD TOPO® photogrammetric plotting of the following objects : contour lines and spot heights, roads, rivers and various limits on the ground (field limits, small walls...). For the results given afterwards, and as far as all the DTM are brought back on the IGN's workstation, the Quality Statistics module of SOCET SET® has been used. The followings indicators are computed : bias, rms and standard deviation errors.
   Additional regular and straight profiles were plotted to complete the control data.
5. Visual control of contour lines by 3D superimposition with the images.

2.3. The choice of areas

In considering the quality of the result, the choice of test areas has to be made carefully. Thus, in order to have the most exhaustive set of control points, the choice of the areas in France is made between existing data in the BD TOPO® made by IGN / France.

Here, for a first step, homogeneous landscapes were chosen in order to compare DTM in precise contexts. At first, the following **landscapes** have to be differentiated :

- free landscape, without any obstructions such as houses, trees... A more precise description should also take into account the nature of the vegetation in the fields ; e.g., cereal fields can generate shapes.
- hedge landscape, with isolated trees and various hedges.
- covered landscapes, such as forest and cities.

The **relief** might also modify the performance of the software, in relation to the slopes : flat, rolling and steep terrain. At last, the following areas were chosen.

1. **Reims** : flat and without trees, with good quality for images and control points.
2. **Agen :** rolling terrain with hedges of trees,
3. **Corbeil** : flat terrain with images of average quality.

2.4. Algorithm used

For this test, two algorithms are presented ; an experimental one made by IGN researchers (Jean Ducloux and Patrick Julien) and ATE (Automatic Terrain Extraction) of SOCET SET®. They are both performed by IGN operators, used to these algorithms which guarantees a relative optimal result.

Some other DTM are also available :

- Reims area : a DTM computed with the T10N algorithm by a MATRA CAP SYSTEMES operator,
- Reims area : a DTM computed with MATCH-T of INTERGRAPH with an ICC (Institute Cartography Catalonia) operator inBarcelone.

It will be interesting to see how the results can improve, by other computations made by different operators. Other results from different algorithms are also expected during the workshop in Lausanne (4-6 march 1996).

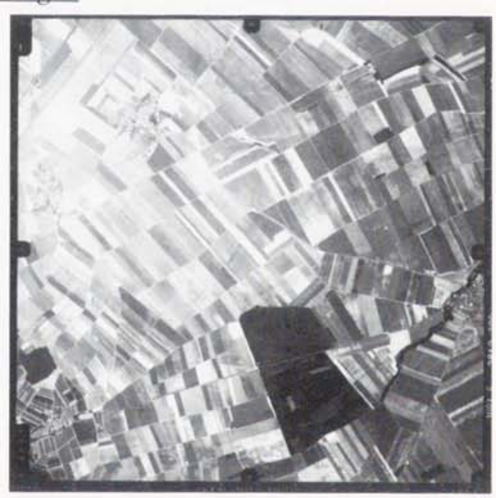
2.5. Reims area

2.5.1. Presentation

The scanning has been done both on the PS1 and the DSW200 scanners.

<u>aerial survey</u> : 1993 F 2812 300
<u>scale</u> : 1 : 30 000
<u>date</u> : 29 06 93 à 9 h 40,

<u>aerial camera</u> : RMK TOP 15
<u>photographic emulsion</u> : Aviphot 200
<u>images</u> : 17 - 19



2.5.2. STATISTICAL RESULTS

			Roads 1700 points		Rivers 60 points		Field limits 300 points	
Algorithm	Scanner	step (μm)	bias	rms	bias	rms	bias	rms
IGN	DSW200	25	0.23	**1.28**	0.46	**0.94**	**0.16**	2.04
ATE	PS1	15	-0.24	**1.76**	-0.15	**1.59**	**-0.73**	2.96
ATE+ edited	PS1	15	-0.12	**0.96**	0.06	**1.52**	**-0.10**	1.39
MATCH T	PS1	15	0.20	**1.52**	0.74	**1.02**	**0.13**	1.99
T10N	PS1	15	-0.40	**1.83**	-0.73	**2.24**	**-0.76**	2.83

			Spot heights 125 points		Profiles 1250 points		Contour lines 5500 points	
Algorithm	Scanner	step (μm)	bias	rms	bias	rms	bias	rms
IGN	DSW200	25	0.17	**0.63**	-0.20	**1.25**	**0.16**	0.72
ATE	PS1	15	-0.28	**0.66**	-0.56	**1.30**	**-0.27**	0.96
ATE+ edited	PS1	15	-0.32	**0.68**	-0.58	**1.35**	**-0.29**	0.89
MATCH T	PS1	15	0.16	**0.67**	-0.33	**2.78**	**-0.07**	2.53
T10N	PS1	15	-0.26	**0.82**	-0.41	**1.50**	**-0.21**	1.26

bias, rms and std of the DTM compared to the different groups of control points
elevation error = checked point elevation - DTM elevation.

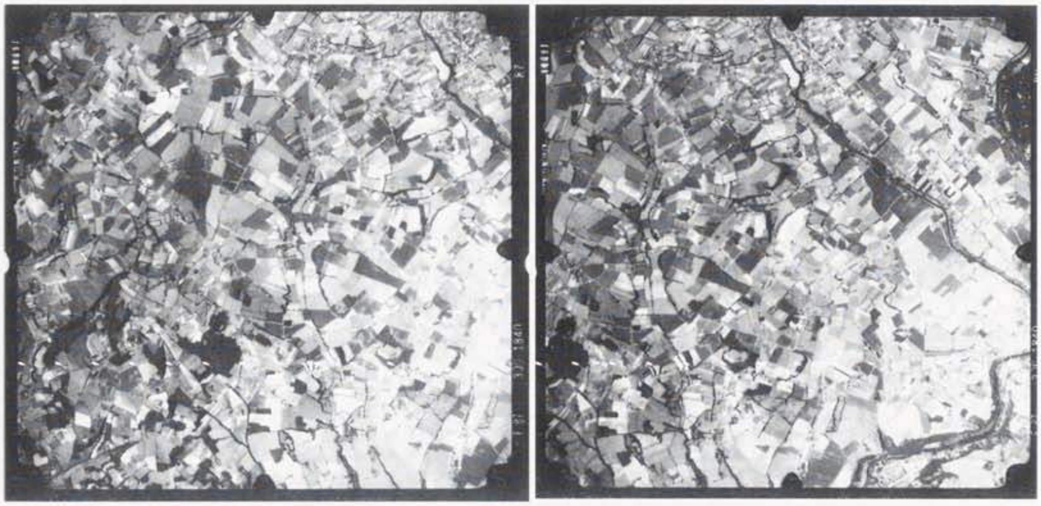
ATE+edited means that the DTM computed with ATE has been edited with correction tools (see chapter 3). The DTM computed with IGN's algorithm is already filtered. The other DTM were not edited and are directly issued from the correlation. With the DTM available now, only IGN and ATE algorithms give visually a smooth and satisfying result to produce contour lines at 1:25000 scale.

