DIGITAL AERIAL TRIANGULATION IN ALPINE REGIONS - A CHALLENGE

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ABSTRACT

Digital aerial triangulation is increasingly being carried out in photogrammetric offices as greater efficiency is being attained through increased automation. Today, vendors and some users report on production rates of better than 10 minutes per image in digital aerial triangulation. However, the high level of automation sets high demands with regard to accuracy and reliability. In our paper we present results from digital aerial triangulation from alpine regions which clearly demonstrate the limits of digital point transfer. Our investigations show that particularly in such extremely difficult terrain as the Alps, semi-automatic point transfer techniques or combinations of automatic and semi-automatic methods have to be conducted to obtain reliable results. The problems and the results from the triangulation of four blocks (two large photo scale blocks and two blocks with varying small photo scales) are presented using HATS (Helava Automated Triangulation System). The limitations of digital triangulation in alpine regions are summarised and suggestions for improvements are discussed in this paper

1. INTRODUCTION

The transition from analytical to digital photogrammetry has already been established in private photogrammetric companies. One of the major advantages of digital photogrammetry is the potential to automate photogrammetric production processes efficiently, thus substantially improving the price/performance ratio for photogrammetric products. Today, the key to an efficient photogrammetric production environment is the degree of automation in data production processes.

Image processing and computer vision techniques have successfully been employed for facilitating automated procedures in digital aerial images such as interior orientation (Schickler, 1995; Lue, 1995; Kersten and Haering, 1997a), relative orientation (Schenk et al., 1990), point transfer in photogrammetric block triangulation (Tsingas, 1992), and the generation of Digital Terrain Models (Krzystek, 1991).

Digital aerotriangulation including image import and image minification, interior orientation, point transfer, control point measurement, bundle block adjustment and quality control, is the most complex process in digital photogrammetry and the automation of this process is one of the challenges in the photogrammetric community in the early nineties.

Investigations in automatic digital aerotriangulation have been performed in scientific institutions like Ohio State University (Agouris and Schenk, 1996; Toth and Krupnik, 1996) and University of Stuttgart (Tsingas, 1992; Ackermann and Tsingas, 1994), by system providers like Leica/Helava (DeVenecia et al., 1996) and Zeiss (Braun et al., 1996), and by software providers like Inpho company, Stuttgart (Krzystek et al., 1996). Currently, there are the following three major software packages for automatic digital aerial triangulation commercially available: Helava Automated Triangulation System HATS (Leica/Helava), PHODIS-AT (Zeiss), and MATCH-AT (INPHO). But few users (Kersten and Stallmann, 1995; Beckschaefer, 1996; Kersten and O'Sullivan, 1996b; Hartfiel, 1997; Kersten and Haering, 1997b) have reported their experiences in digital aerotriangulation using a commercial photogrammetric system although many systems are already in use world-wide.

Since 1995 Swissphoto Vermessung AG, the former Swissair Photo+Surveys Ltd., is using digital stations from LH Systems (LHS). Having used digital triangulation software of LHS for almost three years now, we summarise some of our experiences in this paper. We also introduce our customised and modified approach to digital aerial triangulation through the implementation of additional software to and interface modules (developed by Swissphoto Vermessung AG) for the Helava Automated Triangulation System HATS which increases the automation and efficiency of the commercially available system in our digital photogrammetric production environment. Furthermore, the problems and limitations of triangulation in alpine regions, the results and the production rate with four different blocks are presented. Finally, suggestions for improvements of the digital triangulation software, specially for using in difficult terrain, are summarised.

	Block Disentis	Block Vals	Block Thusis	Block Brienz
Area covered:	54 km^2	28 km^2	1800 km^2	2080 km^2
Ground height:	900 - 1800 m	1200 - 2100 m	550 - 2900 m	430 - 2650 m
Flying height a. s. l.:	~ 2500 m	~ 3000 m	4300 - 9300	4700 - 5700
Camera:	Leica RC30, 15/4 UAGA-F			
Photo scale (average):	~1: 7’500	~1: 9’200	1:22’000-1: 52’000	1:22’000-1: 41’000
Forward/side overlap:	80%/30%	80%/30%	70-90%/10-30%	70-90%/10-30%
Number of strips:	2	3	10	12
Number of images:	35	21	185	270
Date of flight (Strip number):	18.9.97 (1, 2)	27.5.97 (2, 3) 30.5.97 (1)	2.10.95, (83, 92, 94) 9.10.95, (34, 93) 11.10.95, (35) 12.10.95, (36) 13.10.95, (88) 14.10.95, (38) 15.10.95, (38)	8.7.95, (22) 19.7.95, (21) 3.8.95, (23, 26, 27) 4.8.95, (24, 25) 8.10.95, (112) 14.10.95, (30) 22.7.96, (222-225)
Film:	colour diapositive			
Digital imagery:	colour	colour	greyscale	greyscale
Scan resolution [µm]:	12.5	12.5	25.0	25.0

