ORIENTATION OF SATELLITE AND AIRBORNE IMAGERY FROM MULTI-LINE PUSHBROOM SENSORS WITH A RIGOROUS SENSOR MODEL

Daniela Poli

Institute of Geodesy and Photogrammetry, ETH Zurich, 8093 Zurich, Switzerland- daniela@geod.baug.ethz.ch

Commission I, WG I/5

KEY WORDS: Pushbroom, Sensors, Modelling, Orientation, Self, Calibration

ABSTRACT:

Today CCD linear array scanners are widely used on satellite, airborne and helicopter platforms to provide images with along track stereo viewing. For the orientation of this kind of imagery, models based on the rigorous description of the acquisition geometry, on rational polynomial functions or on affine transformations are used. An overview is presented. Among these approaches, the model developed at the Institute of Geodesy and Photogrammetry (IGP), ETH Zurich, belongs to the class of rigorous models and is applicable to a wide class of pushbroom sensors carried on satellite, airplane and helicopter. The model can be used with single-lens and multi-lens sensors with synchronous and asynchronous stereo acquisition. The sensor position and attitude are modelled with 2nd order piecewise polynomials depending on time. Additional pseudo-observations allow the reduction of the polynomial order from 2 to 1 if the trajectory allows it. In case of sensors carried on aircraft, the observations from GPS and INS instruments are integrated in the piecewise polynomials and are corrected from constant shifts ans misalignments between the GPS and INS local systems and the camera one and systematic errors contained in the observations. A self-calibration is also included for the corrections of radial and decentering lens distortions, principal point(s) displacement, focal length(s) variation and CCD line(s) rotation in the focal plane. Using a minimum of 6 Ground Control Points (GCPs) and, additionally, Tie Points (TPs), the external orientation and self-calibration parameters, together with the TPs ground coordinates, are estimated in a least-square adjustment.

In order to demonstrate the model flexibility and potentials, different imagery from pushbroom sensors (TLS, EROS-A1, SPOT-5/HRS, ASTER, MOMS-02, MISR) have been oriented. In this paper a summary of the results obtained are presented and discussed.

1. INTRODUCTION

CCD linear array sensors, also called linear scanners, are widely used for the acquisition of images at different ground resolution for photogrammetric mapping and remote sensing applications. They scan the ground surface with an array of CCD elements in pushbroom mode. The image is formed by a side-to-side scanning movement as the platform travels along its path.

CCD linear array sensors for remote sensing and photogrammetric applications are usually mounted on aerial and satellite platforms. Aerial platforms are primarily stable wing aircraft, but also helicopters are used. Acquisition from airborne sensors are often used to collect very detailed images and facilitate the collection of data over virtually any portion of the Earth's surface at any time. In space, the acquisition of images is sometimes conducted from the space shuttle or, more commonly, from satellites for Earth Observation (EO). Because of their orbits, satellites permit repetitive coverage of the Earth's surface on a continuing basis. Cost is often a significant factor in choosing among the various platform options.

The images provided by linear CCD array sensors have very high potentials for photogrammetric mapping at high and low scales.

The triangulation and photogrammetric point determination of pushbroom systems are rather different compared to standard approaches, which are usually applied for full frame imagery, (Haala et al., 2000). Additionally, the use of linear imaging sensors is more difficult with respect to photogrammetric data processing and requires an increased computational effort during the subsequent processing chain including matching, DTM and orthoimage generation.

This work relates to the analysis of the orientation of CCD linear scanners. Different models can be found in literature. The rigorous ones are based on the photogrammetry collinearity equations, which are modified in order to include any external and internal orientation modelling. Other approaches are based on rational polynomial functions, affine models and direct linear transformations. An overview is given in the next section.

At the Institute of Geodesy and Photogrammetry (IGP), ETH Zurich, a rigorous sensor model for the georeferencing of imagery acquired by multi-line CCD array sensors, carried on airborne or satellite, has been implemented. The model fulfils the requirement of being as flexible as possible and being adaptable to a wide class of linear array sensors. In fact pushbroom scanners show different geometric characteristics (optical systems, number of CCD lines, scanning mode and stereoscopy) and for each data set specific information are available (ephemeris, GPS/INS observations, calibration, other internal parameters). Therefore the model needs to be dependent on a certain number of parameters that change for each sensor. The results obtained with different satellite sensors will be presented.

