Comparison of 3D Physical and Empirical Models for Generating DSMs from Stereo HR Images

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Abstract
This research study addressed and compared 3D physical and empirical models for stereo-processing and the generation of digital surface models (DSMs) from different stereo high-resolution (HR) sensors (Ikonos and QuickBird). The 3D physical model is Toutin’s Model (TM) developed at the Canada Centre for Remote Sensing, and the empirical model is the rational function model (RFM). The study also evaluated the conditions of experimentation to appropriately use these 3D models. The first results on stereo-bundle adjustments demonstrated that TM and vendor-supplied RFMs gave similar results with Ikonos as soon as RFM was refined with a shift computed from one GCP. On the other hand, TM gave better results than vendor-supplied RFMs with QuickBird regardless of the polynomial order and the number of GCPs. Due to its relief dependency, QuickBird RFM needed to be refined at least with linear functions computed from at least 6 to 10 GCPs. Some large errors were, however, noted on forward image RFM in column. The DSMs were then generated using an intensity matching approach and compared to 0.2 m accurate lidar elevation data. Because DSMs included the height of land-cover (trees, houses), elevation linear errors with 90 percent confidence level were computed and compared for the entire area and three land-cover classes (forests, urban/residential, bare surfaces). TM and vendor-supplied RFMs with Ikonos, regardless of the method and GCP number, achieved comparable results for all classes, while TM achieved overall better results than vendor-supplied RFMs with QuickBird. All results demonstrated the necessity of refining Ikonos RFM with a shift and one GCP only and QuickBird RFM with 1st-order linear functions and 6 to 10 GCPs due to its relief dependency.

Introduction
The generation of high-resolution (HR) imagery using previously proven defense technology provides an interesting source of data for digital topographic mapping, such as digital terrain models (DTMs), as well as thematic applications such as agriculture, forestry, and emergency response (Kaufmann and Sulzer, 1997; Konecny, 2000). Ikonos and QuickBird were launched on September 1999 and October 2001, respectively, with these new high-resolution sensors and an off-nadir viewing capability (up to 60° in any azimuth). This 360° pointing capability enables the generation of in-track stereoscopic images from the same orbit with base-to-height ratio (B/H) of around one. Users could then apply traditional 3D photogrammetric techniques with the stereo images to extract accurate planimetric and elevation information.

Due to high spatial resolution of these recent spaceborne sensors, a large number of researchers around the world have investigated (stereo-) photogrammetric methods using different physical and empirical models (Toutin, 2004a): 3D point positioning or feature extraction with empirical models (Di et al., 2003; Tao et al., 2004; Noguchi et al., 2004; Fraser and Hanley, 2005) using manual/visual processes, and the generation of digital surface models (DSMs) with physical models (Toutin, 2004b), or empirical models (Muller et al., 2001; Lehner et al., 2005) using automatic processes. The objectives of this paper are to expand on these results and to compare physical and empirical models for point/elevation extraction and DSM generation and to evaluate the conditions of experimentation of each model. The physical model is the photogrammetric-based multisensor 3D geometric modeling developed at the Canada Centre for Remote Sensing (CCRS) (Toutin, 1995) and adapted to HR stereo-images (Toutin, 2004b) and the empirical models are the rational function models (RFMs), mainly the vendor-supplied RFMs. The paper evaluated the impact of each model on DSM quality when compared to accurate ground truth, and tracked with different parameters the error propagation from the input data to the final DSMs.

Description of the Data

Study Site
The study site is an area north of Québec City, Québec, Canada (47°N, 71°30’W). This study site consists of an urban/residential environment mainly in the southern part and a semi-rural environment mainly covered by boreal forests (deciduous, conifer, and mixed) in the northern part. The site has a hilly topography with 450 m elevation range, a mean slope of 7° and maximum slopes up to 30°.

Ikonos Stereo Data
Ikonos stereo images were distributed in a quasi-epipolar geometry reference where just the elevation parallax in the scanner direction remains (www.spaceimaging.com). For in-track stereoscopic image capture with the Ikonos orbit inclination, the image orientation approximately corresponds to a North-South direction, with few degrees in azimuth depending on the across-track component of the total collection.

