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ORTHORECTIFICATION AND DEM GENERATION FROM HIGH RESOLUTION SATELLITE DATA

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ABSTRACT: The latest additions of IKONOS and EROS-A1 data have created a big impact to the remote sensing industry. Instead of using aerial photos, highly detailed maps of entire city and country can be frequently and easily updated using this data. Different methods can be used to correct the satellite data. In this paper, IKONOS and EROS-A1 data were obtained for the same area. Furthermore, a IKONOS stereo pair was acquired on an other study site. A rigorous model developed at Canada Centre for Remote Sensing (CCRS) was used for the geometric correction and the DEM generation. The results are accurate when compared with the orthophotos, which enables the data to be integrated into a lot of applications. DEM errors of 2-5 meter was obtained depending of the land covers.

1. INTRODUCTION

IKONOS, the commercial satellite with the highest publicly available resolution, was successfully launched in September 1999. The satellite's sensor can generate 1-m panchromatic and 4-m multiband images with off-nadir viewing up-to-60º in any azimuth for a better revisit rate and stereo capabilities. These capabilities enable along- and across-track stereoscopic images to be acquired for digital elevation model (DEM) generation.

EROS-A1, launched by ImageSat International on December 2000 with 1.8-m resolution, is a satellite with high performance, low cost, light, agile, and designed for low earth orbit (LEO). It embodies the creative use of many state-of-the-art technologies, going beyond what conventional wisdom said could be achieved. Because of the satellite's lightness and ability to re-point and stabilize quickly, EROS-A1 satellite is unsurpassed in its ability to acquire numerous specific images of the ground.

The high-resolution imagery that IKONOS and EROS-A1 provide theoretically will have "unlimited" uses in a number of markets (including state and local government) and in various applications such as mapping, agriculture, forestry, and emergency response. Instead of using aerial photos, highly detailed maps of entire countries can be frequently and easily updated using this data. Farmers can monitor the health of their crops and estimate yields with greater accuracy and over shorter intervals. Scientists can look at environmentally sensitive areas and predict trends with greater certainty. Government officials can monitor and plan more enlightened land use policies. City planners can further the development of new housing communities with greater precision and attention. In short, the potential uses for IKONOS and EROS-A1 imagery are limited only by the imagination.

1.1 IKONOS

IKONOS data is produced for five different product levels and is available at five different prices. Table 1 shows an example of the basic panchromatic product. IKONOS is distributed in 8-bit or 11-bit GeoTiff format with ASCII metadata file (including order parameters and also source image and products file descriptions). A minimum order of 100 sq. km is required. The Geo product, which is the most affordable but offers the lowest positioning accuracy, is not corrected for terrain distortions. It has an accuracy of 50m with 90% level of confidence. Accuracy becomes worse in mountainous areas if the images are acquired with off-nadir viewing, which is quite common for the IKONOS data. Hence, the product will only meet the geometric requirements of mapping scale at 1:100,000. Since Space Imaging does not provide the raw data with their ancillary data, which are preferred by the photogrammetrist community, IKONOS stereo images are distributed in a quasi epipolar-geometry reference where only the elevation parallax in the scanner direction remains. For along-track stereoscopy with the IKONOS orbit, it approximately corresponds to a North-South direction, with few degrees in azimuth depending of the across-track component of the total collection angle.

Table 1: Detailed prices for basic panchromatic product from Space Imaging Web Site (http://www.spaceimaging.com/).

Product Code	CE90 Accuracy	Price for North America	Price for International
Geo	50 m	$18	$35
Geo Ortho Kit	-	$29	$62
Reference	25 m	$29	$62
Pro	10 m	$39	$98
Precision	4 m	$55	$136
PrecisionPlus	2 m	Quote	n/a

Note: CE90 is the circular positioning accuracy with a confidence level of 90%. Prices are in US dollars per square kilometer.

The PrecisionPlus product is the most expensive but offers the highest positioning accuracy (2m CE90). To achieve it, the user will have to provide GCPs and a DEM to Space Imaging for generating the ortho-image. Because most of the images are acquired at off-nadir viewing, the accuracy of GCPs should be within one metre accuracy and the DEM should be within 5-m accuracy. Sub-pixel accuracy (which may be obtained with satellites such as SPOT and Landsat) will not be achievable for IKONOS, even for flat terrain.

