TOPOGRAPHIC MAPPING FROM SMALL SATELLITES: A CASE STUDY OF CHRIS/PROBA DATA

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Abstract

The new technology of small satellites (microsatellites) opens a new era in satellite Earth observations. Small satellites such as the ESA's Project for On-Board Autonomy (PROBA), launched on October 22, 2001, are of interest due to their low cost, flexibility of positioning, and capability for multiangular scanning in both across-and along track directions. PROBA's Compact High Resolution Imaging Spectrometer (CHRIS) provides multidirectional, as well as hyperspectral data at 18m resolution and is supplied mainly to the scientific community for experimental environmental applications. This research evaluates the use of various empirical models for satellite orientation and terrain modelling using multidirectional CHRIS data, and evaluates the potential of small satellites with multidirectional viewing capabilities for topographic mapping.

Geometric correction and co-registration of multiangle images is essential for their use for data extraction. Ideally, rigorous mathematical models should be formulated which precisely describe the satellite motion and represent the relationship between the image and the object spaces. The use of rigorous mathematical models has not been fully investigated using CHRIS/PROBA data, because the satellite information provided is not adequate for rigorous sensor modelling. In this paper, several alternative empirical models are tested for the orientation and 3D-geopositioning of CHRIS sensor images.

The images used in this study cover extremely mountainous terrain in central Hong Kong, A set of five images from CHRIS/PROBA taken in December 2005 from different angles are used to test the applicability of different forms of the empirical models for 3D geopositioning. The accuracy of the models is tested for different numbers and distribution, of Ground Control Points (GCPs) using different combinations of observation angles and Base/Height ratios. The results obtained show high integrity of the models used for CHRIS/PROBA image orientation. In some cases, accuracy approaching one pixel could be achieved using a modest number of GCPs, and this is adequate for topographic mapping at the scale of 1:25,000.

KEYWORDS: small/micro satellites, modelling, stereoscopic, three-dimensional, accuracy

INTRODUCTION

SMALL SATELLITES are defined as satellites of mass less than 500 kg and size less than one cubic meter (SSHP, 2007) and they are of increasing interest due to their low cost and manoeuvrability. Since they rely on off-the-shelf technology sensors, they can be built rapidly, but can potentially be used in many of the applications covered by their larger, more expensive counterparts. Such applications include topographic mapping due to the capability of small satellites to manoeuvre and scan areas from different directions both along and across track.

The Project for On-Board Autonomy (PROBA) satellite is the first European Space Agency (ESA) small satellite built for small scientific missions (Jorgenson, et al., 2005), and is classified as a micro satellite with a mass of 94 kg and size of 80x60x60 cm. The satellite payload includes the Compact High Resolution Imaging Spectrometer (CHRIS) providing high spatial resolution of 18m, hyper-spectral and multi-angular data (Table I). The main scientific objectives of CHRIS are to measure the Spectral Bidirectional Reflectance Distribution Function (BRDF) for mapping vegetation cover, and studying the atmosphere and water bodies. Thus each acquisition may comprise five consecutive images of the target from different viewing angles in a defined cone of 55° centered on the target during a single orbital overpass.

Table I. CHRIS/ PROBA main characteristics

CHRIS/ PROBA	Main characteristics
PROBA Launch	22 October 2001
Mass	94kg
Orbit	Sun synchronous
Inclination	97.9º
Altitude	681x561 km
CHRIS Resolution	18 m
Swath	Approx. 14 km
Bands	Mode 1 (62 bands), Mode 2, 3, 3A, 4 (18 bands), Mode 5 (37 bands)
Viewing angles	+-55, +-36, 0

