COMBINED POINT DETERMINATION USING DIGITAL DATA OF THREE LINE SCANNER SYSTEMS

Otto Hofmann
Department ZTA 2
Messerschmitt-Bölkow-Blohm GmbH
P.B. 801109, D-8000 Munich 80
Federal Republic of Germany

Franz Müller
Chair of Photogrammetry
Technical University of Munich
Arcisstr. 21, D-8000 Munich 2
Federal Republic of Germany

Commission III

Abstract

Three line opto-electronic scanner systems allow for digital image recording and three dimensional reconstruction of object points by a rigorous analytical compilation process. The paper summarizes the investigations, which have been performed up to now, to examine the geometric properties of three line scanner systems. Results from adjustments of simulated strips and blocks are given, and the dependence on flight and camera parameters including various arrangements of the CCD-sensors in the focal plane is shown. The use of recorded orientation parameters and of existing terrain models outlines the possibilities of combined point determination with digital three line imagery.

1. Introduction and Review

In recent years there has been a noticeable progress using linear array sensors for the purpose of digital image recording according to the push-broom scanning mode. The advantages of these sensors include precise geometric positioning of the detectors, high sensitivity and no moving optics (Thompson, 1979; Hofmann, 1982). Several systems, based on digital opto-electronic line scanners were or are in use: EOS (Hofmann and Seige, 1979), MOMS (Hofmann et al., 1980), SPOT (Chevrel et al., 1981), MEIS II (Gibson et al., 1983), MEOSS (Lanzl, 1986) or are proposed for future programs: DPA (Messerschmitt-Bölkow-Blohm GmbH, 1985), MOMS-02 (Ackermann et al., 1988). STEREOSAT (Welch and Marko, 1981) and MAPSAT (Colvocoresses, 1982) have been discussed.
The field of applications of these systems ranges from airborne to satellite missions. Concerning the number of sensors being used to generate different perspective views of the object we have to distinguish one, two and three line cameras.
This paper is concentrated on <u>three</u> line scanner systems. The object is simultaneously scanned by three linear CCD-sensors, which provide a forward, a downward and a backward view. Recording the object simultaneously with three sensors makes it possible to determine three dimensional object point coordinates and to reconstruct the exterior orientation.

First investigations, relating to the orientation of continuous strip imagery, have been performed by (Derenyi, 1973). He proposed the introduction of triple-channel recording to enable strip triangulation and scale transfer in connection with line images.
In 1982, a concept of a Digital Photogrammetric System (DPS) for producing digital elevation models and orthophotos by means of three line scanner imagery has been proposed, being a purely digital system from image recording to photogrammetric compilation (Hofmann et al., 1982). In the meantime, comprehensive investigations have been performed to analyse the geometric properties of the object reconstruction based on this system (Hofmann, 1985; Hofmann, 1986; Ebner and Müller, 1987). The used mathematical model has been interpreted as a special case of generalized combined point determination, which is able to process both, image coordinates of frame cameras and imagery of digital line cameras (Ebner and Müller, 1986). Therefore, all possibilities of combined point determination can be exploited in connection with line imagery, too.
Analytical strip adjustment based on the bundle solution in connection with fictitious error equations for the position and attitude parameters among neighbouring projective centers is described in (Konecny and Wu, 1986). An overview and a geometric analysis for image data of stereoscopic three line scanner systems is given in (Wu, 1986).
A different mathematical model for the evaluation of CCD line scanner images is presented in (Konecny et al., 1986). This model accounts for the central perspective along one or more lines and avoids high correlations between the unknown parameters of exterior orientation, which are partly formulated as additional parameters.
In this paper the principle of DPS is reviewed and the strategy for analyzing the geometric properties of this system is described. Results of selected computer simulations are given.

