3D GEOMETRIC MODELLING OF IKONOS GEO IMAGES♥

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ABSTRACT

Digital elevation model (DEM) extracted from IKONOS along-track stereo images with photogrammetric method is evaluated. As few as 12 GCPs are enough for the stereo photogrammetric bundle adjustment, which also filters the errors of the input data. With an area-based image matching users may produce high resolution DEMs with LE68 errors of 1 m to 4 m depending on the land covers. The best results (1.1 m-2.6 m) are obtained in bare soils, lakes, residential areas and sparse forests. The surface elevation of some of the areas (residential/ forests) did not affect too much the errors because the 1-2-storey houses in residential areas are sparse or because the images were acquired when there is no leave in the deciduous forests. An error evaluation as a function of the slope azimuths shows that the DEM error in sun-facing slopes is 1-m smaller than the DEM error in slopes away from the sun. 5-10 m contour lines could thus be derived with the highest topographic standard.

1. IKONOS STEREO DATA

Three main attributes of IKONOS imagery for stereoscopic capabilities are 360º pointing capability, a base-to-height (B/H) ratio of 0.6 and greater, which is similar to aerial photographs, and the highest resolution available to civilian remote sensing and mapping communities. The 360º pointing capability enables the generation of across-track stereoscopy from two different orbits, such as with SPOT-HRV, as well as, along-track stereoscopy from the same orbit, such as with JERS-1's Optical Sensor. The across-track solution has been used more since 1980; however the along-track solution as applied to space frame cameras has received renewed popularity in the past 10 years. In fact, same-date along-track stereo-data acquisition gives a strong 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.

This along-track solution to acquire stereo data is generally chosen by Space Imaging not only for scientific, but also for operational reasons. These stereo data are only available for governmental administrations as long as they are not used for commercial purposes (marketing, selling and distributing). Since Space Imaging does not provide the raw data with their ancillary data, preferred by the photogrammetrist community, only one quite similar to the GEO product can be ordered for stereo data. 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. They are distributed in 8-bit or 11-bit GeoTiff format with an ASCII metadata file (including order parameters, source image and products file descriptions), however, detailed orbital information is not included. Since archive orders are generally not available for stereo-images, newly collected data is typically delivered in two or more weeks, depending upon

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order size, weather, and accuracy.

Largely extrapolated on results from similar systems mounted on aircraft platforms or from scanned aerial photos, IKONOS stereo-images should have a potential for creating DEMs with about 2m accuracy for use in national mapping (Ridley *et al.*, 1997). This accuracy can be consistently achieved only if photogrammetric processing is employed (Li., 1998) and if the DEM is manually edited with 3D capability for surface elevation. Work still need to be carried out to evaluate the possibility for automating some processing steps and for using existing cartographic data, such as breaklines, hydrographic features and buildings. The objectives of this paper are to expand on these preliminary results with real IKONOS stereo images acquired from same orbit. Using a photogrammetric-based stereo-model developed at the Canada Centre for Remote Sensing (CCRS) (Toutin, 1995) and adapted to IKONOS images (Toutin and Cheng, 2000), the paper will evaluate DEM error when compared to ground truth, and track the error propagation from the input data to the final DEM. Different cartographic parameters affecting the accuracy are also evaluated.

2. PROCESSING OF IKONOS STEREO DATA

The photogrammetric method of stereo data processing uses a parametric model that reflects the physical reality of the complete viewing geometry, and that corrects distortions due to the platform, sensor, Earth and deformations as a result of cartographic projection. Even though detailed sensor information for the IKONOS satellite is not released, such photogrammetric method was developed at CCRS for IKONOS stereo data using basic information available from the metadata and image files. For example, approximate sensor viewing angles can be computed using the nominal collection elevation and azimuth in addition with the nominal ground resolution.

