GENERATION OF DTM FROM STEREO HIGH RESOLUTION SENSORS

Thierry Toutin

Canada Centre for Remote Sensing, Natural Resources Canada
588, Booth Street, Ottawa, Ontario K1A 0Y7

KEY WORDS: DEM, high resolution, stereoscopy, geometric evaluation

ABSTRACT:

Digital terrain models (DTMs) were extracted from high-resolution stereo images (SPOT-5, EROS-A, IKONOS-II and QuickBird) using a three-dimensional universal physical model developed at the Canada Centre for Remote Sensing, Natural Resources Canada. DEMs were generated using an area-based multi-scale image matching method and then compared to 0.2-m accurate lidar elevation data. Elevation linear errors with 68% confidence level (LE68) of 5.5 m, 6.5 m, 20 m, 6.4 m and 6.7 m were achieved for SPOT-HRS, SPOT-HRG (5 m), EROS, IKONOS and QuickBird, respectively. The poor results for EROS are mainly due to its asynchronous low orbit, which generated large geometric and radiometric differences. The best relative results are obtained with SPOT5. Since the SPOT, IKONOS and QuickBird DEMs were in fact digital surface models, where the height of land covers was included, elevation accuracy was performed only on bare surfaces (soils and lakes), where there was also no difference between the stereo-extracted elevations and thelidardata. LE68 of 2.7 m, 2.2 m, 1.5 m and 1.2 m were then obtained for SPOT-HRS, SPOT-HRG (5 m), IKONOS and QuickBird, respectively. Relatively sensor resolution, multi-date across-track SPOT, with also a smaller B/H of 0.77**,** achieved three to four times better results than same-date in-track IKONOS and QuickBird with B/H of one: half-pixel versus 1.5 or two pixels.

1. INTRODUCTION

Since the launch of IKONOS-II with agile HR sensors (1-m panchromatic, Pan and 4-m multiband, XS) on September 24, 1999, other push-broom satellite scanners with stereoscopic capabilities are now available with 0.61-5 m resolution: the agile EROS-A, QuickBird, and Orbview, the in-track SPOT-5 HRS and the across-track SPOT-5 HRG. The agile pointing capability enables the generation of same-date in-track stereoscopy from the same orbit, which has a stronger advantage to multi-date across-track stereo-data acquisition because it reduces radiometric image variations (temporal changes, sun illumination, etc.), and thus increases the correlation success rate in any image matching process(Toutin, 2000). Both acquisition methods can generate strong stereo geometry with base-to-height ratio (B/H) of one, and users can apply traditional three-dimensional (3-D) photogrammetric techniques with the stereo-images to extract accurate planimetric and elevation information. The objectives of this paper are to evaluate and to compare, with accurate LIDAR ground truth, DEMs generated from different HR sensors (resolution of 0.61 to 5 m, in-track versus across-track stereo-acquisitions) using a photogrammetric-based 3-D multi-sensor physical geometric model developed at the Canada Centre for Remote Sensing (CCRS), Natural Resources Canada [13], [14].

2. DESCRIPTION OF THE METHOD

2.1. Study Site and High-Resolution Stereo Data

The study site is an area north of Québec City, Québec, Canada (N 47º, W 71º 30') (Figure 1). This study area consists of an urban/residential environment in the southern part and is covered 80% by forests (deciduous, conifer and mixed) in the northern part. The site has a hilly topography, with an elevation range of more than 1000 m from sea level at the St. Lawrence River, located to the southeast, to the mountains in the north, and a mean slope of 10º. Five HR stereo images were acquired in panchromatic mode over this study site: SPOT-5 HRS, SPOT-5 HRG, EROS-A, IKONOS-II and QuickBird. All image characterisitics are given in Table 1. IKONOS and QuickBird stereo-pairs display a B/H ratio of around one, EROS of 0.7, and SPOT HRS and HRG of 0.77 and 0.85, respectively. Most of the images were acquired during the wintertime (January to May) with snow and ice present, and with low sun illumination angles, which resulted in long shadows. On the other hand, QuickBird data acquired on April 1, 2003 displays few shadows due only to vertical structures, but snow in most of the bare surfaces: sand/gravel pits, frozen lakes, power-line corridors, and downhill ski tracks. Nevertheless, snow and ice are less problematic with same-date stereo-pair than with multi-date stereo-pair. SPOT data acquired on May 5, 2003 (Figure 1) displays snow in the forests (upper part) and frozen lakes (lower left and center), for almost 50% of the image, but not the May 25 image. These differences in snow/ice generated large radiometric differences in SPOT stereo-images. However, these differences provide an opportunity to test DEM generation method and address potential problems in difficult conditions instead of working in a perfect environment.

