GENERIC RIGOROUS MODEL
FOR ALONG TRACK STEREO SATELLITE SENSORS

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ABSTRACT:

A generic rigorous sensor model for high resolution optical satellite sensors, with along track stereoscopic capabilities, is introduced. Along track stereo images are acquired on the same orbit by satellites which usually have on board more than one sensor looking at the earth with different angles, or satellites that can rotate their sensor in the along track direction. The advantages of along track stereo images compared with images that are taken from adjacent orbits (across track) are that they are acquired in almost the same ground and atmospheric conditions. The development of a generic rigorous model for satellite sensors with along track stereo capabilities is absolutely essential. This kind of model is introduced in this paper using the collinearity equations in combination with astrodynamics. The main and fundamental point during the development of this model is to benefit, from the same orbit acquisition. The collinearity equations are modified, regarding the characteristic of pushbroom scanner and the number of exterior orientation parameters. The state vector at the origin point of each image is computed. The model that is introduced in this paper provides stability, accuracy and rigorousness of the solution.

1. INTRODUCTION

The German MOMS and the Japanese JERS-OPS were the first satellite instruments with along track stereo capability, allowing stereoscopic coverage in all cases and with only a small difference in time. Obviously the same seasonal conditions can improve the image matching results. For this reason, more and more sensors are following this principle, like TERRA-ASTER with a nadir and 27.7° backward view. Also SPOT 5 is built with a High Resolution Stereo (HRS) instrument with 20° forward and 20° backward view. The Japanese ALOS, with a nadir and two tilted 23.8° sensors looking backward and forward, will be lunched in September 2004. IKONOS and QuickBird high resolution sensors have the ability of rotating their sensor in both along and across track directions. The EROS satellite has the ability of rotating its sensor, too, but is working in non-synchronous mode, where ground scanning velocity is different than the satellite's ground velocity. For this satellite the developed model will be modified in a way to take into consideration the non-synchronous mode.

A new model has been developed to restitute images from along track sensors and was evaluated on imagery acquired by TERRA-ASTER sensor, covering a mountainous area in Northern Greece. Using the developed model, subpixel accuracy is achieved. This model will also be tested using SPOT5 HRS and EROS data.

2. BACKGROUND

2.1 ASTER sensor

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a multispectral imager with high spatial, spectral and radiometric resolution built to fly on TERRA spacecraft which was launched in 1998. The ASTER instrument covers a wide spectral region, from visible to thermal infrared with 14 spectral bands. To meet the wide spectral coverage, ASTER is composed of three subsystems: visible and near-infrared (VNIR) subsystem, shortwave infrared (SWIR) subsystem and thermal infrared (TIR) subsystem. ASTER has the ability of stereoscopic viewing in the near infrared band using two telescopes with a nadir and 27.7° backward view with 15 metres pixel size on the ground. In this paper, stereo images which, are produced using ASTER along track VNIR subsystem, are used to evaluate the developed model. The orbit parameters of TERRA spacecraft are shown in table 1. The ASTER NVIR parameters are shown in table 2 (Abrams et al., 2002).

2.2 Related work

Different general rigorous sensor models have been developed. Gugan and Dowman, (1988) proposed an orbital model with 14 unknown parameters for each image, where the relationship among sampling lines is characterized by the dynamic orientation parameters which are modelled with low order polynomials as a function of the sampling time. In this paper the Dowman and Gugan model is used as a starting point.

Orbit	Sun synchronous
Semi-major axis (Mean)	7078 km
Eccentricity	0.0012
Time of day	10:30 ± 15 min. am
Altitude range	700-737km (705 km at equator)
Inclination	98.2deg± 0.15deg
Repeat cycle	16 days (233 revolutions/16days)
Distance between adjacent orbits	172 km
Orbit period	98.9 min

Table 1. TERRA orbit parameters.

