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BLOCK TRIANGULATION WITH AERIAL AND SPACE IMAGERY USING DTM AS CONTROL INFORMATION

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ABSTRACT

Digital Terrain Models (DTMs) are being generated and are available in regional or country-wide elevation data bases at many mapping institutions. For certain applications of photogrammetric point determination DTM data can be used as control information in the block adjustment.

The paper briefly describes the underlying mathematical model. Simulated block triangulations with small scale aerial imagery are presented and commented with regard to precision and reliability. The results of a large practical project are reported, where DTM data are used in aerial triangulation for the subsequent production of orthophoto maps. Further simulations are described, which were carried out to study the use of DTM information in connection with digital three-line scanner imagery from space, based on the camera and flight parameters of the German MOMS-02/D2 project. From the theoretical and practical investigations possible future applications of the method are derived.

INTRODUCTION

For photogrammetric point determination with analog or digital imagery taken from aircrafts or satellites additional non-photogrammetric information is required at least for the definition of the datum. Moreover, a combined adjustment of photogrammetric observations and additional information can contribute to the compensation of configuration deficiencies of the block, the improvement of precision, the detection of gross errors and the compensation of systematic errors in the observations.

The paper in hand focuses on the use of Digital Terrain Models (DTMs) as control information in photogrammetric point determination. It briefly describes the underlying mathematical model. Then, the results of simulations and of a practical test on block triangulation with small scale aerial imagery are summarized. Further simulations are described, which were carried out to study the use of DTM information in connection with digital three-line scanner imagery from space, based on the camera and flight parameters of the German MOMS-02/D2 project. Finally, possible future applications of the method are outlined.

MATHEMATICAL MODEL

The mathematical model for using DTM information in a bundle block adjustment has been described in *Ebner and Strunz (1988)*. For reasons of clarity, however, it will be shortly reviewed.

In photogrammetric point determination the coordinates of the object points are estimated by a least squares adjustment of photogrammetric observations, complemented by a set of non-photogrammetric observations, which are generally ground control coordinates. If DTM data are available for at least a part of the block area, an additional observation equation can be formulated for each point P_i in the DTM area:

$$\hat{v}_{zi} = \hat{z}_i - z_i(\hat{x}_i, \hat{y}_i) \qquad (1)$$

where

$\hat{x}_i, \hat{y}_i, \hat{z}_i$	are the least squares estimates of the coordinates of P_i
$z_i(\hat{x}_i, \hat{y}_i)$	is the observation value derived from the DTM
$\hat{v}_{zi}$	is the residual of $z_i(\hat{x}_i, \hat{y}_i)$

Linearization using the initial values $\dot{x}_i, \dot{y}_i, \dot{z}_i$ leads to

$$\hat{v}_{zi} = - \frac{\partial z_i}{\partial x_i}\Big|_o \cdot \Delta\hat{x}_i - \frac{\partial z_i}{\partial y_i}\Big|_o \cdot \Delta\hat{y}_i + \Delta\hat{z}_i + \dot{z}_i - z_i(\dot{x}_i, \dot{y}_i) \qquad (2)$$

The observation value $z_i(\dot{x}_i, \dot{y}_i)$ in Eq. 2 is derived from the initial position of P_i, which changes in the iterations of the adjustment. After convergence, $z_i(\dot{x}_i, \dot{y}_i)$ is computed at the final position ($\hat{x}_i, \hat{y}_i$). It can be seen from Eq. 2 that generally the DTM observation contributes to the determination of all three coordinates $\hat{x}_i$, $\hat{y}_i$, $\hat{z}_i$, except when the coefficients $\partial z_i/\partial x_i$ or $\partial z_i/\partial y_i$ are equal to 0.

The formulation of a correct stochastic model is difficult in practice, because in general there is only incomplete information available on the accuracy properties of the DTM data. In the following the DTM observations are simply treated as uncorrelated and equally accurate.

In this chapter the results of simulations and of a practical test on block triangulation with small scale aerial imagery are presented.