2. OVERVIEW OF EXISTING MODELS

For the georeferencing of imagery acquired by pushbroom sensors many different geometric models of varying complexity, rigor and accuracy have been developed, as described in (Fritsch et al., 2000, Hattori et al., 2000 and Dowman et al., 2003). The main approaches include rigorous models, rational polynomial models, Direct Linear Transformations (DLT) and affine projections.

The rigorous models try to describe the physical properties of the sensors acquisition and are based on collinearity equations, which are extended in order to describe the specific geometry of pushbroom sensors. Some rigorous models are designed for specific sensors, while some others are more general and can be used for different sensors. Few models are designed for both spaceborne and airborne linear scanners.

In case of spaceborne sensors, different approaches have been followed. V. Kratky (Kratky, 1989) developed a software, called SPOTCHECK+, the principle of rigorous photogrammetric bundle formulation is combined with the sensor external orientation modelling. The satellite position is derived from known nominal orbit relations, while the attitude variations are modelled by a simple polynomial model (linear or quadratic). For self calibration two additional parameters are added: the focal length (camera constant) and the principle point correction. The exterior orientation and the additional parameters of the sensor model are determined in a general formulation of the least squares adjustment (Gauss-Helmert model). The use of additional information, e.g. from supplemented data files is not mandatory, but if this information is available it can be used to approximate or pre-set some of the unknown parameters. This model has been used for the orientation of SPOT-2 (Baltsavias et al., 1992), MOMS-02/D2 (Baltsavias et al., 1996), MOMS-02/Priroda (Poli et al., 2000), Landsat TM and JERS-1 (Fritsch et al., 2000) scenes. An advantage of this software is that it can easily integrate new pushbroom instruments, if the corresponding orbit and sensors parameters are known. The model was also investigated and extended in (Fritsch et al., 2000).

The principle of ìorientation imagesî was used at DLR for the geometric in-flight calibration and orientation of MOMS-2P imagery (Kornus et al., 1999a, Kornus et al., 1999b). This method is based on extended collinearity equations (Ebner et al., 1992). The exterior orientation parameters are determined in the so-called orientation images and between the orientation images the parameters of an arbitrary scan line are interpolated using Lagrange polynomials. For the modelling of the interior orientation for each CCD array five parameters are introduced. All unknown parameters are estimated in a bundle block adjustment using threefold stereo imagery. For the determination of the unknown parameters a large number of tie points which are automatically measured is required.

In the group of Prof. Ebner at TU Munich a mathematical model of photogrammetric point determination for airborne and spaceborne three-line scanners has been developed and tested on MOMS-02/D2 and P2 (Ebner et al., 1992), MEOSS (Ohlhof, 1995), HRSC and WAOSS (Ohlhof et al., 1994) sensors. The model is based on a polynomial approach in case of airborne imagery, whereas orbital constraints are utilised in case of spaceborne imagery. In the airborne case the exterior orientation parameters are estimated only for some so-called orientation points, which are introduced at certain time intervals, e.g. every 100th readout cycle. In between, the external orientation parameters are expressed as polynomial functions (e.g. Lagrange polynomials) of the parameters at the neighboring orientation points. For preprocessed position and attitude data, e.g. acquired by differential GPS and INS, observation equations are formulated. Systematic errors of the position and attitude observations are modelled through additional strip- or block-invariant parameters. By limitation to constant and time-dependent linear terms, which describe the main effects, 12 additional parameters, namely a bias and a drift parameter for each exterior orientation parameter, are introduced. For the satellite case, the spacecraftís epoch state vector is estimated with the assumption that all scanner positions lie along an orbit trajectory. Due to the lack of a dynamic model describing the cameraís attitude behaviour during an imaging sequence, for the spacecraftís attitude the concept of orientation points is maintained.

The University College London (UCL) suggested a dynamic orbital parameter model (Gugan et al., 1988). The satellite movement along the path is described by two orbital parameters (true anomaly and the right ascension of the ascending node), that are modelled with linear angular changes with time and included in the collinearity equations. The attitude variations are modelled by drift rates. This model was successfully applied for SPOT level 1A and 1B (OíNeill et al., 1991), MOMS-02 and IRS-1C (Valadan Zoej et al., 1999) imagery. In (Dowman et al., 2003) this approach was investigated and extended for the development of a general sensor model for along-track pushbroom sensors.