Table 1: Flight and block data of the triangulation blocks

2. TRIANGULATION BLOCKS AND PHOTOGRAMMETRIC SYSTEMS USED

2.1. Triangulation blocks

In this paper four triangulation blocks are introduced, which represent mountainous terrain in alpine regions. Two of the blocks (Disentis and Vals) consist of large photo scale imagery, while the other two blocks (Thusis and Brienz) consist of varying small photo scale images.

The block Disentis (Vals) consists of 35 (21) large scale photographs with a photo scale of 1: 7'500 (1:9’200)., Both blocks are located in Canton Grisons in the eastern part of Switzerland. The block Vals covers the terrain of a small alpine V-form valley, while the block Disentis is in the middle of a wider alpine U-form valley and contains 30% forested area. The altitudes in these blocks are between 900 - 1800 m (Disentis) and between 1200 - 2100 m (Vals). Block Vals is flown in May while block Disentis is flown in September. Both blocks are flown in without GPS.

The other two blocks (Thusis and Brienz) consist of photos with varying scale between 1: 22'000 and 1: 52'000. These two blocks are part of the *swissphoto* triangulation block system, which covers the entire area of Switzerland and is processed in the project *swissphoto* (Kersten and O’Sullivan, 1996a). These two blocks consist of regular flight lines (scale 1: 35'000 - 1: 52'000), which were flown from east to west or opposite direction as parallel flight lines an azimuth of ~20 resp. 200 degrees, and of valley flight lines (scale 1: 22'000), which were flown along the valleys. Both block Brienz (12 strips and 270 images) and block Thusis (10 strips and 185 images), represent mountainous and alpine terrain characteristics and height differences between 430 m and 2900 m. Block Brienz consist of 11 regular flight lines and one strip from a valley flight, which causes large photo scale differences from 1: 22'000 to 1: 41’000. Block Thusis includes five valley flight lines and five regular east/west strips with large photo scale differences from 1: 22'000 to 1: 52’000.

During the *swissphoto* regular flights, camera stations were recorded by DGPS using a Leica GPS receiver in the aircraft and at each of three reference stations on the ground. Additionally, points of the new Swiss GPS primary network LV’95 were signalised as control points.

Flight and block data of the four introduced blocks are summarised in Table 1. As indicated in this table the two *swissphoto* blocks include flight lines with different exposure times which varied from some days to more than 1 month resp. 1 year (e.g. Block Brienz) and consequently causes vegetation changes from strip to strip.

2.2. Digital image data

All images were scanned on a Digital Scanning Workstation DSW200 of Leica/Helava (LH Systems) in RGB mode. The turn around time for scanning each photo was