Precision and reliability of simulated data

The quality of photogrammetric point determination includes two aspects, namely precision and reliability. The precision is defined by the statistical features of the estimated parameters, if the prior assumptions, i.e. the functional and stochastical model of the adjustment, are considered to be true. The reliability describes the quality of the adjustment model with respect to the detectability of model errors, which can be blunders, systematic errors or weight errors. In the following the term reliability will be used with respect to blunders.

The theoretical precision of the unknowns $\hat{x}$ resulting from a least squares estimation of simulated data is represented by the covariance matrix $K_{\hat{u}}$ of the unknowns. For the evaluation of the reliability of the system the matrix $Q_{\hat{v}\hat{v}}P$ is of importance, where $Q_{\hat{v}\hat{v}}$ is the cofactor matrix of the residuals $\hat{v}$ and P is the weight matrix of the observations l in an adjustment of indirect observations. The matrix $Q_{\hat{v}\hat{v}}P$ determines the propagation of errors in the observations l onto the residuals $\hat{v}$.

The precision of point determination using DTM as additional or exclusive control information is given in *Ebner and Strunz (1988)*. The results of a comprehensive simulation study concerning the precision of block adjustment with general control information (DTM and GPS data) can be found in *Colomina (1988)*. The main results of these investigations concerning the use of DTM can be summarized as follows.

- DTM data can be used as control information, if the quality of the given DTM is appropriate for the accuracy demands of the point determination. This especially applies to small scale blocks, where the utilization of DTM in a combined adjustment fulfills the accuracy requirements of many applications.
- The resulting horizontal and vertical precision significantly improves with the number of points in the adjustment.
- The influence of the DTM data on the resulting planimetric precision depends on the local terrain slopes. The type of the terrain, in particular the derivatives of the function that describes the DTM surface (coefficients $\partial z_i/\partial x_i$, $\partial z_i/\partial y_i$ in Eq. 2), are decisive for a possible replacement of horizontal control points by DTM. Precise elevation data and large slopes in the terrain are necessary for the use of DTM as exclusive control information.
- For the replacement or the reduction of height control points the use of DTM is recommended.

Concerning the reliability of point determination using DTM as control informat-ion simulations were carried out based on the following assumptions:

- image scale: 1 : 70 000
- focal length: 150 mm
- overlap (forward/side): 60 % / 20 %
- number of images: 210 (10 strips, 21 images each)
- number of points: 441 (9 points per image).

From the number of computation runs only some representative examples will be given here. For reasons of comparison a conventional block adjustment with chains of height control points (distance across the strip direction 2 baselengths, distance in strip direction 4 baselengths) and planimetric control points along the block edges (distance 4 baselengths) is simulated (version (C)). Standard deviations of the control points' coordinates of 0.10 m and of the image coordinates of 10 μm are assumed. This simulation is compared with block adjustments, where a DTM is used instead of the height control points. For the precision of the DTM standard deviations of 1.0 m (version D1), 2.0 m (version D2) and 3.0 m (version D3) are assumed. The resulting root mean square (rms) values of the standard deviations of the estimated heights of all points are μ_z = 1.21 m (C), 0.70 m (D1), 1.04 m (D2) and 1.28 m (D3) respectively.
The analysis of the reliability requires the computation of the complete matrix $Q_{\hat{v}\hat{v}}P$. Some main conclusions, however, can be drawn from the diagonal elements $r_i = (Q_{\hat{v}\hat{v}}P)_{ii}$, the so-called redundancy numbers, which reflect the influence of an observational error in the observation l_i onto the corresponding residual $\hat{v}_i$. For different groups of observations (image coordinates, x,y control points, z control points, DTM information) the average, minimum and maximum values $\bar{r}$, r_{min} and r_{max} of the redundancy numbers r_i are computed. They are used as approximate measures of reliability and shown in Table 1.