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angle (Figure 1). The ±27° in-track stereo images (10 km by 10 km; B/H of 1) were acquired on 03 January 2001 when the sun illumination angle was as low as 19°, resulting in long shadows. The data were re-processed in April 2005 to take into account the last RFM processing of Space Imaging, LLC. In addition, each image was subdivided in two sub-images generating two stereo-pairs (West and East) with a B/H of 1 and had to be processed separately. Figure 1 is the backward sub-image mosaic (just for display purposes): one can notice sand/gravel pits (a), frozen lakes with snow (b), and snow over bare soil (c). The stereo-processing was only performed on the East stereo-pair, corresponding to the lidar survey.

QuickBird Stereo Data
QuickBird stereo images, as a courtesy of Digital Globe, were provided as Basic imagery products, which are designed for users having advanced image-processing capabilities (http://www.digitalglobe.com). Basic imagery is the least processed image product of the DigitalGlobe product suite; only corrections for radiometric distortions and adjustments for internal sensor geometry, optical and sensor distortions have been performed on each scene ordered, and the image orientation approximately corresponds to a North-South direction. For users who did not develop or have access to a 3D physical geometric model, DigitalGlobe supplies QuickBird camera model information and RFMs with each Basic Imagery product (Robertson, 2003).

The ±29° in-track stereo images (18 km by 15 km; B/H of 1.1) were acquired 01 April 2003 when snow was still present in most of the bare surfaces, and a 45° sun illumination angle results in shadows from vertical structures. The data were re-processed in July 2005 to take into account the new RFM improvement of DigitalGlobe (Cheng et al., 2005). Figure 2 is the forward image, where general cartographic
and topographic features are well identifiable: sand/gravel pits in (a), snow-covered frozen lakes in (b), snow-covered bare soils in (c), power-line corridors in (d), and a mountain with downhill ski tracks in (e).

**Cartographic Data**
Fifty points were collected on the study site and their cartographic coordinates \((X, Y, Z)\) were stereo-compiled by the Ministère des Ressources naturelles du Québec, Canada from aerotriangulated 1:40,000-scale photographs using a Wild A-10 camera. The accuracy is estimated to be better than 1 m and 2 m in planimetry and elevation, respectively. In addition, accurate spot elevation data was obtained on 06 September 2001 from a lidar survey by GPR Consultants ([www.lasermapper.com](http://www.lasermapper.com)). The Optech ALTM-1020 system is comprised of a high frequency optical laser coupled with a Global Positioning System (GPS) and an inertial navigation system ([GNS](http://www.optech.on.ca)). From a fixed-wing airborne platform, the laser emits pulses at frequencies of up to 5,000 Hertz, and the first-echo pulses are reflected off vegetation or man-made structures and recorded. With 700 to 850 m flying height, 70 m/s velocity, 5,000 Hertz pulse rate, 12 Hertz scanning frequency, and \(\pm 20^\circ\) scan angle (510 to 630 m wide swath), the ground point density was about 300,000 3D points per minute, and the accuracy was 0.30 m in planimetry and 0.15 m in elevation (Fowler, 2001). Ten swaths were acquired covering an area of 5 km by 11 km, which approximately corresponds to the east part of the stereo pairs. The results are then an irregular-spaced grid (approximately 3 m), due also to no echo return in some conditions (buildings with a black roof, some roads, and lakes). Because the objectives were to evaluate the stereo DSMs, the lidar elevation data was not interpolated into a regular-spaced grid to avoid the propagation of interpolation error into the checked elevation and the evaluation.

**Description of the Experiment**

**The 3D Physical and Empirical Models**
The 3D physical model is Toutin’s universal multi-sensor model (TM) embodied into OrthoEngine® photogrammetric
software from PCI Geomatics. It was originally developed to suit the geometry of pushbroom scanners, such as SPOT-HRV, and was subsequently adapted as an integrated and unified geometric modeling to geometrically process multisensor images (Toutin, 1995), and HR images (Toutin, 2003 and 2004b). This 3D physical model applied to multi-sensor images is robust and not sensitive to GCP distribution when there is no extrapolation in planimetry and elevation. Since TM is well explained in the previous references, only a summary is given. The geometric modeling represents the well-known collinearity condition (and coplanarity condition for stereo model), and integrates the different distortions relative to the global geometry of viewing: i.e.,

- the distortions relative to the platform (position, velocity, orientation),
- the distortions relative to the sensor (orientation angles, instantaneous field of view, detection signal integration time),
- the distortions relative to the Earth (geoid-ellipsoid, including elevation), and
- the deformations relative to the cartographic projection (ellipsoid-cartographic plane).

