INVESTIGATION OF 3D GEOPOSITIONING AND DEM ACCURACY OF CARTOSAT-1 STEREO IMAGERY

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ABSTRACT:

Because Cartosat-1 data is one of the ideal sources for topographic map updating, it is important to provide enough geometric accuracy with minimum number of Ground Control Points (GCP). For a 1:25.000 scale topographic map planimetric accuracy requirement is approximately 5 m. and vertical accuracy is approximately is 3 m. In order to maintain these accuracies, geometric orientation better than these values should be achieved. So far many studies have been conducted in 3D positioning matters of Cartosat-1 data. But in a sense, they were somewhat experimental and in a well controlled test site. Here we, as an end user sense with a real study site, conducted our test. Cartosat-1 provides Rational Polynomial Coefficients (RPC) with the raw imagery. It is possible to improve RPCs by a direct or indirect approach. Direct methods update the original RPCs themselves. Indirect approach brings concluding transformations in object space and does not change original RPCs directly. Improvement is achieved by using GCPs with affine transformation or most simple means. In this paper, three different models (polynomial model: 0th order with translation to x and y coordinates, 1st order affine and 2nd order) are used. These different order polynomial models were used in a Cartosat-1 stereo pair covering southern part of Ankara with the different GCP numbers and distributions. GCP and Check Points (CPs) were obtained from an orthophoto mosaic comprising 16K scale air photos with planimetric accuracy better than 1 m. In each step, some of the GCPs are used as CPs to test the absolute accuracy. Also, we produced a DEM from Cartosat-1 stereo pair and we used a DEM produced from 10 m. interval contours obtained from 1:25.000 scale topographic maps as a reference in order to compare the DEMs,. One and half pixel accuracy with 0th order polynomial, nearly one pixel accuracy with 1st and 2nd order polynomials was achieved. Without GCPs the planimetric accuracy was nearly 500 m. The number of the GCPs does not have significant effect on 3D positioning accuracy after 8 GCPs. For a good and reliable solution 1st degree and minimum 8 GCPs are recommended. By autocorrelation method in Leica Photogrammetry Suite (LPS) 9.1, 10 m. grid interval DTM was created. This DTM was subtracted from 1:25.000 scale contour DTM. The accuracy for automatically created DTM without editing is nearly 4 m. This shows that Cartosat-1 has a good potential for generation of DSMs with a grid spacing of about 10 m and accuracy (RMS) of about 4 m. This is a good approximation for 1:25.000 scale topographic maps. Orthophotos can be produced directly from this DTM. Also contours may be generated after some editing processes. In the light of above test, it can be inferred that by using evenly distributed half pixel accurate GCPs, Cartosat-1 imagery meets the geometric accuracy requirements of 1:25.000 scale topographic maps. Then the remaining activity is a little bit more field work than the aerial photo compilation.

1. INTRODUCTION

Satellite remote sensing has begun replacing airborne sensing since 1980's. After 2000, high resolution optical satellite sensors have been subject of scientific investigations and evaluations. Most of them provide a ground sampling distance (GSD) of 1m or less but each image covers a small area, their price is high, and stereo coverage is often rare. In recent years, some sensors have been launched with a GSD of 2.5 – 5 m, covering a much larger area per image, having much lower image price and tailored to acquisition of stereo images and derivation of DTMs by using 2- or 3-line CCDs. Typical examples include Spot-5 HRG, Alos Prism and the last one Cartosat-1. These systems are also suitable for derivation of DEM/DTM, if the absolute geolocation accuracy of the images is good enough (e.g. Spot-5, Cartosat-1).

Cartosat-1 was put into orbit with two improved fore and aft PAN cameras with better than 2.5 m. spatial resolution in May 5, 2005. Cartosat-1 has two state-of-the-art panchromatic cameras that take black-and-white stereoscopic images in the

visible light spectrum at a resolution of 2.5 meters. The cameras cover a swath of about 30 km and take images of the same area during the same pass from two different angles (+26° (band F) and the other at -5° (band A)). The stereo images can be used to create accurate elevation data of the Earth and create three-dimensional image maps. Since the cameras are steerable, Cartosat-1 has a revisit time over any part of the Earth every five days. Cartosat-1 also has an onboard storage capacity of 120 Giga Bits to store images when not in contact with a ground station. Data from Cartosat-1 will be used for large-scale mapping, urban and rural development, land and water resources management, disaster assessment, relief planning and management, environmental impact assessment and various other geospatial and mapping applications. The data is also ideal for updating topographic maps. Cartosat-1 provides Rational Polynomial Coefficients (RPC) with the raw imagery. It is possible to improve RPCs by a direct or indirect approach. Direct methods update the original RPCs themselves. Indirect approach bring concluding transformations in object space and does not change original RPCs directly. Improvement is

achieved by using GCPs with affine transformation or most simple means.