Focal length of nadir telescope	329mm
Focal length of backward telescope	376.3mm
Pixel size (ground) for both telescopes	15m
Pixel size (sensor) for both telescopes	7μm
IFOV nadir	21.3±0.4 (μrad)
IFOV backward	18.6±.03 (μrad)
Scan period in along track for both telescopes	2.199±.002(μs ec)

Table 2. ASTER NVIR characteristics.

Konecny et al., (1987) proposed a model where the unknown parameters for each image are six exterior orientation parameters which are representing the uniform motion and eight additional parameters which are representing the difference between the approximate uniform movement and the reality, totally fourteen parameters. This algorithm is used in the Hanover bundle block adjustment program BINGO. Kratky (1989) proposed a model where the unknown parameters for the stereo pair are 22 in total. In this model potential orbital perturbations are taken into account and also four of the unknown parameters are considered as inner orientation calibration parameters. Westin (1990) proposed a simplified orbital model. A circular orbit instead of elliptical orbit is used with sufficient accuracy. Using data from SPOT ephemeris data seven unknown parameters need to be computed for each SPOT image. O'Neil and Dowman (1991) proposed a model where auxiliary data are used in order to set up the relative orientations. Then typically three GCPs are needed to establish the exterior orientation. The model works accurately with both single SPOT stereo pairs and strips. Gupta and Hartley (1997) proposed a dynamic model where eleven parameters should be calculated. Three for the position, three for the velocity three for the orientation, one for the focal length and one for the offset. Fritsch and Stallman (2000) proposed a model based on an extension of a SPOT model developed by Kratky. The geometric solution combines the principle of rigorous photogrammetric formulation with additional constraints derived from known relations assuming an elliptic orbit. The attitude parameters are modelled by a simple linear or quadratic polynomial model. The parameters of the interior orientation are determined by self-calibration. The total number of unknown parameters is 12 per image. For self-calibration 2 additional parameters are needed.

Specific rigorous sensor models have been developed, mainly for the MOMS-2P sensor, which has 3 along track sensors. Ebner et al (1992) described a simulation study for the MOMS-02. In this model a different approach is introduced. The images are divided in segments (e.g. every 1000 lines) and these segments are treated as individual images with their own exterior orientation, instead of the common approach in which the satellite images are treated as a line segments. The camera geometry is described by 21 parameters. Also more parameters are established as drift and offset parameters. Kornus (1999) used five parameters for self calibration of the MOMS camera. Ebner and et al. (1999) proposed an enhanced model for MOMS: the bundle adjustment algorithm is supplemented by a rigorous dynamical modelling of the spacecraft motion to take orbital constraints into account. The camera position parameters which have been estimated, so far at certain time intervals, are now expressed by the six parameters of the epoch state vector and additional force model parameter. Poli (2002) introduced a general sensor model for both spaceborne and airborne along track sensors. This model is based on the Kornus model (1992). Again as in Kornus model the image is divided into segments and its segment is treated as an independent image. The sensor external orientation is modelled with second order polynomials depending on the time.

The following points should be mentioned in summarising the above literature:

- The satellite images are treated in two ways. The most common approach is that each line of the satellite image is treated as an individual image with correlated exterior orientation parameters (one dimensional). The other alternative is that the images are divided into segments (e.g. every 1000 lines) and these segments are treated as individual images with their own exterior orientation.
- The relationship among sampling lines or segments are modelled with low order polynomials as a function of the sampling time.
- A self calibration process is used especially in the case of segmented images.
- In a few papers some of the orbital elements are used in the solution.
- Some models are over-parameterized.
- The satellite motion in space is not examined deeply.
- Few efforts have been made to use the ephemeris data in combination with ground data.

Having in mind the above points a general model which will restitute any stereoscopic satellite images, and take account of the along track conditions and the orbit, will be introduced.

