DEM with Stereo IKONOS: A Reality if…

Thierry Toutin, NRCan//CCRS, Philip Cheng, PCI Geomatics

A digital elevation model (DEM), as a representation of the Earth's relief, is now one of the most important data structures used for geospatial analysis and modeling. The digital format of a DEM has made it easier to derive additional information for various applications causing elevation modeling to become an important part of international research and development programs related to geo-spatial data. In fact, cartographers, engineers, geologists, hydrologists, and other geo-scientists largely use three-dimensinal (3D) information to understand better the Earth's surface. Unfortunately, DEMs of usable details are unavailable for much of the Earth and when available frequently lack sufficient accuracy.

IKONOS, the commercial satellite with the highest publicly available resolution, was successfully launched in September 1999. Since the satellite's sensors can generate 1m panchromatic and 4m multiband images with off-nadir viewing up-to-60º in any azimuth, stereo capabilities are one of its strongest attributes. General users could apply photogrammetric techniques to IKONOS stereo images with softcopy stereo-workstations so as to extract planimetric features, elevation information, such as DEMs or both. The high-spatial resolution stereo imagery sold by Space Imaging to government agencies will have "unlimited" uses for various applications, such as national mapping, environment monitoring, natural disaster assessment, and watershed management. Stereo data could also be used to help city administrators with 3D city models to plan, develop and manage utilities (gas, water and power transmission or distribution), and telecommunications networks.

Stereo-image Acquisition on IKONOS

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. Are these stereo data now available? Yes, but only for governmental administrations as long as they are not used for commercial purposes (marketing, selling and distributing). A strict customer license agreement governs the usage of the stereo-images and their derivative products.

Since Space Imaging does not provide the raw data with their ancillary data, which preferred by the photogrammetrist community, IKONOS stereo images are distributed in a quasi epipolar-geometry reference where only the elevation parallax in the scanner direction remains. For along-track stereoscopy with the IKONOS orbit, it approximately corresponds to a North-South direction, with few degrees in azimuth depending of the across-track component of the total collection angle. Five different product levels are available for IKONOS data, but only one, which is quite similar to the GEO product, can be ordered for stereo data. 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 order size, weather, and accuracy.

Largely extrapolated on results from similar systems mounted on aircraft platforms or from scanned aerial photos, IKONOS stereo-images have a potential for creating DEMs with about 2m accuracy for use in national mapping. This accuracy can be consistently achieved if the DEM is manually edited with 3D capability, mainly in urban areas for the buildings. 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. Are these accuracy expectations too high in an operational environment?

Processing of IKONOS Stereo Data

IKONOS stereo-data can be processed either by the rational polynomial method or the rigorous method. The purpose of this article is to look at the applicability of these two methods to IKONOS stereo-data to create a DEM using an automatic image matching process and to present elevation accuracy results when compared to ground truth.

The rational polynomial method is a very simple method, which involves a ratio of polynomial transformations that takes into consideration ground elevation. This method does not require satellite and sensor information, nor does it model the physical reality of the image geometry and thus is sensitive to input errors. As a first approach of this method, many ground control points (GCPs) are required to resolve the 2^{nd}- or 3^{rd}-order polynomial unknowns (40 or 80 for 2^{nd}- or 3^{rd}-order, respectively). The rational polynomial method corrects locally at the GCPs; however, distortions between the GCPs are not entirely eliminated, resulting in this method being only useful for small areas with gentle terrain. This approach can only be applied to create ortho-images with existing DEMs, rather than create DEM from stereo-images.

The rational polynomial method can also be used in a second approach to approximate an already solved rigorous model. This approach has been proven to be adequate for aerial photography or for small-area satellite images. When the area that has been imaged is large, the image itself has to be subdivided and separate rational function models are required for each sub-image. Some vendors such as Space Imaging and government agencies such as the National Imagery and Mapping Agency are the main users of this piecewise approach. Having knowledge as to all the rational function parameters for each sub-image this piecewise approach can be used for generating DEMs without GCP, but considered useless when a more precise rigorous parametric method (such as described below) is available. Furthermore, the DEM results are usually not accurate enough for many cartographic applications.

The rigorous 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. When compared to rational polynomial method with piecewise approach the rigorous method produces results of the highest accuracy with relatively few GCPs needed for an entire image.