The CCRS model based upon principles related to orbitography, photogrammetry, geodesy and cartography was adapted for the specificity of IKONOS images. For stereo-images, both collinearity and coplanarity conditions are used to simultaneously compute the interior and exterior orientation parameters in a least-square bundle adjustment process (Toutin, 1995). The CCRS model has been previously applied with only a few ground control points (GCPs) (3 to 6) to VIR stereo data (SPOT, IRS, ASTER and KOMPSAT), as well as stereo SAR data (ERS and RADARSAT). Based on good quality GCPs, the DEM accuracy of this model was proven to be better than one pixel for medium-resolution VIR images, and one resolution cell for SAR images.

The CCRS method is now fully ported into PCI OrthoEngine Satellite Edition V8.0 software. The software supports the reading of satellite data, metadata, GCP and tie points collection, bundle adjustment, ortho-rectification and mosaicking, stereo-model computation, image matching and DEM generation with either manual or automatic editing. After the stereo-model (colinearity and coplanarity equations) are computed using a minimum of six GCPs, an automated image matching procedure is used through a comparison of the respective grey values of the images (PCI, 2001). This procedure utilizes a hierarchical sub-pixel normalized cross-correlation matching method to find the corresponding pixels in the left and right quasi-epipolar images. The difference in location between the images gives the disparity or parallax arising from the terrain relief, which is converted to X, Y, Z map co-ordinates using a 3D space intersection solution. Automatic and 3D-manual editing tools are finally used for the last step to improve DEM quality and coherency.

3. DATA SET

To test the stereo capability of the photogrammetric method, IKONOS stereo product was ordered in autumn 2000 for a area north of Québec City, Québec, Canada (N 47º, W 71º 30’). Figure 1 is the left (backward) image of the stereo pair: one can notice sand/gravel pits (A), frozen lakes with snow (B) and snow over bare soils (C).

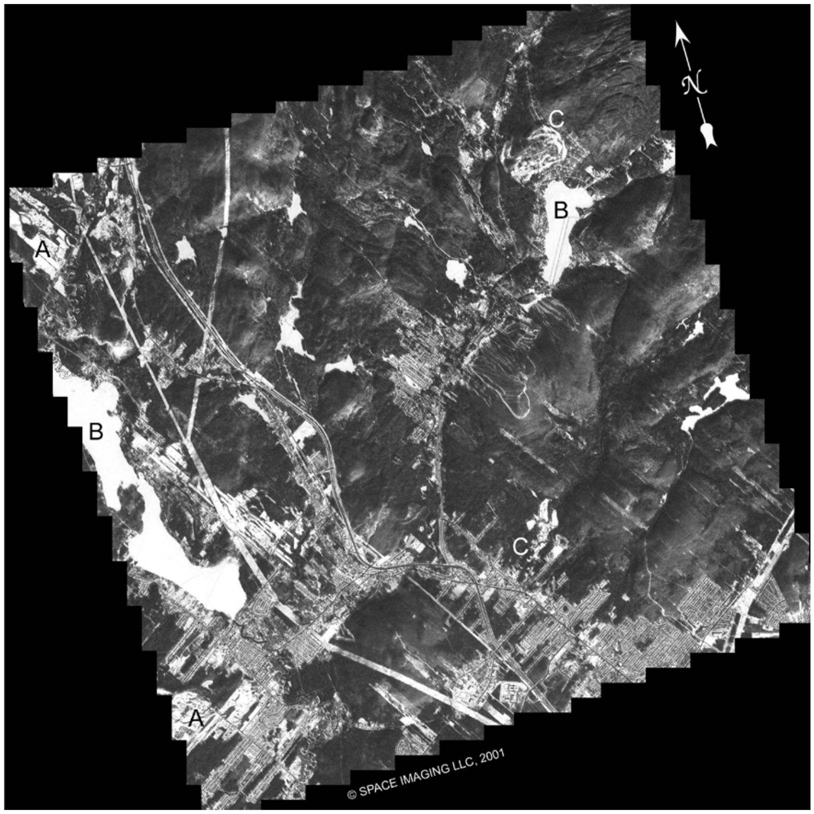

Figure 1: Left (backward) image of the IKONOS stereo pair, north of Québec City, Quebec, Canada acquired January 3, 2001. Note (A) sand/gravel pits, (B) frozen lakes with snow and (C) snow over bare soils. IKONOS Image © Space Imaging LLC, 2001