The IPI Institute in Hannover the program system BLUH/BLASPO is used for the adjustment of satellite line scanner images (Jacobsen, 1994). Just the general information about the satellite orbit together with the view directions in-track and across-track are required. Systematic effects caused by low frequency motions are handled by self-calibration with additional parameters. In this model the unknown parameters for each image are 14, that is, 6 exterior orientation parameters for the uniform motion and 8 additional parameters for the difference between the approximate uniform movement and the reality. This program seems very flexible, because it has been successfully used for the orientation of MOMS-02 (B¸y¸ksalih et al., 2000), SPOT, KFA1000, KVR1000 and IRS-1C (Jacobsen et al., 1998), DPA, IKONOS and Quickbird (Jacobsen et al., 2003) and SPOT-5/HRS (Jacobsen et al., 2003).

In (Westin, 1990) the orbital model used is simpler than in the previous models. A circular orbit instead of an elliptical one is used with sufficient accuracy. Using data from SPOT ephemeris data seven unknown parameters need to be computed for each SPOT image.

Among specific models developed for one sensor, the procedure used at JPL, Pasadena, for the orientation of MISR sensors reproduces the image acquisition using a large number of reference systems and specific MISR parameters measured during laboratory calibration. The external orientation parameters are calculated from precise ephemeris (Jovanovic et al, 1998).

An alternative image orientation approach widely used is the Rational Function Model (RFM), or Rational Polynomial Coefficients (RPC), which provide a means of extracting 2D (3D) information from single (stereo) satellite imagery without explicit reference to either a camera model or satellite ephemeris information. The RFMs describe the relationship between image (line, sample) and object space (typically latitude, longitude and height) coordinates and viceversa through quotients of polynomials, usually of 3^{rd} order (Fraser et al., 2001). In (Grodecki et al., 2003) a block adjustment with Rational Polynomial Coefficients (RPC) is proposed and applied for the orientation of high-resolution satellite images, such as IKONOS. The same model has been implemented at IGP, ETH Zurich, for the orientation of SPOT-5/HRS and SPOT-5/HRG stereo images (Poli et al., 2004).

Other approaches for satellite imagery acquired by CCD linear array scanners are based on affine transformations.

Prof. Okamoto (Okamoto, 1981) proposed the affine transformation to overcome problems due to the very narrow field of the sensor view. The imaging geometry is converted from the original perspective imagery into an affine projection. Later the method was applied to SPOT stereo scenes of level 1 and 2 (Okamoto et al., 1998). The theories and procedures of affine-based orientation for satellite line-scanner imagery have been integrated and used for the orientation of SPOT, MOMS-2/P (Hattori et al., 2000) and IKONOS (Fraser et al., 2001) scenes. Under this approach an initial transformation of the image from a perspective to an affine projection is first performed, then a linear transformation from image to object space follows, according to the particular affine model adopted. The assumption is that the satellite travels in a straight path at uniform velocity within the model space. The model utilises the Gauss-Krueger projection plane and ellipsoidal heights as a reference system, therefore height errors due to Earth curvature must be compensated. The results demonstrated that 2D and 3D geopositioning to sub-pixel accuracy can be achieved (Fraser et al., 2001).

(Gupta et al., 1997) proposed a simple non-iterative model based on the concept of fundamental matrix for the description of the relative orientation between two stereo scenes. The model was applied on SPOT across-track stereo scenes. The unknown parameters for each pair are: the sensor position and attitude of one scene at time 0, the velocity of the camera, the focal length and the parallax in across-track direction.

The Direct Linear Transformation (DLT) approach has also been investigated. The solution is based only on ground control points and does not require parameters of the interior orientation and ephemeris information. The DLT approach was suggested for the geometric modelling of SPOT imagery (El Manadili et al., 1996) and applied to IRS-1C images (Savopol et al., 1998). In (Wang, 1999) it was improved by adding corrections for self calibration.

In general, the approaches based on 2D and 3D empirical models, as those presented, are advantageous if the rigorous sensor model or the parameters of the acquisition system are not available.

In case of pushbroom sensors carried on airplane or helicopter GPS and INS observations are indispensable, because the airborne trajectories are not predictable. Anyway, the original position and attitude measurements are not enough accurate for high-precision positioning and require a correcion.