	version:	C	D1	D2	D3
image coordinates:	$\bar{r}$	0.32	0.36	0.34	0.33
	r_{min}	0.00	0.13	0.12	0.09
	r_{max}	0.53	0.53	0.53	0.53
x,y control points:	$\bar{r}$	<0.01	<0.01	<0.01	<0.01
	r_{min}	<0.01	<0.01	<0.01	<0.01
	r_{max}	0.01	0.01	0.01	0.01
z control points:	$\bar{r}$	<0.01	-----	-----	-----
	r_{min}	<0.01	-----	-----	-----
	r_{max}	0.01	-----	-----	-----
DTM information:	$\bar{r}$	-----	0.51	0.73	0.82
	r_{min}	-----	0.17	0.39	0.54
	r_{max}	-----	0.65	0.81	0.87

Table 1: Reliability measures for different groups of observations

From this example it can be seen that for the use of DTM information instead of height control points we obtain much better reliability of height control, e.g. $\bar{r}$ = 0.73 for DTM observations (version D2) compared to $\bar{r}$ < 0.01 for z control points (version C). However, a more detailed reliability study including aspects like the locatability of blunders and their separability from other errors still has to be performed.

Practical project

In the following a practical test will be described, which has been jointly performed by the Chair for Photogrammetry of the Technical University Munich and the Institut Cartogràfic de Catalunya (ICC). The ICC is the mapping agency of the Autonomous Government of Catalonia, with responsibilities over an area of 32 000 km^2 and about 6 million people. Among other tasks the ICC is responsible for the production of basic topographic maps at scales which range from 1 : 5 000 to 1 : 25 000 as well as of thematic and satellite maps at 1 : 100 000 scale and below. In particular, orthophotos are being produced digitally from digitized aerial images and satellite scenes at scales 1 : 5 000, 1 : 25 000 and 1 : 50 000. Simultaneously to the generation of the 6300 map sheets of the 1 : 5 000 series, a country-wide DTM is being generated which is already completed to more than 80% of the territory. The intended accuracy of the elevation data is 2 m or better depending on the compilation instrument.

The aim of this test was to investigate, whether the utilization of DTM data in a block adjustment is suitable in practice. The image data have been used at the ICC for aerial triangulation and the subsequent digital production of orthophoto maps. The parameters of the test block are:

- image scale: 1 : 75 000
- focal length: 153 mm
- overlap (forward/side): approx. 70 % / 40 %
- number of images: 124 (5 strips, 14 - 32 images each)
- number of points: 1010 (no signalized points)
- control points: 151 x,y,z control points, 32 z control points.

First a rough estimation is performed, which results in standard deviations of 3.0 m for the DTM information. Then the DTM is introduced in the adjustment as exclusive height information instead of height control points. The rms values of the resulting standard deviations of the coordinates of all points are $\hat{\mu}_x$ = 0.48 m, $\hat{\mu}_y$ = 0.65 m and $\hat{\mu}_z$ = 1.15 m. Because the height control points did not contribute to the adjustment, they can be used as independent check points. The empirical height accuracy calculated from 183 points results in 2.1 m. An analysis of the discrepancies shows a systematic shift between the heights resulting from the block with DTM and the heights of the check points. Taking this shift into account, the empirical height accuracy is reduced to 1.7 m.
However, the empirical value is still worse than the theoretical one, which might have the following reasons. The check points are not error-free; they are determined by photogrammetric means. Furthermore, some local systematic errors seem to be present in the DTM data. A closer analysis of the discrepancies shows that the large values can be found at points near the edges of forests or near high buildings like bridges, etc. This is a result of the DTM compilation technique which for the bulk of the elevation data has been automatic image correlation on the Gestalt Photomapper. Probably the main reason for the discrepancy between the theoretical and the empirical accuracy is that the assumed stochastical model (uncorrelated and equally accurate observations) and the functional model (bilinear interpolation in a regular grid for the derivation of terrain heights) are

simplifications of reality.
Summarizing, the results show that DTM in principle can be used as control information for small scale applications. However, research work still has to be done, e.g. on the appropriate mathematical modelling of the data.

POINT DETERMINATION USING DIGITAL IMAGERY FROM SPACE

In this chapter the results of simulations on the use of a DTM as control information for point determination with MOMS-02/D2 imagery are given. They are part of a more comprehensive simulation study *(Ebner et al., 1990)*.