Figure 2: Sub-image of left IKONOS stereo pair, north of Québec City, Quebec, Canada. Note (A) sand /gravel pits in operation and (B) residential and urban areas.
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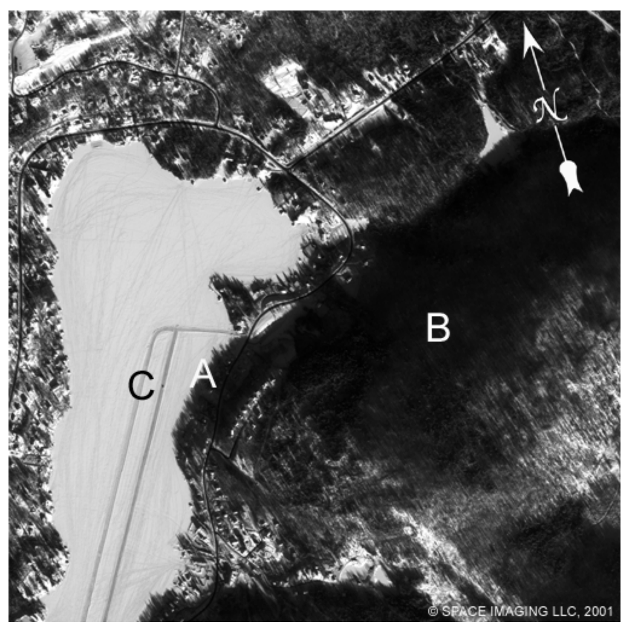

Figure 3: Sub-image of left IKONOS stereo pair, north of Québec City, Quebec, Canada. Note (A) tree shadows on the lake, (B) mountain shadows due19° and 166° solar elevation and azimuth angles and (C) the skater!
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This study is a residential and semi-rural environment (Figure 2) and has a hilly topography with 500-m elevation range (Figure 3). 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: one can notice the tree shadow on the lake (A) and the mountain shadow (B) (Figure 3). The two panchromatic images with a resolution of a little less than one metre (Note the skater (C) on Figure 3) have collection and azimuth angles 63º and 322º, 63º and 252º, respectively generating 54º stereo-intersection angle (base-to-height ratio B/H, of 1.0) were delivered within thirty days of acquisition. Each image of the stereo pair was delivered in two tiles, and stitching them was necessary to re-generate the quasi-epipolar image geometry. The metadata file was processed to compute the satellite and sensor parameters needed for the photogrammetric stereo model.

The cartographic data (six one-metre pixel ortho-photos, a 5-m accurate DEM, and digital vector lines) was provided by the Ministère des Ressources naturelles du Québec, Canada. While only six GCPs are enough with the rigorous method, 56 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 with 3-m accuracy and 5-m grid spacing DEM with 5-m accuracy. However, 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.

4. RESULTS AND ANALYSIS

The first results are given with the root mean square (RMS) and maximum residuals/errors for three different tests performed on stereo IKONOS images to evaluate the robustness of the photogrammetric model:

1. All 56 GCPs are used to compute the stereo-model;
2. All 56GCPs are used to compute the stereo-model with an erroneous point (20-m error in the Y direction); and
3. Only 12 GCPs are used to compute the stereo-model and 34 independent check points (ICPs) are used to check the stereo-model.

Table 1: Comparison of residual/error results (in metres) over GCPs/ICPs for the three tests.

