

3D MODELS FOR HIGH RESOLUTION IMAGES: EXAMPLES WITH QUICKBIRD, IKONOS AND EROS

Th. Toutin^{a, *}, R. Chénier^{ab}, Y. Carbonneau^{ab}

^a Natural Resources Canada, Canada Centre for Remote Sensing, 588Booth Street, Ottawa, Ontario, K1A 0Y7 Canada -
thierry.toutin@ccrs.nrcan.gc.ca

^b Under contract with Consultants TGIS inc., 7667 Curé Clermont, Anjou, Québec, H1K 1X2 Canada –
(rene.chenier; yves.carbonneau)@ccrs.nrcan.gc.ca

Commission IV, WG IV/7

KEY WORDS: 3D models, Parametric and non-parametric, High resolution, QuickBird, IKONOS, EROS

ABSTRACT:

EROS, IKONOS and Quickbird are the three civilian satellites, which presently provide panchromatic images with the highest spatial resolution: 2-m, 1-m and 0.6-m, respectively. They also have off-nadir viewing up-to-60° in any azimuth depending on the sensor, which enables stereo images (along and across track) to be acquired. However, the image acquisition system produces different geometric distortions, which need to be accurately corrected. The paper reviews the image distortions and the different 3D models (non-parametric and parametric) for the geometric processing with their applicability to high-resolution images depending on the type of images and their pre-processing level. Results are then presented with stereo images for the three sensors using different 3D models. In general, the 3D parametric models achieve more consistent results.

RÉSUMÉ :

EROS, IKONOS et Quickbird sont les trois satellites civils, qui fournissent des images panchromatiques avec la meilleure résolution spatiale : 2 m, 1 m et 0,6 m, respectivement. Ils peuvent aussi dépointer jusqu'à 60° dans tous les azimuts pour acquérir des images stéréoscopiques (dans le sens de l'orbite ou perpendiculairement). Par contre, le système d'acquisition des images crée différentes distorsions géométriques, qui doivent être corrigées avec précision. L'article présente les distorsions géométriques et les différents modèles 3D (non-paramétrique et paramétrique) pour le traitement géométrique, ainsi que leur applicabilité aux images de haute résolution suivant le type d'images et leur niveau de prétraitement. Des résultats sont alors donnés avec des images stéréoscopiques des trois capteurs avec les différents modèles 3D. En général, les modèles paramétriques 3D donnent des résultats plus cohérents.

1. INTRODUCTION

The generation of high-resolution imagery using previously-proven defence technology provides an interesting source of data for digital topographic mapping as well as thematic applications such as agriculture, forestry, and emergency response (Kaufmann und Sulzer, 1997; Konecny, 2000). Instead of using aerial photos, highly detailed maps of entire countries can be frequently and easily updated using these data. Petrie (2002) gives a review and comparisons of the characteristics of this new generation of high-resolution satellites.

However, high-resolution images usually contain so significant geometric distortions that they cannot be used directly with map base products into a geographic information system (GIS). Consequently, multi-source data integration (raster and vector) for mapping applications requires geometric and radiometric models and processing adapted to the nature and characteristics of the data in order to recover the original information from each image in the composite geocoded image.

1.1 Image Distortions

The source of distortions can be related to two general categories: **the Observer** or the acquisition system (platform, and imaging sensor) and **the Observed** (atmosphere and Earth). In addition to these distortions, the deformations related to the

map projection have to be taken into account because the terrain and most of GIS end-user applications are generally represented and performed in referenced topographic maps.

The distortions caused by the platform are mainly related to the variation of the elliptic movement around the Earth, caused at first order by the variations of the Earth gravity (Escobal, 1965). Depending of the acquisition time and the size of the image, the variation of the elliptic movement has a various impact on the image distortion. Some effects include:

- the altitude variations in combination with the focal length, the flatness and the relief of the Earth change the pixel spacing;
- the attitude variations in the roll, pitch and yaw axes change the orientation and the shape of high resolution images;
- the velocity variations change the line spacing or create line gaps/overlaps in the images.