The MOMS-02/D2 project

MOMS-02/D2 is an experimental project for digital mapping from space, which is funded by the German Minister for Research and Technology (BMFT). In the course of the second German Spacelab mission D2, which is scheduled for launch in 1992, the MOMS-02 camera is intended to acquire digital imagery of the earth's surface *(Ackermannn et al., 1989)*. The special characteristic of the MOMS-02 camera is the combination of high resolution panchromatic images for three-dimensional geometric information with multispectral images for thematic information. The multispectral data acquisition will be performed by 2 lenses which allow for recording of a maximum of 4 spectral channels. The stereo module basically consists of 3 lenses with one CCD line sensor each, which provide a forward, a downward and a backward looking view. The central lens enables high quality image recordings with a ground pixel resolution of less than $5 \cdot 5\ m^2$. From the photogrammetric point of view the major aims of the mission are the production of high quality maps, the acquisition of digital data for geographic data bases and information systems and the generation of DTMs with an accuracy of 5 m or better. Moreover, the concept for completely digital photogrammetric data acquisition and evaluation is to be developed, realized at an experimental level and tested.
Simulations based on the MOMS-02 camera specifications and the D2 mission parameters were performed in order to obtain a survey of the attainable geometric accuracy and to give recommendations in the planning phase of the project concerning additional measurements during the mission and the technical design of the camera.

Photogrammetric point determination using three-line imagery

The mathematical model for point determination using three-line imagery is based on the concept described in *Hofmann et al. (1984)*. For reasons of clarity the basic principle will be shortly reviewed.
A three-line opto-electronic scanner system consists of three linear CCD-sensors, which are arranged perpendicularly to the direction of flight in the focal plane(s) of one or more lenses. During the flight the sensors continuously scan the terrain and the data are read out with a constant frequency. This dynamic mode of

image recording results in a large number of successive images, each consisting of three lines (Figure 1). For the photogrammetric evaluation of these data conjugate points have to be determined, preferably by digital image matching techniques. The simultaneous determination of the object points and the exterior orientation of the three-line imagery is based on the principle of bundle adjustment. The exterior orientation, however, is calculated only for so-called orientation images, which are introduced at certain time intervals. In between, the parameters of every image are expressed as functions of the parameters of the neighbouring orientation images.