Test Number	**RMS GCPs Residuals**			**Maximum Residuals**		
	X	**Y**	**Z**	**X**	**Y**	**Z**
#1: 55 GCPs	6.0	2.3	2.8	11.6	5.1	6.8
	RMS GCPs Residuals			**Erroneous Point Residuals**		
#2: 55 GCPs/1 error Point	6.4	5.9	3.1	11.6	-17.4	-4.8
	RMS GCPs Residuals			**RMS ICPs Errors**		
#3: 12 GCPs/34 ICPs	5.7	2.5	3.6	7.0	2.4	3.6

The three tests show that the 5-m error in the GCP X-coordinate, as mentioned previously, did not propagate through the rigorous model but is reflected in all X-residuals and in the RMS X-error of Test #3. Test #1 shows that the maximum residual is around two times the RMS residuals, demonstrating stability over the entire stereo-images. Test #2 shows that the Y-residual of the erroneous point is three times higher than the RMS Y-residual. Consequently, the systematic error is immediately detected with its approximate value and direction. Since part of the 7-m X-error on ICPs (Test #3) includes the 5m random error of the ground X-coordinate, Test #3 shows that 12 GCPs are enough to achieve a stereo-model accuracy around 3 to 4m, both in horizontal and vertical directions.

These three tests demonstrate that the photogrammetric method is both stable and robust without generating local errors and filters random or systematic errors. The input GCP error does not propagate through the rigorous model, but is reflected in the residual. Since errors always occur in operational environments, it is thus important to detect all potential errors in the GCPs before starting the extraction of the DEM.

The second result is the qualitative and quantitative comparisons of the stereo-extracted DEM (2-m pixel spacing) using the automatic matching and editing process. Figure 4 is a 3D representation of the extracted DEM: it well reproduces the terrain relief and its specific features visible on the IKONOS images. Different planimetric features are clearly identifiable: sand/gravel pits in A; some repetitive patterns in B, which first look like noise, and linear features in C, related to main roads and power-line clear-cut in the forest environment.

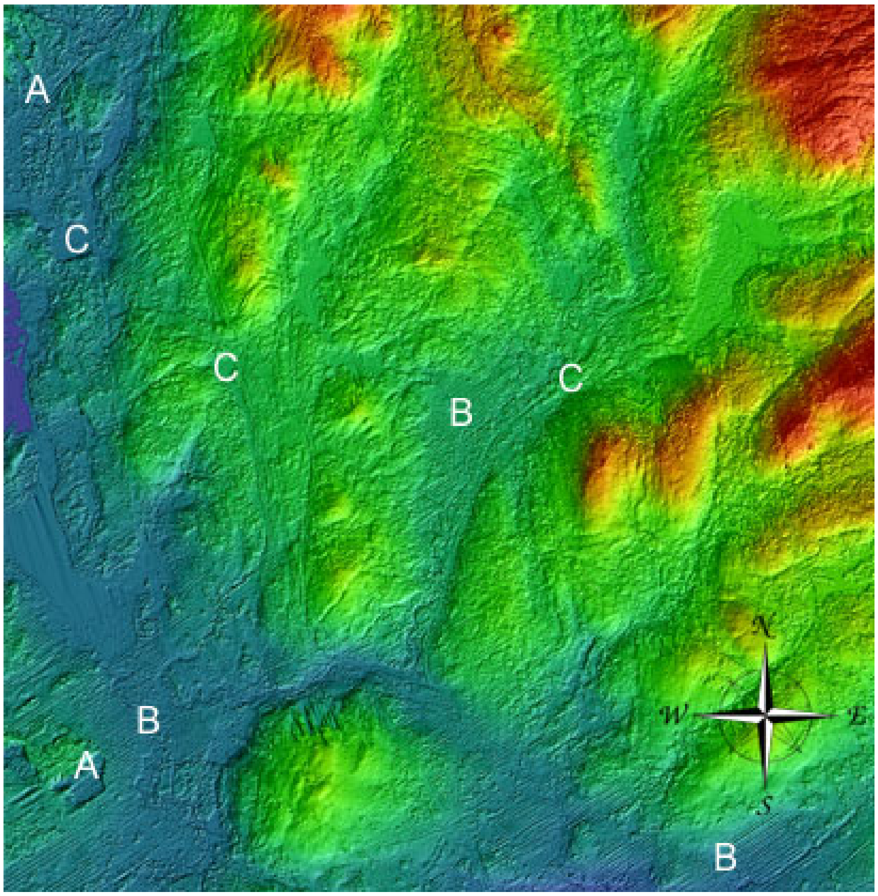

Figure 4: Chromo-stereoscopic image of the IKONOS stereo-extracted DEM. Note (A) sand/gravel pits, (B) repetitive pattern and (C) linear features (power lines and roads).