The distortions caused by the imaging sensor are:

- the calibration parameters, such as the focal length and the instantaneous field of view (IFOV);
- the panoramic distortion in combination with the oblique-viewing system, the Earth curvature and the topographic

relief changes the ground pixel sampling along the column.

The distortions caused by the Earth are:

- the rotation generates lateral displacements in the column direction between image lines depending of the latitude;
- the curvature creates variation in the image pixel spacing;
- the topographic relief generates a parallax in the scanning azimuth.

The deformations caused by the map projection are:

- the approximation of the geoid by a reference ellipsoid;
- the projection of the reference ellipsoid on a tangent plane.

1.2 Image Correction Models

All these geometric distortions require models and mathematical functions to perform the geometric corrections of an image: either with 2D/3D non-parametric models or with rigorous 3D parametric models. With 3D parametric models, the geometric correction can be corrected step-by-step with a mathematical function for each distortion or all together with a “combined” mathematical function.

Since the 2D polynomial functions do not reflect the sources of distortion during the image formation and for the relief, they are limited to images with few or small distortions, such as nadir-viewing images, small images, systematically-corrected images, flat terrain. They also are very sensitive to input errors. The 2D polynomial functions were mainly used in the 70’s and 80’s on images, whose systematic distortions, excluding the relief, where already corrected by the image providers. Since it is well known that 2D polynomial functions are not suitable for accurately correcting remote sensing images, especially high-resolution images, only 3D models are addressed in this paper. Finally, some results on ortho-images generation and 3D data extraction will be presented with these high-resolution images.

2. 3D NON-PARAMETRIC MODELS

The 3D non-parametric models can be used when the parameters of the acquisition systems or a rigorous 3D parametric model are not available. Since these models do not require *a priori* information on any component of the total system (platform, sensor, Earth, map projection), they do not reflect the source of distortions described previously. Consequently, due to the lack of physical meaning, the interpretation of the parameters are difficult (Madani, 1999).

These non-parametric models are based on different XYZ mathematical functions:

- For the 3D polynomial functions, P_{3D} :

$$P_{3D}(XYZ) = \sum_{i=0}^m \sum_{j=0}^n \sum_{k=0}^p a_{ijk} X^i Y^j Z^k \quad (1)$$

- For the 3D rational functions, R_{3D} :

$$R_{3D}(XYZ) = \frac{\sum_{i=0}^m \sum_{j=0}^n \sum_{k=0}^p a_{ijk} X^i Y^j Z^k}{\sum_{i=0}^m \sum_{j=0}^n \sum_{k=0}^p b_{ijk} X^i Y^j Z^k} \quad (2)$$

where: X, Y, Z are the terrain or cartographic coordinates;
i, j, k are integer increments;
m, n and p are integer values; and
m+n+p is the order of the polynomial functions.

The order of the polynomial functions is generally less than three because higher orders do not improve the results. The 3D 1st, 2nd and 3rd order polynomial functions will then have 4, 10 and 20-unknown terms. The 3D 1st, 2nd and 3rd order rational functions will then have 7, 19 and 39-term unknowns. In some conditions, specific terms, such as XZ, YZ² or Z³, could be dropped of the polynomial functions, when these terms can not be related to any physical element of the image acquisition geometry; it thus reduces potential correlations between terms.

2.1 3D Polynomial Models

The 3D polynomial functions are an extension of the 2D polynomial function by adding Z-terms related to the third dimension of the terrain. However, they are subjected to the same problems related to 2D non-parametric functions: application to small images, need lot of ground control points (GCPs) regularly distributed, correct locally at GCPs, very sensitive to input errors, lack of robustness, etc. Their use should be thus limited to small images or to systematically-corrected images, where all systematic distortions except the relief were corrected. They were applied with georeferenced images, such as SPOT-HRV (level 1B) (Palà and Pons, 1995) and IKONOS Geo-products (Hanley and Fraser, 2001).