The IGP at ETH Zurich (Gruen et al., 2002a) investigated three different approaches for the external orientation modelling of the Three-Line Scanner (TLS) developed by Starlabo Corporation: the Direct Georeferencing, in which the translation displacement vector between the GPS and camera systems is estimated for the correction of GPS observations, the Lagrange Polynomials, as used in (Ebner et al., 1992) for spaceborne sensors and the Piecewise Polynomials, where the sensor attitude and position functions are divided in sections and modelled with 1^{st} and 2^{nd} order respectively, with constraints on their continuity. The sensor self-calibration has also been integrated in the processing chain. Further investigations on the models performances are in progress.

In the LH-Systems photogrammetric software for the ADS40 processing, a triangulation is applied for the compensation of systematic effects in the GPS/IMU observations (Tempelmann et al., 2000). These effects include the misalignment between IMU and the camera axes and the datum differences between GPS/IMU and the ground coordinates system. For the orientation of each sensor line the concept of orientation fixes is used. The external orientation values between two orientation fixes are determined by interpolation using the IMU/GPS observations.

From the analysis of the above literature we can see that nowadays both approaches based on rigorous and non rigorous models are widely used. In case of rigorous models the main research interests are the sensor external and internal orientation modelling. The external orientation parameters are often estimated for suitable so-called ìorientation linesî and interpolated for any other lines. A self- calibration process is recommended, as least to model focal length variation and first order lens distortions. In order to avoid over-parameterisation the correlation between the parameters must be investigated and tests on the parametersí significance and determinability are required. Moreover it is recommended to take advantage of additional information for the external orientation estimation (orbital elements and ephemeris for spaceborne sensors, GPS and INS measurements for spaceborne and airborne sensors). Few models can be applied for both airborne and spaceborne sensors.

The orientation methods based on rational polynomials functions, affine projections and DLT transformations are mostly used for high-resolution satellite imagery. They can be a possible alternative to rigorous model when the calibration data (calibrated focal length, principal point coordinates, lens distortions) are not released by the images providers or when the sensor position and attitude are not available with sufficient precision (Vozikis et al., 2003).

3. SENSOR MODEL DESCRIPTION

A rigorous sensor model for the georeferencing of a wide class of linear CCD array sensors has been developed at IGP and already applied to different linear scanners carried on satellite and aircraft (Poli, 2003). The photogrammetric collinearity equations describe the perspective geometry in each image line. The sensor position and attitude are modelled with piecewise 2^{nd} order polynomial functions depending on time. The platform trajectory is divided into segments according to the number and distribution of available Ground Control Points (GCPs) and Tie Points (TPs) and for each segment the sensor position and attitude are modelled by 2^{nd} order polynomials. At the points of conjunction between adjacent segments constraints on the zero, first and second order continuity are imposed on the trajectory functions. Additional pseudo-observations can fix some or all parameters to suitable values. For example, if the 2^{nd} order parameters are fixed to zero, the polynomial degree is reduced to 1 (linear functions). This option allows the modelling of the sensor position and attitude in each segment with 2^{nd} or 1^{st} order polynomials, according to the characteristics of the trajectory of the current case study. In case of sensors carried on aircraft, additional GPS and INS observations can be included in the model (Poli, 2002).

The sensor model includes also a self-calibration, which is required for the correction of the systematic errors due to principal point displacement (d_x, d_y), focal length variation (d_c), radial symmetric (k_1, k_2) and decentering lens distortion (p_1, p_2), scale variation in CCD line direction (s_y) and the CCD line rotation in the focal plane (θ). The model can be applied to single lens sensors with synchronous (i.e. TLS, ADS40, WAOSS) and asynchronous (EROS-A1) along-track stereo capability and to multi-lens sensors (i.e. SPOT-5/HRS, ASTER, MOMS-02, MISR).

The functions modelling the external and the internal orientation are integrated into the collinearity equations, resulting in an indirect georeferencing model. Due to their non-linearity, the complete equations are linearized according to the first-order Taylor decomposition with respect to the unknown parameters. The resulting system is solved with a least square adjustment. As result the coefficients of the polynomials modelling the external orientation, the self-calibration parameters and the coordinates of the tie points are estimated. Statistics on the system s

In case of satellite imagery, the available ephemeris (usually sensor position and velocity at fixed intervals) are used to generate the approximate values for the parameters modelling the sensor external orientation (position and attitude). The required geometric parameters (focal length(s), viewing angles, number and size of CCD elements in each array) are usually available from the imagery provider or from literature. The reference frame used in the adjustment is the fixed Earth-centered Cartesian system, also called ECR.