Looking at the repetitive patterns in more details, they are attributed to the street/house patterns in the residential areas (Figure 5): the matching process worked on the houses and the method then extracted the elevation and shape of the 1-2-storey residential houses. A closer-look comparison (Figure 6) of the IKONOS image (left) and the DEM (right) confirms "the shape extraction" of a large 3-storey commercial building. With some post-processing of the DEM, IKONOS DEM could then be used for 3D building modelling.

For quantitative evaluation, the generated DEM was compared with the topographic DEM (5-m grid spacing and 5-m accuracy) using 4 400 000 points in the statistical evaluation. Even though the images were acquired in January with snow cover, frozen lakes and tree/mountain shadows there is only 5% mismatched areas over the entire stereo-images, of which includes 2.5% for lakes. The remaining 2.5% mismatched areas are mainly located in the northwest slopes of mountains (Figure 1) and are due to the solar shadow (elevation angle of 19º and azimuth of 166º) (Figure 3). These first mismatched results confirm that multi-scale matching well performed with 1m high-spatial resolution data in semi-rural areas.

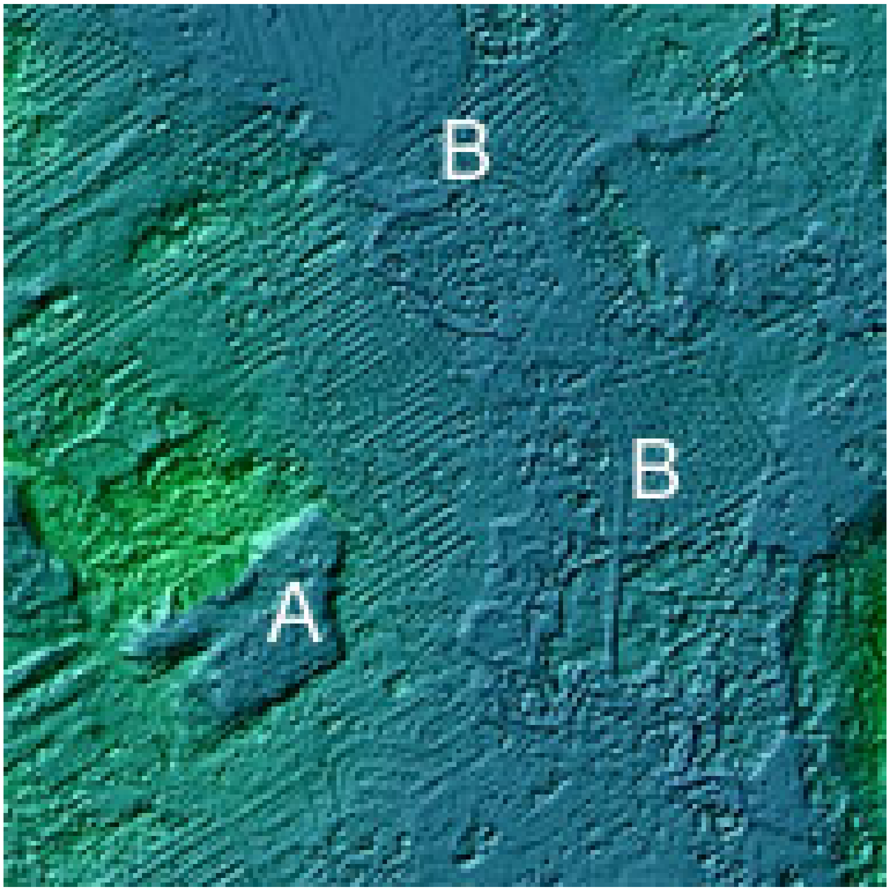

Figure 5: Sub-area of the chromo-stereoscopic image of the IKONOS stereo-extracted DEM. (A) sand/gravel pits and (B) street and building pattern in the residential areas. IKONOS Image © Space Imaging LLC, 2001