In summary, the collinearity equations of a ground point are first written in the instrumental reference system and converted into the cartographic projection system using elementary transformations (rotations and translations), which are functions of the parameters describing the distortions previously mentioned. Each of the model unknown parameters is in fact a combination of several correlated variables of the viewing geometry, so that the number of unknown parameters has been reduced to an independent decorrelated set. This 3D physical model has been applied to medium-resolution visible and infrared (VIR) data (MODIS, MERIS, CBERS, Landsat 5 and 7, SPOT 1 to 5, IRS-1/2/D, ASTER, Kompsat-1 EO, ResourceSat-1), HR-VIR data (IKONOS, EROS, QuickBird); OrbView, Formosat-2, SPOT5, as well as radar data (Seasat, ERS-1/2, IRS, SIR-C, Radarsat-1 and ENVISAT).

The 3D empirical model is the RFM, which are based on ratio of polynomial functions:

\[ R_{i,k}(X,Y,Z) = \frac{\sum_{i} \sum_{j} \sum_{k} a_{ijk} X^i Y^j Z^k}{\sum_{i=0}^{m} \sum_{j=0}^{n} \sum_{k=0}^{p} b_{ijk} X^i Y^j Z^k} \]  

(1)

RFMs can be used in two approaches (Madani, 1999):

1. to approximate an already-solved existing 3D physical model; and
2. to normally compute the unknowns of all the polynomial functions with GCPs.

The first approach, inappropriately called "terrain-independent" because the process still requires some GCPs to refine RFM parameters (see below), 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 physical model. These grid points and their 3D ground and 2D image coordinates are then used as GCPs to resolve the 3D RFM and compute the unknown terms of polynomial functions. Two resellers, which provide 3rd-order RFM parameters with each image, adopted this approach: Space Imaging with IKONOS Geo-product (Grodecki, 2001), as well as DigitalGlobe and MDA with QuickBird-2 Basic product (Hargreaves and Roberston, 2001).

Since errors still exist after applying the vendor-supplied RFMs, the end-users must either (a) compute an other 2D polynomial transformation with fewer precise GCPs to refine the RFM results (Fraser and Hanley, 2005), or (b) post-process the original RFs parameters with linear equations using more precise GCPs (Lee et al., 2002). The use of GCPs by the end-users in the RFM refinement or post-processing is the reason why this approach is inappropriately called "terrain-independent."

The second approach, called “terrain-dependent”, can be performed by the end-users with their own GCPs. The users can define the order of polynomial functions: since there are 40 and 80 parameters for the four 2nd- and 3rd-order polynomial functions, a minimum of 20 and 40 GCPs, respectively are required to resolve the 3D RFMs. However, the RFMs do not model the physical reality of the image acquisition geometry and they are sensitive to input errors (Tao and Hu, 2002). Since this approach is not efficient, it has not been used and addressed in this study.

The Processing Steps for DSM Generation and Evaluation

Because the processing steps of DSM generation from stereo HR images are roughly the same as for other stereo images and are performed for Toutin’s model and RFM within OrthoEngine® of PCI Geomatics (certified by Space Imaging, LLC), only the processing steps are summarized:

1. Acquisition and preprocessing of the remote sensing data (images and metadata) including the 3rd-order vendor-supplied RFM parameters;
2. Collection of ground points (used as GCPs or independent check points, GCPs) with their 3D cartographic coordinates and 2D image coordinates: 34 and 48 were stereo-collected for IKONOS and QuickBird, respectively with an image pointing accuracy of one pixel (but sometimes two pixels in the mountainous areas);
3. Computation of 3D physical model or refinement of the empirical model by an iterative least-squares stereo bundle adjustment with the GCPs (Step 2). Some tie points have to be added in the 3D empirical models to generate stereo constraints in the adjustments;
4. Generation of the quasi-epipolar images using the 3D physical or empirical model parameters (Step 3) for QuickBird only, because IKONOS stereo-images were already provided into a quasi-epipolar geometry;
5. Extraction of elevation parallaxes on the quasi-epipolar images (no transversal parallax) using an intensity matching approach: the multiscale mean normalized cross-correlation method with computation of the maximum of the correlation coefficient. This method is commonly used with satellite images (Gölich, 1991) and gave good results with stereo VIR images (Toutin, 2004);
6. Computation of X, Y, Z cartographic coordinates from elevation parallaxes (Step 5) using the previously computed 3D model (Step 3); and
7. Evaluation of DSMs with the lidar elevation data. About 5,500,000 points corresponding of the overlap area were used in the statistical computation of elevation errors.