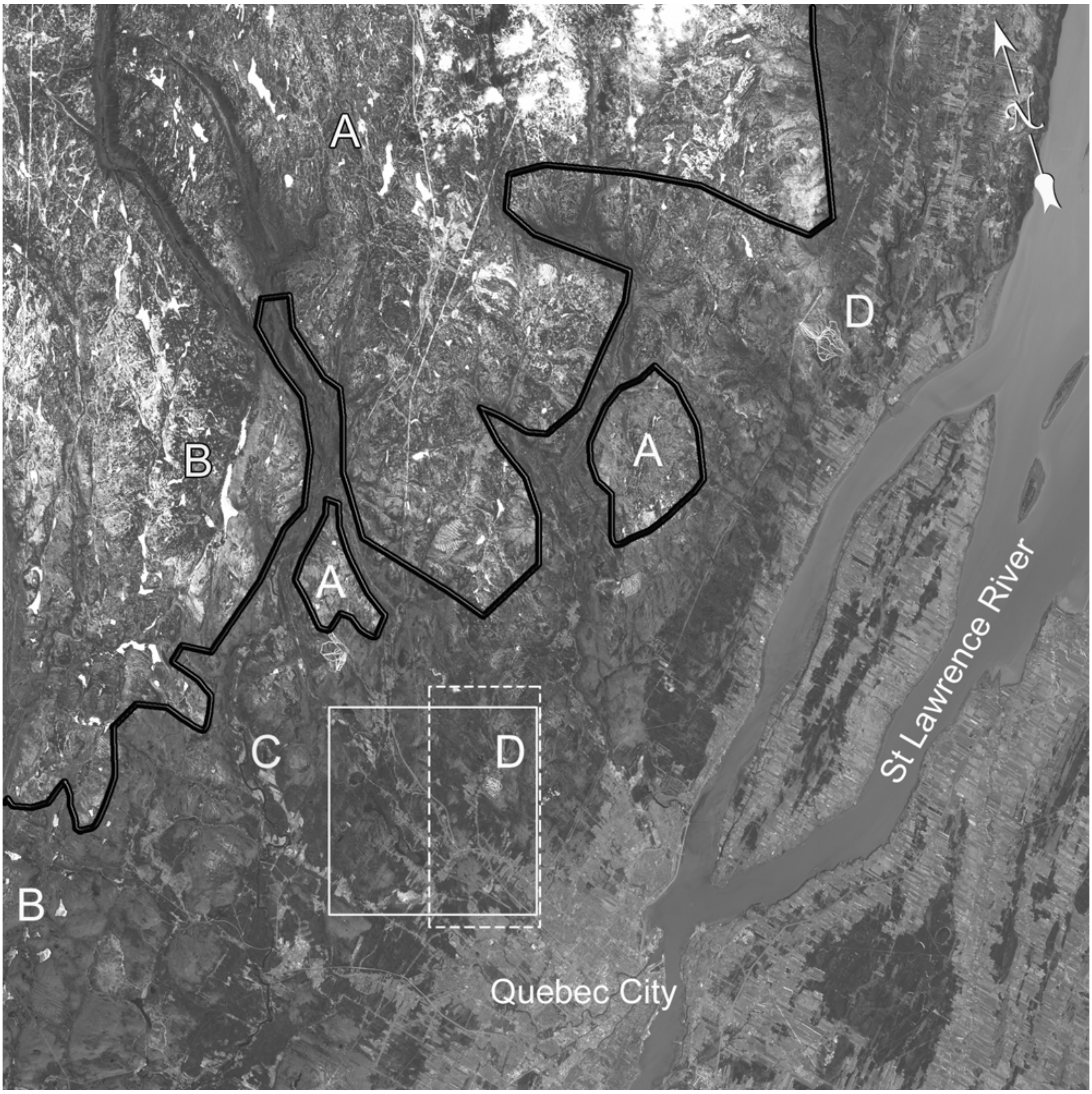

Figure 1. SPOT-5 HRG image (May 5 2003; 23° west-viewing angle; 60 km by 60 km; 5-m pixel spacing) displaying the study site. Québec city is on the center-south and the river is the St. Lawrence River. The white square approximately represents the EROS, IKONOS and QuickBird image location, and the dashed-line rectangle represents the LIDAR acquisition location. Note: (A) the melting snow in the half-north of the image; (B) frozen lakes; (C) lakes with significant melting ice; (D) down-hill ski stations with snow. SPOT Image © CNES, 2003; Courtesy of SPOT-IMAGE.

Stereo-pair	Acquisition Date	Sun	Stereo	View angles	Size (km)	Pixel (m)	GCP Nb.
SPOT-5 HRS	18 Sept. 2003	32º	Same date Along	±22º	120 x 60	10 x 5	98
SPOT-5 HRG	5 May 2003 25 May 2003	52º 55º	Multidate Across	+ 23º -19º	60 x 60	5 x 5	33
EROS-A Pan	6 Feb. 2002	24º	Same date Along	+ 30º-8º - 6º-27º	13 x 13	1.8 to 2.4	130
IKONOS-II Pan	3 Jan. 2001	19º	Same date Along	±27º	10 x 10	1 x 1	55
QuickBird Pan	1 April 2003	45º	Same date Along	±29º	18 x 15	0.61 x 0.61	48

Table 1. Characteristics of the five HR stereo-pairs acquired over the study site, Québec City, Quebec, Canada.

SPOT, IKONOS and QuickBird are synchronous satellites (Bouillon, 2202, Dial, 2000, Robertson, 2003) while EROS satellites are asynchronous (Chen and Teo, 2002). Since EROS is thus "too fast" and must continuously pitch backward and yaw during the image acquisition, the imagery's shape is further distorted and the ground resolution continuously changes, even locally (Figure 2). The SPOT and EROS images are raw level-1A data, orbit oriented, with detector equalization only. Ephemeris and attitude data are available in the metadata as well as general information related to the sensor and satellite. The IKONOS images are geometrically and radiometrically pre-processed and only distributed in a quasi epipolar-geometry reference where just the elevation parallax in the scanner direction remains. For in-track stereoscopy with the IKONOS orbit, the image orientation corresponds approximately to a North-South direction, with few degrees in azimuth depending on the across-track component of the total collection angle. Conversely to other satellites, few metadata on satellite and sensor geometry are available. The QuickBird images (*Basic* product) are also geometrically and radiometrically pre-processed to simulate the imaging geometry of a simple push-broom linear array. To realize this virtual ideal linear array imagery, the detector misalignments and the optical distortions are removed and the attitude jitter are corrected (Robertson, 2003).