Because Cartosat-1 data is one of the ideal sources for topographic map updating, it is important to provide enough geometric accuracy with minimum number of Ground Control Points (GCP). For a 1:25.000 scale topographic map planimetrik accuracy requirement is approximately 5 m. and vertical accuracy is approximately is 3 m. In order to provide these accuracies, we have to achieve geometric orientation better than these values.

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2. THEORETICAL BACKGROUND

A sensor model describes the geometric relationship between the object space and the image space, or vice visa. It relates 3D object coordinates to 2D image coordinates. The two broadly used imaging geometry models include the physical sensor model and the generalized sensor model. The physical sensor model is used to represent the physical imaging process, making use of information on the sensor's position and orientation. Classic physical sensors employed in photogrammetric missions are commonly modeled through the collinearity condition and the corresponding equations. By contrast, a generalized sensor model does not include sensor position and orientation information. Described in the specification of the OGC (1999), there are three main replacement sensor models, namely, the grid interpolation model, the Rational Function Model (RFM) and the universal real-time sensor model (USM). These models are generic, i.e., their model parameters do not carry physical meanings of the imaging process. Use of the RFM to approximate the physical sensor models has been in practice for over a decade due to its capability of maintaining the full accuracy of different physical sensor models, its unique characteristic of sensor independence, and real-time calculation. The physical sensor model and the RFM have their own advantages and disadvantages for different mapping conditions. To be able to replace the physical sensor models for photogrammetric processing, the unknown parameters of the RFM are usually determined using the physical sensor models (Hu et al., 2004).

2.1 Rational Functions

The RFM relates object point coordinates to image pixel coordinates or vice versa, as physical sensor models, but in the form of rational functions that are ratios of polynomials. The RFM is essentially a generic form of the rigorous collinearity equations and the generalized sensor models including the 2D and 3D polynomial models, the projective transformation model and the (extended) direct linear transformation model (Hu et al., 2004).

These 3D rational functions have recently drawn interest from the civilian photogrammetric and remote sensing communities due to the launch of the civilian high-resolution IKONOS sensor in 1999, and subsequently EROS-A1 and QuickBird-2 sensors in 2000 and 2001, respectively. The major reason of their recent interest is that Space Imaging does not release

information on the IKONOS satellite and the sensor. The 3D rational functions can be used in two ways:

1. To approximate an already-solved existing 3D parametric model; and
2. To normally compute the unknowns of all the polynomial functions with GCPs (Toutin, 2004a).

$$R_{3D}\left(XYZ\right)=\frac{\sum_{i=0}^{m}\sum_{j=0}^{n}\sum_{k=0}^{p}a_{ijk}\,X^{i}\,Y^{j}\,Z^{k}}{\sum_{i=0}^{m}\sum_{j=0}^{n}\sum_{k=0}^{p}b_{ijk}\,X^{i}\,Y^{j}\,Z^{k}} \qquad (1)$$

Here; X, Y, Z are the cartographic coordinates; i, j, k are integer increments; m, n and p are integer values, generally comprised between 1 and 3 with m + n + p being the order of the polynomial functions. A 1st order RF contains = 8 + 8=16, 2nd order RF contains = 20 + 20=40 and 3rd order RF contains: 40 + 40=80 unknowns. By eliminating the first coefficient in the denominator, there are 39 RF coefficients in each equation, including 20 in the numerator and 19 in the denominator. Since each GCP produces two equations for image coordinate i and j separately in Eq.(1), at least 39 GCPs are required to solve for the 78 coefficients.

2.2 RFM Refining Methods

As proved by its high approximating accuracy to many physical sensor models, the RFM has high capability of geometric interpolation. However, the RPCs provided by imagery vendors may not always approximate the real imaging process well. The requirements for control information may not be met satisfactorily sometimes, or no ground control information is used when determining the physical sensor model itself for different marketing strategies from imagery vendors. High precision products are sold at a significantly higher price, and even require that users provide GCPs and a DTM. This presents a problem for many users who are prohibited to release topographic data this way (Hu et al., 2004).