Each CHRIS/PROBA mission is defined by the latitude, longitude, and altitude of the target area without ground control which is simply based on time. The satellite starts the mission 390 seconds prior to the acquisition time by calculating the semi/major axis of its orbit using the satellite velocity and position. From that moment and until the end of the acquisition, the satellite is assumed to be moving in a circular orbit with radius equal to the calculated semi-major axis (Alonso and Moreno, 2005). During the mission, the satellite onboard computer with the aid of onboard Advanced Stellar Compass (ASC) and GPS system controls the orientation for image capture. Five acquisitions are defined within a cone of 55º centered on the target. Alonso and Moreno (2005) showed that the above orbital assumption may generate errors in the satellite altitude up to +/- 58 km, which affects the location of the scanned area. Fig. 1 shows the differences in the scanned areas of the Hong Kong data set used in this work due to this problem.
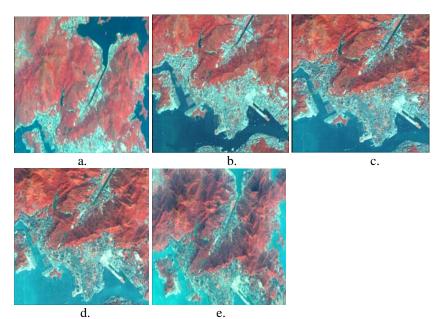

Fig. 1. Areas covered by CHRIS/PROBA data for Hong Kong on 18-Dec-2005, different viewing angles a. -53.03º, b. -33.38º, c. -5.84º, d. +28.95º, e. +50º

The lack of georeferencing information supplied with CHRIS/PROBA images combined with the satellite autonomy in manoeuvring and pointing to the target create difficulties in identifying the satellite location and orientation at the time of image capture. Although the PROBA orbit can be defined by the aid of the information provided by the Two Line Elements (TLE) from NORAD, its accuracy is still under investigation (Kelso, 2007) especially when, as with PROBA, there is no accurate ephemeredes available to validate the TLE data. A second set of information is required to construct the time dependent relationship between the image and the object spaces, including precise identification of the sensor type, scanning technique, time of scan, and the sensor viewing angle.

As with any other satellite, data from CHRIS/PROBA should be calibrated and validated radiometrically and geometrically for product accuracy and quality. Geometric calibration using rigorous sensor modelling requires basic information on the satellite orbit and motion, for which the time dependent relationship between the image and the object spaces should be defined. Since this information is unavailable from CHRIS/PROBA, the exact location and viewing angles of the sensor should be estimated. Some previous attempts to achieve accurate orientation of CHRIS/PROBA images are described below.

Alonso and Moreno (2004) proposed a quasi-automatic parametric method to model the satellite orbit/attitude and reconstruct the position and orientation of the sensor at any time of the acquisition based on the available information from the satellite. A general scheme is proposed for geometric correction of the images, but, no experimental results were introduced. In 2005, Alonso and Moreno (2005) modified the proposed method based on more auxiliary information on the satellite. Errors in the satellite pointing and attitude are estimated for a tested area but results on complete geometric correction of the images are under investigation.

Kneubuhler et al. (2005) discussed the use of the parametric approach proposed by Toutin (2004) for the geometric correction of CHRIS/PROBA images covering a rugged, mountainous terrain. The proposed 3D physical model relies on the available information from the satellite and only a few GCPs to describe the satellite motion in space and construct the relationship between the image and the object spaces. The number of GCPs required for the process depends on the available orbit and sensor information (Kneubuhler et al., 2005). They evaluated the accuracy of image geometric correction by overlaying available digital and vector maps on the corrected CHRIS scenes, showing that the overlay vector data fits well to the CHRIS corrected image data. Although the results were not evaluated mathematically, a general conclusion is that less information on the satellite orbit and sensor will require more GCPs.

As discussed above, positioning and orientation of the sensor in the satellite orbit can be estimated using models to represent the transformation between the image and object spaces in the georeferencing process. However, this is still under investigation for small satellites, and there are no previous studies which present

quantified accuracy levels for geometric correction and 3D geopositioning. The present study evaluates multiangle CHRIS images for topographic mapping using empirical mathematical models for 3D geopositioning. The mathematical models used in this research are described below.

