Processing and Display of Three-Line Imagery at a Digital Photogrammetric Workstation

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ABSTRACT

This paper deals with the integration of three-line imagery into digital photogrammetric workstations. Specific aspects of the integration including the orientation procedure, stereo viewing and image point measurement are presented. The implementation of these aspects into the digital stereoplotter PHODIS ST from Carl Zeiss is dicussed. The results of first tests using MOMS-02 imagery shows the applicability of the implemented algorithms.

KURZFASSUNG

Im vorliegenden Beitrag wird die Integration von Dreizeilenbilddaten in digital photogrammetrische Arbeitsstationen behandelt. Es werden spezielle Aspekte wie z.B. das Orientierungsverfahren, die Stereobetrachtung und die Bildpunktmessung diskutiert. Die Implementierung dieser Aspekte in den digitalen Stereoplotter PHODIS ST von Carl Zeiss wird beschrieben. Die Ergebnisse von ersten Tests mit MOMS-02 Bilddaten zeigen die Anwendbarkeit der implementierten Algorithmen.

1 INTRODUCTION

Processing of optoelectronic sensor data at a digital photogrammetric workstation (DPWS) is an increasingly common demand in practice. Today such data is generally provided by spaceborne sensors. In future, however, airborne sensor data will become more and more relevant. Since the improving ground resolution of the sensors increases the information content of these scenes and thus the image detail considerably, usage will become more common. The most advanced sensor concept makes use of 3 linear CCD arrays. In this case stereo images are acquired quasi simultaneously. The 3 CCD-lines are imaging different terrain at the same time, as the sensor platform moves.

The demand for a „stable three-line geometry" dates back to the year 1970. In his thesis at the Univerity of Brunswick (see Konecny 1996, p. 48), Eugene Derenyis came to the conclusion that only convergent three-line scanning would allow sufficiently precise determination of the mutual orientations of line images.

This idea was implemented successfully in 1993 for the first MOMS-02/D1 mission. Later stereoplotting of the data from this mission has demonstrated the field of usability in cartography. Dorrer (1995) has shown that the data can be plotted down to a map scale of 1:25000. The relevance of high resolution remote sensing data is shown by Konecny (1996), who states that especially in third-world countries the use of such sensors is the only feasible way to achieve cartographic inital and updating measurements in the forseeable future.

The benefits of three-line imagery can be used in particular with a DPWS. This conveniently allows combining the three image strips into displayable stereo scenes, for example. The integration of three-line imagery in an existing DPWS makes sense because existing structures can be used. Procedures such as image and project data manangement, image coordinate measurement, stereoimage display techniques and functions for manual and automatic measurement in stereoscenes may be mentioned.

Currently, further missions with three-line sensors are beeing prepared. The Russian MARS96 mission merits special mention. The German optoelectronic High Resolution Stereo Camera (HRSC) and Wide-Angle Optoelectronic Stereo Scanner (WAOSS) will be used in 1997-1999 to survey the Mars surface in three dimensions by means of digital photogrammetry (Ebner et al. 1994). For the processing of the image data from this mission, the PHODIS ST stereoplotter from Carl Zeiss (Dörstel 1995; Dörstel and Willkomm 1994) will be used for stereoscopic image display and interactive point mesurement. For topographic mapping, the PHOCUS photogrammetric and cartographic data acquisition system from Carl Zeiss will be used.

Methods developed for three-line imagery should in principle also be suited to be used with MOMS-02/D2 or MOMS-2P/PRIRODA data.

This paper describes the conceptional requirements for processing of three-line images at DPWS. Apart from the used orientation and display methods, the processing procedures are illustrated by describing the integration in PHODIS ST.