In case of airborne imagery, the GPS and INS observations are included in the piecewise polynomial equations. The polynomial coefficients model the shift and offset between the GPS and INS local systems and the camera system (centred in the lens perspective centre) and 1st and 2nd order systematic errors contained in the observations.

For the orientation of the pushbroom imagery preliminary tests are made with these objectives:

- determination of best degree for piecewise polynomials and best GCPs configuration, by solving the adjustment without self-calibration, with quadratic functions modelling the external orientation and varying the number of segments and GCPs configuration;
- external orientation modelling with linear and quadratic functions, using the best GCPs configuration and best trajectory segments, without self-calibration;
- self-calibration with best external orientation modelling configuration.

The choice of the unknown self-calibration parameters to include in the modelling is based on the analysis of the cross-correlation between the self-calibration parameters, the external orientation parameters and the ground coordinates of the TPs. Statistics on the adjustment performance and RMS values for the GCPs and Check Points (CPs) are considered for the quality assessment.

4. ORIENTATION OF SATELLITE IMAGES

The model has been applied for the orientation of satellite and airborne images with different acquisition geometry (one-lens and multi-lens optical systems, synchronous and asynchronous acquisition) and ground resolution. As satellite applications concern, in (Poli, 2003), (Giulio Tonolo et al., 2003) and (Poli et al., 2004) the results obtained by the orientation of MOMS-02/P, MISR, EROS-A1 and SPOT-5/HRS are presented, while in (Poli, 2002) the tests carried on the Three Line Sensor (TLS), carried on helicopter, are reported. In the following paragraphs the latest results obtained from SPOT-5/HRS and ASTER are summarised.

4.1 SPOT-5/HRS

Within the HRS-SAP Initiative (Baudoin et al., 2004), a DEM was generated from two stereo images acquired by the High Resolution Stereoscopy (HRS) sensor carried on the newest satellite of SPOT constellation. The sensor model was applied in order to orient the stereopair and estimate the ground coordinates of the CPs. The available ephemeris (sensor position and velocity) were used to generate the approximate values for the parameters modeling the sensor external orientation (position and attitude) in fixed Earth-centred geocentric Cartesian system. From the available 41 object points, a group of them was used as GCPs and the remaining as CPs. The best results in terms of RMSE in the CPs were obtained by modelling the external orientation with two 2nd order polynomials and with self-calibration. The self-calibration parameters that mostly influenced the model were k_1, k_2, p_2 and s_y for both lenses. The other self-calibration parameters could not be estimated due to the high correlation with the TP coordinates and external orientation parameters. By changing the number of GCPs and CPs, the RMSE were always less than 1 pixel. For a more detailed description of the data and processing, see (Poli et al., 2004).

4.2 ASTER

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is a high-resolution, multispectral/ hyperspectral imaging instrument which is flying on Terra, a satellite launched in December 1999 as part of NASA's Earth Observing System (EOS). ASTER takes data in 14 spectral bands within the Visible and Near Infrared (VNIR), the Shortwave Infrared (SWIR) and the Thermal Infrared (TIR) at ground resolution of 15m, 30m and 90m respectively.

The generation of DEMs is possible with the VNIR instrument, that provided stereo images in along-trak direction. VNIR consists of two independent telescopes operating in band 3 (0.76-0.87μm), viewing nadir (channel 3N) and backward (channel 3B, 27.6∫ off-nadir) with respect to the spacecraft trajectory. The telescopes scan the ground in pushbroom mode using arrays of CCDs with size 7μm x 7μm. The number of CCD elements in each array is 4100 for channel 3N and 5000 for channel 3B (4100 are active). The two telescopes allow simultaneous stereo imaging with a 64 sec time delay between the scanning of the same ground target and a B/H of 0.6. Each scene is 4100x4200 pixels large and cover an area of about 60km x 60km. Several types of ASTER data are available at different processing levels. For our purposes, the level 1A is used, because at this level the images are not geometrically processed.

The scene used in this work covers the valley of Shaxi, in the South-East part of China. The images were kindly provided by the Institute for Spatial and Landscape Planning, ETH Zurich, who is involved in a World Monuments Fund project for the economic development of the Shaxi valley. The scenes were acquired on 23rd November 2000 in the morning.