The terms related to terrain elevation in the 3D polynomial functions could be reduced to aZ for high-resolution images, whatever the order of the polynomial functions used.

2.2 3D Rational Models

These 3D rational functions have recently drawn interest in the civilian photogrammetric and remote sensing community due to the launch of new civilian high-resolution sensors. The major reason of their recent interest is that some image vendors, such as Space Imaging do not release information on the satellite and the sensor. The 3D rational functions can be used with two approaches:

- 1) To approximate an already-solved existing 3D parametric model; and
- 2) To determine by least-squares adjustment the coefficients of the polynomial functions (equation 2) with GCPs.

The first approach is performed in two steps. A 3D regular grid of the imaged terrain is first defined and the image coordinates of the 3D grid ground points are computed using the already-solved existing 3D parametric model. These grid points and their 3D ground and 2D image coordinates are then used as GCPs to resolve the 3D rational functions and compute the unknown terms of polynomial functions.

This approach has been proven adequate for aerial photographs or satellite images (Tao and Hu, 2001). However, they found that the results are sensitive to GCP distribution with satellite images. When the image is too large, the image itself has to be subdivided and separate 3D rational functions are required for each subdivided image. It sometimes results in “less user-friendly” processing than a direct 3D parametric model. Image vendors or government agencies, which do not want to deliver satellite/sensor information with the image, utilize this approach. They thus provide with the image all the parameters of 3D rational functions. Consequently, the end-users can directly process the images for generating ortho-images or DEM and also post-process these products to improve their final accuracy. However, this approach is useless for the end-users because it requires the knowledge of a 3D parametric model. In this condition, the end-users can directly apply the 3D parametric model. Furthermore, the approximation of a 3D parametric model will not generally be as precise than a 3D parametric model by itself, depending on the image, its distortions and its processing level.

The second approach can be performed by the end users with the same processing method than with polynomial functions. Since there are 38 to 78 parameters (two equations (2) for column and for line) for the four 2nd and 3rd order polynomial functions, a minimum of 19 and 39 GCPs respectively are required to resolve the two 3D rational functions. As with the polynomial functions, rational functions do not model the physical reality of the image acquisition geometry and are sensitive to input errors. Consequently, much more GCPs are needed to reduce error propagation in operational environment.

Such as the 3D polynomial functions, the rational functions mainly correct locally at the GCPs, and errors and inconsistencies between GCPs can be found (Davies and Wang, 2001). They should not be used with raw and large-size images but only with small-size or georeferenced/geocoded images. Otherwise, a piecewise approach as described previously should be used for large raw images, and the number of GCPs should be increased proportional to the number of sub-images. However, the 3D rational functions are certainly the best selection among the non-parametric functions, when 3D parametric solution is not available.

3. 3D PARAMETRIC MODELS

Although each sensor has its own specificity, one can draw generalities for the development of 3D parametric functions, in order to fully correct all distortions described previously. The 3D parametric functions should model the distortions of the platform (position, velocity, and attitude), the sensor (viewing angles, panoramic effect), the Earth (ellipsoid and relief) and the cartographic projection. The geometric correction process can address each distortion one by one and step by step or all together. In fact, it is better to consider the total geometry of viewing: platform + sensor + Earth + map, because some of the distortions are correlated (Toutin, 1995). It is theoretically more precise to compute one “combined” parameter than each individual component of this “combined” parameter, separately.

As examples of combined parameters, we have:

- the orientation of the image is a combination of the platform heading due to orbital inclination, the yaw of the platform, the convergence of the meridian;
- the scale factor in along-track direction is a combination of the velocity, the altitude and the pitch of the platform, the detection signal time of the sensor, the component of the Earth rotation in the along-track direction; and
- the levelling angle in the across-track direction is a combination of platform roll, the viewing angle, the orientation of the sensor, the Earth curvature.