<div align="center">MATHEMATICAL MODELS</div>

The use of the empirical mathematical models presented by the 3D affine model and higher order polynomials for satellite image orientation and terrain modelling have been investigated for several satellite images such as SPOT 4 (Okomoto et al., 1998), IRS/1D (Shaker and Shi, 2003), and IKONOS (Hanely and Fraser, 2001; Shi and Shaker, 2003). These studies indicated that the 3D affine and polynomial models may be successfully used for satellite sensor orientation, depending on adequacy of the ground reference coordinates system, accuracy of the control information, and size of the area covered by the images. Similar to any mathematical model, some assumptions are made to simplify the presentation of the relationship between the image and the object spaces and to validate the use of empirical mathematical models for the satellite image orientation and geo-referencing. These assumptions are: a) the satellite sensor moves linearly in space in a stable altitude, b) the sensor orientation angles are constant, and (c) the satellite flight path is almost straight. It is important to mention that these assumptions can be considered for small areas and single image coverage. Generally, these simplifications of the presentation of the satellite sensor motion may constrain the accuracy and add restrictions on how the model can be used. However, the special conditions of small satellites and the limited information obtained from PROBA, which is also expected for most other small satellites, necessitates the application of these assumptions. The function of the 3D affine and polynomial models used in this paper is expressed in equation 1. The 3D affine model can be presented by utilizing the first order terms of the form.

$$\left(\binom{l}{p}, \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}, \begin{pmatrix} a_1 & a_2 & a_3 & ... & a_n \\ b_1 & b_2 & b_3 & ... & b_n \end{pmatrix} \right) \rightarrow \binom{f_1}{f_2}$$

$$\qquad \text{Obs.} \qquad\qquad\qquad \text{Par.}$$

$$f_1(obs., par.) = a_1 X + a_2 Y + a_3 Z + a_4 X^2 + ... + a_n - l$$
$$f_2(obs., par.) = b_1 X + b_2 Y + b_3 Z + b_4 X^2 + ... + b_n - p \qquad\qquad (1)$$

Where: (l, p) are the image coordinates of a point (observations), (X, Y, Z) are the ground coordinates of the corresponding point (observations), and a_1, a_2,…, a_n , b_1, b_2,…, b_n are the model coefficients (parameters).

The models presented above rely on Ground Control Points (GCPs) to build the relationship between the image and the object spaces and to calculate the image orientation parameters. The minimum number of GCPs required to
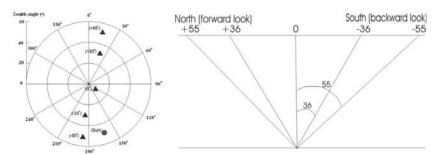
calculate the orientation parameters depends on the number of coefficients of the model. Least square adjustment is utilized when more than the minimum number of GCPs is used. For each CHRIS/PROBA image, first the orientation parameters of the 3D affine model are calculated by least square adjustment. Different combinations of images from different viewing angles are then utilized to build a stereo model in an intersection process. Based on the results obtained from using the 3D affine model, additional terms are added to model some discrepancies in different directions as is explained in section 4. The following section shows details of the CHRIS/PROBA data set used in this work.

STUDY AREA AND DATA SET

The nadir image (Fig. 1c) comprises 14x14 kilometres located at 22º2´N, 114º1´E and shows the Hong Kong harbour and the urbanised Kowloon Peninsula in the southern portion. Flat urban areas near the coast give way to steep convex slopes farther north, rising to elevations of 800m only 3km from the coast, and with slopes commonly 40-50°. The proposed satellite positions and angular configuration of the five images of the multiangle dataset used is shown in Fig. 2, and the real estimated viewing angles is presented in Table II. Digital maps referenced to the local, Hong Kong 1980 grid system were available for the extraction of GCPs and checkpoints for construction of the stereo models and for subsequent accuracy verification. These maps, known as the B5000 series from the Hong Kong Survey and Mapping Office are stated to have horizontal accuracies of 15 to 150cm, and vertical accuracies of +/-5m. The 10m resolution DEM used for accuracy testing was derived from these maps.