The new IKONOS product, Geo Ortho Kit, consists of a high-resolution Geo image derived from the IKONOS satellite and an Image Geometry Model (IGM) digital file. The IGM is a mathematical way of expressing the complex sensor geometry of the IKONOS camera, which is necessary to correct the imagery for terrain distortions. By incorporating the IGM and a Geo image into the leading commercial imagery software suites, users will now be able to create an accurate ortho image by using their own DEMs and GCPs. Since IGM provides the complete and accurate sensor geometry, the metric accuracy of the final orthorectified image is limited only by the accuracy of the DEM and GCPs. The product is available as a part of the Geo product suite in 1-meter black-and-white, 1-meter colour, or 4-meter multispectral.

Although the Geo Ortho Kit product seems to be the best solution for the user, more testing is necessary to determine the accuracy of the Geo Ortho Kit products for different terrain. In addition, it is still expensive when compared with the Geo product. Hence, most users still prefer to use the Geo product. In this paper, we will focus on the geometric correction of IKONOS Geo product.

1.2 EROS-A1

EROS-A1 is provided in 3 different levels, i.e. 0A, 1A and 1B. Level 1A data, which is raw data with radiometric correction applied, is always the best choice for geometric correction because the geometry of the image related to the satellite and sensor is always preserved. Although the EROS-A1 has a slightly lower resolution than the IKONOS (1.8-m verses 1-m), the price of EROS-A1 is much less. The price range of EROS-A1 is about $10 per square km. Hence, it provides a very attractive alternative for users who want to use high resolution data but cannot afford IKONOS.

2. GEOMETRIC PROCESSING

Three methods can be used to correct the IKONOS Geo or EROS-A1 level 1A data: the simple polynomial method, the rational polynomial method, and the rigorous (or parametric) model method. Often considered outdated, the simple polynomial method is a very uncomplicated method for correcting images. It corrects for basic planimetric distortions at the GCPs. Because this method does not take ground elevation into consideration, it is limited to small and flat areas.

Rational polynomial method (OGC 1999) is similar to simple polynomial method, except that it involves a ratio of polynomial transformations and it also takes ground elevation into consideration. Therefore, this method can be useful for areas with gentle terrain. Both simple polynomial and rational polynomial methods do not require satellite and sensor information. Since neither method is not rigorously modeled, they require many GCPs and only correct at the GCPs. Distortions between the GCPs are not entirely eliminated.

Rigorous models reflect the physical reality of the complete viewing geometry and correct distortions due to the platform, sensor, Earth, and sometimes the deformations due to the cartographic projection. It then takes into consideration the satellite-sensor information. When compared to simple polynomial and rational polynomial methods, the rigorous model method produces the highest accuracy results with relatively few GCPs.

The fact remains that detailed sensor information for the IKONOS satellite has not yet been released. Despite this, Toutin and Cheng (2000, 2001) have successfully developed a rigorous IKONOS model using basic information from the metadata and image files for orthorectification and DEM generation. For example, approximate sensor viewing angles can be computed using the nominal collection elevation and the nominal ground resolution in the across and along scan directions. The model is based upon principles related to orbitography, photogrammetry, geodesy and cartography. It has been successfully applied with only a few GCPs (3-6) to VIR data (Landsat 5 & 7, SPOT, IRS, ASTER, and KOMPSAT), as well as SAR data (ERS, JERS, SIR-C and RADARSAT). Based on good quality GCPs, the accuracy of this model was proven to be within one-third of a pixel for VIR medium resolution images and one resolution cell for SAR images. Since the development of the rigorous model for IKONOS Geo product, different applications were used together with the rigorous model and Geo products and accurate results were obtained (Davis & Wang 2001). In this paper, we apply this rigorous 3D model to both IKONOS and EROS-A1 data and to stereo IKONOS data.

3. EXPERIMENT

To test the three different ortho-rectification methods, an IKONOS Geo data and an EROS-A1 data, were acquired in April 2000 and June 2001, respectively. The area is the Town of Richmond Hill, located north of Toronto, Ontario, Canada. This study area has an elevation range of 180 to 240 meters. The metadata file was processed to compute the satellite parameters for the rigorous model method. EROS-A1 data was provided by the Core Software Technology. Thirty GCPs and 23 GCPs were collected uniformly on the IKONOS and EROS-A1 images, respectively. The map coordinates were obtained from 20-cm ortho photos and a 2-m spacing DEM. Most GCPs were collected at the intersection of sidewalks. Figures 1 and 2 show an example of the orthorectified image of IKONOS and EROS-A1 resampled at 1-m resolution.