2.6. Agen area

2.6.1. Presentation

aerial survey : F 87 300 1840
scale : 1 : 30 000
date : 12 07 87, 10 h 45

aerial camera : RC10 1043
photographic emulsion : Aviphot 50
images : 87 - 89



2.6.2. Statistical results

			roads		rivers	
Algorithm	Scanner	step (μm)	bias	rms	bias	rms
IGN	DSW200	25	0.6	1.79	-0.35	1.61
ATE	DSW200	12.5	-0.92	1.86	-2.31	2.73

			spot heights		profiles		contour lines	
Algorithm	Scanner	step (μm)	bias	rms	bias	rms	bias	rms
IGN	DSW200	25	-0.22	0.87	-0.99	1.68	-0.78	1.67
ATE	DSW200	12.5	-0.93	1.52	-1.90	2.55	-1.66	2.23

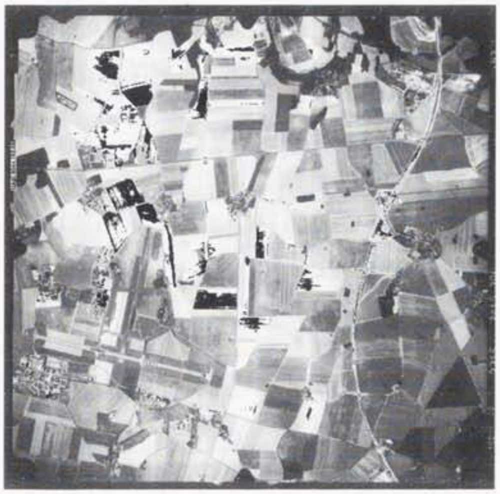
bias, rms and std of the DTM compared to the different groups of control points

2.7. Corbeil area

2.7.1. Presentation

aerial survey : 1992 FP 2315-2415
scale : 1 : 30 000
date : 28 07 92 à 10 h 25

aerial camera : RC10 6044
photographic emulsion : Aviphot 50
images : 153 - 155



2.7.2. Statistical results

			roads		rivers	
Algorithm	Scanner	step (μm)	bias	rms	bias	rms
IGN	DSW200	25	0.34	**1.73**	-0.29	**1.70**
IGN	DSW200	50	-0.89	**2.03**	-1.40	**2.17**
ATE	DSW200	12.5	-0.65	**1.85**	-1.41	**2.07**

			spot heights		profiles		contour lines	
Algorithm	Scanner	step (μm)	bias	rms	bias	rms	bias	rms
IGN	DSW200	25	-0.10	**1.01**	0.49	**0.99**	-0.58	**0.85**
ATE	DSW200	12.5	-1.05	**1.27**	-0.27	**1.01**	-1.06	**1.45**

bias, rms and std of the DTM compared to the different groups of control points

3. Transformation of the DTM

3.1. Data merge

3.1.1. The merge problem

As far as a DTM can be considered as an image, the tools commonly used in image processing for combining various informations can be applied to transform a DTM. The problem is to choose a good altitude between different sets of data, such as TIN (Triangular Irregular Network), DTM or profiles of various steps and accuracy. The theory offers different means to come to the correct decision such as the Bayesian decision, fuzzy sets, possibility theory, evidence theory. Those have been used in an industrial context for more than 20 years (measurements of pressure, temperature...). In image processing, it is happening progressively now, with an approach due to the specificity of the image : size, structure, various sensors.. <BLOCH> gives an interesting overview of the basic concepts.

In fact, the so-called *data merge* should be reserved for a simultaneous use of heterogeneous images tending to help the process of a unique decision ; in our case, the aim is to choose a correct altitude when different sets of elevations are available.

In a few words, here is exposed what should be the full process leading to the choice or decision of an appropriate altitude within a set of data of different origins:

1. geometrical merge : this step aims at the superimposition of all the sets of altitudes, according to an absolute geographical reference. This functionality seems to be correctly provided by numbers of softwares, according to the users' needs. For other purposes than aerial imagery, a lot of techniques are used. <MAIT91> gives a wide survey of what can be done in spatial, aerial and medical imagery. It often requires a resampling leading to an incertitude that needs to be carried out until the decision is made.
2. merge models : the general situation corresponds to l images (or DTM) representing heterogeneous data. Then you need to make a decision referring to the element x that can be a pixel (or an altitude) or a more complex object coming from the image. Referring to the space of decision $D =\{C1,C2, ..Cn)$ (this can be an altimetric interval), the problem is to affect a value Ci to x. The decision is taken by considering the measures $M_i^J(x)$given by the informations available in the image Ij on the potential decision Ci for x. These measures depend on theory used for the merge process.

	I1	I2	...	Il
C1	M_1^1	M_1^2		M_1^l
C2	M_2^1	M_2^2		M_2^l
...	...	...	...	...
Cn	M_n^1	M_n^2	...	M_n^l

measures from the l images relatives to the n classes

- the ideal way to choose is called the <u>global merge</u> ; the decision is made by taking into account the $(M_i^j(x))$ matrix for all images and decisions. Unfortunately, this model is hard to implement.
- the second way is to make a primary decision $d(j) \in D$ for the Ij image from all the measures made on it. This could be called the decentralised images' merge. In a second step, a final decision on x is made by using all the primary decisions. Practically, this model is necessary when the images are not simultaneously available. This model does not really care about the links that may exist between the different sensors and the possible correlation that might exist between the images ; in addition, the user will probably have to manage conflicts such as $d(j) \neq d(i)$ *for* $j \neq i$.
- the third model, orthogonal to the previous one, consists in combining all the measures in relation to the *Ci* decision from all the images to generate a new *Mi* measure. Then, a decision is made out of this combination. Therefore, just as in the first model, this is a centralised one that requires simultaneously all the images. Rather easy to be used, this model is not appropriate if a new sensor must be added during the process.
- The last model might be called the hybrid one. It consists in choosing the useful informations for a given problem taking into account the specificity of the images. This copies the human expert's process.