All GCPs used in the study as well as different numbers of checkpoints for accuracy testing were taken from the B5000 maps. Thus the maximum expected error of the GCPs which is attributable to the map data, is 1.5m in X and Y, and 5m in Z directions. Table II presents more information on the data set by showing the actual angles of each image, number of GCPs and checkpoints, and the base-to-height ratio (B/H) performed from each combination of two images of the data set. The x and y axes of the image coordinate system refer to across-track (almost east-west) and along track (almost north-south) directions respectively, which are almost parallel to the X and Y directions of the Hong Kong 1980 grid system used.

The relatively coarse resolution of the images limits the precision with which the GCPs and checkpoints can be identified to approximately 0.5 pixel (or 9m) in X and Y directions, and this error would affect the extraction of the Z coordinates in the space intersection process of the stereo models. In evaluating the suitability of small satellites for topographic mapping therefore it is more meaningful to consider accuracy in terms of pixels, since absolute accuracy is limited by the resolution of the sensor on board the satellite.

Fig. 2. Angular plots and of satellite positions for images of Hong Kong of 18-Dec-2005used in this study

TABLE II. Hong Kong CHRIS/PROBA data set

Stereo Images	Observation angles		No. of GCPs		No. of Checkpoints	B/H
	Image1	Image2	Image1	Image2		
+36&-36	+28.95	-33.38	10	10	11	1.21
+55&-55	+50.0	-53.03	10	10	12	2.52
+36&0	+28.95	-5.84	10	16	10	0.66
-36&0	-33.38	-5.84	16	16	8	0.56
+55&0	+50.0	-5.84	16	16	8	1.29
-55&0	-53.03	-5.84	10	16	8	1.23
+36&-55	+28.95	-53.03	10	16	8	1.88
+36&+55	+28.95	+50.0	16	10	8	0.64
+55&-36	+50.0	-33.38	10	10	8	1.85
-55&-36	-53.03	-33.38	10	10	8	0.77

METHODS

The 3D affine model and different forms of the 3D polynomials were utilized to calculate the CHRIS/PROBA image transformation parameters and to study the potential of the use of these models for topographic mapping. Several factors were examined, including the number and accuracy of the GCPs, the Base-to-Height ratio (B/H) for the stereo images, and the image viewing angles. The effects of earth curvature and the reference coordinate system used were assumed to be minimal, due to the small size of area covered by the stereo images and the use of the local (Hong Kong 1980) grid coordinate system. Since the GCPs were obtained from the same high quality B5000 map series, it was assumed that any error between them was constant (see Kardoulas et al. (1996)), and therefore we only consider the effect of the overall accuracy of the GCPs on the accuracy of the models. Additionally, since the 3D affine model is a linear model it may not fully represent satellite instability and unpredictable viewing angles. Therefore, additional terms such as X^2, Y^2, X^2+XY+Y^2 were added to the basic affine model, to simulate these distortions.

The study included four main steps: 1) identification and extraction of the image coordinates of the GCPs on each of the five images in the data set, 2)

computation of the model coefficients (image transformation parameters) using the GCPs and least square adjustment for each image of the data set, 3) calculations of the 3D coordinates of independent checkpoints, for different combinations of images to build stereo models by space intersection (Table II), and 4) accuracy testing using the independent checkpoints and existing DTM.

Since, as explained above, the images do not correspond to the same ground area, different numbers of GCPs (from 4-to-16), well-distributed over each image, were used to calculate the coefficients of the affine model, which represent the rotation angles, change in scale, and translation parameters of the images. Ten different configurations of stereo models, having different base-to-height ratios were constructed from the five images of the data set (see Table II). Then, the model coefficients of the images of each stereo pair were utilized to calculate the 3D coordinates of the independent checkpoints which were used to check the model performance for each combination of the stereo images.