The general starting points of these research studies to derive the 3D parametric functions are generally the well-known collinearity condition and equations (Light *et al.*, 1980), which are only valid for a scanline acquisition. However, the parameters of neighbouring scanlines of scanners are highly correlated, it is thus possible to link the exposure centres and the rotation angles of the different scanlines with supplemental information. Ephemeris and attitude data can be integrated using 2nd order polynomial functions (Konecny *et al.*, 1986) or benefiting from theoretical work in celestial mechanics (Toutin, 1995).

4. APPLICATIONS TO HIGH RESOLUTION IMAGES

4.1 QuickBird

Raw images with detailed metadata are provided to the end users (DigitalGlobe, 2002). The adaptation and application of 3D parametric models already developed for push-broom scanner (Konecny *et al.*, 1986; Toutin, 1995) can be easily done. On the other hand, it is not advised to use 3D non-parametric models, which do not reflect the geometry of viewing and are sensitive to GCP errors and distribution.

DigitalGlobe provided a test image (16 x 17 km) acquired over Reno, USA for testing the CCRS 3D parametric model capability (Toutin, 1995). The image is raw-type with 61-cm pixel spacing. However, the sensor resolution seems better. As an example, Figures 1 & 2 show a sub-image (61-cm pixel spacing) over an urban area and a sub-image (10-cm pixel spacing) resampled six times, respectively. The quality and the details of Figure 2 give an idea of the sensor resolution and easily demonstrate the high mapping potential of this data.

The image is presently processed at CCRS and preliminary results using 22 10-cm accurate GPS GCPs with rational and CCRS-parametric models are only given. 3D polynomial models were not used on raw images with large distortions. The results (Table 1) show the adaptability and the superiority of CCRS 3D parametric model for QuickBird. The parametric model was not sensitive to the number and distribution of GCPs, while the rational model was. Since the main errors come from GCP definition and plotting (around 1-2 pixels), sub-metre accuracy could thus be achieved with better-defined GCPs.

Correction Method	RMS (m)		Maximum (m)	
	X	Y	X	Y
Rational 1 st order	4.0	2.1	9.5	4.3
Parametric	1.4	1.3	2.5	2.8

Table 1. Comparison of RMS and maximum errors over 12 ICPs from 1st order rational model and Toutin’s parametric model computations with 10 GCPs

An in-track stereo pair has just been acquired over an area North of Quebec City, Canada with good control data and laser DTM. It is a residential and semi-rural environment with a hilly topography (500-m elevation range). More results on 3D parametric and non-parametric models, ortho-image generation and 3D extraction (DTM, canopy and building heights) will be shown at the Symposium. Due to the raw image type and its size (16 x 17 km), a piecewise approach should be used with the rational models to improve the previous results (4-m accuracy in Table 1), but leading to the increase of GCP number.



Figure 1: Sub-image (200 x 200 pixel; 61-cm pixel spacing) of Quickbird image acquired over Reno, USA. Courtesy and copyright of DigitalGlobe, 2002

4.2 IKONOS

The raw images are not available and the basic product provided by Space Imaging is the map-oriented Geo product. It has an accuracy of 50-m CE90, which means that any point within the image is within 50 meters horizontally of its true position on the earth's surface 90% of the time (Space Imaging, 2002). 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.

The fact remains that detailed sensor information for the IKONOS satellite has not yet been released. Despite this, the integrated and unified 3D parametric model (Toutin, 1995) developed at CCRS, Natural Resources Canada has successfully been adapted to IKONOS Geo product using basic information from the metadata and image files (Toutin, 2001). The main reason is that this CCRS model integrated the correlated parameters into a reduced number of "combined" parameters.