Even though detailed sensor information for the IKONOS satellite is not released, the first author of this article has successfully developed a rigorous IKONOS model 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. The CCRS model has been successfully applied with only a few GCPs (3 to 6) to VIR single or stereo data (Landsat 5 & 7, SPOT, IRS, ASTER, KOMPSAT and IKONOS), as well as, SAR data (ERS, JERS, SIR-C and RADARSAT). Based on good quality GCPs, the accuracy of this model was proven to be within one-third of a pixel for medium-resolution VIR images, and one resolution cell for SAR images. Previous results using this model by different users have shown 2 to 4m accuracy for panchromatic and multi-band IKONOS images on different study sites (urban, semi-rural, rural, rolling and mountainous relief) depending on the GCPs and DEM accuracy.

Stereo Experiment

To test the stereo capability of the rigorous method, we ordered an IKONOS stereo product in autumn 2000 for a semi-urban area north of Québec City, Quebec, Canada (N 47º, W 71º 30’). This study area has an elevation range of 150 m to 500 m (Figures 1&2).

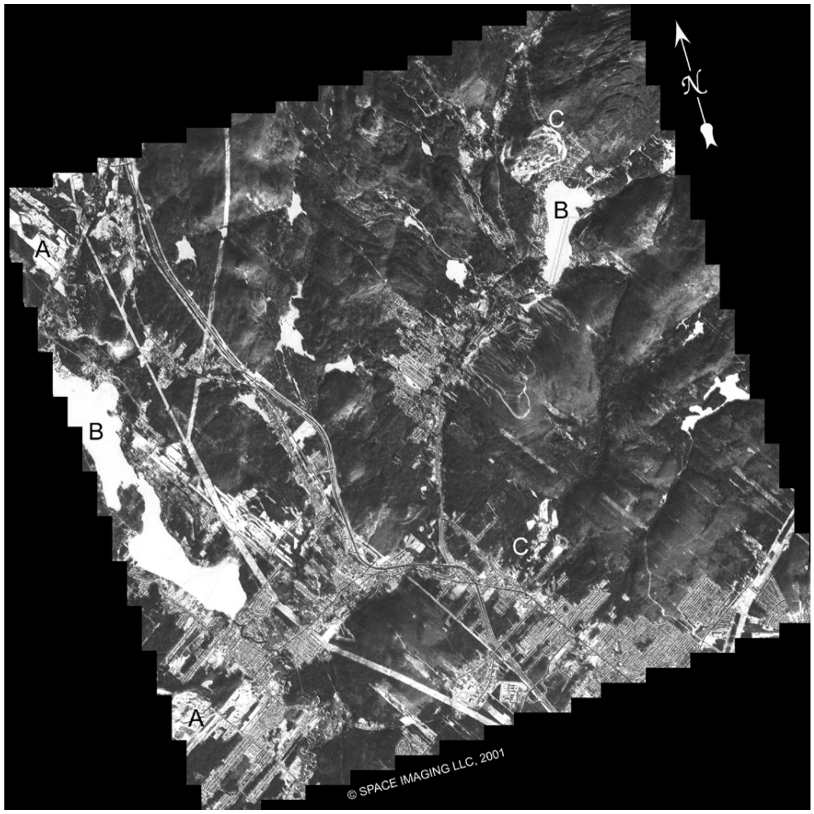

Figure 1: Left (backward) image of the IKONOS stereo pair, north of Québec City, Quebec, Canada acquired January 3, 2001. Note: (A) sand/gravel pits, (B) frozen lakes with snow and (C) snow over bare soils. IKONOS Image © Space Imaging LLC, 2001

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 area**s**. IKONOS Image © Space Imaging LLC, 2001

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 (Figure 3). The images with a resolution of a little less than one metre and a 54º stereo-intersection angle (B/H=1.0) were delivered within thirty days of acquisition. Each image of the stereo pair was delivered in two tiles, and stitching 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 rigorous model.