2 PROCESSING OF THREE-LINE IMAGERY

2.1 Digital Photogrammetric Workstations

As defined by Heipke (1993), Digital Photogrammetric Workstations are systems consisting of hardware and software for deriving GIS/CAD input data and other photogrammetric products from digital imagery using manual, semi-automatic and automatic techniques. Compared with analytical plotters DPWS offers numerous advantages, e.g. the automation of substantial parts of the photogrammetric processing chain, simultaneous processing of any number of images, integration of image processing facilities and stereo viewing of several operators simultaneously. Besides these components, DPWS should be equipped with subpixel measuring facilities and should allow for continuous roaming, zooming and rotating images. The stereo viewing on the screen enables the human operator to interactively measure tie and control points, to check the correctness of the measurements and to perform stereo plotting. Comprehensive descriptions of the various design and application aspects of DPWS can be found in Dowman et al. (1992) or Heipke (1993, 1995, 1996).

The existing commercial DPWS are designed for images acquired by frame cameras. For processing of digital three-line imagery, special adaptations of the DPWS software are required. The main requirements are:

- Consideration of the three-line geometry
- At least 3 images should be processed simultaneously

In the past some procedures have been developed for the stereophotogrammetric processing of SPOT (Dowman et al. 1987, Kratky 1989) and MOMS-02/D2 (Hoch and Dorrer 1992, Dorrer et al. 1995) imagery on analytical plotters. To this end, the digital images must be first of all converted to hardcopy images. Although the tests carried out with the analytical plotters were successful, the future processing baseline will be fully digital. First attempts on digital stereo processing of MOMS-02/D2 imagery were based on standard SUN SPARC workstations with a special graphics accelerator (Siebe and Schiewe 1993). These attempts were not really successful due to hardware problems.

2.2 Processing Chain

For better understanding of the role of the DPWS, the entire chain for the photogrammetric processing of three-line imagery is shown in Figure 1.

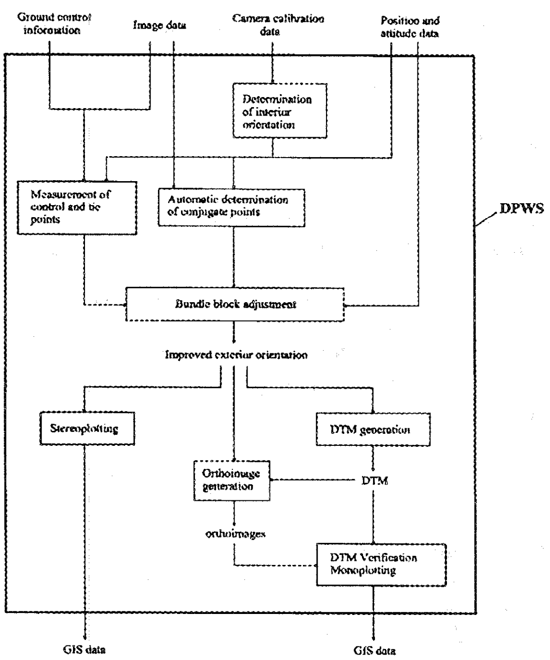

Figure 1: DPWS within the photogrammetric processing chain

The input data for photogrammetric processing are image data, camera calibration data, preprocessed position and attitude data as well as ground control information. Conjugate points, especially control and tie points, which are visible in two or more images, establish a link between images taken at different camera exposure stations and thus provide the basic information for photogrammetric processing of the three-line imagery. One of the DPWS basic tasks respresents the manual (interactive) or semi-automatic measurement of control and tie points in the images.

By means of multi-image matching a sufficient number of conjugate points can be determined automatically. The bundle block adjustment combines all data and delivers improved exterior orientation parameters for the images. With the help of the improved exterior orientation DTM and orthoimage generation can easily be accomplished. Stereoplotting, DTM verification and monoplotting are other basic tasks of the DPWS, which provide 3-dimensional data for geoinformation systems (GIS).

2.3 Consideration of the Three-Line Geometry

Images acquired by three-line cameras are characterized by central projection in the direction of the CCD arrays and by parallel projection perpendicular to that direction. Thus the laws of perspective geometry are valid only in the direction of the CCD arrays. Consequently, the well-known models for the interior and exterior orientation of frame images have to be extended for the treatment of three-line imagery.

Interior Orientation. As depicted in Figure 2 the two forward and aft looking (stereo) lenses of the MOMS-02 camera are inclined (app. 20 degrees) with respect to the nadir looking lens. The CCD arrays of HRSC are mounted on different sensor plates which are tilted with regard to the central plate. For optimal focusing, moreover, the CCD arrays of WAOSS are nominally not arranged in a common focal plane, but are slightly shifted in z-direction.