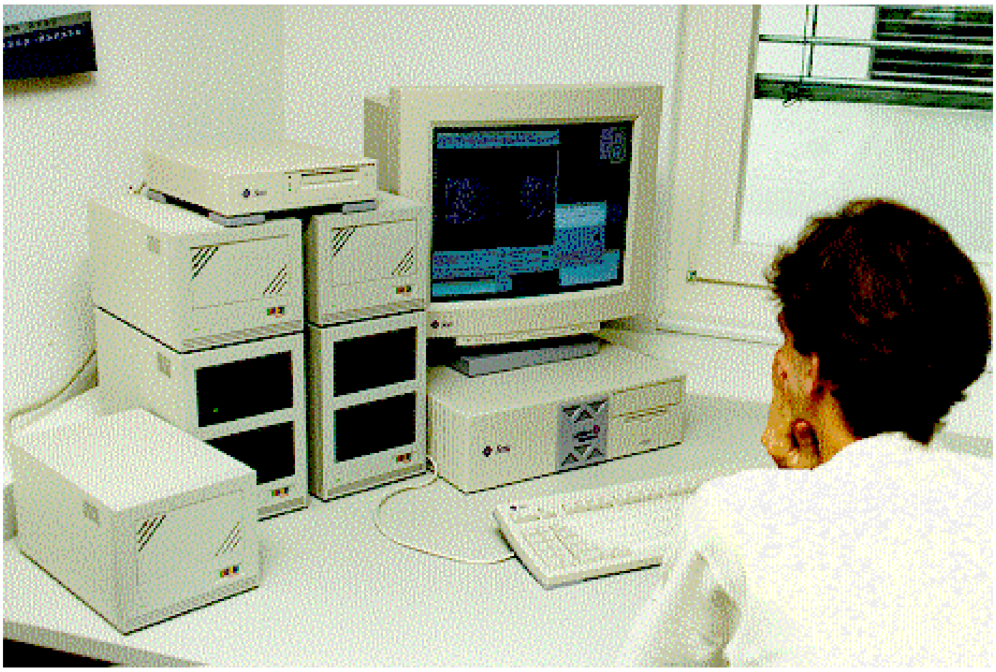

Figure 1: Digital aerial triangulation station at Swissphoto Vermessung AG

about 30 minutes (Block Brienz and Thusis) using a SUN Sparc 20/71 resp. 20 minutes (Block Disentis and Vals) using a SUN Ultra 1. The resolution of the images was 12.5 µm (Disentis/Vals) and 25 µm (Brienz/Thusis), which corresponds to a footprint of approximately 10 cm resp. 0.7 m on the ground. For triangulation of the two swissphoto blocks the digitised colour images were converted into greyscale images in order to reduce disc space usage. The size of each greyscale image was about 80 MByte, while each of the high resolution colour images was about 1 Gbyte.

2.3. Hardware

The aerial triangulation was performed on a digital photogrammetric workstation DPW670 (Mono-station) of LH Systems (Fig. 1). As a computer platform a SUN Ultra 2 (167 MHz) was used. For the triangulation data in total 105 GByte disc storage capacity was available.

2.4. Software

For the four triangulation blocks the software release 3.1.2 (Brienz) and 3.2 (Vals, Disentis, Thusis) of SOCET SET (Softcopy Exploitation Tools) was used. HATS is a module of SOCET SET for performing block triangulation of suitably overlapping images. The tedious process of selecting and measuring image coordinates of pass and tie points is highly automated, with the possibility of operator override. The system flags unacceptable tie points and displays the required images for measurement without operator intervention. All the operator has to do is to re-measure these unacceptable points by moving the floating mark to their proper locations, if requested.

3. DIGITAL AERIAL TRIANGULATION

In an automated production, the digital aerial triangulation (AT) is divided into several processing steps, which include data preparation (photos and control points), automatic data import and image minification, automatic interior orientation, automatic AT measurements, GPS supported bundle block adjustment, and quality control. To facilitate the use of the highly automated AT processing modules by the operator some additional software for batch processing and easy-to-use graphical user interfaces (GUIs) were developed by Swissphoto Vermessung AG.

3.1. Data preparation

The data preparation includes configuration of the photo block (providing images, loading digital images from tape, if not available on disk) and providing control point data (co-ordinates, overview plot, available sketches). To obtain sufficient ground control points five different sources are used for these two *swissphoto* blocks:

- signalised points from the new Swiss GPS primary network LV'95
- points from additional GPS campaigns
- control points from the 1: 10'000 canton map series
- height control from the Swiss 1: 25'000 map series

Ground control preparation for the *swissphoto* triangulation blocks is a very time consuming process, which differs from block to block. This part of the triangulation requires the most intervention resp. preparation by the operator.

For the two small blocks (Disentis/Vals) 17 (25) control points, which were signalised and measured in a GPS campaign, were available.

3.2. Automatic data import and image minification

Before starting the measurements, the image import into the photogrammetric station and the minification of the images (building-up image pyramid levels for display and zooming) is performed fully automatically in a batch mode, which takes between 30 and 60 seconds per image on the SUN Ultra 2. If available, the GPS photo centre co-ordinates of each image can be also automatically imported to provide approximate values for the overlaps between images in the blocks. Additionally, the preparation of the triangulation file which contains all parameters for the automatic measurements, can also be performed automatically. Thus using such customisation the operator input is significantly reduced in comparison to when using the non-enhanced commercial software package HATS.