For the orientation of the channels 3N and 3B from the ASTER scene, six GCPs that have been used. The ground coordinates of these points were available from in-situ GPS measurements or measured in local maps. As the sensor external orientation concerns, the ASTER scene metadata file contained the satellite position and velocity in ECR (fixed Earth-centred Cartesian coordinate system) every 400 image lines. These data were used to calculate the satellite attitude at the observations times and calculate the initial approximations for the polynomial coefficients modelling the sensor external orientation. Due to the limited number of object points, only the RMSE for the GCPs have been calculated: 8.1m in X, 8.4m in Y and 10.4m in Z. After the production of five pyramid images, interest points were matched and found progressively in all pyramid levels starting from the low-density features on the images with the lowest resolution. After the process, 320,000 points were successfully matched. The failed matches were mostly in correspondence of areas covered by clouds, due to the cloud movement between the nadir and backward images acquisition.

Using the software Geomatic Studio v.4.1 by Raindrop, the DEM was cleaned by points on clouds and a DSM was generated. In Figure 2 the DSM in the Shaxi valley is shown.

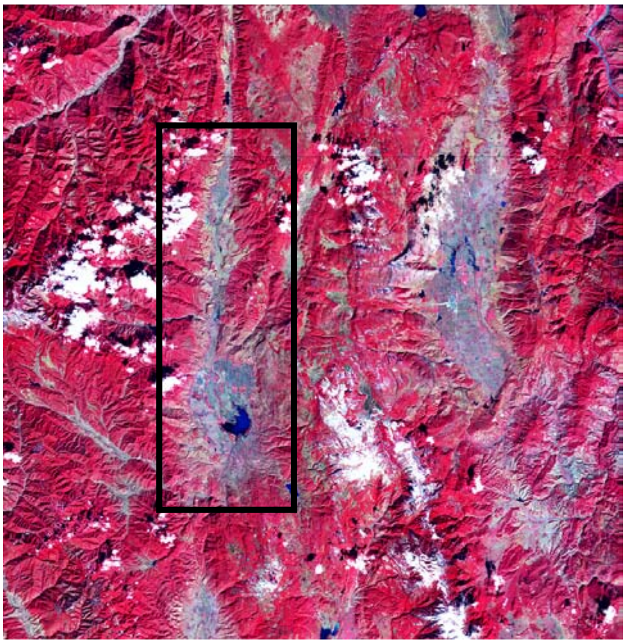

Figure 1. False-colour ASTER-VNIR scene (bands 1, 2, 3N). The Shaxi valley is located in the black box.

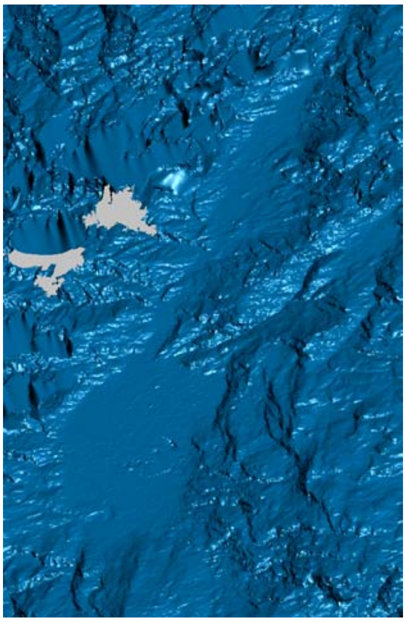

Figure 2. DSM in the Shaxi valley. The holes are due to deleted points on clouds.

5. CONCLUSIONS

In this paper an overview on the alternative models used for the orientation of pushbroom imagery is given. Some of these approaches rigorously describe the physical acquisition geometry and are based on the collinearity equations. Other methods describe the relationship between image and ground coordinates through rational polynomial functions or affine transformations, donít depend on the specific Ö and are mostly used when the physical sensor model or the required geometric parameters are not available. The model developed at IGP belongs to the class of rigorous models and has the advantage to be usable with a wide class of pushbroom sensors. The model has been tested on different sensors with different geometric characteristics. In the paper the application on SPOT-5/HRS and ASTER have been briefly presented. In all cases, RMSE in the CPs up to 1 pixel have been reached.

AKNOWLEDGMENTS

The author would like to thank the Institute for Spatial and Landscape Planning, ETH Zurich for providing the ASTER images and the object points location.

REFERENCES

Baltsavias E. P., Stallmann D., 1992. Metric Information Extraction from SPOT Images and the Role of Polynomial Mapping Functions. IAPRS, Vol. 29, Part B4, Washington, pp. 358 - 364.