3. MODEL DESCRIPTION

3.1 Basic principles

In this paper a specific model for along track satellites using photogrammetry in combination with astrodynamics is introduced. From the literature the following fundamental points are adopted:

- The satellite is moving along a well defined, smooth, close to circular elliptical orbit.
- The images are acquired with a pushbroom scanner using a constant time interval. As a result the coordinates along the flight path have the same scale.
- A single image consists of a number of consecutive one-dimensional scan lines. The relationship among sampling lines is characterized by the dynamic orientation parameters which are modelled with low order polynomials as a function of the sampling time. As a starting point the Dowman and Gugan (1988) and Gugan (1987) model is used. In this model second order polynomials are used for the position vector and the k rotation. The ω and φ rotations are constants.
- A stationary world is assumed, and a moving camera.
- The sensor array is approximately perpendicular to the direction of motion.
- Attention must still be paid to the solution instability that can arise from over-parameterization of the model.

3.2 Initial research assumptions

In this research three initial assumptions are established for along track satellite pushbroom sensors. These assumptions are expected to be valid even for very high resolution satellites. These assumptions are the following:

- The motion of the satellite is a Keplerian motion during the acquisition of along track stereo images. For ASTER stereo images the acquisition time interval between the nadir and back image is about 50sec.
- The attitude (ω, φ and k rotations) of the satellite remains constant during the acquisition time of each image.
- During the satellite's flight a perspective projection is maintained across track. On the other hand a curvilinear projection is maintained along the flight direction.

3.3 Image space coordinate system

Generally in photogrammetry, the origin of the image space coordinate system is the centre of the image. However for satellite images this statement is not compulsory. As it has already been accepted a pushbroom image consists of a number of consecutive one-dimensional scan lines with their own exterior orientation parameters. The relationship among sampling lines are modelled with low order polynomials as a function of the sampling time.

This means, that one sampling line can act as the base line and the exterior orientation parameters of others lines are modelled with respect to the exterior orientation parameters of the base line. For simplicity this line is assumed to be the first line of the pushbroom image, and the origin is the middle point of this line. The directions of the image coordinate system are the following:

- The x-direction is the flight direction.
- The y-direction is perpendicular to x-direction

3.4 Object space coordinate systems.

In this paper, an inertial coordinate system should be used, in order to meet the principal assumption of Keplerian motion.

3.5 Along track stereo model

The challenge of developing an along track sensor model is to find common parameters for all images or to establish their relative orientation. The benefit is that the number of unknown parameters is reduced which is also gain a reduction of the correlation between the unknown parameters.

The Gugan and Dowman model (1987/88) has 14 unknown parameters for the exterior orientation of each image. Statistical tests were done in order to reduce more the number of unknowns.

The most important goal at that stage was to understand the satellite motion, to represent this motion using a combination of equations from photogrammetry and astrodynamics and most importantly to investigate the possibility to derive from these equations, the state vector or the orbital elements at a specific point of the trajectory. If the state vector or the orbital elements are computed, the next step is to assume that some of them are common for along track images or to calculate the relation between them. Generally, for pushbroom satellite images the relationship among sampling lines, or segments, is modelled with low order polynomials as a function of the sampling time, the state vector of the satellite is computed at the origin of each image.

In the developed sensor model more than one along track image can be used and these are treated as a whole. The unknown parameters of all images are computed together.

The developed model is very flexible. A solution can be derived using the information of ephemeris data. The accuracy of the solution is directly dependent of the accuracy of the data provided. However it is possible to refine the solution using a small number of GCPs (one or two).

Three GCPs in each image of a stereopair are needed to solve the along track model without using any information according to the exterior orientation parameters from the ephemeris data.

Finally, it is possible to handle satellites having different focal length in their cameras or pixel size for each sensor or even no square pixel.

4. EVALUATION

4.1 Data sets

Two TERRA-ASTER data sets have been used to date to evaluate this model. These data sets were acquired on 8 Oct 2001 on the same orbit, covering high mountainous areas around Vegoritis Lake and Grevena Town in Northern West Greece. The difference in height within the images is about 1000m and the slopes in some areas are very large. EROS data is also available for this area.