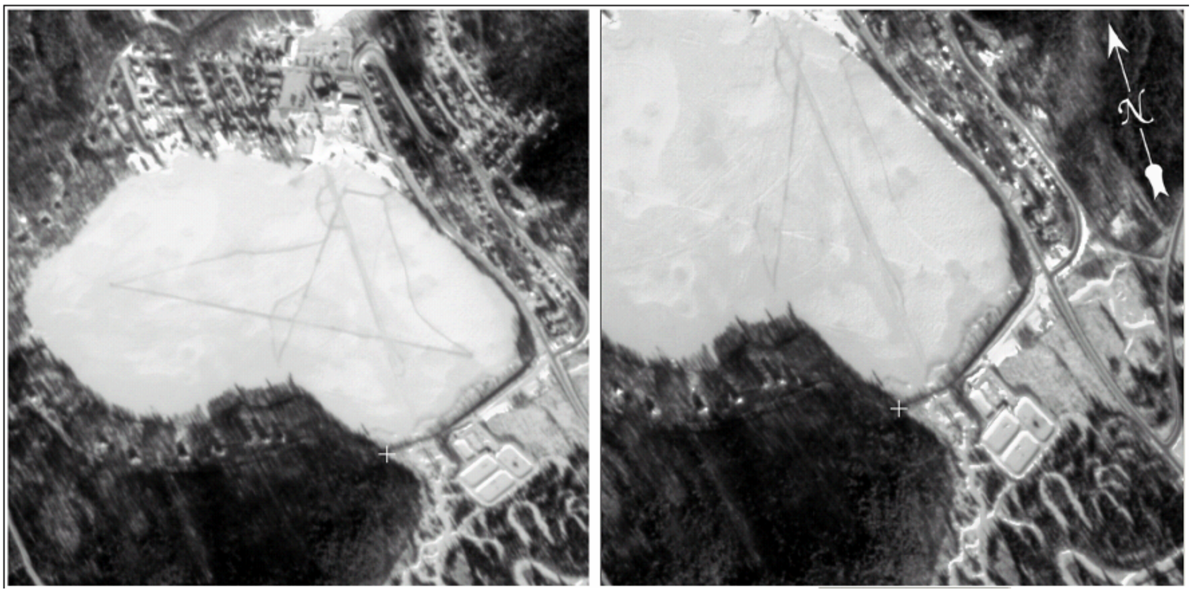

Figure 2. Sub-image of the EROS-A stereo pair (512 x 512 pixels) acquired over Québec, Canada. Note the shadows on the lake and the impact of attitude variations of the asynchronous EROS satellite, such as the shape and size variations of the lake, skidoo tracks, and roads. EROS Images © and courtesy ImageSat Intl., 2002.

Ground control points (GCPs) were collected in stereoscopy for the different tests on the bundle adjustment of the stereoscopic pairs. For SPOT and EROS, GCP cartographic coordinates (*X*, Y, *Z*) were obtained from 1:20,000 digital topographic maps provided by the *Ministère des Ressources naturelles du Québec*, Canada. The accuracy of these maps is estimated to be around 2 m in planimetry and 3 m in elevation. Because of the good resolution of the IKONOS and QuickBird sensor, GCP cartographic coordinates (*X*, Y, *Z*) were stereo-compiled using a Wild A-10 by the same *Ministère* from aero-triangulated 1:40,000 photos. GCP accuracy is estimated to be better than 1 m and 2 m in planimetry and elevation, respectively.

To evaluate the accuracy of the stereo-extracted DEMs, accurate spot elevation data was obtained from a LIDAR survey conducted by GPR Consultants (www.lasermap.com) on September 6th, 2001. The Optech ALTM-1020 system is comprised of a high frequency optical laser coupled with a Global Positioning System and an Inertial Navigation System (Fowler, 2001). The 1st echoed pulses are reflected off vegetation or man-made structures and recorded, and the ground point density is about 300,000 3-D points per minute and the accuracy is 0.30 m in planimetry and 0.15 m in elevation. Since it was impossible to cover the study site (120 km by 60 km), ten swaths covering an area of 5 km by 13 km (Figure 1) and representative of the full study site were acquired. Since the objectives of this research study were to evaluate the stereo DEMs, the lidar elevation data was not interpolated into a regular spacing grid so as to avoid the propagation of interpolation error into the checked elevation and evaluation.

2.2 3-D CCRS multi-sensor physical model

The 3-D CCRS multi-sensor physical model was originally developed to suit the geometry of push-broom scanners, such as SPOT-HRV, and has been subsequently adapted as an integrated and unified geometric modelling to geometrically process multi-sensor images. More details on the mathematic model, development (colinearity equations) and its applicability to HR images can be found in (Toutin, 2003). In summary, the geometric modelling represents the well-known collinearity condition (and coplanarity condition for stereo-model), and takes into account the different distortions relative to the global geometry of viewing, such as the total distortions relative to the platform, the sensor, the Earth and the deformations relative to the cartographic projection. This 3-D physical model has been applied to visible and infrared (VIR) data (MODIS, MERIS, Landsat-5/7, SPOT1-4, IRS-1C/D, ASTER, Kompsat-1 EOC), HR VIR data (SPOT-5, EROS-A, IKONOS-II, OrbView, QuickBird and airborne data), as well as radar data (ERS-1/2, JERS, SIR-C, RADARSAT, ENVISAT and airborne data) with three to six GCPs. This model is robust and not sensitive to

GCP distribution as soon as there is no extrapolation in planimetry and elevation (Toutin and Cheng, 2003, Toutin, 2003). Based on good quality GCPs, the accuracy of this model is within one-third of a pixel for medium-resolution VIR images, better than one pixel for HR images and one resolution cell for radar images.