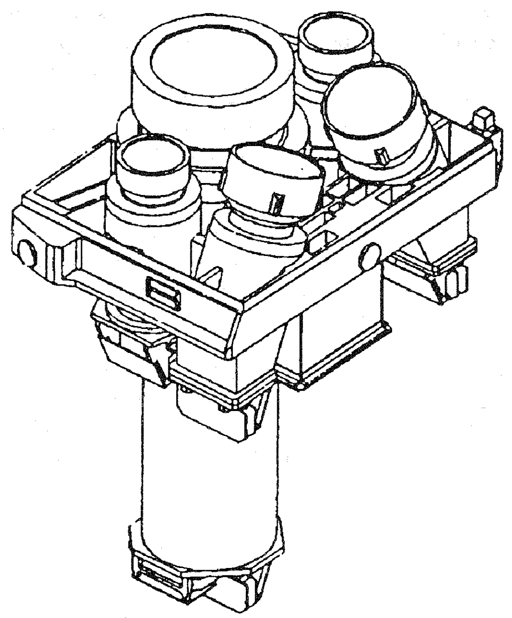

Figure 2: MOMS-02 Platform

In principle, each CCD array located in the focal plane of one or more camera lenses can therefore be interpreted as a separate sensor with a separate image coordinate system (Ebner et al. 1994, Ohlhof and Kornus 1994). For the outer CCD arrays an additional 6 parameter transformation is introduced to model the displacements dx, dy, dz of the projection centers and the rotations dω, dφ, dκ of the image coordinate system with respect to the image coordinate system of the central CCD array. Besides these 12 parameters, the image coordinates x_0, y_0 of the principal point and the calibrated focal length c are incorporated for each lens. Thus, the interior orientation of a three-line camera is described by 15 or 21 parameters in case of 1 and 3 lenses respectively. Normally these parameters will be treated as constants in the bundle adjustment, determined by geometric camera calibration in the laboratory.

Exterior Orientation. Due to the dynamical mode of image recording, each image line has its own exterior orientation. The exterior orientation parameters, however, cannot be estimated for every single image line in the bundle adjustment. Instead, orbit models and polynomial functions are used to describe the position and attitude behaviour of the camera platform (Ebner et al. 1994, Ohlhof 1995). Note, that different approaches are applied for airborne and spaceborne imagery respectively, because the spaceborne trajectory is smooth and proceeds along an orbit, whereas the airborne trajectory jitters.

In most cases, precise a priori information about the exterior orientation of the three-line images is available. GPS and tracking data provide position information. Attitude information can be derived from IMU (Inertial Measurement Units) data.

Object coordinate system. In satellite photogrammetry a global object coordinate system with the origin in the center of mass of the planet is often used. On the other hand, the operator at the DPWS prefers a local object coordinate system where X,Y are the planimetric and Z are height coordinates. Note, that both coordinate systems are cartesian ones. The global coordinate system can be easily transformed into the topocentric coordinate system by defining a reference point with given (X,Y,Z) coordinates in both systems. The reference point may have the topocentric coordinates (0,0,Z=H), where the X-axis is parallel to the flight direction, the Y-axis is parallel to the direction of the CCD-arrays, and the Z-axis points upwards in parallel to the optical axis, completing the right-handed system.

Model coordinate system. The movement of the 3D cursor is related to the model coordinate system. For a pair of frame images the origin of the model coordinate system is usually defined as the average of the object coordinates of the two projection centers. In case of three-line imagery, the origin of the model coordinate system may be located in the middle of the strip. If very long strips have to be processed (e.g. one WAOSS strip runs from the Mars north pole to the south pole), piecewise models may be set up taking the planetary curvature into account.

2.4 Stereo Viewing

Stereo viewing is indispensable for the high precise measurement of image points, stereoplotting and DTM verification. It requires the knowledge of the orientation parameters, either in connection with original images or to generate epipolar images.