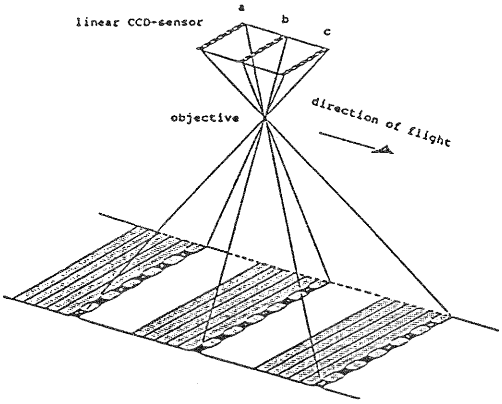
2. Digital Photogrammetric System (DPS) Based on a Three Line Scanner System

The process of combined point determination using digital data of three line scanner systems consists of the three main steps: image recording, determination of homologous points and model reconstruction.

2.1. Image Recording

A three line opto-electronic scanner contains in the focal plane(s) of one or more objectives three linear CCD arrays a, b and c. The sensors are oriented perpendicularly to the direction of flight. During the flight the sensors continously scan the terrain with a constant frequency, whereby three image lines are recorded. In consequence the terrain surface is covered by three image strips analogous to the push-broom principle. By the adaption of the read cycle frequency to the velocity of the camera carrier, the image scale and the size of the sensor elements, nearly quadratic ground pixels are generated (Fig. 1a). Generally, each object point is projected into three images per flight strip, the points at the beginning and at the end of the strip are projected into two images. If blocks with

20% or 60% sideward overlap are used, object points are projected into as many as six or nine images. In contrast to conventional aerial photogrammetry with frame cameras (Fig. 1b) the image recording is performed in dynamic mode. A great number of successive images, which consist of only three lines form three image strips. In general each three line image has its own set of parameters of exterior orientation.



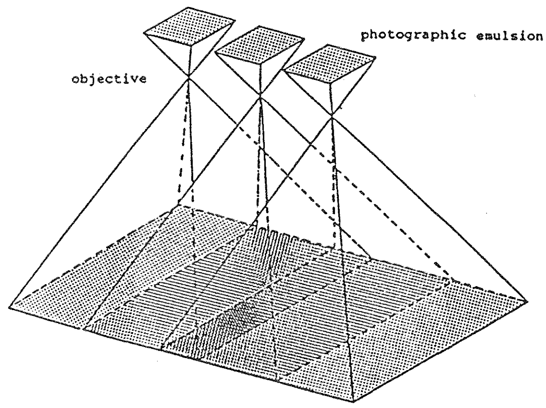


Image recording using a

Fig.1a: three line scanner Fig.1b: frame camera

2.2. Determination of Homologous Points

For the photogrammetric point determination based on the bundle solution, image coordinates of homologous points have to be measured. This task can be done either by a human operator or by image matching techniques. Procedures, developed for digitized or digital images of frame cameras (Förstner, 1984) can be used in connection with three line imagery, too. By applying interest operators, suitable points are selected in the image strip generated by the downward looking sensor and their corresponding points are determined in the two other image strips. Tests of digital image correlation within the MEOSS-project, using simulated triple stereoscopic imagery are given in (Lehner, 1986).

The result of these processes are the non-integer read cycle numbers d_j and the non-integer pixel numbers a_{ij}, b_{ij} or c_{ij} for the object point P_i in the sensor a_j, b_j or c_j of the image I_j. The corresponding image coordinates x_{ij}, y_{ij} are derived from a_{ij}, b_{ij} or c_{ij} and the calibrated location of the linear sensor arrays in the focal plane (for the notations see Fig.2).

2.3. Model Reconstruction

The simultaneous object point determination and reconstruction of the exterior orientation of three line scanner imagery based on the image coordinates of homologous points has been described in (Hofmann et al., 1982). For the analytical solution, three points are important.

a) The three linear sensors substitute in parts the image plane of a frame camera.
b) Threefold coverage of the object is given.
c) The parameters of the exterior orientation don't have to be calculated for each read cycle but can be interpolated within certain intervalls.