3.3. Automatic interior orientation

Before starting HATS the interior orientation must be determined for each image. To avoid the time consuming semi-automatic measurements of the interior orientation, a fully operational automatic interior orientation (IO) of digital aerial images was developed at Swissphoto Vermessung AG and integrated into SOCET Set on the DPW670/770. This operation can be performed in batch mode without any operator intervention. The IO of an unlimited number of images related to one specifically defined camera type can be automatically determined in one step including quality control. The speed of the measurements and IO determination is approximately 5 seconds per image. The used algorithm is described in Kersten and Haering (1997a).

3.4. Automatic AT measurements

The processes of AT measurements as currently used in HATS are divided into four steps which includes Automatic Points Measurements (APM), Interactive Point Measurements (IPM), and Simultaneous Solve (Re-measurements) and Blunder Detection.

Before running APM a tie point pattern was selected and edited to obtain a well distributed point configuration in each image for connecting the block. A very dense tie point pattern consisting of 98 points is used as a standard pattern for all described blocks. APM runs as a batch process mostly overnight or during the weekend. On the SUN Ultra 2 APM takes approximately 10-30 minutes per image. After APM the following rate of successfully measured points could be achieved for the blocks: Block Disentis 47%, Vals under 25%, Thusis over 60%, Brienz 64%. In comparison, the success rate of APM was between 70-94% for the *swissphoto* blocks in the northern part of Switzerland. This clearly demonstrates that the success rate of APM is depending on the terrain characteristics, the variation in the photo scale within each block and flight date differences between strips.

Ground control points and additional points were measured with IPM in a semi-automatic mode. If the datum is fixed by measurements of three control points or by GPS camera stations, the program drives the operator to the approximate positions of the subsequent ground control points automatically.

Due to the bad success rate of APM all automatically measured points of block Vals were eliminated and new points were measured with IPM in a semi-automatic mode. The measured tie points were set into the von-Gruber positions. In block Disentis some gaps without any point occurred due to forested areas and steep areas with hang sliding. In these areas additional tie points were also measured in the semi-automatic mode of IPM.

After the first quality control it was realised that the valley flight lines of the two *swissphoto* blocks were very poorly connected to the other strips, which consequently required a manual connecting of these strips by time-consuming semi-automatic measurements. This problem can be attributed to the large scale differences between valley flight lines and the regular strips.

After all measurements were performed, the observations were adjusted using the „Simultaneous Solve“ module of HATS. Instead of re-measuring all errors a blunder detection routine eliminates all observations with residuals over a user specified threshold. Simultaneous solve and blunder detection were performed in an iterative mode until a certain specified precision was obtained. This blunder detection uses only a special threshold criterion and assumes high redundancy in the observations. But with this method it could occur that too many observations, especially between strips, were eliminated due to bad quality of APM. Nevertheless, areas of weak block connections were detected later in the quality control, and gaps without any points had to be filled by semi-automatic measurements. Unfortunately, simultaneous solve was often disturbed by so called „pseudo“ observations, where the system tried to connect images which were impossible to connect. These gross errors influenced all other observations significantly and it was always time consuming to remove all those blunders. As a quality control the computations of spatial intersections for each point would clearly indicate the blunders for subsequent automatic elimination.

3.5. Bundle block adjustment

All measured image co-ordinates of each block were exported in a PATB-format and transferred from the DPW670 to a PC, where the bundle block adjustment was performed for each block. All observations (image co-ordinates, control point co-ordinates and if available GPS photo centres) were adjusted in a bundle block adjustment with self-calibration using the bundle block

Block	Images	Control H/V	Signalised control pts	σ_0 [µm]	RMS X [m]	RMS Y [m]	RMS Z [m]	RMS X_0 [m]	RMS Y_0 [m]	RMS Z_0 [m]
Disentis	35	17/17	17	7.3	0.06	0.05	0.05	-	-	-
Vals	21	24/25	25	5.8	0.03	0.04	0.04	-	-	-
Thusis	185	10/108	4	12.6	0.45	0.35	1.25	0.29	0.22	0.36
Brienz	270	13/128	3	11.7	0.26	0.31	1.04	0.47	0.34	0.13

Table 2: Results of the bundle block adjustments of Swiss alpine blocks

adjustment program BLUH of the University of Hannover. After each run of the bundle block adjustment an automatic blunder detection was performed to eliminate all image point residuals over a specified threshold (finally over 30 microns, but only for the two *swissphoto* blocks).