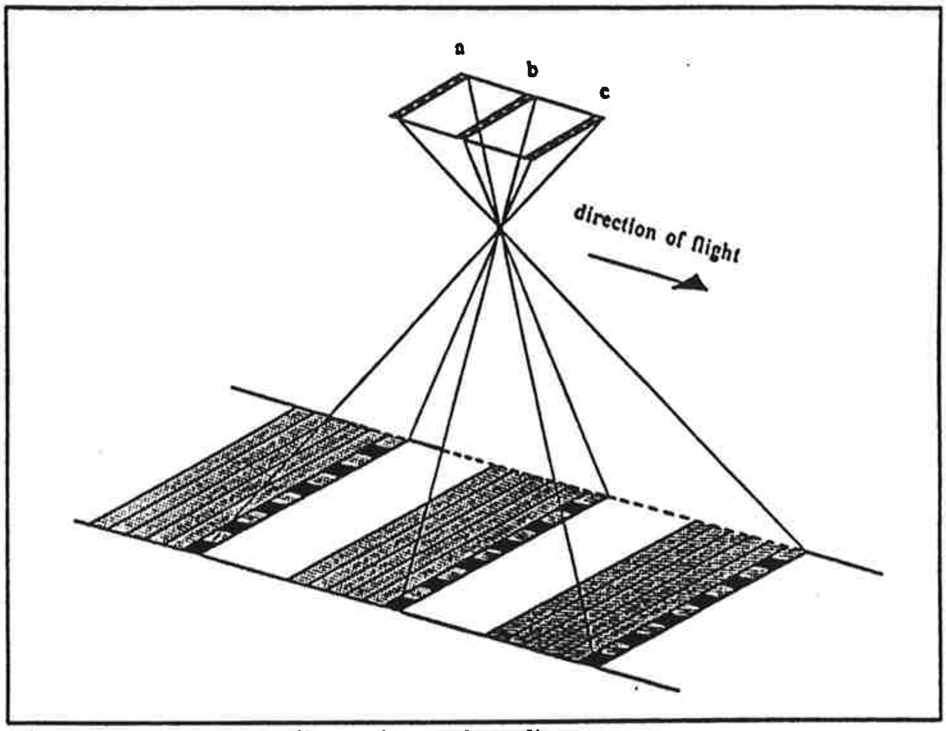

Figure 1: Image recording using a three-line scanner

Simulation study

The simulations are based on system parameters which match to a large extent the specifications of the MOMS-02 camera and the flight parameters of the mission.

The following system parameters are assumed (see Figure 2):

- focal length:	f	=	660 mm
- convergence angle:	γ	=	27.1933 grad
- distance of 2 sensor lines:	s	=	300.418 mm
- ground pixel resolution:			$5 * 5\ m^2$
- flying height above ground:	H	=	334 km
- base length:	B	=	152 km
- strip width:	W	=	36 km
- strip length:	L	=	606 km.

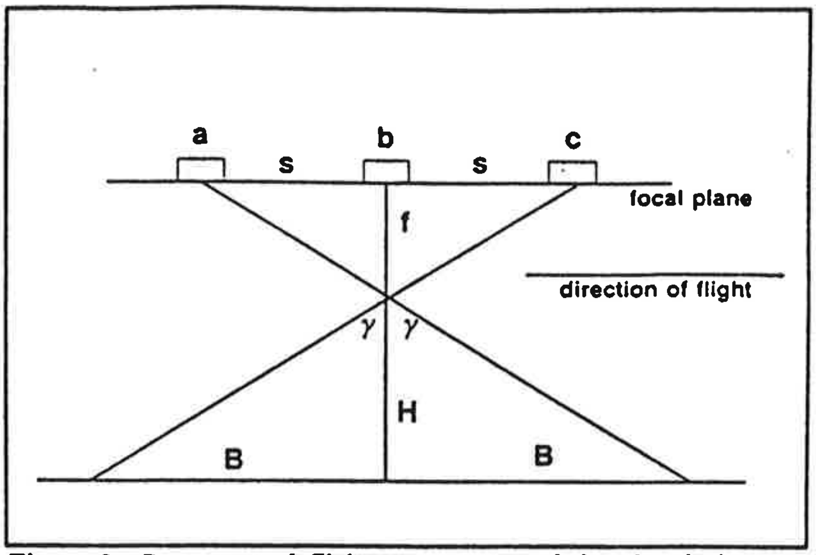

Figure 2: Camera and flight parameters of the simulation

Unlike the stereo module of the MOMS-02 camera, which consists of three lenses with one sensor line each, a one-lens camera is used in the simulations. A straight forward flight path is assumed. A regular arrangement of the object points is used with a distance of 2 km along flight direction and of 9 km across flight direction.

A peculiarity of the MOMS-02 configuration is the extremely small image angle, which results in an unfavourable ratio between the strip width and the flying height of approximately 1:9. For point determination using three-line imagery only control information for the definition of the datum is in principle necessary for rigorous object reconstruction. The above mentioned configuration, however, leads to rather poor accuracy. Consequently, observations of the exterior orientation parameters have to be considered in the evaluation process.

A large number of simulations was performed to investigate the influence of the arrangement of the three sensor lines in the focal plane of the camera, of the precision of the observed exterior orientation parameters, of the distance between the orientation images, of the number of ground control points and of the precision of the given DTM on the resulting accuracy of point determination. For all computations standard deviations of the image coordinates of 5 μm are assumed.

Results and discussion

In this paper only the simulations concerning the use of DTM information will be given. The rms value μ_z of the theoretical standard deviations of the z coordinates of all points, which are projected into three images, is calculated for each version. Using these values, summarized accuracy measures for the simulations can be given.
In Figure 3 the influence of different precision levels of observed exterior orientation parameters and of a given DTM on the resulting rms values μ_z is shown.