RESULTS AND ANALYSIS

In most cases, accuracy better than three pixels can be achieved in all directions, and increasing the number of GCPs above eight gave no improvement (Fig. 3). In most cases the accuracy in X-Y directions was slightly better than in the Z direction, but the Z direction accuracy improved when the B/H ratio was greater than 0.6 (Fig. 3d). The best results, of less than two pixels accuracy in all directions, were obtained from the +55&0 and -55&0 stereo combinations (Figs. 3e and 3f) with a B/H ratio of about 1.25. On the other hand, Fig. 3d (-36&0) and 3h (+55&+36) with very low B/H ratios show accuracies less than 4 pixels. Generally the results indicate that most of the distortions in the CHRIS/PROBA data were in the Y direction, which is the along-track scanning direction of the images. This is consistent with other satellites, where studies have shown most distortions to be in the along-track direction.

Adding an X^2 term to the original form of the 3D affine model did not improve the accuracy, and some cases (Figs. 4a, 4e, 4g, and 4j) were less accurate. Furthermore, no effects were recorded from increasing the number of the GCPs above 8, or varying the stereo geometry and B/H ratio. These suggest that there is no significant distortion in the X (or across-track) direction to be modeled on the images.

However, accuracy does improve for all combinations of stereo models when a Y^2 term is added (Fig. 5). The major improvement was in the Z direction, and slight improvement was observed in X and Y directions. Again, increasing the number of the GCPs above about 8 did not improve the accuracy, and five appears adequate to construct a viable model (Fig. 5).

Further refinement of the polynomial model by adding X^2+XY+Y^2 to the original form, to more accurately present the relationship between the image and the object spaces (Fig. 6) produced considerable improvement such that in all

cases, accuracy of within two pixels was achieved in all directions. The only cases with errors exceeding two pixels were those having the lowest B/H ratios (-36&-0 and +36&+55) (Figs. 6d and 6h).

<div align="center">CONCLUSIONS</div>

Accuracies of between 1 and 2 pixels have been obtained for image coordinates in all three directions using an adaptation to the affine model, which can better represent distortions in image geometry which are not provided with the image data. The vertical accuracies from 1 to 2 pixels obtained during this study by adding extra terms to the 3D affine model, are similar to results obtained by Nichol et al. (2006) using an RPC-based model with IKONOS stereo images for landslide monitoring. However with IKONOS stereo images, Rational Polynomial Coefficients (RPCs) are supplied with the images for modeling the relationship between the image and the object space, whereas these are not available for the CHRIS sensor.

Data quality standards of the USGS for topographic map scale of 1:20,000 or larger (USGS, 2007) are specified as being that not more than 10% of points tested shall be in error of greater than 1/30 inch measured on the map publication scale. This is equivalent to 23m horizontal ground distance. The same distance at 1:25,000 scale corresponds to +/-28.75m on the ground. Therefore the horizontal accuracy achieved from the CHRIS/PROBA data in this study would be acceptable for either scale, especially when the extra terms in the affine model are used. For example, Figs. 6c, 6e, 6g and 6i indicates X and Y accuracies approaching 1 pixel (18m) for models constructed with B/H ratios between 0.66 and 1.88. Vertical accuracy standards are specified as not more than 10% of points tested shall be in error of more than half the contour interval (CI), and for the USGS 1:24,000 topographic Quadrangle sheets the CI varies from just a few metres in gentle terrain up to 100m in very steep areas (USGS, 2007). Thus for a 20m CI, which is used for 1:20,000 scale topographic mapping in Hong Kong, accuracy of +/-10m would be required, and cannot be obtained from the CHRIS images used in this study. However, for a 40m CI, only +/-20m would be required. Since our study achieved similar accuracy in the Z direction as for X and Y, ie. approaching 1 pixel (18-20m) for the same models noted above (Figs. 6c, 6e, 6g and 6i), it is suggested that CHRIS/PROBA can support topographic mapping with a 40m CI or lower. Since it was observed that the geometry of the images forming the stereo appears to affect the accuracy, with stereo models formed from low B/H ratios producing significantly higher error, B/H ratios between 0.7 and 2 may be recommended for future missions.