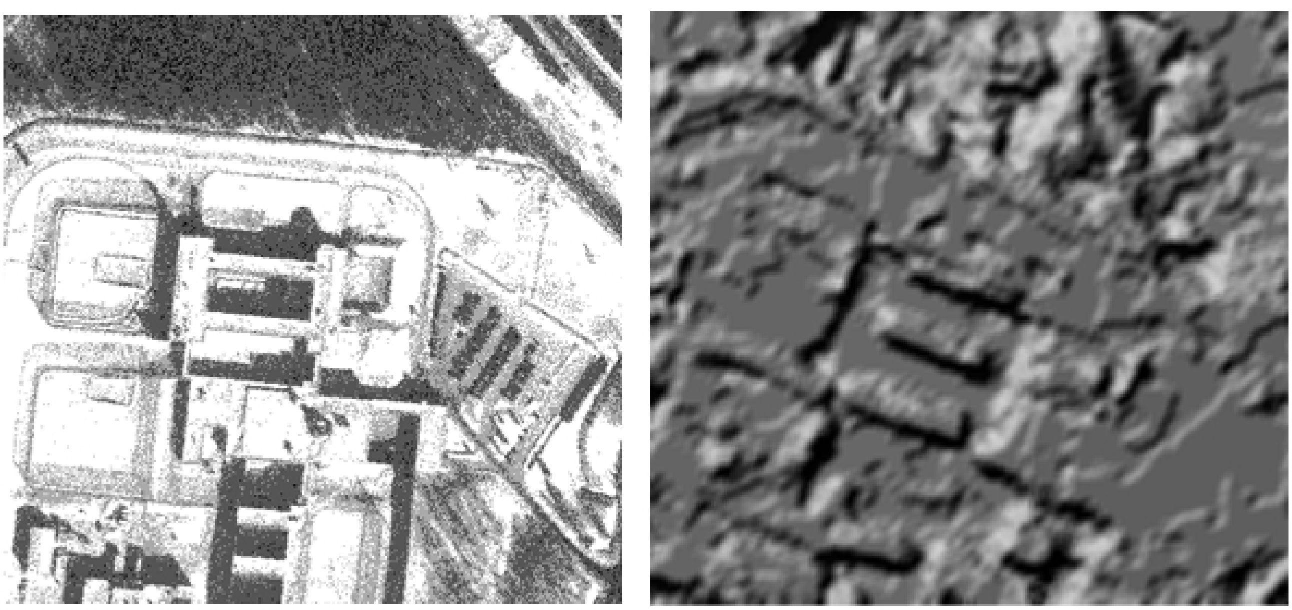

Figure 6: Comparison of the IKONOS image (left) with the stereo-extracted DEM (right).
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Table 2 gives the statistical results for different areas of the study sites, the linear error with 68% and 90% levels of confidence (LE68 & LE90, respectively), the bias and the maximum/minimum errors (in metres). The 3.8-m LE68 and 7.7-m LE90 with almost no bias for the entire study site are a good result because not only does it includes the 5-m error of the topographic checked DEM but also includes the canopy/building heights as mentioned previously. It then enables 10 m to 15 m contour lines to be derived with the highest mapping standard. However, the largest errors (-50/37 m) are out of tolerance and cannot be acceptable for DEM in a topographic sense. In order to understand and locate these largest errors, the errors have been colour coded (from blue for the lowest and red the highest) and draped over the DEM in a southwest-northeast perspective view (Figure 7): orange and red colours correspond to 9 m and 15 m errors, respectively. The largest errors are located in the sand/gravel pits (A) and in the northwest slopes of the mountains where solar shadows occur (B) due to solar elevation and azimuth angles of 19º and 166º, respectively. An error evaluation as a function of the slope azimuths shows that the DEM errors in the sun-facing slopes (azimuths from 76º to 256º) is 1-m smaller than the DEM errors in the slopes away from the sun (azimuths from 256º to 76º). These more-than-9-m errors are then representative of our study site and stereo-images, but are not representative of the general IKONOS stereo-performance for DEM generation.