2.3 The processing steps of DEM generation

Since the processing steps of DEM generation from HR stereo images are roughly the same as for other stereo images (data collection and pre-processing, stereo bundle adjustment with GCPs, elevation parallax measurements, DEM generation), the five processing steps are summarized:

1. Acquisition and pre-processing of the remote sensing data (images and metadata) to determine an approximate value for each parameter of 3-D physical model for the two images;
2. Collection of stereo GCPs with their 3-D cartographic coordinates and two-dimensional (2-D) image coordinates. GCPs covered the total surface with points at the lowest and highest elevation to avoid extrapolations, both in planimetry and elevation. The image pointing accuracy was around half-pixel for SPOT (2.5-5 m), more than one pixel for EROS (2 m) and one to two pixels for IKONOS and QuickBird (1-2 m).
3. Computation of the 3-D stereo model, initialized with the approximate parameter values and refined by an iterative least-squares bundle adjustment with the GCPs (Step 2) and orbital constraints. GCP residuals and Independent Check Points (ICPs) errors are the differences between the "true" cartographic coordinates and the computed cartographic coordinates. Theoretically three to seven accurate GCPs, depending upon the sensor, are enough to compute the stereo model. More GCPs were acquired so as to have an overestimation in the adjustment, reduce the impact of input data errors (cartographic and image pointing) and to perform accuracy tests with ICPs.
4. Extraction of elevation parallaxes using multi-scale (three steps) mean normalized cross-correlation method with computation of the maximum of the correlation coefficient. This method gave good results and was commonly used with satellite images (Gülch, 1991);
5. Computation of *XYZ* cartographic coordinates from elevation parallaxes in a regular grid spacing (Step 4) using the previously-computed stereo-model (Step 3) with 3-D least squares stereo-intersection.

3. RESULTS AND DISCUSSIONS

3.1. Stereo-Bundle Adjustment Results

Ten GCPs were used for SPOT, IKONOS and QuickBird data because previous results demonstrated that this was a good compromise with this dataset to avoid the propagation of input data error (cartographic and mainly image pointing) into the 3-D physical stereo-models (Toutin, 2003, Toutin and Cheng, 2002). More GCPs (18) were used with EROS data due to the increased number of unknown parameters, which physically model the largest attitude variations, in order to keep the same degree of freedom in the least squares adjustment. The remaining points as ICPs, which were not used in the 3-D stereo-model calculations, are used for performing unbiased validations of the modelling accuracy (Table 2).

Stereo Bundle Tests	GCP Number	ICP Number	RMS GCP Residuals (metres)				RMS ICP Errors (metres)			
			X	Y		Z	X	Y		Z
SPOT5 HRS	10	88	7.1	6.4		3.1	13.9	8.7		4.7
SPOT5 HRG	10	23	1.5	1.4		1.3	2.6	2.2		2.9
EROS-A	18	112	2.4	2.8		3.8	4.2	4.2		5.9
IKONOS-II	10	45	1.2	1.6		1.9	2.4	2.1		3.0
QuickBird	10	38	0.6	0.7		0.4	1.5	1.6		1.4

Table 2. Results of stereo-bundle adjustment for two different sets of tests: the number of GCPs and ICPs and the root mean square (RMS) residuals on GCPs (in meters) for both Sets with either the maximum residuals (in meters) on GCPs for Set 1 or the RMS errors (in meters) on ICPs for Set 2.

These tests enabled unbiased validation of the positioning and restitution accuracy with ICPs. RMS errors on ICPs range from 1.5 m to 5 m (except for HRS) reflect approximately the image pointing errors: 10 m for SPOT HRS; 2.5 m for SPOT HRG; 2-3 m for EROS; 1-2 m for IKONOS and 1 m for QuickBird with a B/H of 0.77, 0.7 and one, respectively. However when compared to sensor resolution, the RMS errors range from half-pixel for SPOT-5 to around two pixels for the three other sensors. The main reasons why SPOT achieved the best results, when compared to resolution, are the strongest stability of synchronous versus asynchronous satellites as well as its 820-km altitude (less orbital perturbations) versus the 500-600 km altitudes for EROS and IKONOS.