Baltsavias, E. P., Stallmann, D., 1996. Geometric potential of MOMS-02/D2 data for point positioning, DTM and orthoimage. IAPRS, Vol. 31, Part B4, Vienna, pp. 110-116.

B¸y¸ksalih G., Jacobsen K., 2000. Geometric Aspects of MOMS-2P Three-Line Imagery for Mapping Applications. Annual Meeting of the Remote Sensing Society, Lancaster, UK.

Dowman, I. J., Michalis, P., 2003. Generic rigorous model for along track stereo satellite sensors. ISPRS Workshop ìHigh Resolution Mapping from Space 2003î, Hannover, 4-6 October (on CDROM.)

Ebner, H., Kornus, W., Ohlhof, T., 1992. A simulation study on point determination for the MOMS-02/D2 space project using an extended functional model. IAPRS, Vol. 29, Part B4, Washington D.C., pp. 458-464.

El-Manadili Y., Novak, K., 1996. Precision rectification of SPOT imagery using the direct linear transformation model. PE&RS, 62(1), pp. 67-72.

Fraser, C.S., Hanley, H.B., Yamakawa, T., 2001. Sub-metre geopositioning with IKONOS GEO imagery. ISPRS Workshop ìHigh-resolution Mapping from Space 2001î, Hanover, September 19-21 (on CDROM).

Fritsch, D., Stallmann, D., 2000. Rigorous photogrammetric modelling processing of high-resolution satellite imagery. IAPRS, Vol.33, Part B1, Amsterdam, pp.313-321. Gruen, A., Zhang L., 2002b. Sensor modeling for aerial mobile mapping with Three-Line-Scanner (TLS) imagery. IAPRS, Vol. 34, Part 2, Xi'an, pp. 139-146.

Giulio Tonolo, F., Poli, D., 2003. Georeferencing of EROS-A1 high-resolution images with rigorous and rational function model. ISPRS Workshop ìHigh resolution mapping from Space 2003î, Hannover, 4-6 October (on CDROM).

Gruen, A., Zhang, L., 2002. Sensor modeling for aerial mapping with Three-Line Scanner (TLS) Imagery. IAPRS, Vol. 32, Part B2, Xian (on CDROM).

Grodecki, J., and Dial, G., 2003. Block Adjustment of High-Resolution Satellite Images Described by Rational Functions. PE&RS, Vol. 69, No. 1, pp. 59-70.

Gugan, D. J., Dowman, I. J., 1988. Accuracy and completeness of topographic mapping from SPOT imagery. Photogrammetric Record, Vol. 12, No. 72, pp. 787-796. Gupta, R., Hartley, R. I., 1997. Linear Pushbroom Cameras. IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 19, No 9, September 1997, pp. 963-975.

Gupta, R., Hartley, R. I., 1997. Linear Pushbroom Cameras. IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 19, No 9, September 1997, pp. 963-975.

Haala, N., Fritsch, D., Stallmann, D., Cramer, M., 2000. On the performance of digital airborne pushbroom cameras for photogrammetric data processing: a case study. IAPRS, Vol. 33, Part B4/1, Amsterdam, pp. 320-331.

Hattori, S., Ono, T., Fraser, C.S. & Hasegawa, H., 2000. Orientation of high-resolution satellite images based on affine projection. IAPRS, Vol. 33, Part 1, Amsterdam, pp. 359-366.

Jacobsen, K., 1994. Comparison of mapping with MOMS and SPOT iamges. IAPRS, Vol. 30, Part B4, pp. 225-230.

Jacobsen, K., Konecny, G., Wegman, H., 1998. High Resolution Sensor Test Comparison with SPOT, KFA1000, KVR1000, IRS-C and DPA in Lower Saxony. IAPRS, Vol.32, Part 4, Stuttgart, pp. 260-269.

Jacobsen, K., Konecny, G.,Wegmann, H., 1998. Analysis of SPOT HRS stereo data. ISPRS Workshop ìHigh resolution mapping from Space 2003î, Hannover, 4-6 October (on CDROM).

Jacobsen, K., Passini, R., 2003. Accuracy of digital orthophotos from high resolution space imagery. ISPRS Workshop ìHigh resolution mapping from Space 2003î, Hannover, 4-6 October (on CDROM).

Jovanovic, V. M., Smyth, M. M., Zong, J., Ando, R., Bothwell, G. W., 1998. MISR Photogrammetric Data Reduction for Geophysical Retrievals. IEEE Transactions on Geoscience and Remote Sensing, Vol. 36, No. 4, July 1998, pp. 1290-1300.