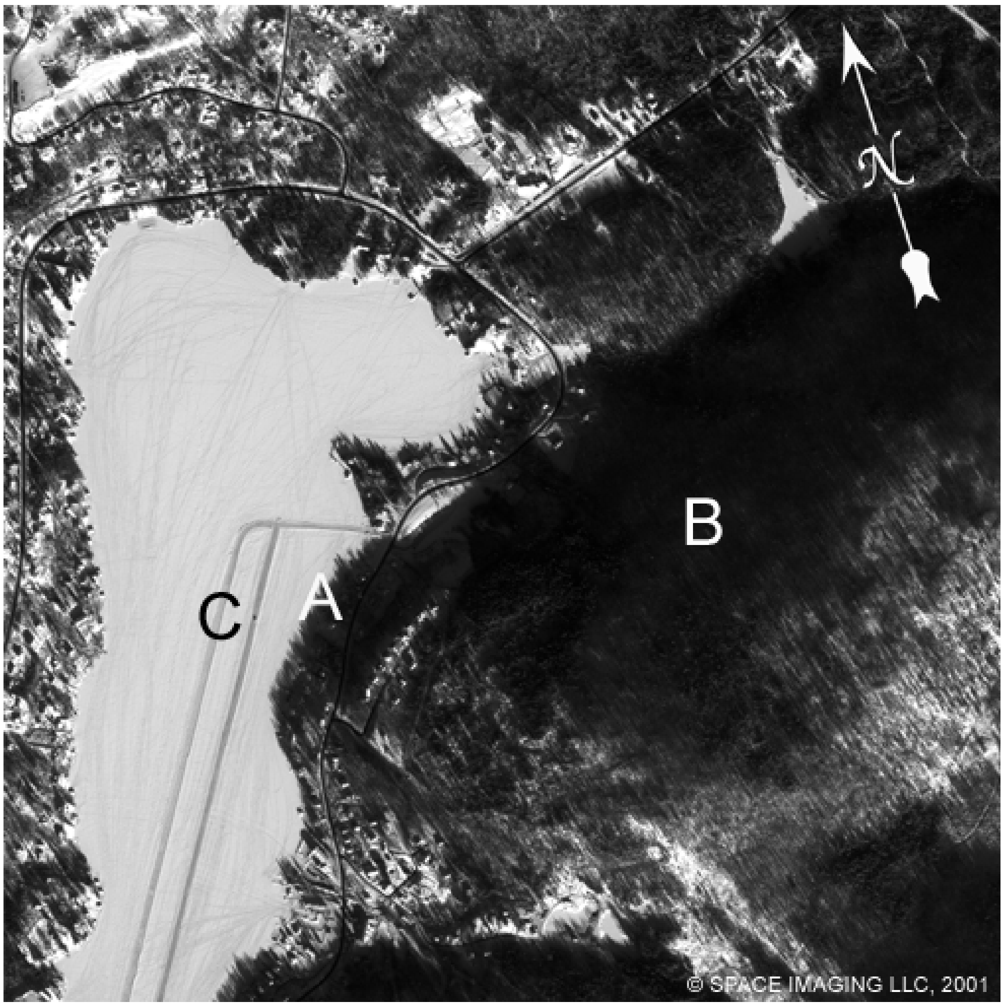

Figure 3: Sub-image of left IKONOS stereo pair, north of Québec City, Quebec, Canada.
Note: (A) tree shadows on the lake, (B) mountain shadows due19° and 166°solar elevation and azimuth angles and (C) the skater! IKONOS Image © Space Imaging LLC, 2001

The cartographic data (six one-metre pixel ortho-photos, a 5m 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, 55 GCPs were collected in stereoscopy from the stereo-images for the different tests. Their map coordinates (X, Y, Z) were obtained from six ortho-photos and the DEM. A mean positioning error of 5m in the X direction was found between the different ortho-photos; this error is mainly due to 5m DEM error during the ortho-photo generation.

To test IKONOS stereo capability for DEM generation, PCI OrthoEngine Satellite Edition V8.0 software (a product that supports the two mentioned correction methods) was used. The software also supports the reading of different satellite data, GCP and tie points collection, geometric modeling, ortho-rectification and mosaicking, stereo-model computation, image matching and DEM generation with either manual or automatic editing.

The second author of this article developed the automatic DEM generation software. This software can be used to generate DEMs from aerial photos and satellite stereoscopic sensors such as IKONOS, IRS, SPOT, KOMPSAT and RADARSAT. After the rigorous models (colinearity and coplanarity equations) are computed simultaneously for the stereo-images using a minimum of six GCPs, an automated image matching procedure is used through a comparison of the respective grey values of the images. 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.

Results and Analysis

Table 1 shows the root mean square (RMS) and maximum residuals/errors for three different tests performed on stereo IKONOS images to evaluate the robustness of the rigorous model:

1. All 55 GCPs are used to compute the stereo-model;
2. All 55 GCPs 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 33 independent check points (ICPs) are used to check the stereo-model.