The stereo capability can only be tested with the rigorous method. CCRS ordered an IKONOS stereo product in Autumn 2000 for a semi-urban area north of Québec City, Quebec, Canada (N 47º, W 71º 30'). This study area has an elevation range of 150-m to 500-m. Unfortunately, the along-track stereo-data was acquired on January 3, 2001 with a sun illumination angle as low as 19º, generating long shadows due to trees. The images with a resolution of a little less than one metre and a 54º stereo-intersection angle (B/H=1.0). While only six GCPs are enough with the rigorous method, 55 GCPs were collected in stereoscopy from the stereo-images for the different tests. Their map coordinates (X, Y, Z) were obtained from six 1-m ortho-photos and a 5-m spacing DEM (5-m accurate). A mean positioning error of 5-m in the X direction was found between the different ortho-photos; this error is mainly due to 5-m DEM error during the ortho-photo generation. Unfortunately, no stereo EROS data was available to test its stereoscopic capability.

To test the geometric correction and DEM generation process, PCI OrthoEngine software (a product that supports all three of the mentioned correction methods) was used. PCI OrthoEngine also supports the reading of different satellite data, GCP collection, geometric modeling, orthorectification, image matching,, DEM generation and either manual or automatic mosaicking and editing.

4. RESULTS AND ANALYSIS

4.1 IKONOS

Table 2 shows the root mean square (RMS) and maximum residual of the calculation of the three different methods for IKONOS data. Second order polynomial transformations were used for both simple and rational polynomial methods. Table 2 shows the rational polynomial method provided the best residuals. However, assessing accuracy with only GCP residuals is misleading and biased because both polynomial methods correct locally at the GCPs.

Table 2: Comparison of residuals results with 30 GCPs using simple polynomial, rational polynomial, and rigorous model for IKONOS data.

Correction Method	RMS Residuals (m)		Maximum Residuals (m)	
	X	Y	X	Y
Simple Polynomial	1.0	3.2	2.4	6.2
Rational Polynomial	0.5	0.7	1.1	1.4
Rigorous Model	0.8	1.1	1.9	2.8

During the acquisition of GCPs, a mistake was made in collecting one of the GCPs. The error was about 20m in the Y-direction. Both simple and rational polynomial methods were unable to detect the erroneous point. Table 3 shows the RMS and the residuals of the erroneous point. The Y-residual of the erroneous point from the rigorous model was four times higher than the RMS residuals and was detected immediately with its error value and direction.

Table 3: Comparison of residual results with 30 GCPs including one erroneous point using simple polynomial, rational polynomial, and rigorous model for IKONOS data.

Correction Method	RMS Residuals (m) X	Y	Erroneous Point (m) X	Y
Simple Polynomial	1.2	3.9	2.2	6.7
Rational Polynomial	0.6	1.3	0.3	1.4
Rigorous Model	1.1	3.0	2.2	11.8

Unbiased validation of the positioning accuracy has to be done with independent check points (ICPs), which are not used in the model calculations. Consequently, 23 of the 30 GCPs were changed to ICPs in the second test. Second order was used for the simple polynomial method and first order for the rational polynomial method due to the reduced number of GCPs. Table 4 shows the RMS and maximum errors over the 23 ICPs using the three methods. The errors are smaller with the rigorous method than with both polynomial methods and are also consistent with the residuals of Tables 2 & 3. This shows that the rigorous model is both stable and robust without generating local errors and filters errors. An evaluation of these image parameters computed from the rigorous method (such as the viewing angles) validates the basic assumptions and estimations computed from the metadata file.

Table 4: Comparison of error results with 23 ICPs and 7 GCPs using simple polynomial, rational polynomial, and rigorous model for IKONOS data.

Correction Method	RMS Errors (m) X	Y	Maximum Errors (m) X	Y
Simple Polynomial	1.7	4.1	4.1	7.5
Rational Polynomial	2.2	5.2	5.1	10.4
Rigorous Model	1.3	1.3	3.0	3.0

A final evaluation was done by performing a quantitative and qualitative comparison of the ortho-image generated from the rigorous method and a DEM with the 20cm ortho-photos. It confirms the previous results over the ICPs that there is no error larger than 4-5 m. Consequently, the accuracy of the rigorous model is within the accuracy of the IKONOS Precision product.