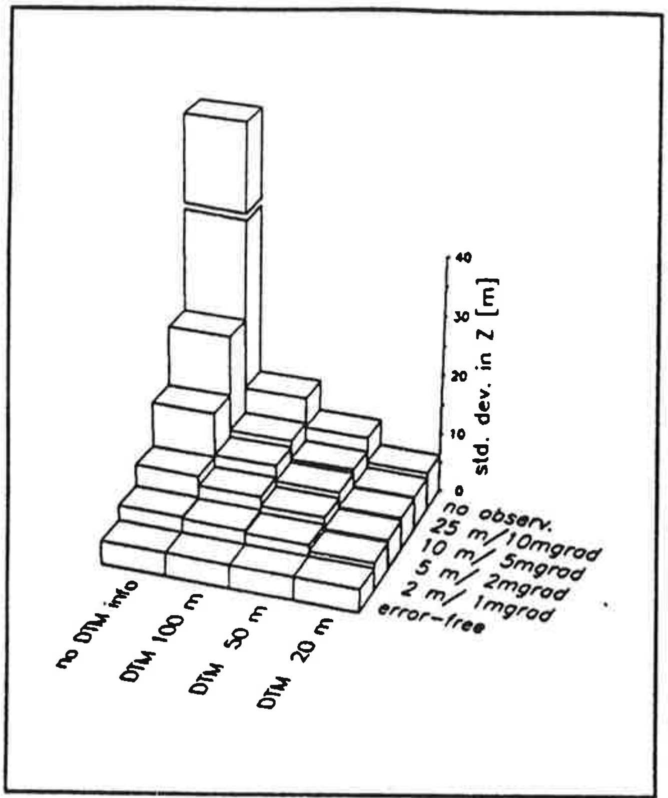

Figure 3: Rms values μ_z, assuming parallel sensor lines, 8 km distance between orientation images, 4 x,y,z ground control points

The following abbreviations are used in Figure 3:

- *DTM 20m, ..., DTM 100m:* standard deviations of the DTM used as control information,
- *no DTM info*: no DTM information available,
- *error-free*: error-free exterior orientation parameters,
- *2m/1mgrad, ..., 25m/10mgrad*: standard deviations of observed position/attitude orientation parameters,
- *no observ.*: no observations for the orientation parameters available.

A break in the graphic representation means that the respective value is not given true to scale.

Figure 3 shows a significant improvement of the resulting rms values μ_z, even when a DTM with only low precision is introduced into the adjustment. If observations of the exterior orientation parameters with standard deviations of 25m/10mgrad (position/attitude) are available, the height accuracy requirement of 5 m is met by DTM information with a precision of 20 m or better. DTM data, which might e.g. originate from digitized contours of existing topographic maps, can thus effectively be used in the adjustment.

Outlook on the use of DTM data for point determination with SPOT imagery

A practical test on the use of DTM data for the orientation of SPOT imagery will be carried out by the Chair for Photogrammetry and the ICC where SPOT panchromatic scenes are being used since 1988 for the production of orthophoto maps at 1 : 50 000 scale. For that purpose, a SPOT stereopair is available (scene identification 42-267, Priorat, South Catalonia). The scenes were recorded at 3.9.1986 and 7.9.1986 with 13.5° and 17.3° sensor inclination angles respectively.

CONCLUSIONS

DTMs are being generated and are available in regional or country-wide elevation data bases at national and local mapping organizations. They are usually established for predefined applications, e.g. the production of orthophoto maps in a certain scale. However, the need for DTM data in a variety of new applications is rapidly growing. Therefore, the DTM has to meet much higher requirements than in the past and research is being performed on high quality DTM in order to fulfill these requirements *(Ebner et al., 1988)*.

For certain applications of photogrammetric point determination the DTM data can be used as control information in the block adjustment. In the paper this task has been investigated for small scale aerial imagery and for digital imagery from space. The results are promising, although further research is required. Applications of the method are conceivable in topographic mapping and map revision, when a DTM is available and the establishment of classical control points is too expensive. This may especially be true for photogrammetric and remote sensing applications based on image data from satellites. Another possible application is the production of orthophoto maps, because for that task a DTM is needed anyway.

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