The use of overabundant GCPs in the least squares adjustment reduced or even cancelled the propagation of different input data errors (image pointing error of 1-2 pixels and cartographic error of 1-2 m) into the 3-D physical stereo-models, but conversely these input errors are reflected in the residuals. Consequently, it is "normal and safe" to obtain RMS errors from the least squares adjustment in the same order of magnitude as the input data error, however, the internal accuracy of the stereo modelling is better (around one pixel or less) (Toutin, 2003).

3.2 DEM Evaluation Results

Quantitative evaluation of DEMs was conducted with the comparison of the lidar elevation data and five to six million elevation points were used in statistical computations. The general results for SPOT HRS, SPOT HRG, EROS, IKONOS and QuickBird were obtained: LE68 of 5.5 m, 6.5 m, 20 m, 6.4 m and 6.7 m are respectively, good, poor and medium when compared to the stereo bundle adjustment RMS *Z*-residuals (Table 2), but also in relation with the pixel for each stereo-image (5m, 5 m, 1.8-2.5 m, 1 m and 0.61 m, respectively) combined with B/H of 0.85, 0.77 for SPOT, 0.7 for EROS and one for IKONOS and QuickBird.

Figure 3 is the stereo-extracted DEM form QuickBird images, with some enlargements of specific areas to demonstrate that DEM is a DSM, which includes surface heights.