Recent studies have found that RPCs can be refined in the domain of the image space or of the ground space, when additional control information becomes available. For example, the Ikonos Geo products and Standard stereo products will be improved to sub-meter absolute positioning accuracy using one or more high quality GCPs (Grodecki and Dial, 2003; Tao and Hu, 2004) or be close to the accuracy of the GCPs whose quality is low. So the RFM refining methods will definitely promote the use of low pricing products for many applications (Hu et al., 2004).

The RFM may be refined directly or indirectly. It means that one can improve the geopositioning accuracy of satellite imagery. The direct refining methods update the original RPCs themselves. The vendor-provided RF coefficients used as initial values in the computations. Such high quality initial values of the RF make the solution of the new RPCs more stable and the computational process faster to converge. If the rigorous sensor model is not available, high quality CPs cannot be produced by the rigorous sensor model. Consequently, this method requires a large number of GCPs to compute the new RPCs. In fact, more than 39 GCPs are required for the third-order RF. So the updated RPCs can be transferred without the need for changing the existing image transfer format. While the indirect refining

introduces complementary or concatenated transformations in image or object space, and they do not change the original RPCs directly. It improves the ground coordinates derived from the vendor-provided RPCs by a polynomial correction whose parameters are determined by the GCPs. The vendor-provided RFs are employed to perform the photogrammetric intersections to compute the ground coordinates from the corresponding image points for all measured points including the GCPs and check points. A polynomial transformation is then applied to all the ground coordinates computed from the RF. Each ground coordinate of a point (XRF, YRF, ZRF) undergoes a first-(or second-) order polynomial: i.e., (Di et al, 2003)

$$X = a_0 + a_1 X_{RF} + a_2 Y_{RF} + a_3 Z_{RF}$$
$$Y = b_0 + b_1 X_{RF} + b_2 Y_{RF} + b_3 Z_{RF} \qquad (2)$$
$$Z = c_0 + c_1 X_{RF} + c_2 Y_{RF} + c_3 Z_{RF}$$

where X, Y, and Z are the improved ground coordinates. To solve fort he coefficients of the polynomials, at least four GCPs are required fort he first order polynomials and then ten GCPs fort he second order polynomials.

3. STUDY AREA AND DATA

In this study one Cartosat-1 stereo pair covering southern part of Ankara, Turkey was used. This region is called Gölbaşı. The terrain is partly rough and the elevations in the region change between 900 m. and 1500 m. In this region, there are low urban areas, and a small lake. The other parts of the terrain contain open fields without any trees. There are partly some woods and plant cover (Figure 1).
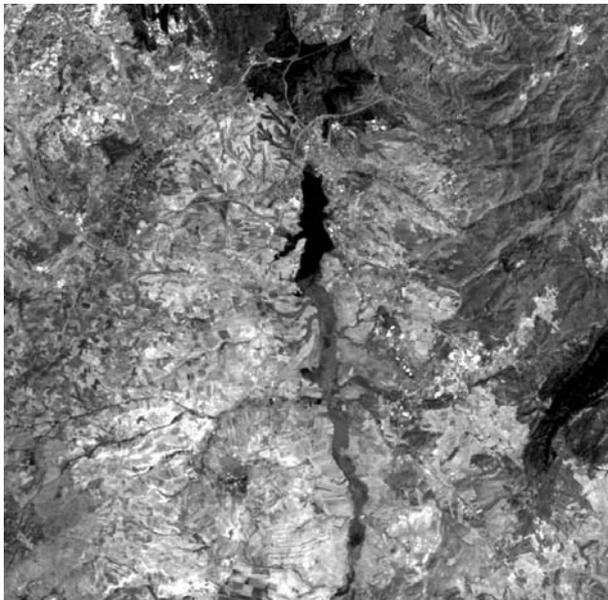

Figure 1. Cartosat-1 imagery

The two stereo images were acquired on 3rd August 2005 in the morning; the time interval between the two images is 54 sec. Each image is 12.000 x 12.000 pixel large, with a ground resolution of 2.5 m. The overlapping is almost 95%. The scenes cover an area of approximately 30 x 30 km2. The scenes were acquired in panchromatic mode with attitude angles (roll, pitch, yaw) close to zero and approximately equal for both of them; as already mentioned the stereo viewing is guaranteed (with a B/H ratio of about 0.6) by the sensor structure which is configured such that one camera scans the ground with off-nadir angle of +26° (forward image: band F) and the other with off-nadir angle of -5° (backward image: band A). The metadata files contain information on the acquisition time, image location, mean attitude angles and sensor geometry (detectors looking angles), but no data about ephemeris (Crespi et al, 2007). the nominal collection elevation of this imagery is approximately 68 degrees. RPC files are provided with the imagery. The RPC file provides camera model data for 3D photogrammetric compilation, for production of digital elevation model and orthorectification. The stereo reference images are the least processed images.