Konecny, G., Lohmann, P., Engel, H., Kruck, E, 1987. Evaluation of SPOT imagery on analytical photogrammetric instrument. PE&RS, Vol. 53, No. 9, pp.1223- 1230.

Kornus,W., Lehner, M., Schoeder, M., 1999a. Photogrammetric block adjustment using MOMS-2P imagery of the three intersecting stereo-strips. ISPRS Workshop "Integrated Sensor Calibration and Orientation", Portland, Maine, USA, June 16-17, 1999.

Kornus W., Lehner M., Schroeder M., 1999b. Geometric inflight calibration by block adjustment using MOMS 2P imagery of three intersecting stereo strips. ISPRS Workshop ìSensors and Mapping from Spaceî, Hanover, September 27-30 (on CDROM).

Kratky, V., 1989. Rigorous photogrammetric processing of SPOT images at CCM Canada. ISPRS Journal of Photogrammetry and Remote Sensing, No. 44, pp. 53-71.

Ohlhof, T., Montenbruck. O., Gill, E., 1994. A new approach for combined bundle block adjustment and orbit determination based on Mars-94 three-line scanner imagery and radio tracking data. IAPRS, Vol., 30, Part B3/2, Munich, pp. 630-639.

Ohlhof, T., 1995. Block triangulation using three-line images. Proceedings of ìPhotogrammetric Week 1995î, Wichmann Verlag ed., Stuttgart, pp. 197-206.

Okamoto, A., 1981. Orientation and construction of models, Part III: Mathematical basis of the orientation problem of one-dimensional central-perspective photographs. PE&RS, Vol. 47, No. 12, December, pp. 1739-1752.

Okamoto, A., Fraser, C., Hattori, S., Hasegawa, H., Ono, T., 1998. An alternative approach to the triangulation of SPOT imagery. IAPRS, Vol. 32, Part 4, pp. 457 462.

OíNeil M., Dowman I, 1991. A new camera model for the orientation of the SPOT data and its application to the OEEPE test of triangulation of SPOT data. OEEPE Publication, Issue 26, pp. 153-163.

Poli D., Seiz G., Baltsavias E. P., 2000. Cloud-top height estimation from satellite stereopairs for weather forecasting and climate change analysis. IAPRS, Vol. 33, Part B7/3, Amsterdam, pp.1162-1169.

Poli, D., 2003. Georeferencing of MOMS-02 and MISR stereoimages with strict sensor model. ISPRS Workshop ìHigh resolution mapping from Space 2003î, Hannover, 4-6 October (on CDROM).

Poli, D., Zhang, L., Gruen, A., 2004. SPOT-5/HRS stereo images orientation and automated DSM generation. IAPRS Vol. 34, Part B1 (to be published).

Savopol F., Armenakis C., 1998. Modelling of the IRS-1C satellite PAN imagery using the DLT approach. IAPRS, Vol. 32, Part 4, Stuttgart, pp. 511 514.

Tempelmann, U., Boerner, A., Chaplin, B., Hinsken, L., Mykhalevych, B., Miller, S., Recke, U., Reulke, R., Uebbing, R., 2000. Photogrammetric software for the LH systems ADS40. IAPRS, Vol. 33, Part B2, Amsterdam, pp. 552-559.

Valadan Zoej, M. J. V., Foomani, M. J., 1999. Mathematical modelling and geometric accuracy testing of IRS-1C stereo-pairs. ISPRS Workshop ìSensors and Mapping from Space 1999î, Hannover (on CDROM).

Vozikis, G., Fraser, C., Jansa, J., 2003. Alternative sensor orientation models for high resolution satellite imagery. Band 12 "Publikationen der Deutschen Gesellschaft f¸r Photogrammetrie, Fernerkundung und Geoinformation", Bochum (2003), pp. 179- 186.

Wang Y., 1999. Automated triangulation of linear scanner imagery, 1999. Verˆffentlichungen des Instituts f¸r Photogrammetrie und Ingenieurvermessungen, Universit‰t Hannover, Nr. 18. ISPRS Workshop ìSensors and Mapping from Spaceî, Hanover, September 27-30 (on CDROM).

Westin, T., 1990. Precision rectification of SPOT imagery. Photogrammetric Enginnering and Remote Sensing, Vol. 56, No. 2, February 1990, pp. 247-253.