The Experimental Tests

In order to compare the impacts of TM and RFMs (only the 1st “terrain-independent” approach) on the full stereo-processing, different tests (with their code) applying each model using various numbers of GCPs were performed for each stereo-pair (IKONOS and QuickBird):

1. TM was computed with 10 and all GCPs (TM-10 and TM-all);
2. Supplied RFMs were directly applied (RFM);
3. Supplied RFMs were refined using zero-order polynomial functions (shift only) computed with one GCP (RFM-ref_1); and
4. Supplied RFMs were refined using first-order polynomial functions (linear) computed with 6, 10, and all GCPs (RFM-ref_6, etc.).

While six accurate GCPs (0.1 to 0.3 m) are enough for computing TM with HR data previous experiments showed that 10 to 12 GCPs were a good compromise when they were
only 1 to 2 m accurate in order to reduce the propagation of errors in the stereo-modeling due to a large degree of freedom in the least-squares adjustment (Toutin, 2003). In the “terrain-independent” approach, the supplied RFMs are refined with 2D polynomial functions (Di et al., 2003; Tao et al., 2004; Noguchi et al., 2004; Fraser and Hanley, 2005); one GCP is used for a bi-directional shift (zero-order) and 6, 10, and all GCPs for a linear 1st-order. When more GCPs are available, a least square adjustment is used to compute the parameters of the polynomial functions, as mentioned previously. For each test, the stereo adjustment with GCPs was computed and evaluated on GCPs and remaining ICPs. Depending of results of each stereo-bundle test the DSMs, which include the height, or a part, of natural and human-made surfaces (trees, hedges, houses, etc.) were thus generated and compared to lidar elevation data. Since land-cover can affect DSM evaluation and comparison 3D visual classification on the stereo QuickBird images was thus performed to discriminate different classes: forest, urban/residential, and bare surfaces. DSMs were also evaluated with lidar data as a function of these three classes.

Results and Discussion

Error propagation can be tracked along the processing steps with 3D stereo-bundle adjustment results (Step 3) and during DSM generation (Steps 4 and 6).

3D Bundle-Adjustment Results

As mentioned, tests were performed as a function of numbers and location of GCPs used in 3D bundle adjustments of TM and RFM for Ikonos and QuickBird, and Table 1 summarizes these results in the image space with the GCP residuals (root mean square; RMS) and the RMS errors at the remaining ICPs, when available.

Test 1 confirmed previous results on the applicability of the physical model, TM, to stereo HR data. When there are more GCPs than the minimum required for computing a 3D physical model, the residuals mainly reflect the error of the input data, and, it is thus normal and “safe” to obtain residuals from the least squares adjustment in the same order of magnitude as the GCP/RMS error (1 to 2 m), but the internal modeling accuracy is thus better, in the order of a sub-pixel (Toutin, 2004b).

Test 2 RFM (not refined) demonstrated and confirmed that the vendor-supplied RFMs (both for Ikonos and QuickBird) cannot achieve one meter accuracy. The 68.3 m ICP error in the column for QuickBird is from the forward image (90 m), while the ait image has only a 10 m error. Since TM and Test 2 RFM (ICP error in row direction of 2 m) gave good results with QuickBird, a tentative explanation in this large error is an error in column direction during the RFM generation, and discussions with DigitalGlobe recently confirmed this problem. Equivalent results in column than in row (2 m) could be obtained with newly-generated RFMs. However, errors of 3 to 4 m for Ikonos and 2 m for QuickBird can be acceptable for some applications in remote areas where no control is available.