The present study is the first to empirically evaluate the capability of small satellites for topographic mapping. It was conducted in rugged terrain where very steep slopes compound the challenging image geometry from multiangle images and unknown satellite orbital parameters. The results indicate that accuracies approaching one pixel can be obtained even when few orbital parameters are

available, and this permits topographic mapping at scales of 1:20,000 or 1:25,000 and a contour interval of 40m. If more detailed topographic mapping is required, higher resolution sensors such as PROBA's High Resolution Camera (HRC) with 5m resolution may be used.
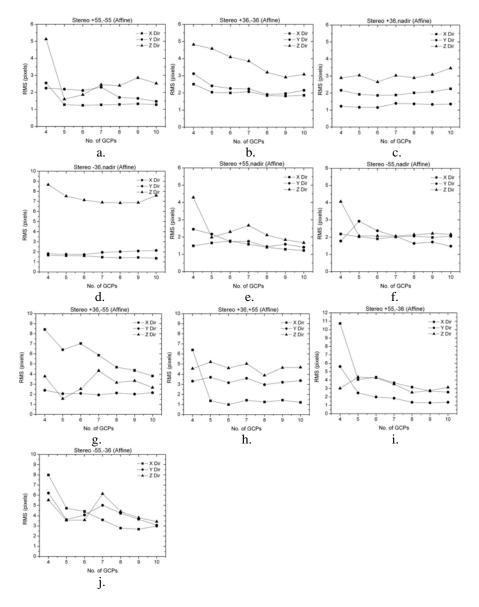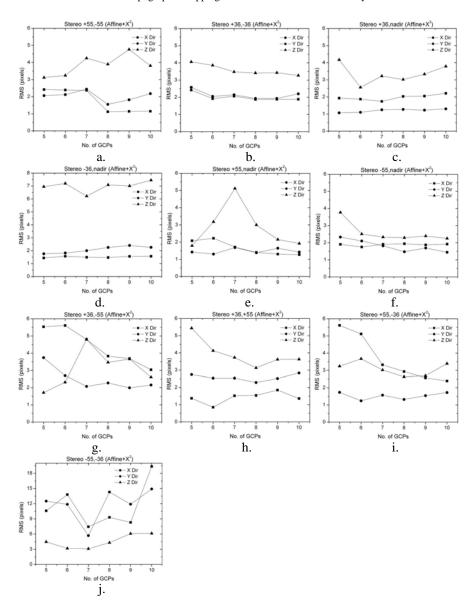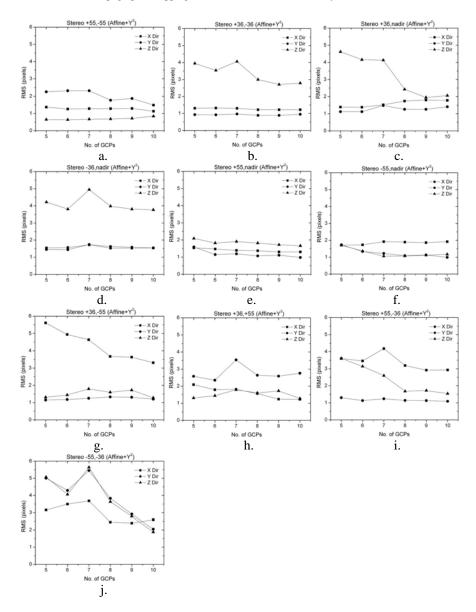

Fig. 3. Results of the 3D affine model

Fig. 4. Results of the 3D affine model with X^2 term

Fig. 5. Results of the 3D affine model with Y^2 term

Fig. 6. Results of the 3D affine model with X^2+XY+Y^2 terms

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