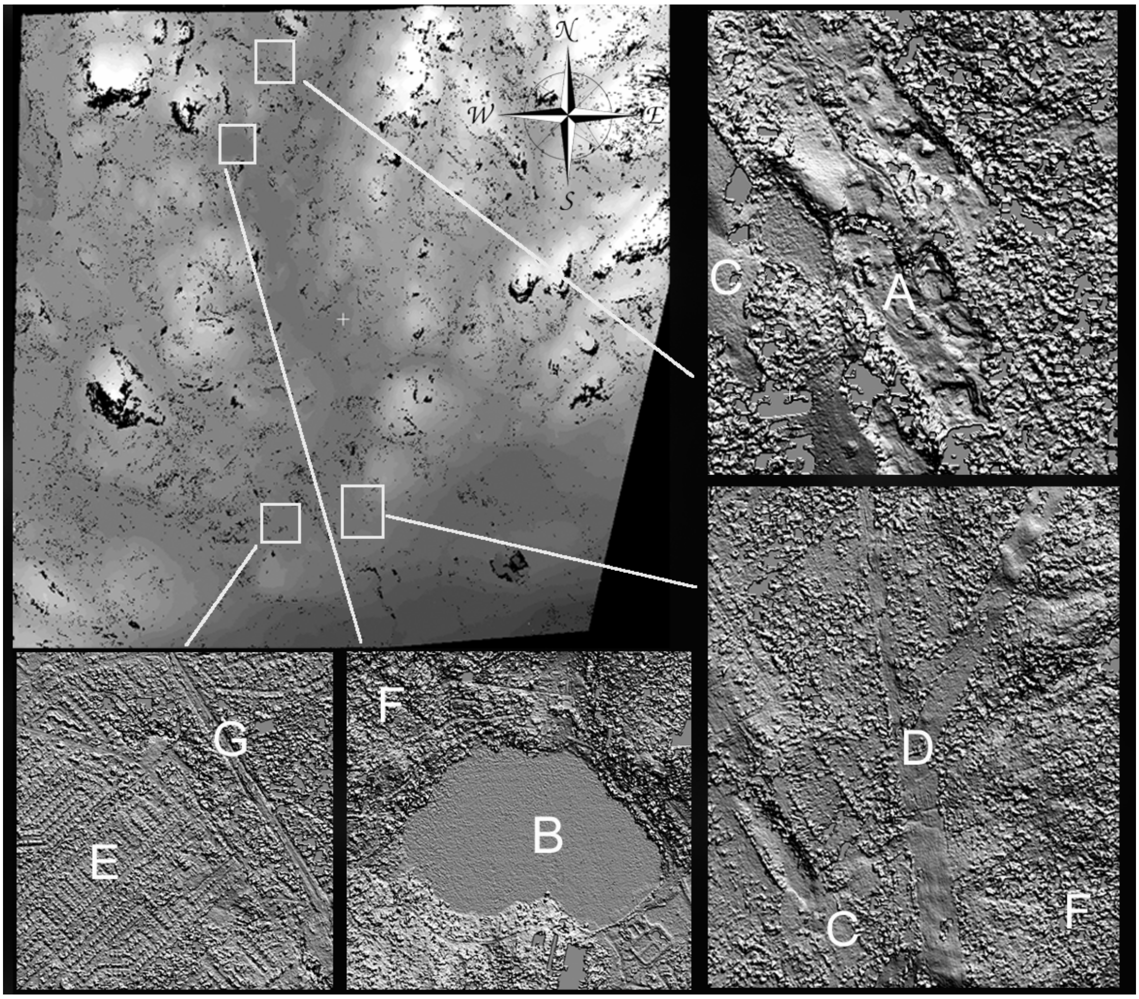

Figure 3. Stereo-extracted DEM (18 km by 15 km; 1-m pixel spacing) extracted from the QuickBird stereo-pair with shaded relief enhancement for some sub-areas. Black areas are the mismatched areas (6% of the total area). Note (A) sand/gravel pits, (B) lakes, (C) bare soils, (D) power-line corridors, (E) residential areas, (F) deciduous and sparse trees without leaves, and (G) highways.

In fact, these DEMs stereo-extracted from HR data are digital surface models (DSMs), which include the height of natural and human-made surfaces. The more accurate the DEM, the more noticeable are the height of some surfaces and the resulting cartographic features. Consequently, a second elevation accuracy evaluation was performed only on bare surfaces (soils and lakes), where there is also no difference between the stereo-extracted elevation and the lidar data (Table 3). EROS was not considered due to its poor results (20 m), which were not affected by surface heights. Table 3 gives the results computed from elevation errors for the three DEMs: the linear errors with 68% and 90% levels of confidence (LE68 and LE90, respectively), the bias and the percentage of class over three times LE68 (in meters).

Sensors	LE68	LE90	Bias
SPOT5 HRS	2.7 m	5.6 m	-0.2 m
SPOT5 HRG	2.2 m	5.0 m	-2 m
IKONOS-II	1.5 m	3.5 m	1 m
QuickBird	1.2 m	2.8 m	0 m

Table 3. Statistical results (in meters) from the comparison of DEM generated from stereo SPOT-5, IKONOS and QuickBird data with lidar elevation data over bare surfaces (soils and lakes) only: the linear errors with 68% and 90% level of confidence (LE68 and LE90, respectively) and the bias.

The results over bare soil/lakes demonstrate better the real stereo-performance for elevation extraction and DEM generation of SPOT HRS and HRG, IKONOS and QuickBird: LE68 of 2.2 m, 1.5 m and 1.2 m, respectively. These results are more consistent with *a priori* 3-D restitution accuracy from the bundle adjustments (around 2 m in *Z*). Even with a multi-date acquisition, SPOT achieved "half-pixel" errors while IKONOS and QuickBird with a same-date acquisition achieved only "1.5-pixel" errors and "two-pixels" errors: three-to-four time degradation. The first reason could be the use of raw SPOT data (original geometry and radiometry) while IKONOS data were processed as a map-oriented product resulting in a "non-original" geometry and both IKONOS and QuickBird data have a resampled radiometry. A second reason could be the 820-km altitude for SPOT (less orbital perturbations) versus the 500-600 km altitudes for IKONOS and QuickBird.