3.1.2. The Shannon theory

What is the amount of information due to a new image (or DTM) I_{l+1} to the available set $\{I_1, I_2 ... I_l\}$? Shannon has fixed the basis of the theory of information. The entropy characterises the information contained in the available data. For the l first images, this function is defined by

$$H(I_1,...I_l) = -\sum p(I_1,...I_l)\log p(I_1,...I_l)$$

and the entropy brought by the $l+1^{th}$ image is

$$H(I_{l+1}\, I_1,...I_l) = H(I_1,...I_{l+1}) - H(I_1,...I_l) = -\sum p(I_1,...I_l)\log p(I_1,...I_l)$$

The redundancy between two images is defined by

$$R(I_1, I_2) = H(I_1) + H(I_2) - H(I_1, I_2)$$

The complementarity between two images is defined by $C(I_1, I_2) = H(I_1, I_2)$.

Therefore, this leads to $H(I_1) = R(I_1, I_2) + C(I_1, I_2)$.

Highly redundant images will be used to confirm an doubtful decision and as complementary images to widen the decisional set.

3.1.3. Modelisation

At first, one must be aware of the difference between the two following notions : imprecision and incertitude. Those terms must not be confused. The precision of the information deals with the quantitative evaluation of its value ; the certitude is linked with the veracity of the information.

i.e. : « this is tall » is imprecise;
« you'll get this letter tomorrow » is uncertain,
« it will rain a lot » is uncertain and imprecise.

It is fairly necessary to deal with them. They are always present, according to the reality or to the processes performed on the data. Imprecision and incertitude can be antagonistic and one must explicitly deal with both ; otherwise, there is a risk of incoherence.

The different theories to manage with these notions are : the probabilistic or Bayesian model, the fuzzy sets and the beliefs theory of Dempster and Shafer. They allow one to organise the necessary steps that leads to the decision :

1. ***the modelisation*** creates a mathematical representation of the information contained in the DTM or images.
2. ***the combination*** uses the rules specific to the type of model to merge the data.

3.1.4. Merge : state of the art

At the present moment, the photogrammetrical manufacturers have implemented a few functionalities that do not seem to follow theoretical models. These are rather interpolation tools than mathematical models to merge altitudes. The following functionalities are sometimes available :

- merge of several DTM, but with an exclusive precedence according to the post spacing, the order they are given with or another information linked to the altitude such as a correlation coefficient... An additive treatment can be performed to smooth each side of a DTM's boundary concerned by the overlap area frontier.
- merge a DTM with elevations from a TIN of different classes of objects. Each one of them can be attached to a kind of profile (that will be restored in the DTM after resetting the elevations) inside a region defined by the posts of DTM within a distance (entered by the user) from the delineation axis. The imposed terrain profiles can be U or V shaped, linear or bulldozer.

To be fully efficient, these functionalities should be attached not only to an entire class but also to the user's designed objects ; furthermore , the distance selected by the user should not be unique for all the classes to improve the merge. The merge is naturally performed after the correlation pass. It is also interesting to give these TIN as a constraint during the correlation.

3.2. Editing a DTM

In an industrial context, edition is a critical task. It requires an operator used to image processing. The variety of landscapes or relief generate various kind of surfaces for the DTM. If the proper treatments are not used, this can easily lead to a loss of time, especially if an improper set up of displaying the DTM is used.

3.2.1. Representation of a DTM

a. Generalities

Various kinds of set up can be used to draw a DTM. There is no ideal way of displaying. It depends also on the purpose for which the data are made and of the hardware available. 3D vision is probably necessary, and it can be performed either on a 2D or 3D screen. In the last case, one can use a stereoscope and be able to display two images at the same time, positioned as in a stereogram.

b. Representations of elevations

These representations can be superimposed on the images. This helps to check the DTM's quality.

- the contour lines give the idea of the global shape of the relief, but only where they are localised. No information is known between them. Their shape depends on the kind of resampling algorithm used and on the post spacing of the DTM.
- regular networks of dots or various icons can give the idea of the shape of the DTM if they are superimposed on the images in a 3D mode.

c. Representations of extracted informations

- a shaded representation gives the idea of the texture of the surface in the DTM. This is very useful to evaluate the quality of the elevations and give an exhaustive overview of the surface.
- various types of informations can be displayed, such as the correlation value...

3.2.2. Post edition

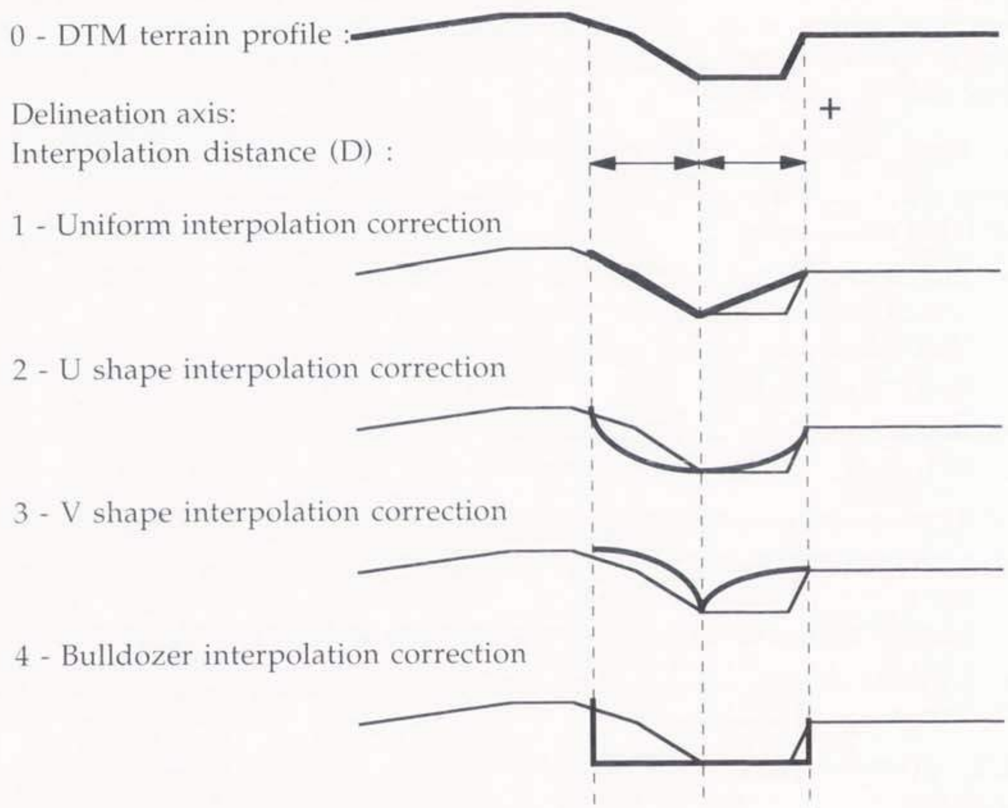
An interactive post edition shows the values of the elevation and various informations given by the correlation. Then, it is possible to adjust them by manual measures moving the floating mark.