Table 2: Statistical DEM results (linear errors with 68% and 90% confidence levels, LE68 and LE90 respectively, bias and minimum/maximum errors in metres) for the entire study site and different land covers.

Area	**Percentage**	**LE68**	**LE90**	**Bias**	**Min./Max.**
Entire	100%	3.8 m	7.7 m	-0.9 m	-50/37 m
Dense forests	61%	4.4 m	8 m	-2.1 m	-37/29 m
Sparse forests	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	2.7 m	2.5 m	-29/20 m
Urban/Residential	15.5%	2.4 m	5 m	0.2 m	-26/18 m
Sand/gravel Pits	1.5%	8.5 m	18 m	0.5 m	-50/37 m

For these different reasons: sensibility to the land covers, no digital surface model (DSM) available and many fine details in the stereo extracted DEM, its error evaluation must be realized for different land covers: dense forests, sparse forests, bare soils, lakes, urban/residential areas and sand/gravel pits (Table 2). The best results (around 1.1-2.6 m LE68) are obtained for four classes of no- or low-elevation cover (bare soils, lakes, sparse forest, and urban/residential areas). Even if house elevations are extracted in the method, the 1-2-storey houses in the residential and urban areas, not very dense (10-15% of the residential areas) and high (4-6 m), do not affect too much the statistics for this land cover. Furthermore, since the images were acquired on January, there was not leave in deciduous trees and the rays went through the canopy. It explains the small bias for the sparse and dense forests and the 2.4-m LE68 for the sparse forests. 5-10 m contour lines could thus be derived in these areas. Finally, the largest errors (8.5-m LE68 and –50m/37-m min./max.) are in the sand/gravel pits, located northwest and southwest of the images, where elevations changed over time.

4. CONCLUSIONS

One major drawback of the efficient and appropriate use of IKONOS stereo-data was the difficulty by the users to geometrically process and to extract 3D information using photogrammetric method. The CCRS-developed model that is available in the PCI operational environment can now be used for 3D modelling. As few as 12 GCPs are enough for the stereo photogrammetric bundle adjustment, which also filters the errors of the input data. With area-based image matching users may produce high resolution DEMs with LE68 errors of 1 m to 4 m depending on the land covers. The best results (1.1 m-2.6 m) are obtained in bare soils, lakes, residential areas and sparse forests. 5-m contour lines could thus be derived in these areas. The surface elevation of some of the areas did not affect too much the errors because the 1-2-storey houses are sparse or because the images were acquired when there is no leave in the deciduous forests. An error evaluation as a function of the slope azimuths shows that the DEM error in sun-facing slopes is 1-m smaller than the DEM error in slopes away from the sun.