For this investigation 30 ground points, well distributed over the whole area and suited for acting both as Ground Control Points – GCPs and as Independent Check Points – ICPs, were available (Figure 2). All these points were collected from 0.5 m. resolution orthoimages with a geometric accuracy of 0.5 m. and they were used as GCPs when needed and the remaining part of these points are used as ICP. Z coordinate of the points were acquired from DEM created from 1/5.000 scale contours. Also a reference DEM has been extracted from 10 meter interval 1/25.000 scale contours.
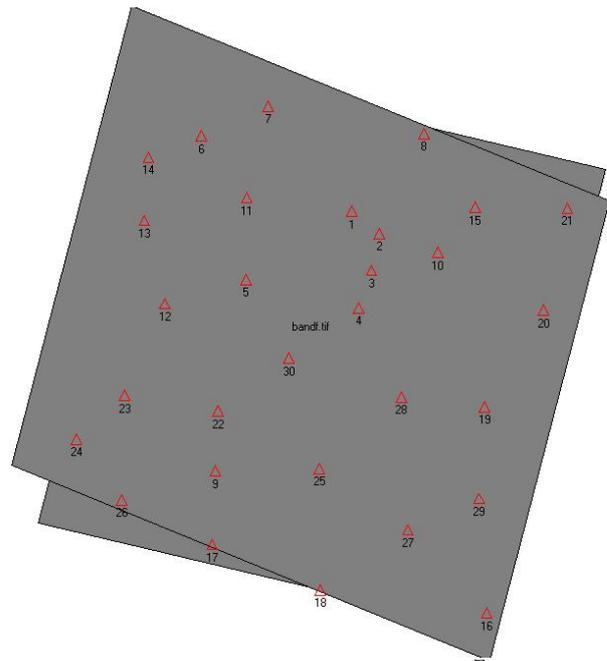

Figure 2. Ground Control Point distribution

4. METHODOLOGY

Three different polynomial models (polynomial model: the 0th order results in a simple shift to both image x and y coordinates, the 1st order is an affine transformation, the 2nd order results in a second order transformation) were used to refine the rational function derived ground coordinates. At first, image coordinates of the GCPs were measured on the images. RF based triangulation was applied to calculate the ground coordinates. Then, according to the Table 1, different number and configurations of the points were used as GCPs. Three

equations were established for each GCP. A least squares adjustment was used to compute the unknowns of the polynomials. ICPs were used to evaluate the accuracy of the models. These ICPs were the ground points that were not used

as GCPs. The difference between the known and the refined coordinates was the root mean square error of each model.

Order of the Polinomial	Number of GCPs	ID of the GCPs	RMS of GCPs (±m)			RMS of ICPs (±m)		
			x	y	z	x	y	z
0	1	6	0.001	0.003	0.177	2.456	0.976	5.281
	1	15	0.001	0.004	0.247	2.818	1.645	3.360
	1	27	0.004	0.001	0.227	1.487	0.933	5.248
	1	24	0.004	0.002	0.301	1.478	1.372	5.010
	1	30	0.003	0.002	0.194	1.903	0.934	3.244
	2	6, 27	0.893	0.140	0.203	1.833	0.961	5.361
	2	21, 29	0.003	0.004	0.383	1.504	0.951	3.309
	4	6,15,27,30	1.632	0.555	2.290	1.433	1.055	3.850
	8	6, 15, 27, 30, 12, 28, 8, 9	2.491	1.190	1.948	0.920	0.826	4.650
1	4	6,15,27,30	0.079	0.004	1.829	2.720	1.369	4.431
	8	6, 15, 27, 30, 12, 28, 8, 9	2.221	1.235	1.967	1.378	0.983	4.510
	12	6, 15, 27, 30, 12, 28, 8, 9, 19, 1, 20, 5	1.852	1.061	2.474	1.258	0.871	4.379
2	10	6, 15, 16 30, 12, 8, 9, 19, 1, 5	1.008	0.748	2.176	3.318	2.140	4.413
	14	6, 15, 27, 30, 12, 28, 8, 9, 19, 1, 20, 5, 4, 7	1.106	0.858	2.183	2.991	1.174	4.345

Table 1. Accuracy of refined ground coordinates.

5. APPLICATION

Different numbers and distribution of GCPs were used for the three polynomial models. The number of GCPs used for refinement, the id of GCPs, root mean square errors of GCPs and ICPs were given in Table 1. Readers can check the distribution of the GCPs in Figure 2.