For stereo viewing the DPWS is equipped with the following hardware components (Heipke 1993):

- Graphics subsystem including a true color (24 bit/pixel) image memory and non-destructive overlay for continuous zoom, rotation and subpixel roaming
- High resolution stereo color monitor
- Comfortable 3D mouse

The necessary image separation is achieved through temporal separation, where the two images are alternating displayed and synchronized with a shutter device. The vertical resolution of the displayed images, however, is only half of the horizontal one due to limitations of the analog electronics in the monitor. The refresh rate of the stereo monitor having a typical size of 1280x1024 pixels is mostly 120 Hz (60 Hz per image) in a so called interlaced mode.

In case of three-line imagery, the following requirements have to be considered :

- Storage of at least 3 images in the image memory in order to switch between any two of the three images of a strip arbitrarily
- Display of several overview images in mono to select the stereo pairs
- Stereo viewing and measurement with the highest image resolution
- Individual zoom for each image, e.g. MOMS-02 nadir + for-/backward (factor 3) or HRSC + WAOSS (factor 8)

For stereoscopic viewing a relative movement between the image pair and the cursor is necessary, that can be realized

- either by cursor movement in front of fixed images
- or by roaming images behind a fixed cursor in the middle of the screen.

The latter case is more comfortable for the human operator than the first one, because he can freely move through the whole image in the same way as in an analytical plotter. This, however, requires a powerful hardware, to ensure that the images can be moved smoothly and simultaneously in real-time.

In order to obtain a stereoscopic impression, the y-parallaxes in the images have to be removed. In the mode fixed images moving cursor (FIMC) the original images must be previously transformed to epipolar images, whereas epipolar images as well as original images can be used in the mode moving images fixed cursor (MIFC). Both the generation of epipolar images and the utilization of original images require the knowledge of the orientation parameters.

Epipolar images can easily be generated for frame images characterized by central perspective geometry. In case of line-scanner imagery, however, each individual image line must be shifted in y-direction and may be also in x-direction as a function of the 6 orientation parameters, which must be given for each image line. A resampling of the original grey values can be avoided, if the image lines are shifted by integer steps.

Since original images are treated, they are shifted by Δx(left image), Δy(left), Δx(right), Δy(right) using the real-time loop described in section 2.5. Note, that the shift values Δx and Δy are applied for the complete image at the time. In case of line-scanner imagery these shift values remove the y-parallaxes actually only for the central image lines in the left and right images respectively, which comprise the cursor position. This model permits a sufficient visual stereo impression in case of spaceborne three-line imagery, due to the smooth trajectory of the camera carrier. The flight behaviour of an aircraft, however, is usually quite fitful, leading to a disturbed stereo impression while using original images. To this end, a geometric image transformation with a resampling of the original grey values has to be performed, that can be done either (preferably) in real-time or as off-line process. The stereo viewing of airborne three-line imagery is thus based on preprocessed instead of original images.

2.5 Real-Time Loop

The stereoscopic viewing in the mode MIFC requires a continous connection beween the object/model coordinate system represented by the cursor, and the two corresponding image coordinate systems represented by the associated floating marks. Thus, all transformations between the object, model and image coordinate system are carried out within the real-time loop.

Starting with the given model coordinates of the actual cursor position and approximate exterior orientation parameters of a certain image line, the model coordinates are transformed to image coordinates (x,y) using the collinearity equations. In case of line images the x component of the image coordinate is equal to zero, if the correct image line has been found. From the computed x coordinate a new image line z is derived taking the pixel size of the CCD arrays into account. In the next step, the model coordinates are transformed again to image coordinates using the orientation parameters of the new image line. The procedure is repeated until the image line shift Δz is below a threshold (e.g. 0.1). Normally 3 iterations are sufficient. The image movement values are calculated from the final image coordinates. Note, that the loop is preformed for each image separately. The principle of the real-time loop is shown in Figure 3.