The model reconstruction can be performed based on the collinearity equations according to the bundle solution. Figure 2 represents the geometry of the imaging process. The condition of collinearity formulates the relationship between the observed image coordinates x_{ij}, y_{ij} and the unknown object point coordinates $\hat{x}_i$, $\hat{y}_i$, $\hat{z}_i$ of the point P_i and the unknown parameters of exterior orientation $\hat{x}_j$, $\hat{y}_j$, $\hat{z}_j$, $\hat{\omega}_j$, $\hat{\phi}_j$, $\hat{\kappa}_j$ of the image I_j:

$$x_{ij} + \hat{v}_{xij} = -f_j \frac{\hat{r}_{11j}(\hat{x}_i-\hat{x}_j)+\hat{r}_{21j}(\hat{y}_i-\hat{y}_j)+\hat{r}_{31j}(\hat{z}_i-\hat{z}_j)}{\hat{r}_{13j}(\hat{x}_i-\hat{x}_j)+\hat{r}_{23j}(\hat{y}_i-\hat{y}_j)+\hat{r}_{33j}(\hat{z}_i-\hat{z}_j)}$$

$$y_{ij} + \hat{v}_{yij} = -f_j \frac{\hat{r}_{12j}(\hat{x}_i-\hat{x}_j)+\hat{r}_{22j}(\hat{y}_i-\hat{y}_j)+\hat{r}_{32j}(\hat{z}_i-\hat{z}_j)}{\hat{r}_{13j}(\hat{x}_i-\hat{x}_j)+\hat{r}_{23j}(\hat{y}_i-\hat{y}_j)+\hat{r}_{33j}(\hat{z}_i-\hat{z}_j)}$$

with:

x_{ij}, y_{ij} = image coordinates of point P_i in image I_j

$\hat{v}_{xij}$, $\hat{v}_{yij}$ = residuals of x_{ij}, y_{ij}

f_j = calibrated focal length of image I_j

$\hat{x}_i$, $\hat{y}_i$, $\hat{z}_i$ = unknown object coordinates of point P_i

$\hat{x}_j$, $\hat{y}_j$, $\hat{z}_j$ = unknown object coordinates of the perspective centre of image I_j

$\hat{r}_{11j}..\hat{r}_{33j}$ = unknown elements of the rotation matrix $\hat{R}_j$ of image I_j with three rotation parameters $\hat{\omega}_j, \hat{\phi}_j, \hat{\kappa}_j$