The results of the adjustments are summarised in Table 2. For the two *swissphoto* blocks the root mean square (RMS) values of the control point co-ordinates are better than 0.6 m in X and Y, and less than 1 m in height, while the RMS values of the station co-ordinates are also better than 0.5 m in X and Y, and better than 0.4 m in Z. The σ_0 from the adjustment varies between 11.5 and 12.6 micron, which corresponds to approximately 1/2 of the pixel size. The precision level of digital AT with automatic digital point transfer depends on the matching algorithm applied and on the pixel size of the digitised images. With feature based matching a precision of 0.3-0.4 pixels can be assumed for point transfer, while with least squares matching a precision of 0.1-0.2 pixels can be achieved. More details about accuracy considerations of digital AT are contained in Ackermann (1996). Theoretically it should be possible to obtain at least a precision of 1/3 of a pixel using the area based matching algorithm in SOCET SET, which corresponds to 8.3 µm and 0.22 m in planimetry at a photo scale of 1: 27'000. The reasons for the worse results achieved with these two *swissphoto* blocks could be addressed to bad ground control quality (especially the height control from the maps) and the large number of measurements (many tie points with bad quality) in each block which also include residuals larger than one pixel (25 µm). From our experiences in digital orthophoto production using the results of the *swissphoto* block triangulation, the large number of measured points per image provides a higher reliability in the adjusted station co-ordinates. In general, the obtained results are similar to results achieved in other *swissphoto* blocks (Kersten and O'Sullivan, 1996b; Kersten and Haering, 1997b).

The RMS results of the two small blocks with the large photo scale are optimal (better than 5 cm in XYZ) in comparison to high precision triangulation with analytical plotters. The excellent results of block Vals can be addressed to the manual point selection by the operator and the semi-automatic measurement mode.

3.6. Quality control

After the final bundle adjustment an update of the orientation data for each image support file and the measured image point files is performed at the DPW670 using interfaces between BLUH and SOCET SET. The geometric quality control for the block is given by the results of the bundle adjustment (σ_0, RMS, etc.). Furthermore, due to high automation of the measurements and gross error elimination it is absolutely essential to check the photo connections within each strip and across the strips, in order to confirm a reliable point distribution and connection in the triangulation block. Therefore an additional software module was developed by Swissphoto Vermessung, which provides a fast and easy-to-use visualisation of all point connections in the block (Fig. 2). Using this module the operator is able to scan quickly through the block, photo by photo, strip by strip to check visually the number of rays per point, the distribution of points in each photo, and, by clicking on the photo number in the display window, the connections to each photo (see Figure 2). Thus, the operator is able to analyse the connections within the block and to measure additional points in weakly connected areas.

4. TIME REQUIRED

The time required for digital aerial triangulation of each introduced block is summarised in Table 3. In this table only the operator's time is counted, while the computation time of the computer for running batch processes, which is mostly done over night, is neglected.

In our investigations of triangulation in alpine regions a total time of 22 min per photo required for the triangulation of block Disentis, excluding scanning and ground control preparation, was currently achieved as the best result. For this block which is mainly covered by forest and steep slopes, automatic point transfer and subsequent interactive point measurement (semi-automatic mode) was used.