A 10x10-km Geo image (1-m pixel) acquired over semi-flat area has been processed with the three 3D models (parametric and non-parametric), using 30 50-cm accurate GCPs. A 3D



Figure 2: Partial resampling of Figure 1 using 16pt. $\sin(x)/x$ kernel (400 x 400 pixels; 10-cm pixel spacing). Courtesy and copyright of DigitalGlobe, 2002

polynomial model can be used because IKONOS images are already georeferenced. Table 2 shows the RMS and maximum errors over the 23 ICPs of the three models computed with only seven GCPs. The errors are smaller with the parametric model than with the polynomial or rational models. Furthermore, the maximum errors are much greater with non-parametric models. This shows that the parametric model is both stable and robust over the full image without generating local errors while the non-parametric models mainly cancel the errors locally at the GCPs but can generate large local errors elsewhere.

Correction Method	RMS (m)		Maximum (m)	
	X	Y	X	Y
Polynomial 2 nd order	1.8	2.4	4.1	7.9
Rational 1 st order	2.2	5.2	5.1	10.4
Parametric	1.3	1.3	3.0	3.0

Table 2. Comparison of RMS and maximum errors over 23 ICPs of 2nd order polynomial, 1st order rational and Toutin's parametric model computations with 7 GCPs

4.3 EROS

The EROS-A imaging concept, by which the space scanlines are acquired, derived from military technology to follow a target. Since the satellite is moving "too fast" according to the ground sampled distance, the orientation of the linear array sensor is continuously backward pitching to acquire a continuous image without gap between the scanlines (ImageSat Intl., 2002). Consequently, the distortions due to attitude will be much higher than with the normal push-broom scanners. Therefore, more precise attitude model is requested to integrate linear and non-linear variations of the rotation angles in the 3D model. This point already suggests that non-parametric models, which do not reflect the image geometry and attitude distortions, will not be able to accurately correct such large attitude distortions, and especially their high-frequency variations.

A raw sub-image (3x3 km; 2-m pixel) acquired over a flat area was processed with the CCRS 3D generalized sensor model, using 24 50-cm accurate GCPs. A small image size was voluntarily chosen to see the adaptability of rational functions to this type of image. Table 3 gives the RMS and maximum errors over the 14 ICPs of the two models computed with 10 GCPs. The RMS and maximum errors are much smaller with the parametric model than with the rational model. Even applied on a small image size and over a flat area, the resulting accuracy (4-6 pixels) of the 1st order rational model is poor. In addition, a great variability in the results of this rational model and local errors were noticed when varying the GCP number and distribution, while the parametric model was stable.

Correction Method	RMS (m)		Maximum (m)	
	X	Y	X	Y
Rational 1 st order	8.0	13.2	20	23
Parametric	3.9	3.5	6.2	6.0

Table 3. Comparison of RMS and maximum errors over 14 ICPs of 1st order rational model and Toutin's parametric model computations with 10 GCPs

5. CONCLUSIONS

3D models (parametric or non-parametric) were used to correct geometric distortions of new high-resolution images. The non-parametric models (polynomial or rational) can be applied on small-size images when the systematic distortions are already corrected, such as IKONOS Geo product. The rational models can be applied on raw images, such as QuickBird or EROS. Parametric models can be applied to any image type or size.

Among the non-parametric models, the rational models are certainly the most appropriate, only if parametric models are not available. However, results over three different high-resolution images (level of pre-processing, pixel spacing, size) show that the 3D non-parametric models are less precise than the 3D parametric model, such as Toutin's model developed at CCRS. While non-parametric models could have given similar results than parametric models in specific and limited conditions and in a well-controlled environment where input errors are limited, these present results confirm that they can be non-consistent, unstable and sensitive to GCP number and distribution (see also Madani, 1999; Davies and Wang, 2001). In operational environment where input errors are common, the parametric models should be primarily used because they will insure, in addition of better accuracy, more robustness and consistency whatever the data and its level of pre-processing.