Table 5 shows the statistical DEM results extracted from the stereo IKONOS data. As seen in the first line of Table 5, the 3.8m error with 68% level of confidence obtained for the full study site is a good result because not only does it includes the 5m error of the topographic checked DEM but also includes canopy height. Since there are so many fine details in the stereo extracted DEM, its accuracy evaluation must be realized for different land covers. Six classes of land covers are used in this area: dense forest, sparse forest, bare soils, sand/gravel pits, lakes and cities. These results are also presented in Table 5. The best results (around 2-2.5 metres) are obtained for four classes of no- or low-elevation cover (bare soils, lakes, sparse forest, and urban/residential areas). While the houses in the residential and urban areas, which lack tall buildings or skyscrapers present in many North-American cities do not affect the statistics too much, the canopy height of the dense boreal forest does generate results that are slightly worse (4.4 metres and a larger negative bias). Finally, the largest errors (8.5 metres and –50m/37m min./max.) are in the sand/gravel pits, located northwest and southwest of the images, where elevations changed over time. Furthermore, the errors larger than 10m are located in the northwest slopes of mountains where shadow due to sun elevation angle and azimuth of 19º and 166º, respectively is present. These specific errors are representative of our study site and the stereo-images, but are not representative of the general IKONOS stereo potential for DEM generation in semi-rural areas.

Table 5: Statistical DEM results for the entire study site and as a function of the land cover.

Area	Percentage	68% Level of Confidence	90% Level of Confidence	Bias	Min./Max
Entire	100%	3.8 m	7.9 m	-0.9 m	-50/37 m
Dense forest	61%	4.4 m	8 m	-2.1 m	-37/29 m
Sparse forest	11.5%	2.4 m	5 m	1.1 m	-34/31 m
Bare soils	6.5%	2.6 m	5.6 m	2.0 m	-33/28 m
Lakes	4%	1.1 m	4.6 m	2.3 m	-29/20 m
Pits	1.5%	8.5 m	18 m	0.5 m	-50/37 m

Urban/Res.	15.5%	2.4 m	5 m	0.2 m	-26/18 m

4.2 EROS A-1

Table 6 shows the root mean square (RMS) and maximum residual of the calculation of the three different methods for EROS-A1 data. Second order polynomial transformations were used for both simple and rational polynomial methods. Similar to the previous IKONOS example, the rational polynomial method provided the best residuals. Again, assessing accuracy with only GCP residuals is misleading and biased because both polynomial methods correct locally at the GCPs.

Table 6: Comparison of residual results with 23 GCPs using simple polynomial, rational polynomial, and rigorous model for EROS-A1 data.

Correction	**RMS Residuals (m)**		**Maximum Residuals (m)**	
Method	**X**	**Y**	**X**	**Y**
Simple Polynomial	1.8	1.2	3.7	2.7
Rational Polynomial	0.7	0.9	0.7	2.2
Rigorous Model	1.8	1.5	2.7	2.5

Consequently, 16 of the 23 GCPs were changed to ICPs in the second test. Second order was used for the simple polynomial method and first order for the rational polynomial method due to the reduced number of GCPs. Table 7 shows the RMS and maximum errors over the 16 ICPs using the three methods. The errors are smaller with the rigorous method than with both polynomial methods and are also consistent with the residuals of Table 6. Again, this shows that the rigorous model is both stable and robust without generating local errors and filters errors.

Table 7: Comparison of error results with 23 ICPs and 7 GCPs using simple polynomial, rational polynomial, and rigorous model for EROS-A1 data.

Correction	**RMS Errors (m)**		**Maximum Errors (m)**	
Method	**X**	**Y**	**X**	**Y**
Simple Polynomial	3.4	2.2	8.1	4.1
Rational Polynomial	14.0	2.4	36.8	5.9
Rigorous Model	2.1	2.1	4.1	3.9

5. CONCLUSIONS

IKONOS Geo products have an accuracy that is relatively low and inconsistent with their image content quality and their large-scale maps. Precision products can be difficult to generate outside some countries and are otherwise expensive. Although IKONOS Geo Ortho Kit product allows the user to orthorectify their images, it is still expensive when comparing with the Geo product. Now, users can apply a rigorous model (one that is available in an operational environment) to correct the low-cost Geo products or to generate stereo DEM. When accurate ground data is available, users may produce consistent orthoimages, which are in the same order of accuracy than the expensive Precision products. Furthermore, DEM with an accuracy of 2-5 metres can be generated depending of the land covers. Another alternative is to use the EROS-A1 data. Although the data has slightly lower resolution than the IKONOS, it is much cheaper than the IKONOS data. Stereoscopic of EROS data is also under evaluation. Both IKONOS and EROS-A1 data, together with rigorous model described in this paper, is capable to meet National Map Accuracy Standard (NMAS) of 1:4800 scale.

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Figure 1: Orthoimage of IKONOS (1-m)

Figure 2: Orthoimage of EROS A-1 (1-m)