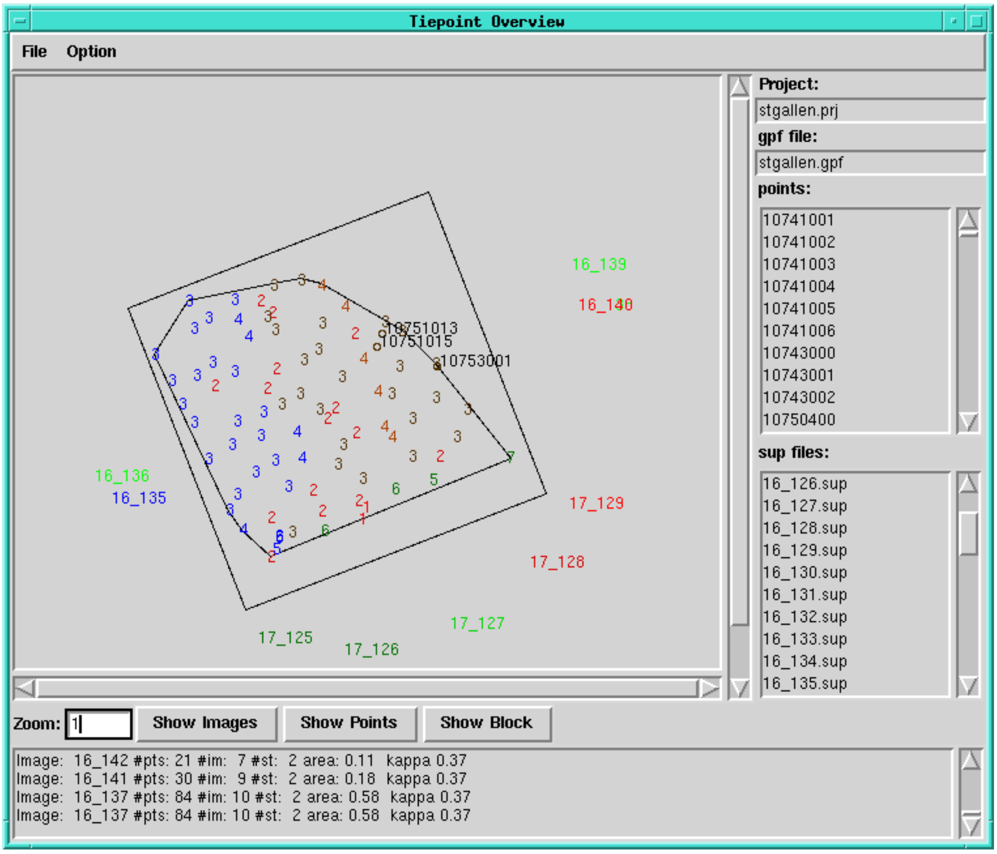

Figure 2: Visualisation of photo connections within a triangulation block for quality control

A slightly worse result (22.8 min per image) with respect to efficiency was achieved with the *swissphoto* block Brienz. The problems of this block for the automatic point transfer are: (a) extreme height differences in the alpine region of this block, (b) photo scale differences between strips, and (c) the time intervals between the flight dates of the strips (up-to one year).

With the second *swissphoto* block Thusis 36 min per photo for triangulation was obtained. Similar to block Brienz the problems of the digital triangulation for this block can be mainly attributed to the large photo scale differences between regular and valley flight lines. Furthermore, the extreme height differences within the block, even within one photo, played an important role for the worse performance of the triangulation. Both *swissphoto* blocks were measured in a combination of APM and IPM.

Although the RMS result of the triangulation of block Vals is very good (see Table 2), the production rate for this small block is even worse than for triangulation on analytical plotter. Here, the automatic point transfer failed due to the narrow valley with huge height differences (up to 900 m). All points were measured semi-automatically in an interactive mode and in rocky areas with steep slopes it was very difficulty to measure successfully points. In general, the use of an initial DTM could help the correlation algorithm for the automatic point transfer significantly.

The productivity rate obtained with these four triangulation blocks is significantly worse in comparison to the results achieved with the triangulation of other *swissphoto* blocks. For these blocks the time required for triangulation was up to 9 minutes per image for a hilly and mountainous terrain (Kersten and Haering, 1997b). Krzystek (1998) reports about the triangulation of a Swiss block (400 b/w images, scale ~1: 30'000, area Bern-Fribourg-Interlaken) in mountainous terrain using MATCH-AT. For this block a production rate of better than 5 minutes per photo (operator time) was achieved.

Other authors report good productivity for digital triangulation in flat terrain. DeVenecia et al. (1996) report a total working time of around 10 minutes per image, which was achieved with two test blocks using HATS. The two test blocks (Forssa and Wisconsin) have a large photo scale of around 1: 4’000 and represent a very flat area with maximum height differences of 10 meters. Beckschaefer (1996) reports about 66 images per eight hour shift as the best result for digital aerotriangulation on the INTERGRAPH Image-Station, which corresponds to a production rate of 7.3 minutes per image.