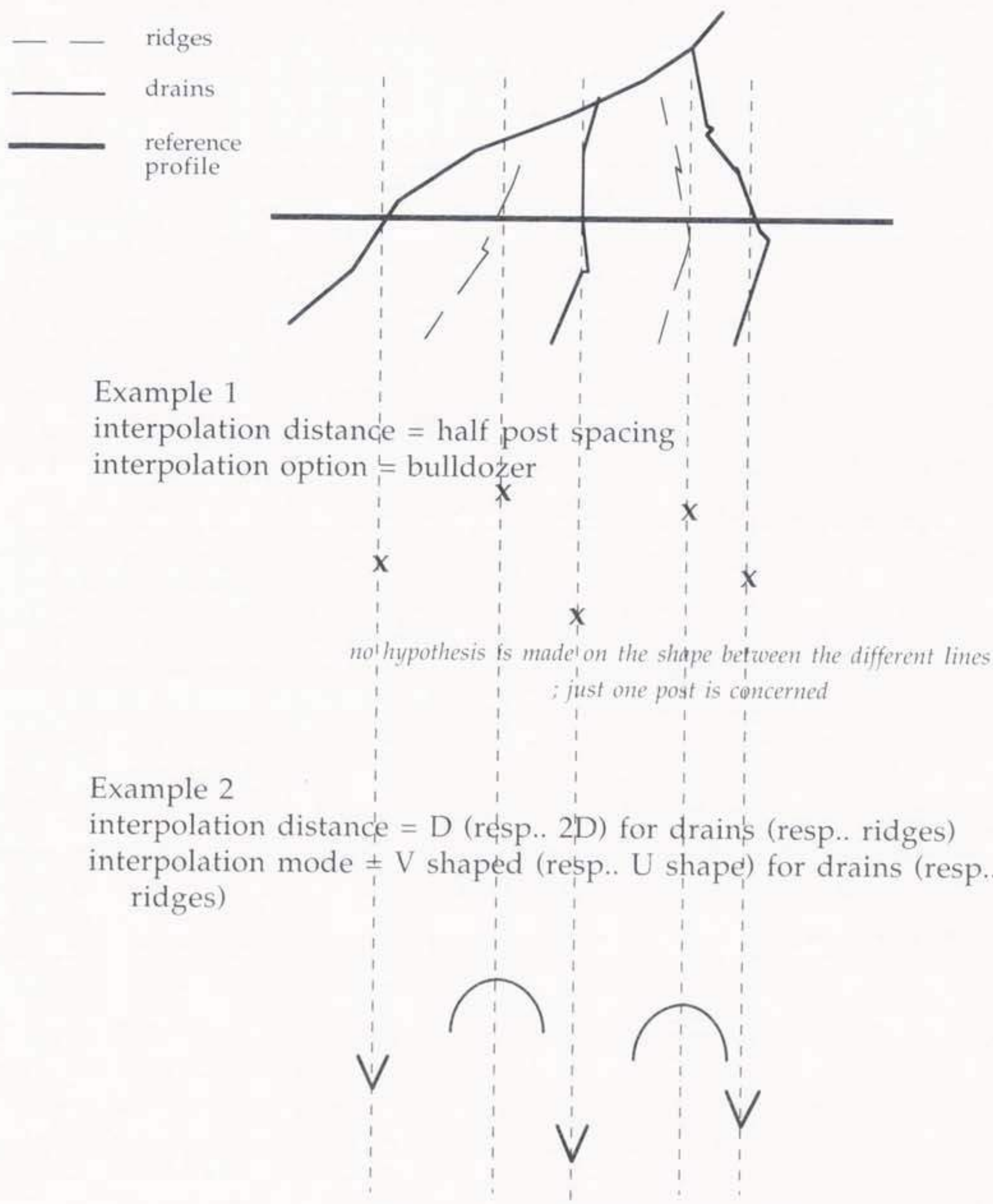
According to the correlation, over ground details often generate shapes, that are neither similar to the detail's shape, nor on the ground, but in both cases, they involve a group of posts. With a post editor, it would become necessary to modify a lot of data and the use of a post editor leads to a loss of time. Therefore, this kind of edition is rather recommended for showing values rather than modifying them.

3.2.3. Linear edition

A linear editor is useful for various purposes :

- **removing artefacts** such as hedges or anything leaving a linear signature in a DTM. The user shows the axis in the DTM of the shape that has to be removed. In a DTM, such a tool resets the elevations closer than an interpolation distance D from a delineation (both indicated by the operator). 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 and Bulldozer option





*nothing makes sure that D or 2D is well chosen.
Elevations are not known between those segments of profiles (they could also overlap). The surface is known with more points than in example 1 but this added information is not reliable.*

- **caricaturing the DTM**, to improve the relief modelling, that is often smoothed by the correlation. In that case, the user forces DTM to conform to break lines. The same options as above are available. The problem encountered here is that ridges and drains do not necessarily have the same width or profile along their axis. The best way here is to indicate the axis with an interpolation distance that is small enough (i.e. half of the post spacing) to make sure that the area composed by the drain axis and the interpolation is reduced to a single post large line. The bulldozer option is recommended here. In this way, no option is made on the shape around the drain. An area editor has then to be used to create the surface. If the elevations are dense enough and the gap between them not too large, then a correct interpolation will work (see area edition). Otherwise, with an interpolation distance greater than half of the post spacing, the surface will be partially rebuilt, with forced shaped areas and with unknown areas. The result will be incomplete and not smooth.

3.2.4. Area edition

An area editor is necessary to change all posts within an area delineated by a polygon. The most useful tools to remove artefacts from the correlation, and to modify the surface are described below.

1. **Smoothing convolution :** whatever the window's size is, it is convenient to remove or to reduce noise from the elevation data ; the smoothing effect increases with the size of the window.
2. **Interpolation from a 2D polygon :** when a small artefact or obstruction is surrounded by correct elevations in the DTM, it is helpful to use an algorithm that interpolates from posts just outside the polygon perimeter. The area delineation does not have to lie exactly on the ground.
3. **Interpolation from a 3D polygon :** useful to remove artefacts or to fill-in obscured areas (clouds, shaded parts...). The posts within the area are filled by smooth interpolating from the perimeter delineation. The effect of smoothing can vary with the kind of algorithm used for the interpolation.
4. **Interpolation under constraints** : sometimes, it is helpful to interpolate from a 3D polygon, by taking into account a set of inside elevations, for example marked with a specified flag (e.g. manually measured, high correlation...). All the elevations that are not marked are interpolated from the TIN composed of points of the external polygon and those with the correct flag. This kind of tool is useful to give constraints along the ridges and drains. It is necessary to control the degree of interpolation inside the area.
5. **Segmentation :** to divide the working area into parts is often useful, especially when one has to surround places where correlation is not needed or obviously bad (sea, snow, outside boundary...). If this is used

before correlation is performed, the time of computation is reduced. Otherwise, it is useful to reduce the amount of data or to optimise the post treatments applied after the correlation that might be disturbed by wrong elevation : terrain shading, contour lines resampling...