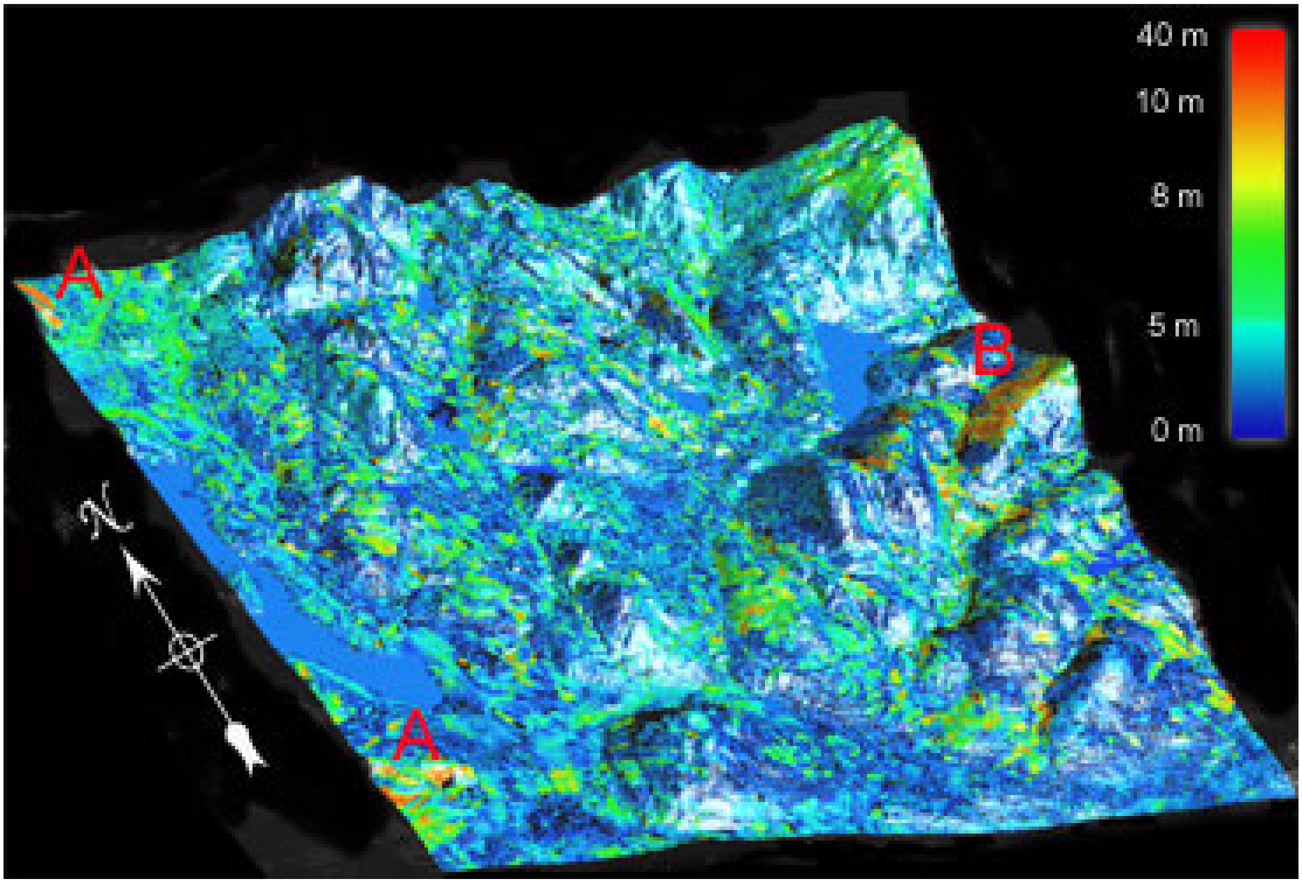

Figure 7: Perspective view of the DEM error (Topographic DEM minus IKONOS DEM) draped over the IKONOS DEM. Note the errors larger than 9m (orange to red) are located in (A) sand/gravel pits (NW and SW) and (B) the northwest slopes of mountains.

Since many cartographic features and fine topographic details are present in the stereo IKONOS DEM, the DEM is in fact a DSM, which includes house elevations and part of canopy heights of dense forests. It can be thus be used as a complementary tool to ortho-images for automatically classifying planimetric features (roads, power lines), urban areas (streets and houses), and for extracting house or canopy heights.

Work still needs to be carried out to evaluate the possibility of integrating some existing cartographic data, such as buildings in urban areas or hydrographic features and canopy heights in rural areas in the post-processing procedures, as well as, extracting cartographic features from the DEM. Evaluation is still ongoing at CCRS using more precise GCPs and topographic DSM, including canopy and building heights. More results on these evaluations as a function of inter-dependent parameters (precise GCPs and DSM, slopes, aspects, land covers) will be presented at the ISPRS Workshop.

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