AT processing steps	Block Disentis	Block Vals	Block Thusis	Block Brienz
Preparation inkl. Import, Minif., Int. Ori.	2 h	1 h	20 h	9 h
AT Measurements	10 h	16.5 h	90 h	78.5 h
Bundle block adjustment	1 h	3 h	7.5 h	15 h
Total elapsed time	13 h	20.5 h	117.5	102.5 h
Number of images	35	21	185	270
Elapsed time per image	22 min	61 min	38 min	22.8 min

Table 3: Elapsed time for digital AT using a customised and modified approach

5. ALGORITHMIC ASPECTS

The quality of the results and the efficiency of triangulation are dependent on the quality of automatic point transfer and correlation (measurement algorithm), which again depend mainly on image quality (including scanning and weather conditions) and terrain characteristics (e.g. texture and height differences). In summary, the following aspects caused problems for the correlation algorithm in our investigations:

- Extreme height differences in the images resp. block
- Strips with different flight dates (vegetation changes in summer)
- Shadows from early morning flights (bad quality terrain representation)
- Densely forested areas and lakes
- Triangulation blocks with variable photo scale within the block (from strip to strip)

To improve HATS with respect to speed, precision, robustness, flexibility, and user-friendliness for the use in difficult terrain as it occurs in the Swiss Alps we suggest the following software improvements which are summarised below:

(1) The use of an existing DTM (Digital Terrain Model) in APM speeds up the APM process and increases the precision and robustness significantly, especially in mountainous and alpine regions, so that the rate of successfully measured points can also be increased. In Switzerland, for example, a hectare-raster DTM covering the whole country is available.

(2) The implementation of an image matching technique (Gruen, 1985b), which uses two shift parameters as well as two shears and scales, improves the precision of the measurements slightly. A small drawback due to slightly reduced speed should be ignored due to the increasing performance of each computer generation.

(3) The use of GPS data, additional parameters and an efficient band ordering algorithm for the re-linearisation of the normal equation system in simultaneous solve leads to more flexibility and speed-up of the adjustment module.

(4) The use of on-line quality control by computations of spatial intersections of the measured points during the measurements reduces the number of blunders significantly.

(5) The use of on-line triangulation algorithms (sequential estimation in bundle block adjustment and data snooping in blunder detection) during APM to increase the quality of the automatic measurements through elimination of gross errors during the data capture phase (Gruen, 1985a).

In the currently available release 4.0.10b (May 1998) the use of an existing DTM and GPS is implemented.

6. CONCLUSIONS AND OUTLOOK

In this paper it was shown that very good results (RMS value of the control points better than 5 cm) can be achieved with digital aerial triangulation even in difficult terrain like the Swiss Alps. Furthermore, it was demonstrated that through customisation and modification of commercial triangulation software a higher degree of automation can be reached in the workflow of digital aerial triangulation in order to reduce the intervention of the operator to a minimum.

But, it was also shown that the production rate for triangulation in alpine regions is much worse than in flat or non-difficult terrain. This demonstrates that the production rate resp. the efficiency of digital aerial triangulation is mainly dependent on the type of the terrain and the block configuration. Specially, the variation of the photo scale within the block and extreme height differences in the terrain like the Swiss Alps are causing problems to the correlation algorithm. This leads to a bad performance in the automatic point transfer. To fulfil the requirements for successful digital triangulation in difficult terrain, improvements of the automatic point transfer approach must be done. Therefore, the use of an initial DTM and an on-line triangulation algorithm including quality control could reduce the problems in automatic point transfer. But as a major problem for the automatic point transfer the variation of the photo scale will still occur, which will require the necessity of interactive point measurements in the semi-automatic mode.

However, we believe that, in general, there is still potential for more improvements in digital AT to increase the productivity so that a triangulation rate of better than 5 minutes per image could be possible in the future, even with difficult terrain characteristics as appear in the Swiss Alps. Currently, it seems that analytical aerial triangulation is still competitive to digital AT in difficult terrain like in the Swiss Alps, if also variable photo scales occur in the blocks.

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