6. **Plane fill :** whether horizontal or not, and according to the scale or the result needed, it is often useful to set all the posts within an area to lie on a plane whose delineation is given in 3D by the operator. The option of feathering the outside edge of the area to the surrounding reduces the noise along the delineation.
7. **Constant fill :** inside a polygon, 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.
8. **Bias :** the possibility of adding a constant to all the elevations inside a given polygon might be useful to remove over-ground obstructions such as canopies or huge buildings.
9. **Filtering the DTM:** by giving a height and a width, the operator parameterises the filtering that removes all the objects by specifying the values. This is useful to remove trees, hedges and houses.
10. **Filtering the data :** considering the neighbourhood of an elevation, a number of DTM posts gives a redundant information about the surface. A useful criteria to mark or not a point as redundant is the rms error of the planarity within the DTM. If a region is plane within the threshold given by the operator, then the centred post is flagged as redundant and will not be used during posterior treatment, such as resampling or exporting.

4. Conclusion

The conclusion here concerns contour lines production for the BD TOPO® by using black and white images at 1:30 000 scale with SOCET SET ®.

4.1. Performances and using

The generated DTM had a step of 5 meters, leading to a maximum of 500 x 1000 posts for a simple model. The full resolution images had a size 350 Mbytes (12,5 µm) or 250 Mbytes (15µm). This required a space disk of about 1 Gbyte/model. The experimental IGN algorithm was running on a 20 MIPS computer and needed from 4 to 8 hours. ATE was performed on a 130 MIPS computer and needed up to 2 or 3 hours of computation.

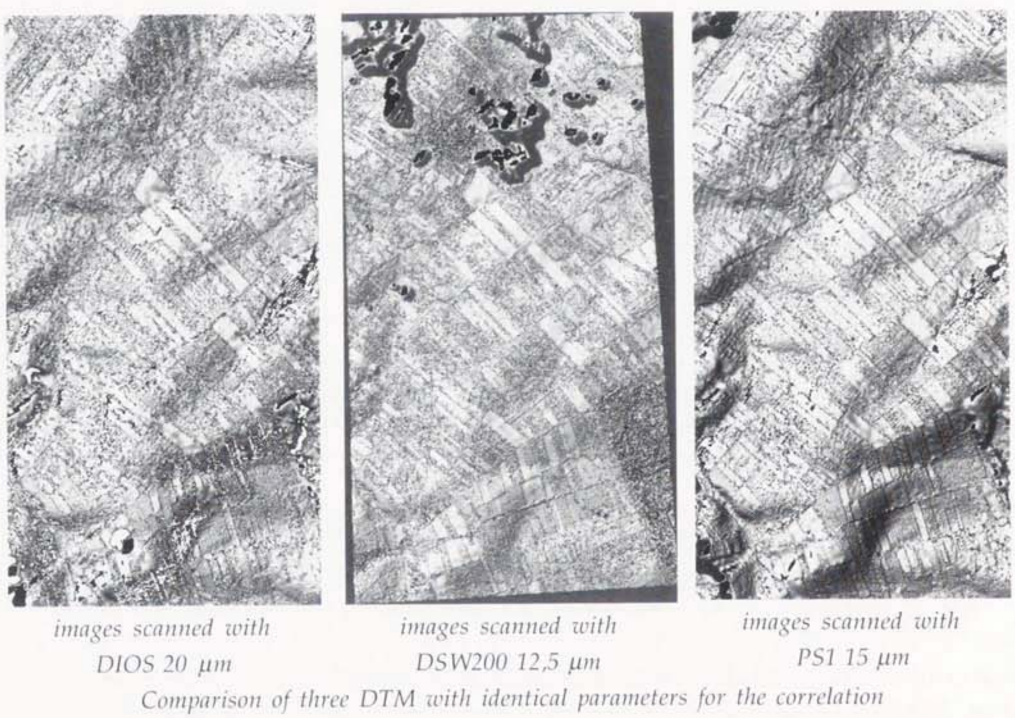
For both, an operator expert is required to perform the computation and edition. To reduce problems along the overlap areas between models, several DTM can be merged together (more than ten).

4.2. The pre-correlation elements

The aerial camera might affect the quality of the images. On the tests made above, there is nothing to prove that the compensation of movement of the camera is giving a real improvement to the quality of the correlation, even if Reims looks better ; the intrinsic quality of the reference data could just make that difference. The IGN's aerial department links the choice of the camera with the photographic emulsion : RMKTOP with Aviphot 200, RC30 or 10 with Aviphot 50. Nevertheless, these choices have been made out of a long experience to satisfy the specifications required for the databases, made with manual plotting. At present, the plotting with the digital workstations is based on manual measurements. As far as the correlation for surface determination is not the basic tool of the plotting process, these elements must be considered as a constraint.

The intrinsic properties of the analogic photography are also relevant to the atmospheric conditions during the flight. The smaller the diffusion effects are, the shorter the aperture time is. The shorter the time elapsed between the successive images is and the better will be the aptitude of the image to describe the ground contrasts, so needful for the correlation.

Both the used scanners (DSW200 and PS1) have given similar results, according to the control methods chosen. The **geometric accuracy** must not be altered by the scanning, but this is quickly checked with the inner orientation. The **radiometric** accuracy depends not only on the scanner but also on the operator who has to optimise the calibration with the images to perform a good rendering of the contrast. On the image used, the processes of correlation have given equivalent results on 12.5, 25 or 30 µm. The quality of the DTM decreases with scanning steps of 50 µm or more.



images scanned with DIOS 20 µm — *images scanned with DSW200 12,5 µm* — *images scanned with PS1 15 µm*

Comparison of three DTM with identical parameters for the correlation

4.3. Correlation algorithm

The IGN and HELAVA tested algorithms have given similar results (the other tests on Reims did not look good enough to be edited for the purpose of contour lines product). The differences are tiny, and can often be quickly corrected by editing tools. The differences occur specially when the images have a poor radiometry. In the IGN's production context, this is hardly ever the case but it might become preponderant for a private company that deals with images made with various types of sensors.