0th order polynomial offers just a translation to RPC derived coordinates. It needs only one GCP. With one GCP, good accuracies can be achieved (2.5 m. in horizontal and 5 m. in vertical). As seen in the table, there is no logical relation with the location of the GCP. Also, the number of the GCPs used for the computation does not seem to affect the results. But, the accuracy of the GCP directly affects the resulting accuracy. So, using one GCP is prone to errors of GCPs used for calculation.

1st order polynomial offer slightly better results than 0th order polynomial. But, it requires more GCPs (minimum 4 GCPs). Increasing the number of GCPs does not seem to generate any significant improvement. By a 1st order polynomial it is better to use more than 4 GCPs.

2nd order polynomial does not provide better results though it's usage of great number of GCPs. Even, in some cases it is prone to the errors, especially in case the distribution of the GCPs is not even.

GCP RMS residuals reflect modelling and GCP accuracy, while ICP RMS errors reflect restitution accuracy, which includes feature extraction error and thus are a good estimation of the final positioning accuracy of planimetric features. However, the final internal accuracy of the 3D modelling will be better than these RMS errors. Consequently, it is thus normal and "safe" to obtain residuals from the least-squares adjustment in the same order of magnitude as the predominant GCP error (Toutin, 2004b).

Analysis of the general results shows that 3D physical model is stable over the stereo model and does not create local errors independent from the number of GCPs. These statements are backed up by the unbiased ICP errors.

The role of the GCPs is to effect an image coordinate translation and thus their location within the scene is of no real consequence; addition of further GCPs makes no contribution to the geometric strength of the triangulation process per se. Instead the extra control points simply provide more information from which to evaluate an appropriate 'average' image coordinate correction. It can be seen in Table 1 that there is no clear link between the accuracy level attained and the location or number of GCPs. Nevertheless, with the use of redundant control points one can be more confident about the reliability of the geopositioning process (Fraser, 2004).

By comparing the reference DEM and the DEM acquired from stereo Cartosat-1 imagery, 35 m. systematic error was met. So 35 meter constant error was subtracted from the difference of the DEMs. Thus, an error nearly 1 meter was achieved (Figure 3).
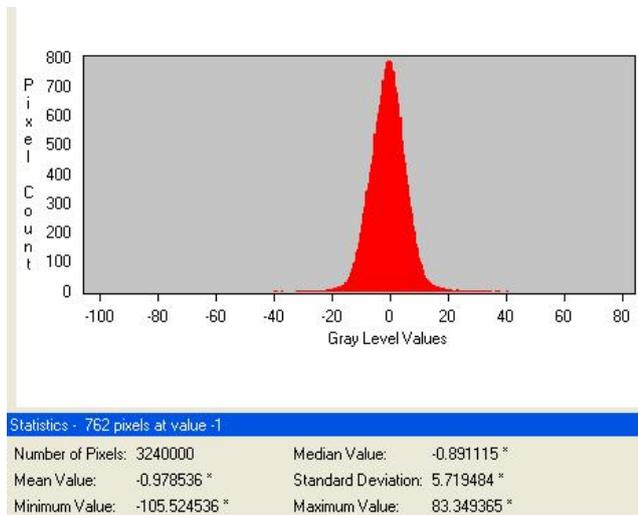

Figure 3. DEM Statistics.

6. CONCLUSIONS

In this paper, three polynomial models were used to improve RPC derived coordinates of Cartosat-1 stereo images. Highly accurate GCPs were used in the test by 0.5 meter resolution orthoimagery. With these three models also different configurations of GCPs were used. The study area has generally a smooth terrain. The elevations change between 900 m. and 1500 m. in this area. There are not so many trees or plant coverage in the area. Also, the GCPs reflect the whole range of elevations of the area. Here are some conclusions drawn from this test:

Generally, there is no important difference between three models. Even, with 0th order polynomial (one translation), accuracies 2 m. in horizontal and 4 m. in vertical can be achieved. It is understood that RPCs of Cartosat-1 imagery contain mostly translation errors. Because using one GCP is prone to errors of GCPs used for calculation, it is recommended that using one more GCP is enough for most of the applications. But it is more robust to use 1st order polynomial, although it needs more GCPs. Also, the distribution of the GCPs is of no importance. Although 2nd order polynomial provides also good results, it requires more GCPs and sensitive to GCP configuration. Because the precision and accuracy of the GCPs are so high (0.5 m.), it is inferred that the errors come from the GCPs measurement (0.5-1 pixel) on the images.

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