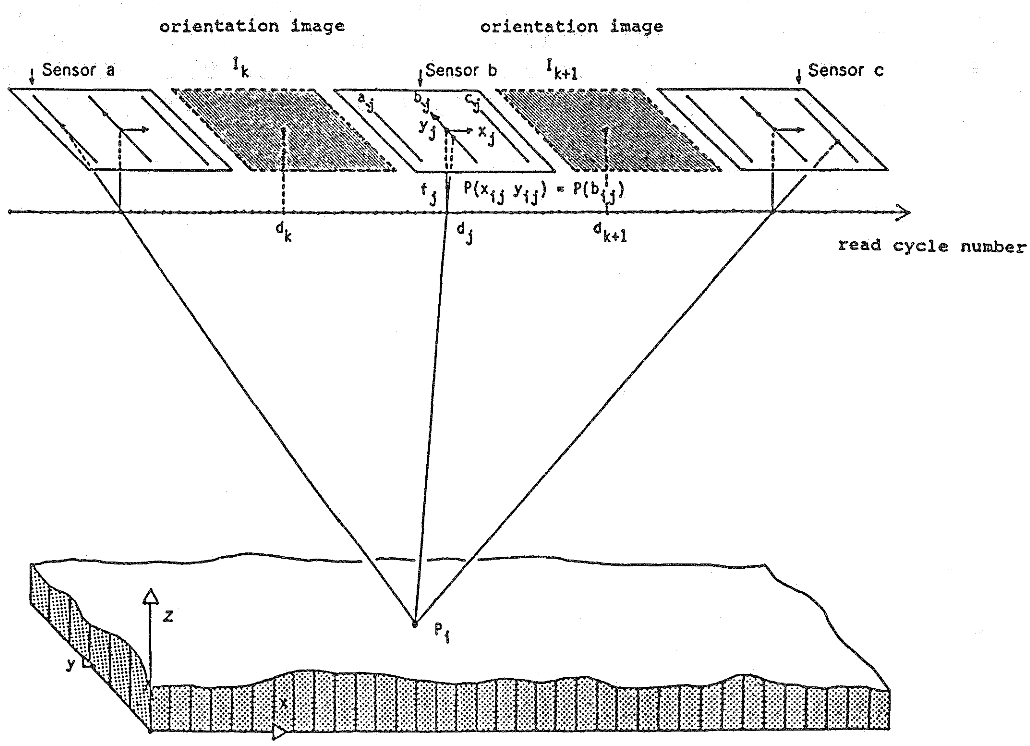


Fig. 2: Geometry of the imaging process

Since it is not possible to determine the exterior orientation of all images I_j, so-called orientation images or update points I_k (k=1...l) are introduced. The exterior orientation is in fact only computed for the images I_k. The parameters of an image I_j are then represented as functions of the parameters of neighbouring orientation images. In case of linear functions we obtain:

$$\hat{x}_j = \frac{d_{k+1} - d_j}{d_{k+1} - d_k} \hat{x}_k + \frac{d_j - d_k}{d_{k+1} - d_k} \hat{x}_{k+1}$$

$$\vdots$$

$$\hat{\kappa}_j = \frac{d_{k+1} - d_j}{d_{k+1} - d_k} \hat{\kappa}_k + \frac{d_j - d_k}{d_{k+1} - d_k} \hat{\kappa}_{k+1}$$

with:

$\hat{x}_j \ldots\ldots \hat{\kappa}_j$ = unknown parameters of image I_j

$\hat{x}_k \ldots\ldots \hat{\kappa}_k$ = unknown parameters of orientation image I_k

$\hat{x}_{k+1} \ldots \hat{\kappa}_{k+1}$ = unknown parameters of orientation image I_{k+1}

d_j = read cycle number of orientation image I_j

d_k, d_{k+1} = read cycle numbers of orientation images I_k, I_{k+1}

The image coordinates are considered as observations of a least-squares adjustment, and together with additional control information the adjustment is performed in the well-known manner of analytical photogrammetry. The unknowns of the adjustment are the 3*n coordinates of the object points P_i (i=1..n) and the 6*l parameters of the orientation images I_k (k=1..l). In contrast to the classical photogrammetric bundle method, in this case the collinearity equations contain the unknowns of <u>two</u> orientation images. Therefore we may speak of generalized photogrammetric point determination.

2.4. General Control- and Object Information

Within photogrammetric point determination non-photogrammetric information is necessary to define the parameters of a datum and to improve accuracy and reliability. In combination with or instead of control points various control- and object information may be used (Ebner, 1984). The processing of non-photogrammetric data in a combined block adjustment is described in (Strunz, 1986) and is in principle applicable to three line imagery, too.

In connection with line imagery especially information about the parameters of the exterior orientation is of interest, which may be derived either from navigation systems or from orbit models within space missions. The possibilities of using data from the Global Positioning System (GPS) for the position parameters within aerotriangulation are discussed in (Ackermann, 1986). The application of inertial navigation systems (INS) with airborne line imagers is investigated in (Gibson, 1985).

An expansion of the mathematical model of the DPS concerning the use of additional data from INS and GPS systems is described in (Ebner and Müller, 1987).
Models for satellite orbits and attitude dynamics are investigated in (Drescher et al., 1986). An application within the MEOSS project is discussed.
The effect of aircraft attitude changes on the image geometry of linear sensors has been analyzed by (Dorrer, 1978). The proposal to use image inherent information for supporting the reconstruction of the exterior orientation is promising within three line systems.

3. Analysis of the Geometric Accuracy of Three Line Scanner Systems

3.1. Computer Simulations

Based on the mathematical model described in chapter 2.3 computer simulations have been performed to investigate geometric aspects of the three dimensional object reconstruction with digital data of three line scanner systems. The computations have been carried out at the Messerschmitt-Bölkow-Blohm GmbH and at the Chair of Photogrammetry at Technical University Munich with independently developed software packages. As a means for the analysis, the theoretical standard deviations of the unknowns of the adjustment are used. Formulating the mathematical model according to the rules of an adjustment of observations the covariance matrix of the unknowns is given by:

$$\hat{K}_{\hat{x}\hat{x}} = \hat{\sigma}_0^2 (A^T P A)^{-1}$$

with:
$\hat{x}$ .... vector of the unknowns
A .... design or Jacobian matrix
P .... weight matrix of the observations
$\hat{\sigma}_0^2$ ... à posteriori reference variance