The opportunity of storing the parameters in user-defined strategy allows an optimal preparation of the work before the correlation. But nowadays, the manual prepared by the manufacturer does not give this opportunity nor does it help the operators to modify the contents of the strategy. This requires operators used to image processing. A direct algorithm requires less parameters from the operator than the hierarchical algorithms. Whatever the choice is, it is necessary to give the operator the opportunity of modifying the behaviour of the algorithm to adapt it to the quality of the images and to the expected result.

A quick statistical method to study the quality of the image should help to optimise the parameters.

4.4. Evaluation of the quality of the DTM

By taking into account only the two areas of Reims and Corbeil with the number of points of each set of data and with only the spot heights and the profiles like reference data, the global **statistical result** can be resumed to :

	rms/spot heights	rms/profiles	global rms
IGN	0.81	1.17	1.15
ATE	0.99	1.22	1.21

One has to be careful when using control data in altimetry. Here, except for the profiles, the reference data came from an analytical plotter. The type of measurement also seems to have an important effect. The static measurement is always better (spot heights) than the dynamic measurement. In this last case, the data seem more reliable when the operator makes better measurements for objects that present a good contrast with their neighbourhood (roads). As far as it is also the case for correlation algorithms, it is normal to find good statistics on such points. In addition, it also seems that the manual measurements are better when the operator chooses his points himself, even in a dynamic mode (contour lines), rather than when he is constrained to follow a profile for which the altimetric position has to be all the time adapted.

The **visual control** of the data was done by superimposition of the contour lines (directly derived from the DTM) on the images. The following facts appear on the tests made :

- the DTM made by correlation appear to be over the ground
- the ground obstructions such as trees or buildings can easily be removed when isolated. When their dimensions exceed about a hundred meters, it is necessary to perform an additional plotting, unless the destination of the data does not require a great accuracy.
- the data merging function allows the creation of DTM that describe properly the surface and the objects on it.
- the editing functions are absolutely necessary to transform the surface's DTM. The correlation brings a good description of the ground surface but cannot take account of the artefacts due to the bad correspondence conditions that may occur between the two images : variations in photometry (specular reflectance), objects movements, obstruction (clouds, shading...), influence of the atmosphere and of the meteorology (wind...).

A complementary study has been done to compare the contour lines plotted by two different operators. Compared to a first manual plotting, the rms of the second manual plotting is even a little bit higher (1.1 m.) than for the two DTM (0.72 and 0.83 m.). The visual control shows that the contour lines automatically plotted might look slightly smoother than the others, especially along the break lines ; one has to remember only that the differences between several operators are located there also.

In conclusion, when the landscape contains just some ground obstructions, the correlation might help the operator by giving good quality contour lines. With edition tools such as described above, artefacts can be removed. At that stage, it is **technically** reliable.

Now, the **economical** aspect must be evaluated, according to the production context. The DTM's edition is probably the critical task. For the IGN production of contour lines, less than one hour for an easy model and two hours in the case of a hard one should be spent. At last, with counting the CPU cost and all the time spent in pre and post processes, the aim is to divide by two the cost of the contour lines' plotting. If the tests done at the moment confirm the reliability of these algorithms (IGN or SOCET SET®), IGN should begin to produce contour lines at the end of the year 1996

4.5. DTM TRANSFORMATION

A complete toolbox for edition is essential. The present experience of IGN tends to the following post-correlation process :

1. Removing the artefacts by using the interpolation and plane fill tools
2. Merge of add-on profiles with reliable elevations, such as road or field delineation, obtained during the manual measurement of the planimetry,
3. Complete manually the altimetric measurement for any place where no correlation was efficiently processed (islands, wood, cities...)
4. Modification or addition of break lines, to obtain nice contour lines, starting with the upper part,
5. Global smoothing, to have a homogenous rendering.

These are only some recommendations. It is up to the user to decide what he wants to perform. At the moment, experimentation tries to evaluate the ratio quality/cost of all these steps, to determine the optimal process.

An IGN made process, called the **cartographical smoothing** is also tested now. The determination of the break lines is done automatically in the DTM, so as to give a constraint to a specific smoothing process. The result gives very smooth contour lines, without any modification along the break lines.

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Discussion after the Conference:
Automatic Derivation of a DTM to Produce Contour Lines,
by A. Dupéret

Quessette:
As a service company, I am very happy to say that even when we are talking about DTM, we are talking about automatic DTM and I could not help, but presume that there is still a lot of manpower necessary. In a way, this is also good for our service company.

Dupéret:
In fact, we initially could not imagine having a fully automatic process. The operator's job now is so different from what he used to do. He is now working with raster data, but he still sees contour lines in vector form. If he wants to move them, he has to keep in mind that inside the polygon drawn for an edition operation, an interpolation algorithm is performed on the posts of a regular grid. This transition period is not easy for the operator and to explain to him takes time.

Adam-Guillaume:
I think it also depends on what kind of DTM you want; you can have a nice and smooth DTM, or a DTM including buildings to generate the orthophotos. You can afford to leave some noise if you want an ortho image, but if you want a good DTM, it is definitely laborious.

Dupéret:
Let me tell you, we do not intend to work on hard landscapes, we leave these areas out if it is too hard. We will still continue doing manual plotting and we definitely need more experience before the operator can start working on harder things. Many people now often ask for contour lines and DTM data as well, so it is almost inevitable that we will have to manage two jobs very soon, perhaps we need two DTMs.

Experiences with MATCH-T for Orthophoto Production

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1. Introduction

The aim of this paper is to describe the practical experiences of the ICC with MATCH-T (Ackermann 91) in a production environment.

MATCH-T generates a regular mesh of points from a stereoscopic pair of oriented photographs. The process is split into two parts:
a) the extraction of interest points.
b) the matching of these points and the surface reconstruction by finite elements.
All processes are carried out by iterating on different levels of image and DTM pyramids.

Since late 1994 we have been using MATCH-T to produce the DTM for three orthophotomapping projects.

Project	Map scale	Image scale	Surface (Ha)
Venezuela (color)	1:25,000	1:60,000	1,000,000
Medea (B&W)	1:25,000	1:60,000	570,000
Asturies (color)	1:20,000	1:60,000	425,000

2. MATCH-T DTM

Image matching with a stereopair is an ill-posed problem. It can be solved only through regularization, assuming that the DTM is smooth almost everywhere. MATCH-T (Krzystek 92) uses a constant step grid to:

- Regularize the equations' system.
- Guide the matching of interest points.
- Remove the wrong matches.

A grid DTM with bilinear interpolation is a smooth representation of the topographic surface. With this model it is difficult to represent geomorphological characteristics. MATCH-T tries still to get smoother models by applying conditions over the second differences by columns and rows and conditions over the cross derivative. These smoothing conditions enter to the linear equations system as observations instead of entering as constraints. Since a robust adjustment is performed, the observations that are not compatible enough with the current surface are removed.