ACKNOWLEDGEMENTS

The authors thank DigitalGlobe and CORE Technologies for providing the Quickbird and EROS images, respectively to adapt and test 3D Toutin's parametric model developed at CCRS. They also thank Dr. Philip Cheng of PCI Geomatics for integrating 3D Toutin's parametric model and algorithms for high-resolution images into Geomatica OrthoEngine^{SE} of PCI.

REFERENCES

Davies C. H., and X. Wang, 2001. Planimetric Accuracy of IKONOS 1-m Panchromatic Image Products, *Proceedings of the 2001 ASPRS Annual Conference*, St. Louis, MI, USA, April 23 - 27, CD-ROM.

DigitalGlobe, 2002. <http://www.digitalglobe.com/> (accessed 06 March 2002).

Escobal, P.R., 1965. *Methods of orbit determination*, Krieger Publishing Company, Malabar, USA, 479 pages.

Hanley H.B. and Fraser C.S., 2001. Geopositioning accuracy of IKONOS imagery: Indications from two-dimensional transformations, *Photogrammetric Record*, 17(98), pp. 317-329.

ImageSat Intl., 2002. (accessed 06 March 2002), <http://www.imagesatintl.com/1024/company/eros.html>

Kaufmann, V., und W. Sulzer, 1997. Über die Nutzungsmöglichkeit hochauflösender amerikanischer Spionage-Satellitenbilder (1960-1972). *Vermessung und Geoinformation*, 3, pp.166-173.

Konecny G., 2000. Mapping from Space, *Remote Sensing for Environmental Data in Albania: A Strategy for Integrated Management*, NATO Science Series, Vol. 72, Kluwer Academic Publishers, pp. 41-58.

Konecny, G., E. Kruck and P. Lohmann, 1986. Ein universeller Ansatz für die geometrische Auswertung von CCD-Zeilenabstasteraufnahmen, *Bildmessung und Luftbildwesen*, 54(4), pp. 139-146.

Light, D.L., D. Brown, A. Colvocoresses, F. Doyle, M. Davies, A. Ellasal, J. Junkins, J. Manent, A. McKenney, R. Undrejka and G. Wood, 1980. Satellite Photogrammetry, in *Manual of Photogrammetry 4th Edition, Chapitre XVII*, Editor in chief: C.C. Slama, American Society of Photogrammetry Publishers, Falls Church, USA, pp. 883-977.

Madani, M., 1999. Real-Time Sensor-Independent Positioning by Rational Functions, *Proceedings of ISPRS Workshop on Direct Versus Indirect Methods of Sensor Orientation*, Barcelona, Spain, November 25-26, pp. 64-75.

Palà V. and X. Pons, 1995. Incorporation of Relief in Polynomial-Based Geometric Corrections, *Photogrammetric Engineering & Remote Sensing*, 61(7), pp. 935-944.

Petrie, G., 2002. Optical Imagery from Airborne & Spaceborne Platforms. *GeoInformatics*, 5(11), pp. 28-35.

Space Imaging, 2002. (accessed 06 March 2002), <http://www.spaceimaging.com/carterra/geo/>

Tao V. and Y. Hu, 2001. 3-D Reconstruction Algorithms with the Rational Function Model and their Applications for IKONOS Stereo Imagery, *Proceedings of ISPRS Joint Workshop "High Resolution Mapping from Space"*, Hannover, Germany, September 19-21, CD-ROM, pp. 253-263.

Toutin, Th., 1995. Multisource data fusion with an integrated and unified geometric modellelling. *EARSeL Journal Advances in Remote Sensing*, 4(2):118-129. <http://www.ccrs.nrcan.gc.ca/ccrs/eduref/ref/bibpdf/1223.pdf>

Toutin Th., 2001, Geometric processing of IKONOS Geo images with DEM, *Proceedings of ISPRS Joint Workshop "High Resolution Mapping from Space"*, Hannover, Germany, September 19-21, CD-ROM, pp. 264-271. <http://www.ccrs.nrcan.gc.ca/ccrs/eduref/ref/bibpdf/13116.pdf>