The main diagonal elements of the covariance matrix yield the theoretical standard deviation $\hat{\sigma}_{\hat{x}i}$ for an unknown $\hat{x}_i$ with:

$$\hat{\sigma}_{\hat{x}i} = \mathrm{sqrt}(\mathrm{diag}(\hat{K}_{\hat{x}\hat{x}})_i)$$

In the simulations the adjustment is performed with computer generated and error-free observations. Therefore, instead of the à posteriori estimate of the reference variance $\hat{\sigma}_0^2$ the σ_0^2 à priori is used for the calculations of the standard deviations. The σ_0 à priori is chosen adequate to the expected image error, which is influenced by calibration, correlation, and the effect of interpolation errors.
The interpolation errors are due to the approximation of the real variations of the exterior orientation parameters between neighbouring orientation images by a functional model (e.g.linear interpolation). By adapting the distance between the orientation images to the flight characteristics of the camera carrier, and by using a stabilized suspension device for the scanner within airborne missions, these errors can be reduced to a certain extent. In space applications they are small, because of the low-frequent changes in the orientation parameters.

Whereas σ_0 à priori is a scale factor, the design matrix contains information about the geometric quality of the process. Computer simulations performed in this way and yielding an estimation of the theoretical standard deviations are a powerfull tool to investigate the geometric characteristics of complex processes, which cannot be interpreted in a direct analytical way.
In the discussed investigations especially the standard deviations $\sigma_{\hat{x}i}, \sigma_{\hat{y}i}, \sigma_{\hat{z}i}$ of the unknown object point coordinates $\hat{x}_i, \hat{y}_i$ and $\hat{z}_i$ were analysed, but the errors of the unknown parameters of orientation are of interest, too.
For the purpose of comparison of the accuracy potential of different configurations, for most of the investigations the so-called accuracy limits have been calculated. Assuming error-free parameters of exterior orientation for all images the process of bundle adjustment is reduced to an intersection and the standard deviations of the object point coordinates are in this case a function of the image error and the geometry of the ray intersection.

3.2. Analytical Approach

For critical configurations, which lead to a singular system of normal equations, an analytical analysis of the design matrix A can be performed and interpreted. The normal equation matrix A^TPA has a rank deficiency, if the columns of the design matrix A are not linearily independent. Using simulated data of a three line camera with parallel sensors derived from an undisturbed straight forward flight above horizontal terrain the system becomes singular, if the ratio between the baselength and the distance of the orientation images results in an integer value. This effect can be interpreted by an analysis of the design matrix (Ebner et al., 1988b).
Preceding theoretical considerations (Hofmann, 1986) pointed out, that instabilities of the model reconstruction are possible, due to the use of three line cameras with parallel sensor arrangement. Hofmann proposed a special arrangement of the sensor lines in the focal plane of the camera: the outer lines are not parallel to the central line, but they are rotated or form an arrow (Fig. 3). By this way an improvement of the geometry of the strip model is possible.

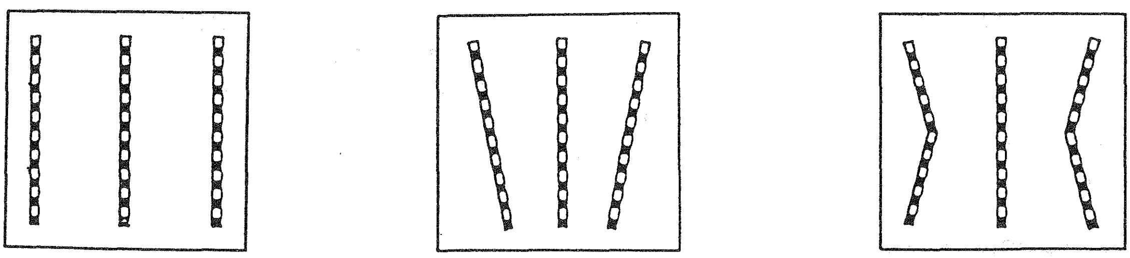


Fig. 3: Arrangements of the CCD-sensors in the focal plane

4. Results of Selected Computer Simulations

The geometric accuracy of the three dimensional object reconstruction using digital data of three line scanner systems is controlled by various parameters:

a) distance between orientation images,
b) distribution of object points in position and height,
c) strip length, strip width (strip adjustment),
d) block arrangement (block adjustment),
e) camera geometry (calibrated focal length, sensor arrangement and sensor distance),
f) control and object information.