Breaklines can be entered but they are not rigorously included into the model that MATCH-T uses in the search of matching pairs. We found that the effect of breaklines is too local.

3. MATCH-T workflow

The general workflow is:

1.- Epipolar sampling and image pyramids at 15 microns (level 0).

2.- MATCH-T first run at the first level of the pyramid (30 microns).

Only default parameters for fiat, hilly or mountainous terrain are used. The grid spacing for the aforementioned projects was 30x30 meters. The output is a graphic file with the grid points.

3.- Quality control and editing procedure. It is based on the revision of the output results by operators.

4.- Triangulation of the complete set of elevation points and conversion into grid format.

5.- Insertion into a DTM database. Quality control is done before the insertion with the help of statistical and visual tools (ie: hypsometric representation and shading).

MATCH-T and the editing and revision processes run in an Imagestation 6887 with a 4 GB disk.

The following table shows the timing for each MATCH-T step:

	Batch time (minutes)	Interactive time (minutes)
Epipolar sampling	45	0
MATCH-T 1st run	35	0
QC and edition	0	90

Since the two first steps are not interactive, the whole MATCH-T process takes 90 minutes of interactive work. The compilation of profiles and breaklines of the same area would take up to 10 hours.

4. Quality control and editing procedures

General considerations

From our experience, surfaces generated by MATCH-T are almost everywhere correct except from certain areas where the surface does not fit properly.

- Geomorphological characteristics are filtered out by the robust estimation process because they are considered as blunder errors.

- Areas with low redundancy are those where the program has not been able to match enough points, due to low texture or because matched pairs were not compatible with the surface achieved before. In these areas the model turns flat because of the smoothing conditions prevail.

Fail-prone areas are:

- Ravines and ridges: where the slope is discontinuous.
- Valleys and slopes surrounded by forests or by very poor textured areas.
- Linear man-made features (ie: roads) that could cause distortions in the orthophoto.
- Other very poor textured areas.

We can distinguish two aspects in quality control: accuracy control and blunder error detection.

Accuracy estimates can be given through the measurement of control points. These estimates do not provide any information about blunder errors that must be detected with redundant observations. As it has been said before, image matching is an ill-posed problem and observations are not redundant at all. Also, accuracy estimates are not reliable if blunder errors have not been previously detected and removed.

MATCH-T provides internal quality estimates that are not reliable enough to guide the edition process. We have found that redundancy figures are the most useful information in editing time. Any additional point measured in low redundancy areas is an important observation for a next run of MATCH-T.

We have done some quality control tests using the image of differences between the two orthophotos that can be rectified from a stereopair: one orthophoto generated from the left image and the other from the right one (Heipke 1993). Only big errors are detected and there are many false errors, mainly due to the different occluded areas that appear in each orthophoto. This image of differences provides a mean to detect at a glance many outliers of the model -blunders-, but it is difficult to convert this image of differences into numerical estimations.

After these considerations and some tests performed in controlled areas with many check points, it was decided that a systematic external control was needed. Now it is carried out only through operator inspection.

The quality control and editing process

- The early 94 workflow was based on:
- Terrain type parameters: Flat, hilly or mountainous.
- Adding measured points close to the incorrect grid points after the first run of MATCH-T.
- MATCH-T 2nd run at first pyramid level with the measured points included as mass points.

The number of points added per model was over 2,500 and the editing process took from 2.5 to 3 hours.

After some tests we decided to modify the editing process to reduce the number of points measured and the time needed for the revision. Only two types of terrain setup are chosen:

- Mountainous in case of terrain type hilly or mountainous.
- Flat otherwise.

This setup reduces the number of low redundancy points. For example, in a specific mountainous area from Venezuela the results obtained were:

Terrain type setup	High redundancy grid points	Low redundancy grid points
Hilly	45348	17503
Mountainous	54895	7956

After the first run of MATCH-T, depending on the results of the visual inspection, the operator decides:

- Edit MATCH-T points

or

- Define obscure areas and measure new points inside. Collect breaklines if needed. Run MATCH-T again.

With this workflow the quality control and editing time have been slown down to 1.5 hours.

It is very important to work with good quality images, otherwise the matching processes will fail and the edition time will drastically increase (the standard editing time increases more than twice)

Where to place mass points and breaklines?

Breaklines are added in:

- Valleys and slopes. When these features are surrounded by forests or by very poor textured areas we measure additional points, otherwise the second run is not useful to improve the results.
- Linear man-made features that could cause orthophoto distortions.

Points are added in:

- Very poor textured areas. Without these points the resulting surface is a plane or has plenty of outliers.

5. MATCH-T new features

From the August´95 release there are some new features that improve the MATCH-T surface reconstruction process and that make easier the quality control process. The most useful features are:

• Better handling of collected breaklines: There is no limit in the number of breaklines that MATCH-T can handle. Also, there is the possibility of removing the points within a user-defined buffer along the breaklines.

• Better integration with other Intergraph software, mostly with the one that helps to edit the grid and to collect a new one (ISDC).

• Integration of the final step that writes the points in the file. In previous releases it was necessary to enter into the Design Graphic File (DGN) and to recover the information from the raster result files. In the current release it is possible to send all the process together.

6. Remarks and conclusions

Up to now, we have used the DTM delivered by MATCH-T only for orthophoto production purposes.

We have found that even with the addition of some breaklines it is difficult to obtain cartographic- quality contours, but more tests should be done to use MATCH-T for contouring purposes.

Output statistical results are not helpful enough, since they do not correspond with the visual inspection, except the redundancy figure of each patch.

After some tests it was decided to stop the MATCH-T process at level 1 of the pyramid (Colomina 95). For the projects in which we have been working, stopping at 30 microns was a tradeoff between accuracy and throughput.

7. References

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Heipke C., 1993. Performance and state-of-the-art of digital stereo processing. In: Fritsch D., Hobbie D. (eds), "Photogrammetric Week'93". Wichmann.

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Discussion after the Conference:

Experiences with Match-T for Orthophoto Production,
by M. Torre

Becker:
I have a question concerning the DTMs as for the ridges between the adjacent models. Are you sure that the software you are using takes into account earth curvature? Because I have seen similar results as you showed if earth curvature is not included.

Torre:
We are always careful about the overlapping area. It is mandatory that we follow strict measures to ensure good continuity in the orthophotos, for example, we always introduce into the Match-T a security boundary in order to avoid problems. In addition, when we edit, we also use the adjacent model as a reference model and if it is not satisfying enough, we add more points.