Because there was no improvement on ICPs with Ikonos when using 1st-order polynomial functions computed with 6 or 10 GCPs (Tests RFM-ref_6 and RFM-ref_10), Tests 3 and 4 RFM refined with GCPs confirmed previous experiments on point positioning (Fraser and Hanley, 2005) that a shift (Test RFM-ref_1) is enough to improve supplied RFM of Ikonos to 1 to 2 pixels. On the other hand, the supplied RFM of QuickBird has to be refined at least with 1st-order polynomial functions computed with 6 to 10 GCPs, because the results improved significantly. The largest errors in column for the different tests were still due to the forward image, but the refinement of RFMs with GCPs largely corrected the previous large error in the column direction. In fact, the last test RFM-ref_all corrected most, if not all, ICP error in the column direction. Equivalent results in column than in row (1 to 2 pixels) could be obtained with newly-generated RFMs. The ICP error in row direction (1 to 2 m) can then be an indicator on the potential of using RFM with QuickBird if there was no error in the RFM generation in column direction. These results confirm previous experiments (Cheng et al., 2005) using linear functions for refining QuickBird RFM, but refute other experiments (Noguchi et al., 2004; Fraser and Hanley, 2005) where a shift with or without a time-dependent drift, respectively, was used. In fact, Fraser’s results (2005), which mentioned time-dependent drift did not correct for systematic errors, were already in contradiction with results of his previous co-author (Noguchi et al., 2004), who demonstrated that a linear drift has to be added to the shift for correcting some “unexplained” systematic errors. Apart from potential errors in the RFM of our forward image, a likely explanation for these contradictions on QuickBird RFM refinement is mainly the RFM dependency to terrain relief. Cheng’s study site and ours were 1,000 m and 450 m elevation range, respectively (1st-order polynomial refinement), while Noguchi’s study site was 240 m (shift and time-dependent drift refinement), and Fraser’s study site was 50 m (shift refinement).

In addition, RFMs were not more precise than the physical model TM, for both stereo-pairs, except the larger error with QuickBird forward-image RFM only in the column direction. These RFM problems (potential errors in supplied RFMs, post-processing, 6 to 10 GCP requirement, inconsistent results in different experiments and study sites, relief dependency) could thus reduce the advantages of the so-called “terrain-independent” RFM approach versus a physical model in operational environments.

| Table 1. Stereo Bundle-adjustment Results in the Image Space for Each Test with their Code. The Root Mean Square (RMS) residuals (in meters) on GCPs and the RMS errors (in meters) at the Remaining ICPs when Available are Computed for the Two Images of the Stereo Pair. As Examples, TM-10 and RFM-ref_10 are the Tests of TM and RFM, Respectively, with 10 GCPs |
|----------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Stereo-Pair | Ikonos (1 m pixel) | QuickBird (0.61 m pixel) | | | | |
| Test Number | GCP RMS | ICP RMS | GCP RMS | ICP RMS |
| and Code | Column | Row | Column | Row | Column | Row |
| 1. TM-10 | 0.5 | 0.4 | 1.8 | 1.8 | 0.7 | 0.7 |
| 1. TM-all | 1.2 | 1.5 | — | — | 1.2 | 1.3 |
| 2. RFM | — | — | 3.7 | 3.6 | — | — |
| 3. RFM-ref_1 | 0.0 | 0.0 | 1.7 | 1.8 | 68.3 | 2.0 |
| 4. RFM-ref_6 | 0.5 | 0.8 | 1.8 | 1.9 | 4.9 | 1.4 |
| 4. RFM-ref_10 | 1.3 | 1.2 | 1.8 | 1.9 | 3.1 | 1.3 |
| 4. RFM-ref_all | 1.6 | 1.6 | — | — | 1.4 | 1.3 |
DSM Evaluation Results

The second results are quantitative evaluations of DSMs (1 m pixel spacing) extracted from the two stereo pairs. The evaluations are related to the transversal parallaxes between the quasi-epipolar images, the matching successes (Table 2), and the comparison of DSMs with lidar elevation data to compute the bias (Table 2), and the linear errors with 90 percent level of confidence (LE90) (Figures 3 and 4). LE90 were computed for the entire overlap areas and for the three classes (forest, urban/residential, and bare surfaces).