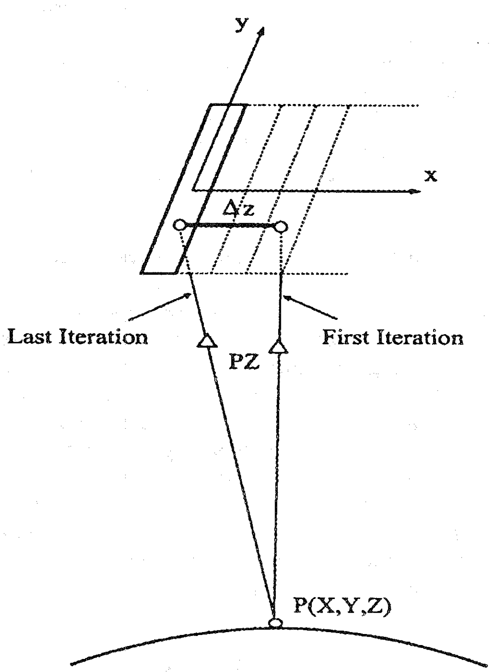

Figure 3: Principle of iterative real-time loop

2.6 Image Point Measurement

As mentioned above, one of the main DPWS features is the ability to measure image coordinates of control and tie points with subpixel accuracy. The required subpixel accuracy is achieved (see e.g. Heipke 1995)

- either by a zoom function which enlarges the image pixels, but not the cursor,
- or by roaming the images by a fraction of the image pixel using on-line resampling without zoom.

The first possibility is used in the mode FIMC, whereas the second one is used in connection with MIFC.

In Table 1 different manual and semi-automatic methods for the point measurement in a strip consisting of 3 images taken by a three-line camera are listed. If the measurement shall be carried out in stereo, the orientation parameters are required. The current realization status with regard to the digital stereoplotter PHODIS ST is given in the last column of the table and described in more detail in chapter 3.

The preferred procedure starts with the stereoscopic measurement of the point in image 1 and 2. After that, the point is automatically transferred from image 1 to image 3 and also from image 2 to image 3. For automatic point transfer digital image matching techniques are applied (Tsingas 1992, Gülch 1994). Note, that the image coordinates in image 3 are measured twice and independently. This consistency check can be done in all cases except in case 4, where the point is measured in mono in all 3 images.

Priority	Measuremet method	Measuremet procedure	Orientation parameters required	Realized in PHODIS ST
1	semi-automatic	stereo 1-2, point transfer to 1 3, 2 3	yes	no
2	manual	stereo 1-2, 1-3, 2-3	yes	in preparation
3	semi-automatic	1 mono, point transfer to 1 2, 1 3, 2 3	no	yes
4	manual	1 mono, 2 mono, 3 mono	no	yes

Table 1: Measurement of control and tie points in three-line images at DPWS

2.7 Stereoplotting

One of the main applications of DPWS is stereoplotting, comprising

- the thematic image evaluation for generating and updating topographic maps,
- the acquisition of 3D GIS data,
- the DTM verification.

After building up the stereo model, three-line imagery can be treated in the same way as images taken by conventional frame cameras.

3 IMPLEMENTATION IN PHODIS ST

The core tasks of an DPWS can generally be described as shown in Figure 1 :

- Measurement of control and tie points for image orientation
- Bundle block adjustment
- Stereoplotting

In an existing prototype, the tasks of control point measurement as well as stereoplotting are carried out by PHODIS. Bundle block adjustment for three-line imagery is carried out by an external program (Ohlhof 1995). This program uses the control and tie point measurement data supplied by PHODIS and the approximate exterior orientation data. The result is the adjusted exterior orientation of the individual lines. The used bundle block adjustment program was developed by the Technical University of Munich and can in principle be integrated into the PHODIS environment.

Processing of line-scanner data essentially corresponds to the classic method. The particularities and some implementation details are described below. The following items are covered :

- Sensor data management
- Model setup
- Point measurement for orientation process
- Stereoplotting

The processing of three-line data in PHODIS starts with the definition of a *sensor platform* carrying at least three sensors. Figure 2 illustrates the MOMS-02 platform. The spatial location of each sensor on the platform can be defined relative to a reference point. Up to 6 additional parameters are obtained that have to be managed for every sensor, namely a three-dimensional translation vector with the elements dx,dy and dz and the directions of the CCD array defined by the angles $d\omega$, $d\varphi$ and $d\kappa$. The individual sensors of a platform and the associated parameters (see section 2.3) are defined in PHODIS as regular cameras.