To study the influence of these parameters on the model reconstruction fictitious observations for image coordinates of homologous points, based on the imaging process of three line cameras have been computed. The camera- and flight parameters as well as the object point distribution have been varied.

4.1. Strip Adjustment

Results of comprehensive studies concerning the accuracy of three line imagery strip adjustment are presented in (Hofmann, 1986). The most important scientific findings are shortly summarized.

The choice of an appropriate distance between two neighbouring orientation images is of great importance for the compilation of three line imagery. A greater distance yields better accuracy of point determination, if the image errors are assumed constant. In practical operation, however, the image error increases by the interpolation errors (see chapter 3.1) , if the selected interval is not adapted to the movements of the carrier.

Short distances require a greater number of homologous points and may even lead to poor geometry of the strip model. In this case a stabilization can be obtained by using a camera with rotated outer sensors (see chapter 3.2).

In the simulations the object points have been arranged in several chains parallel to the direction of flight. A high density of object points within the chains increases the accuracy of the model reconstruction. A minimum of three chains is necessary at least. A great number of chains affects the accuracy only to a certain extent.

To build up a stabil model, the strip length has to be greater than three baselengths (baselength = distance between the forward or backward looking sensor and the nadir looking sensor).

The ratio of the strip width to the flying height also influences the accuracy. A small strip width increases the errors. In the extreme case the accuracy of the model reconstruction is influenced in a way that additional information for the parameters of the exterior orientation becomes necessary (Ebner et al., 1988a). This effect, however, is not due to the described model for the compilation of three line imagery but a general geometric problem.

4.2. Block Adjustment

The advantages of block adjustment of three line scanner imagery have been investigated in (Ebner and Müller, 1987). In this study a block, consisting of two strips arranged like a cross, was simulated. The computations showed that in this case a perfect stabilization can be obtained even with parallel sensors. Further investigations (Müller and Strunz, 1987) pointed out that if the common area is larger than one baselength, a stabilization over the entire strips is achieved, even in the parts which are not projected into both strips. Studies concerning this property, are also mentioned in (Drescher et al., 1986). This effect is important for the MEOSS project were a three line scanner with parallel sensors is used and overlapping strips can be recorded. In (Ebner et al., 1988a) special simulations for this mission are given.

4.3. Control- and Object Information

A further point of investigations is the use of control- and object information. There are four subjects which are of special interest:
a) distribution of control points,
b) use of data from Inertial Navigation Systems (INS), and from the Global Positioning System (GPS),
c) use of orbit models,
d) use of a given Digital Terrain Model (DTM).
Control points should be arranged in the threefold area of the image strips. Within long strips additional and well distributed control points should be used to improve accuracy and reliability.
In (Ebner et al., 1988a) the influence of additional observations for the position and attitude parameters, derived from navigation systems and/or orbit models are discussed for the space projects MEOSS and MOMS-02.
The use of a given digital terrain model (DTM) as control information was investigated at first in (Ebner and Müller, 1986) and showed that in principle classical control information can be replaced by an available DTM. Further investigations, based on data of frame cameras (Müller and Strunz, 1987; Ebner and Strunz, 1988) pointed out the possibilities of this method.

5. Conclusions

The investigations demonstrate the principal applicability of three line scanner systems for precise photogrammetric point determination. By using the possibilities of combined adjustment and by applying three line cameras with proper design, geometric problems due to the image recording analogous to the push-broom principle can be overcome. When the model reconstruction is performed, the line imagery may be used for various tasks: generation of DTMs, production of orthophotos, digital or analytical stereo and mono compilation. The use of three line scanner systems in aircraft or spacecraft allows for topographic and thematic map production in a wide range of scales.

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