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

Test Number: GCPs/ICPs	RMS GCPs Residuals			Maximum Residuals		
	X	Y	Z	X	Y	Z
#1: 55 GCPs/ 0 ICP	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/35 ICPs	5.7	2.5	3.6	7.0	2.4	3.6

The three tests show that the 5m 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 7m 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 rigorous 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 most interesting result is the comparison of the stereo-extracted DEM using the automatic matching and editing process. The generated DEM was compared with the topographic DEM (5m grid spacing; 5m 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 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 and are due to the sun shadow (elevation angle of 19º and azimuth of 166º). These first mismatched results confirm that multi-scale matching well performed with 1m high-spatial resolution data in semi-rural areas.

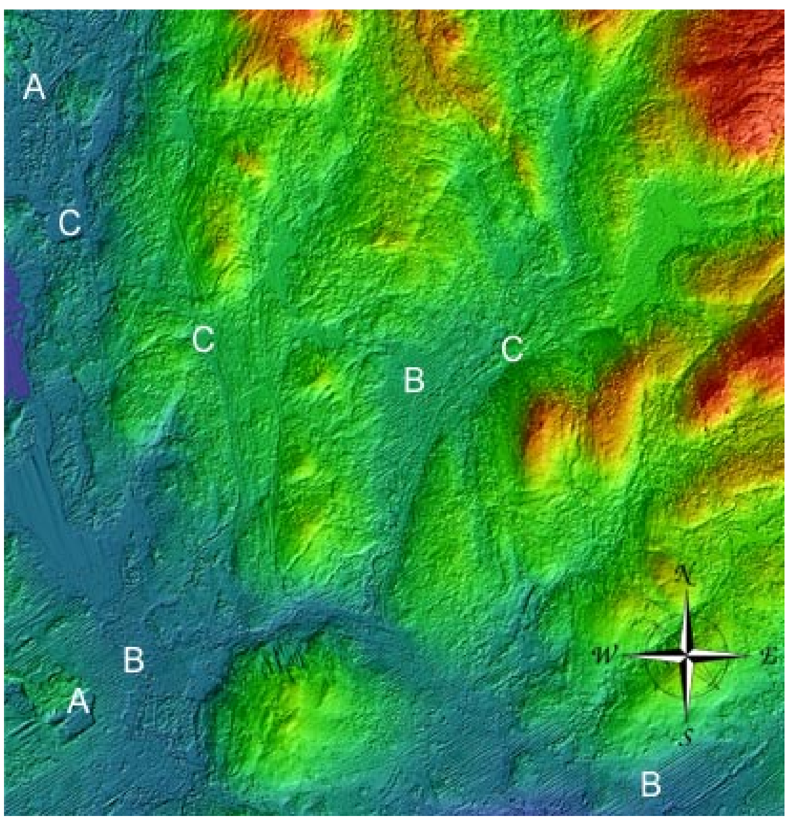

Figure 4: Chromo-stereoscopic image of the IKONOS stereo-extracted DEM. Note (A) sand/gravel pits, (B) repetitive pattern and (C) linear features (power lines and roads).

As seen in the first line of Table 2 (yellow line), the 4.9m error obtained with a 74% level of confidence is a good result because not only does it includes the 5m error of the topographic checked DEM but also includes canopy height. Since there are so many fine details in the stereo extracted DEM, its accuracy evaluation must be realized for different land covers. Six classes of land covers are used in this area: dense forest, sparse forest, bare soils, sand/gravel pits, lakes and cities. These results are also presented in Table 2 (green lines). The best results (around 3.5 m) are obtained for four classes of no- or low-elevation cover (bare soils, lakes, sparse forest, and urban/residential areas). While the houses in the residential and urban areas, which lack tall buildings or skyscrapers present in many North-American cities do not affect the statistics too much, the canopy height of the dense boreal forest does generate results that are slightly worse (5.2m with 73% and a larger negative bias). Finally, the largest errors (10m with 71% and –50m/37m min./max.) are in the sand/gravel pits, located northwest and southwest of the images, where elevations changed over time. Furthermore, the errors larger than 10m are located in the northwest slopes of mountains where shadow due to sun elevation angle and azimuth of 19º and 166º, respectively is present. These specific errors are representative of our study site and the stereo-images, but are not representative of the general IKONOS stereo potential for DEM generation in semi-rural areas.