Table 2 shows that results (transversal parallax in quasi-epipolar images, matching success and bias) are equivalent when using TM or RFM with Ikonos regardless of the number of GCPs. Because there is no transversal parallax between the epipolar images, resulting from a sub-pixel accurate stereo-modeling (Table 1), the matching has a very high success rate even with this challenging study site (snow, frozen lakes, and low sun illumination). The same remarks applied to results when using TM with QuickBird. Most of the mismatched areas correspond to snow-covered frozen lakes and shadowed areas due to a low solar illumination angle in January or April. On the other hand, RFM results are poor with QuickBird. The transversal parallaxes between the quasi-epipolar images, however, were well reflected and are correlated with the RMS errors of the stereo-modeling (Table 1) because QuickBird quasi-epipolar images are approximately rotated 90° versus the original images: the larger the RMS errors in column direction, the larger the transversal parallaxes. The consequence was of course a bad matching result with a one-direction correlation method or with other methods. In fact, the results with the last test RFM-ref_all, where RFM error in column direction was largely corrected, is a good indicator of the potential results for RFM-ref_6 and RFM-ref_10 if there was no RFM error in column direction. Better results (less transversal parallax and higher matching success rate) could be obtained with newly generated RFMs. The bias is only a problem for the Test 2 RFM (8 m with Ikonos and ~135 m with QuickBird) because the other biases can easily be corrected with GCPs.

Figure 3 shows the other statistical results of the comparison lidar/Ikonos DSMs: the different LE90 are relatively equivalent (small percent difference, but not significant) indifferently when using TM or RFM regardless of the number of GCPs and the land-cover class. Some general trends can be derived:

- Both TM and RFM performed well with stereo Ikonos;
- The number of GCPs do not affect the elevation accuracy for TM and RFM;
- RFM with 1st-order linear refinement does not improve DSM accuracy;

<table>
<thead>
<tr>
<th>Stereo-Pair</th>
<th>Ikonos (1 m pixel)</th>
<th>QuickBird (0.61 m pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Number and Code</td>
<td>Transversal Parallax</td>
<td>Matching Success</td>
</tr>
<tr>
<td>1. TM-10</td>
<td>&lt;1 line</td>
<td>89%</td>
</tr>
<tr>
<td>1. TM-all</td>
<td>&lt;1 line</td>
<td>89%</td>
</tr>
<tr>
<td>2. RFM</td>
<td>&lt;1 line</td>
<td>92%</td>
</tr>
<tr>
<td>3. RFM-ref_1</td>
<td>&lt;1 line</td>
<td>92%</td>
</tr>
<tr>
<td>4. RFM-ref_6</td>
<td>&lt;1 line</td>
<td>92%</td>
</tr>
<tr>
<td>4. RFM-ref_10</td>
<td>&lt;1 line</td>
<td>92%</td>
</tr>
<tr>
<td>4. RFM-ref_all</td>
<td>&lt;1 line</td>
<td>92%</td>
</tr>
</tbody>
</table>

Figure 3. Statistical results computed from the difference between the lidar elevation data and the stereo Ikonos DEM: the linear errors with 90 percent level of confidence (LE90 in meters) for the full overlap area (all classes), the forest, the urban/residential, and the bare surface classes.

Figure 4. Statistical results computed from the difference between the lidar elevation data and the stereo QuickBird DEM: the linear errors with 90 percent level of confidence (LE90 in meters) for the full overlap area (all classes), the forest, the urban/residential, and the bare surface classes.
RFM without GCP being less accurate could still be an appropriate method for DSM generation in remote area without control; refining RFM with a shift and GCP is the solution with few GCPs (1 to 3); and TM and RFM can be indifferently used when more GCPs are available.

Figure 4 shows the other statistical results of the comparison lidar/QuickBird DSMs: the different LE90 are better when using TM than RFM for all GCP tests. Since LE90 over all surfaces for RFM was large (352 m), it was not useful to compute the statistics for the other sub-classes. These differences between TM and refined-RFM LE90 are consistent for the three other land-cover classes: on bare surface areas TM is 50 to 100 percent better than RFMs. Some general trends can also be derived:

- TM performed well with stereo QuickBird in regard to sensor resolution and stereo-geometry (B/H of 1:1).
- The potential error in RFM forward image is maybe the cause of the bad performance of the RFM with stereo QuickBird.
- The number of GCPs do not affect the elevation accuracy for TM but does for RFM.
- RFM refined with only a shift and one GCP cannot achieve good results in regard to sensor resolution and stereo geometry (B/H of 1:1). This result confirms the bundle adjustment results and explanations; and
- For achieving the best results with RFM (less than 3 m LE90), a refinement with 1st-order linear functions and 6 to 10 GCPs is mandatory. The results with the last test, RFM-ref_all, where RFM error in column direction was largely corrected, is a good indicator of the potential results for RFM refinement with 1st-order linear functions (RFM-ref_6 and RFM-ref_10) if there were no RFM error in column direction.