The data sets are Level 1A. The ASTER Level-1A data consists of the image data, the radiometric coefficients, the geometric coefficients and other auxiliary data, without applying the coefficients to the image data. Level-1A is the most appropriate data to use for photogrammetric applications, because the geometry and the pixel values are the same as when they are acquired.

ASTER images are distributed in HDF (Hierarchical Data Format) format. It is a free library and platform independent data format for the storage and exchange of scientific data.

The advantage of using this format is that important information regarding the images is included in the same file. The acquisition time for the nadir (for 13 lines along the image) and back image (for 16 lines along the image) is given. Also the position, velocity and attitude vectors are given for the same lines. In this model using the observation time values the time interval between the nadir and back image was calculated. For both data sets this value is 49.12314606 seconds. It is assumed that this value was calculated very accurately and it is used as a known parameter in the model. At this stage all other information, (position, velocity and attitude vector), are used as initial values in the model.

Three ground control points (GCPs) Ground Control Points are needed to solve the model. 20 GCPs are measured for Vegoritis data set and 12 GCPs for Grevena data set to be used as check point. The whole process will be explained in the next section.

4.2 Evaluation results

The ground control points were measured from orthophotos with 5 meters pixel size. These orthophotos were provided by the Hellenic Military Geographical Service (HMGS). The horizontal accuracy is better than ten meters. For vertical control a Digital Terrain Model with 30m pixel size was used. The DEM was provided by the Hellenic Military Geographical Service (HMGS), too. The vertical accuracy is better than fifteen meters.

For the Vegoritis data set 20 GCPs for both nadir and back images were measured and were divided into sets of 5 and 10 GCPs having a good distribution in the images, in order to evaluate the solution using these different data sets. For the Grevena data set 12 GCPs for both nadir and back images were measured and were divided into sets of 6 in order to evaluate the solution using these different data sets. The control points that are not involved in the solutions are used as check points.

Table 3 shows the Root Mean Square Error (rmse) for these data sets for different sets of control points and check points. According to the rmse of the control points the conclusion is that the accuracy of the solution is better than a pixel. As the unknown parameters of all images are computed together this accuracy refers to both along track stereo images. The accuracy on check points is between one and two pixels which is expected having in mind the mountainous terrain.

Finally a comparison was done on the Vegoritis data between the sensor model of ERDAS OrthoBASE and the developed model for check points. In this comparison ten GCPs are used as control points and the rest of them as check points (another 10 points).The rmse using OrthoBASE model is 33m against 26m when the developed model is used.

The improvement of the check point accuracy using the developed model is about 20% compared to the ERDAS OrthoBASE model. This accuracy is good enough, bearing in mind that the examined area is highly mountainous. Finally, it should be mentioned that for OrthoBASE model 5 GCPs are needed in order to have a solution while for the developed model just 3 GCPs are needed.

Vegoritis data set		
Number of control points used in the model	rmse(pixels) for control ooints	rmse(pixels) for check points
5	0.36 - 0.66	1.26-1.87
10	0.49 - 0.86	1.73-1.78
20	0.82	-
Grevena data set		
Number of control points used in the model	rmse(pixels) for control points	rmse(pixels) for check points
6	0.43 - 0.77	1.12-1.62
12	0.67	-

Table 3. Total rmse for ASTER data set up with 3 GCPs.

5. CONCLUSION

In this paper, a generic rigorous along track stereo satellite sensor model is proposed. The version that is tested in this paper is not the final as further improvements are possible. The main and fundamental point during the development of this model is to benefit, from the same orbit acquisition. In the developed sensor model the pair, triple or more along track stereo image are treated as a whole. The unknown parameters of all images are computed together. The achieved accuracy is referred in all images and it is better than the pixel size.

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