Haumann:
You said that there were more than 50'000 points used, to which area do you refer? Because this would correspond to a point in every millimeter of the photograph, which seems to me is highly redundant.

Torre:
Yes, it is true that we collect many, many points.

SOME CONSIDERATIONS ABOUT FEATURE MATCHING FOR THE AUTOMATIC GENERATION OF DIGITAL ELEVATION MODELS

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ABSTRACT

The paper refers to the MATCH–T system for automatic generation of digital elevation models by digital image processing and reviews some general items, like feature matching and redundant data capture. The resulting accuracy and system performance is sketched. Also some problem areas are pointed out because of which interactive editing is a necessary and essential part of any automatic DTM system. The basic limitation of dense vegetation cover can only be overcome by a multi– sensor approach.

1. INTRODUCTION

This short presentation is confined to submitting some deliberations and background considerations about the automatic generation of digital terrain (elevation) models (DTM) by digital image processing. The considerations are based on the concept of and some experience with the MATCH–T program of INPHO company which represents some of the features to be discussed. But the implications are of a more general nature and concern partly other systems, too.

The **MATCH–T** program (Ackermann, Krzystek, 1995) operates with pairs of digital images the orientation of which is supposed to have been established. The basic procedural steps are quickly listed: First the photo–pairs are normalized (on the basis of the given orientation parameters), in order to subsequently exploit the epipolar geometry. **Image pyramids** are formed, with 8 or 9 levels, together with complete feature extraction and feature pyramids. The basic feature extraction, on all levels, utilizes the (1 D modification of the) Förstner operator. On each level **feature matching** is performed, made efficient by epipolar constraints and bounded search spaces. The matched image points are processed analytically to 3D model (terrain) points, from which a **finite element fitting** is derived, in tiles, representing the respective DTM. Each level of the feature pyramid gives a better approximation to the final DTM, see Fig.1. As initial approximation a horizontal plane is sufficient to start from. The final DTM is edited as a **rectangular grid**, defined by the finite elements. Normally, an **interactive editing** phase concludes the DTM generation.

The method is originally based on the assumption of smooth terrain. **Refinements** are introduced by additional break lines (and excluded areas) which are pre–determined interactively on the image station. The feature matching can, optionally, be supplemented by least squares matching. A characteristic item of the system is **high redundancy**. Normally more than 100 times more terrain points are captured than in conventional analytical DTM capture. Nevertheless, the system is programmed to be fast, resulting in economy and accuracy.

2. DISCUSSION OF SOME KEY ITEMS

2.1 When evaluating resp. characterizing a method a clear distinction has to be made between general **system** considerations about approach and principles and between the actual **realisation** in a computer program and its possibly interactive working functionalities. Here, we only consider the general aspects of the MATCH–T system, some of which refer to other systems as well.

2.2 When DTM methods are discussed the applied **matching method** usually receives prime attention. It is true that there are considerable differences between feature matching and area matching. And each approach has certain consequences for the system and its performance. It is well known that pairwise matching gives parallax accuracy in the order of 0.3 – 0.4 pixel for feature matching resp. of 0.1 – 0.2 pixel for area matching. Feature extraction and matching, especially the 1 D version, is quite robust and requires less close approximations. Also, it is quite fast. Area matches on the other hand require locally flat areas, a condition which has to be checked in each case. Also, they have a small convergence radius, and the computation is more elaborate. However, the question loses importance, as DTM programs can have **options** with 2 or more implemented matching methods. The MATCH–T program, for instance, still operates basically with feature matching, but has the option for least squares matching. The option may be used in case the accuracy of individual points is essential.

With the MATCH–T system normally feature points are extracted at an average distance of about 10 pixel, and the DTM grid width is in the order of 30 pixel. Accordingly, with 20 μm pixel size for instance, at least 600000 terrain points are measured per stereo–pair and the edited DTM would have about 70000 grid points per stereo–pair. It means that the derived **DTM grid** is **more dense** than conventionally interpolated DTM grids.

2.3 The above figures mark a fundamental difference against **conventional** analytical **data capture** for DTMs. In a stereo–model normally between 2000 and 10000 DTM points used to be measured. The DTM grid derived by interpolation would be denser by a (linear) factor of 2 or 3, resulting in perhaps 20000 or 30000 grid points per stereo–model. The actual parameters always depend, of course, on the type of terrain and on the specifications for the DTM. The implicit philosophy has been that for economic reasons as few points as possible were to be measured which would suffice to meet the given specifications. That implies that the measured points had to be placed well in order to sufficiently represent the terrain, which in turn required human insight and intelligence to a certain degree. It also means that the final grid is derived by **interpolation** between the captured data points. The same philosophy also explains why in conventional practice **many break lines** were measured, as they represent a highly effective catching method, with relatively few points. Often more than 50 % of the DTM data capture used to be break line points.

The philosophy for **automatic data capture** is entirely different. The measurements are made blindly, not guided by insight nor specific intelligence. Instead, the principle of **redundancy** is applied, as 100 or 200 times more points than conventionally are measured, see Fig.2. One can say again (as in the case of automatic aerial triangulation) that intelligent setting of points is replaced by redundant capture of points. The idea is that an algorithmic approach with sufficient redundancy to allow subsequent data analysis can produce similar results as were conventionally obtained by a skilled human operator. One could also say that in the automated data capture the individual point means nothing, in favour of a cloud of points.

The high redundancy of the automatic data capture has a number of far reaching **consequences** (see Fig.2 and Fig.3):
- The DTM moves from interpolation to adjustment. A grid mesh now may contain 10 or more observed points. The result is that the derived DTM, realized in the (smaller) finite elements, is **more accurate** than the individual point, and it is considerably more accurate than previously the interpolated DTM, where grid meshes could easily contain no observed points at all. Indeed, test results have shown that the resulting DTMs can achieve vertical DTM accuracies of better than 1/10000 of the flying altitude, which was never obtained in the past (except perhaps for very flat and smooth terrain).
- The adjustment principle also provides internal **quality parameters** for assessing the resulting DTM, which was also not possible in conventionally interpolated DTMs.
- The density of observed points also implies that the **dependency** of DTM accuracy **on slope** and roughness of the terrain should be less.
- The high density of observed points also has the consequence that the number of **break lines** is considerably **reduced**, restricted to the real breaklines.
- Redundancy also allows automatic **blunder detection**. This does not only include the identification of mismatches, but also **obstacles** (like houses, trees, bushes) can be automatically identified and deleted which do not belong to the terrain surface.
- In principle even **automated break line detection** is possible based on the high redundancy of observations.

All these observations are confirmed by the experience with the MATCH-T, and with the MATCH-I program for industrial applications as well.