Finally, the results (Figures 3 and 4) over bare surface areas (2 to 3 m LE90) better demonstrated the Ikonos/QuickBird stereo performance and the potential to generate 5 m contour lines meeting the highest topographic standard. For the residential class, the results are a little worse because 1- and 2-storey houses (10 to 15 percent of the residential areas, and 4 to 6 m in height) degrade the statistics a bit for this class.

Some tentative explanations for these general results (stereo-bundle adjustment and DEM) inherent to the nature of physical and empirical models are:

- RFMs are better suited for pre-processed map-oriented images with less geometrical/terrain distortions and small sizes, such as Ikonos Geo-images; and
- Physical models, such as TM, are better suited for raw orbit-oriented images regardless of the size and the terrain, with the possibility of using metadata (ephemeris, attitude, etc.), such as QuickBird Basic images, which are still in their original viewing geometry.

Conclusions

The objectives of the research were to compare 3D math geometric modeling: the CERS 3D physical model (Toutin’s model) and an empirical model using the vendor-supplied RFMs, as well as to evaluate their impact on the generation of DSMs from in-track QuickBird/Ikonos stereo images (B/H of approximately 1) acquired over a residential/rural hilly area in Quebec, Canada. The first results on stereo-bundle adjustment demonstrated that TM and RFM with Ikonos gave equivalent results, as soon as the supplied RFM is refined with a shift and one GCP. Larger polynomial order and GCPs did not improve the accuracy. On the other hand, TM better performed than RFM with QuickBird regardless of the polynomial order and GCP number used in RFM refinement. Large error (68 m) was, however, noticed for the RFM (in column only) of the forward image: it is probably due to an error in RFM generation in column direction. Because this RFM error was largely corrected when refining RFM with all GCPs, similar results could be expected with fewer GCPs (6 to 10).

In conjunction with previous experiments, the results also confirmed that QuickBird RFM is relief dependent: the stronger the relief, the polynomial order should be larger to refine the RFM.

The stereo-extracted DSMs were then compared to accurate elevation lidar checked data. Because the surface heights were included in terrain elevation, the elevation errors were also evaluated and compared as a function of the land-cover (forests, urban/residential, and bare surfaces). The best results (TM/RFM Ikonos and TM QuickBird: 2 to 3 m LE90), which were obtained on bare surfaces where there was no elevation difference between the stereo DSM and lidar data, are a good indication of HR stereo performance for DSM generation. Because both TM and RFM performed well with stereo Ikonos and the number of GCPs did not affect LE90, the math model to be chosen is thus dependent on GCP availability. RFM with Ikonos is thus more useful when no control is available to generate 3 to 4 m accurate DSM (LE90).

With stereo QuickBird, TM generally performed better than RFM, without and with refinement. It was noticed that stereo processing and LE90 improved when RFM were refined with larger polynomial order (1st versus zero order) and more GCPs. However, an error in RFM generation in column direction of the forward image was noticed, and this RFM error was corrected, but only in the stereo bundle adjustment when using 1st-order linear functions computed with all GCPs. If there was no RFM error in column direction, the same conclusion than with Ikonos on the performance of math models (with slightly better results for TM) could thus be drawn, except that RFM has to be refined using 1st-order linear functions and few GCPs (6 to 10) to generate 3 m accurate DSM (LE90).

These general results on stereo-processing and DEM generation from two HR stereo sensors, Ikonos and QuickBird, confirmed:

1. The equivalence of a 3D physical model, TM, and an empirical model, vendor-supplied RFM, with slightly better results of TM with QuickBird; and
2. The necessity to refine RFM of pre-processed map-oriented Ikonos Geo-stereo images with a shift and at least one GCP, and to refine RFM of raw orbit-oriented QuickBird Basic stereo pairs with 1st-order linear functions and 6 to 10 GCPs.

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