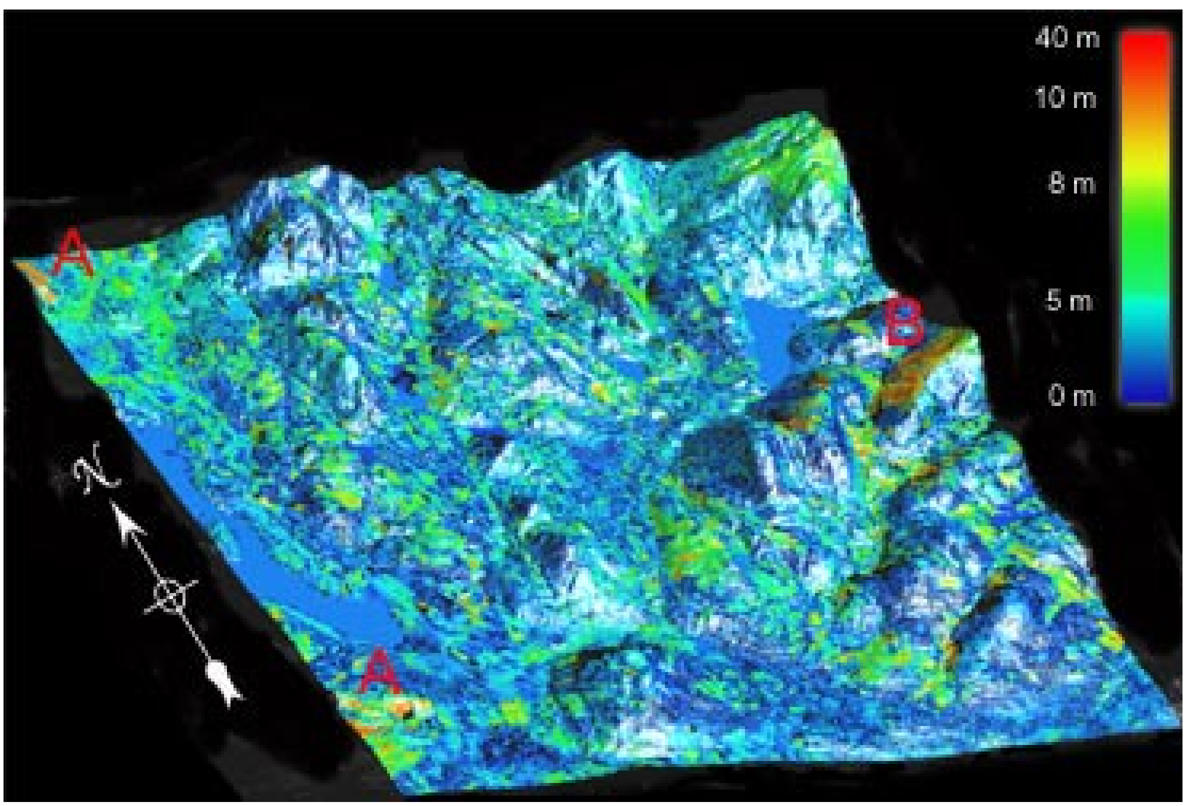

Figure 7: Perspective view of the DEM error (Topographic DEM minus IKONOS DEM) draped over the IKONOS DEM. Note the errors larger than 9m (orange to red) are located in (A) sand/gravel pits (NW and SW) and (B) the northwest slopes of mountains.

Table 2: Statistical DEM results for the entire study site and as a function of the land cover.

Area	Percentage	Error with Level of confidence	90% Level of Confidence	Bias	Min./Max
Entire	100%	4.9 m; 74%	7.9 m	-0.9 m	-50/37 m
Dense forest	61%	5.2 m; 73%	8 m	-2.1 m	-37/29 m
Sparse forest	11.5%	3.4 m; 75%	5 m	1.1 m	-34/31 m
Bare soils	6.5%	3.5 m; 72%	5.6 m	2.0 m	-33/28 m
Lakes	4%	2.1 m; 87%	2.7 m	2.3 m	-29/20 m
Pits	1.5%	10.2 m; 71%	18 m	0.5 m	-50/37 m
Urban/Res.	15.5%	3.3 m; 77%	5 m	0.2 m	-26/18 m