Model setup for three-line imagery allows the definition of 3 models for each strip. Normally the forward and aft look are combined into a stereo scene for stereoscopic viewing. However, to exploit the high resolution of the nadir look for high-precision stereoplotting, it makes sense to provide also for forward-look / nadir-look models and nadir-look / aft-look models. This involves the need to compensate the scale differences in the images resulting from the use of different camera focal lengths. PHODIS offers this option. The image scale differences of the two scenes can be adjusted by means of continous zoom.

The image coordinates of the tie and control points can be measured interactively or semi-automatically in PHODIS (see Table 1) using an Intensity-based least-Squares Matching (ISM) algorithm (IfP 1996).

Stereoscopic display of the model area and stereoplotting itself are based on the finally adjusted orientation parameters for the individual lines.

The stereoscenes can be processed with either one of two product versions of the stereoplotter :

- PHODIS ST 10 with MIFC
- PHODIS ST 30 with FIMC

For stereoscene setup, PHODIS ST 10 uses the original images and allows moving the images behind a fixed floating mark (MIFC), while in PHODIS ST 30 the floating mark is moved over the preprocessed epipolar image pair (FIMC). Further particularities of PHODIS ST 10 are the independent continous zoom for the two images and subpixel-accuracy positioning with real-time resampling in the greyscale or color imagery. Scale adjustment during processing is especially relevant for the plotting of three-line or terrestrial imagery.

During *stereoplotting* of line imagery, the parallel prespective in the flight direction requires accounting for a special geometric model. Since each image line has a separate exterior orientation the required time for computing and moving to a position is immense (see real-time loop).

In PHODIS ST, the 3D mouse (P-Mouse) supplies motion pulses every 20 msec. This high frequency ensures jerk-free and precise positioning. The motion pulses act on the so-called model coordinate system (see section 2.3). In the real-time loop, the corresponding positions in the object coordinate system, the photo coordinate system, and the pixel coordinate system are determined for each incoming motion pulse. The position obtained in this way is used to create the stereoscene in the MIFC case. During interactive measurement, two transformation cases are distinguished :

- Point measurement
- Move to a position

These cases differ fundamentally. During *point measurement*, the two pixel positions are known. The exterior orientation of the two lines can be accessed directly and the associated positions in the model and object coordinate systems are determined in one step.

When *moving to* a point, the position in the image space has to be determined iteratively by the real-time loop as described in more detail in section 2.5. Iterative computation for moving to a position has to be done in the real-time loop of the stereoplotter and is therefore subject to the high time requirement of 50 complete iteration cycles per second. Measurements made with SUN SPARC 20 computer showed for the used geometric model that one single successful iteration cycle can be performed in about 1 msec.

When points are to be measured, the coordinates are transformed in the stereoplotter. The linked data acquisition system only receive the object coordinates. However, if vectors are superimposed in the stereoscene, the coordinates are transformed by the linked program. Since PHODIS supports the linkage of various data acquisition systems, special attention has been paid to this fact. The functions required for coordinate transformation have been included in a program library where they are provided to both, the attached measuring program and the PHODIS system. By implementing modular transformation functions, it is furthermore possible to support different program packages with identical transformation geometries, but without modifying the programs specifically for three-line geometry.

4 CONCLUSIONS

Three-line geometry has been integrated sucessfully in the real-time loop of PHODIS ST. Convenient processing of this data with a digital photogrammeric workstation is possible by use of this standard product. Workflow optimization is relatively easy, e.g. by integrating the bundle block adjustment for three-line imagery directly in the PHODIS orientation process. Practical experiences with the system presented here will be obtained by compiling from MOMS-02, HRSC and WAOSS data.

Past obstacles in the workflow such as restrictions on the processing speed of the computer and the available graphical subsystems as well as the digital-analog conversion of the image data have been overcome. Thus the spectrum of the image data that can be processed with the standard product PHODIS ST has been expanded.

Still unresolved is the optimum use of the information content of three-line images. This could be done by matching in the third image (e.g. HRSC channel).

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