4. CONCLUSIONS

DEMs were extracted from five different HR stereo images (B/H of one, except EROS and SPOT HRS and HRG with a B/H ratio of 0.7, 0.85 and 0.77, respectively) using the 3-D CCRS physical geometric model and multi-scale image matching: across-track multi-date SPOT5 HRS (5 x 10 m) and in-track SPOT5 HRG (5 m), agile same-date EROS-A (1.8 m), IKONOS-II (0.8 m) and QuickBird (0.61 m). These images were acquired over a hilly residential/rural area in Québec, Canada. The stereo bundle adjustments of geometric models using 10-18 GCPs enabled *a priori* 3-D restitution accuracy, which includes feature extraction error, to be estimated (around 2-5 m in the three axes). However, the internal accuracy of the stereo-models is better than one pixel. The stereo-extracted DEMs, using a multi-scale cross-correlation method, were then compared to accurate elevation lidar data, and LE68 of 5.5 m, 6.5 m, 20 m, 6.4 m and 6.7 m were obtained for SPOT HRS, SPOT HRG, EROS, IKONOS and QuickBird, respectively. The poor results for EROS were due to the asynchronous sensor, which generated large geometric and radiometric differences in the images of the stereo pair. Since the surface heights were included in terrain elevation and its evaluation, elevation errors were thus evaluated on bare surfaces (soils and lakes), where there is no elevation difference between the stereo DEMs and the LIDAR data. The results (1.2-2.2 m LE68) over bare surfaces are a good indication of the general SPOT, IKONOS and QuickBird stereo-performance for DEM generation. However, SPOT (raw data, high orbit, B/H of 0.85 and 0.77) achieved better results than same-date IKONOS or QuickBird (pre-processed data, low orbit, B/H of one): half-pixel versus 1-2 pixels.

ACKNOWLEDGEMENTS

The author would like to thank M. Bernard and D. Giacobbo of SPOT-Image for the SPOT data; R. Hellerman and ImageSat Intl. for the EROS data; R. Matte (*Ministère des Ressources naturelles du Québec*, Canada) for the topographic data; GPR Consultants (Québec, Canada) for the LIDAR survey; the two anonymous reviewers, A. Chichagov and K. Naluzny of CCRS, NRCan for reviewing and improving the manuscript; R. Chénier (Consultants TGIS inc., Canada) and S. Grassi (Università degli Studi di Perugia, Italy) for data processing.

REFERENCES

Bouillon, 2002, A., E. Breton, F. de Lussy, and R. Gachet, "SPOT5 HRG and HRS first in-flight geometric quality results," in *Proc. of SPIE, Vol. 4881A Sensors, system, and Next Generation Satellites VII*, Agia Pelagia, Crete, Greece, 22-27 September 2002, (Bellingham, WA: SPIE), CD-ROM (Paper 4881A-31).

Chen, L.C. and Teo, T.-A., 2002, "Rigorous Generation of Orthophotos from EROS-A High Resolution Satellite Images," *International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences*, Ottawa, Canada, July 8-12, 2002, (Natural Resources Canada: Ottawa, Ontario), vol. 34 (B4), pp. 620-625.

Dial, D., 2000, "IKONOS Satellite Mapping Accuracy," in *Proc. ASPRS Congress*, Washington DC, USA, 26 May 2000, CD-ROM.

Fowler, R.A., 2001, "The Thorny Problem of LIDAR Specifications," *Earth Observation Magazine*, vol. 10, no. 4. pp. 13-17, Available Online: http://www.lasermap.com/laserM/english/princ.htm.

Gülch, E., 1991, "Results of Test on Image Matching of ISPRS WG III/4," *ISPRS J. Photogramm. Remote Sens.*, vol. 46, no. 1, pp. 1-8.

Robertson, B., 2003, "Rigorous Geometric Modeling and Correction of QuickBird Imagery, " in *Proc. IGARSS 2003*, Toulouse, France, 21-25 July 2003, (Toulouse: CNES) CD-ROM.

Toutin, Th., 2000, "Elevation modeling from satellite data," *Encyclopedia of Analytical Chemistry: Applications, Theory and Instrumentation* (R. A. Meyers, editor), vol. 10, John Wiley & Sons, Ltd., Chichester, UK, pp. 8543-8572, Avalaible Online: http://www.ccrs.nrcan.gc.ca/ccrs/rd/sci_pub/bibpdf/4622.pdf.

Toutin, Th. and Ph. Cheng, 2002, "QuickBird: a milestone for high resolution mapping, Earth Observation Magazine," Vol. 11, No. 4, pp.14-18. Avalaible Online: http://www.ccrs.nrcan.gc.ca/ccrs/rd/sci_pub/bibpdf/13212.pdf

Toutin, Th., 2003, "Error tracking in IKONOS geometric processing using a 3D parametric modelling," *Photogramm. Eng. Remote Sens.*, vol. 69, no. 1, pp.43-51. Avalaible Online: http://www.ccrs.nrcan.gc.ca/ccrs/rd/sci_pub/bibpdf/13102.pdf.