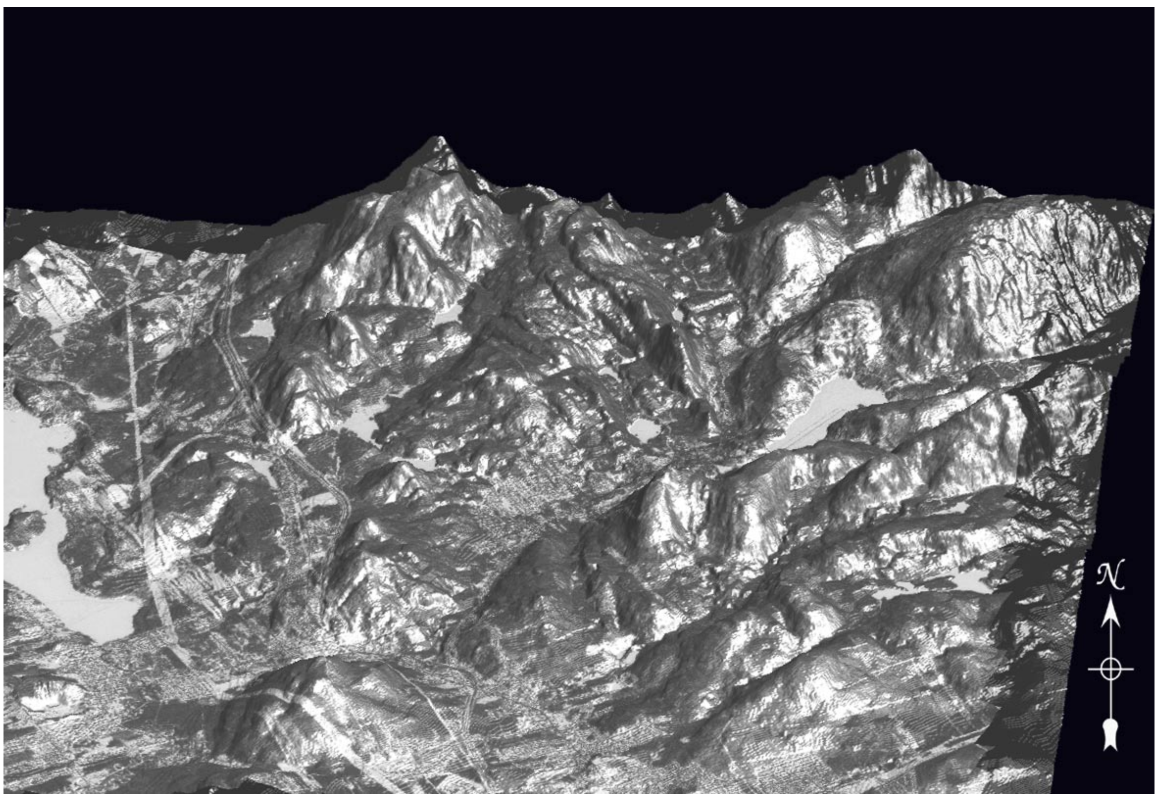

Figure 6: Perspective view of the IKONOS ortho-image draped over the stereo-extracted DEM.

CONCLUSIONS

One major drawback of the efficient and appropriate use of IKONOS stereo-data is the difficulty to geometrically process and to extract 3D information by the users. Whatever its recent popularity in some mapping communities, the rational polynomial model for geometric correction cannot provide DEM accuracy that users expect from high-spatial resolution data. Conversely, the CCRS-developed rigorous model that is available in the PCI operational environment can be used to adequately and accurately process stereo-images and to extract 3D information. Consequently, with accurate ground data users may produce their own DEMs with its own characteristics (projection, datum, grid spacing), and obtain an accuracy of 3 to 5m depending on the land covers. These accuracies can be consistently achieved if the automatic DEM is manually edited with performing 3D capability.

Therefore, this CCRS-PCI technology should promote the acquisition and the use of stereo data in many applications since a DEM is one of the most important data structures used for geospatial analysis and modeling. Since many cartographic features and fine topographic details are present in the stereo IKONOS DEM, the DEM is in fact a digital surface model (DSM). 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 elevation. DEM from IKONOS stereo data thus becomes a reality if the data becomes available to end-users of photogrammetry, mapping and remote sensing communities...

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 a more precise (around 1 to 2m) topographic DSM including canopy and building heights. Other IKONOS stereo-images over different topographic terrain including North American cities and high relief are also evaluated.

Dr. Thierry Toutin is a principal research scientist at the Canada Centre for Remote Sensing, Natural Resources Canada, Ottawa, Ontario, Canada. His email address is thierry.toutin@ccrs.nrcan.gc.ca.

Dr. Philip Cheng is a senior scientist at PCI Enterprises, Richmond Hill, Ontario, Canada. His email address is cheng@pcigeomatics.com.