DEM Generation from New VIR Sensors: IKONOS, ASTER and Landsat-7[Ä]

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

DEM generation is a living R&D topic since new-launched satellite images can be used to generate stereoscopic images. Using a coplanarity equation model developed at CCRS and an automatic matching method developed at PCI, DEMs are generated with new VIR stereo data. Accuracy of 4.9 m with high-resolution IKONOS images, and 33 m and 101 m with medium-resolution ASTER and Landsat-7 ETM^+ images respectively are obtained. The same matching accuracy of one-pixel is translated into worse results with Landsat due to a small B/H ratio of 0.15.

INTRODUCTION

Satellites launched in 1999 provide a new opportunity for users to take advantage of stereo imagery for digital elevation model (DEM) generation. To obtain stereoscopy with images from VIR scanners, two solutions are possible: the along-track stereoscopy from the same orbit using fore and aft images and the across-track stereoscopy from two different orbits. In fact, the same-date along-track stereo-data acquisition gives a strong advantage versus the multi-date across-track stereo-data acquisition. It reduces the radiometric image variations (refractive effects, sun illumination, temporal changes) and thus increases the correlation success rate in any image matching.

IKONOS, the commercial satellite with the highest publicly available resolution, was successfully launched in September 1999. Since the satellite's sensor can generate 1-m panchromatic and 4-m multiband images with off-nadir viewing up-to-60º in any azimuth, stereo capabilities are then possible in across-track and along-track directions [1].

ASTER, launched in December 1999, has a VNIR subsystem with two independent backward and nadir looking telescope assemblies to minimize image distortion. They are used for along-track stereo-imaging with 27.7º intersection angle and 0.6 base-to-height (B/H) ratio [2]. The two telescopes can be rotated ± 24 degrees to provide extensive cross-track pointing capability with a better B/H ratio (close from 1) and 5-day revisit capability. However due to different scientific, technologic and commercial reasons, the "default" along-track stereo imaging is favoured for IKONOS and ASTER.

Landsat-7 launched in April 1999, the across-track stereoscopic acquisition is only possible from two adjacent orbits since the satellite acquires nadir viewing images, and the tracking orbit ensures repeat path consistent within a few kilometres. The stereoscopic capabilities of "adjacent orbit" satellite data remain limited because (i) it can be used only in latitude higher than 45º; (ii) it generates a small B/H ratio; and (iii) only medium to high relief areas are suitable [3].

Users can then apply traditional and digital photogrammetric techniques with these new stereo-sensors to extract planimetric features and/or elevation information, such as DEM [4]. This paper then addresses the evaluation of stereo DEM from new sensors: IKONOS with high resolution (HR: 1 m) and costs (US $4000), and ASTER or Landsat 7 ETM^+ with medium resolution (MR: 15 m) and low costs (free or US $600).

DEM GENERATION EXPERIMENT

The study sites for HR and MR images are located in Canada in a semi-rural area in the North of Quebec City, and in the Canadian Rocky Mountains, respectively (Table 1, left part). The two sites have 500-m and more than 3000-m elevation difference, respectively. The checked DEMs were derived from digital 10-m contour lines from 1:20,000 and 1:50,000 maps with accuracies of 5 m and 10 m, respectively.

The along-track IKONOS stereo-data was acquired in January 03^{rd}, 2001 with a sun illumination angle as low as 19º, generating long shadows (tens of pixels) due mainly to trees but some to buildings in the rural cities. The images are free of clouds. The 10x10-km images have a resolution of 1.0 m and a 54º stereo-intersection angle (B/H=1.0). The images are delivered in an epipolar reference system, where only the 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.

The ASTER images are acquired on September 25^{th}, 2000. The Level 1A data (images, ephemeris and attitude) have been directly downloaded from the NASA web. Only the backward (27.7º) and nadir images (15-m pixel spacing) generating along-track stereo with 0.6 B/H are used in DEM generation. Clouds and their shadows recover 10% of the images.

The Landsat-7 ETM^+ data are two level 1G images (15-m pixel spacing), acquired August 24^{th} and September 16^{th}, 1999 from paths 44 and 45, respectively and row 24. With 40% overlap, they generate a adjacent-track stereo-pair (75 km by 180 km) with 0.15 B/H ratio. Glaciers and snow (12%), clouds and their shadows (5-10%) recover both images.

[⊗] Published in IEEE-IGARSS 2001 Proceedings, Sydney, Australia, July 9-13, 2001

Table 1. Description of VIR stereo-data set, study sites and statistical results of the DEM extraction

Satellite Sensor	Resolution (m)	Look Angles	Base to Height Ratio	Study Site Topography	Checked DEM Accuracy	Standard Deviation (STD)	% in Standard Deviation	Mean	Minimum Value	Maximum Value
IKONOS	1.0 m	+27º/-27º	1.0	Rolling	5 m	4.9 m	74 %	-0.9 m	-75 m	37 m
ASTER	15 m	0º/27.7º	0.6	Mountainous	10 m	33 m	87 %	1.6 m	-151 m	167 m
Landsat7 ETM	15 m	±7º	0.15	Mountainous	10 m	101 m	73 %	-38 m	-460 m	410 m

Whatever the image data, the main digital processing steps for DEM generation are [4]: (i) the stereo model set-up, (ii) the data extraction by image matching, (iii) the 3D stereo intersection and (iv) the DEM editing. The stereo model set-up and the 3D stereo intersection are geometric issues and use a CCRS developed parametric geometric model already tested on different data sets [5] and adapted for these new sensors [6, 7]. The stereo model set-up is computed with an iterative least square bundle adjustment that enables the parameters of the geometric model to be refined with GCPs.

The image matching is principally a radiometric issue and relies on normalized area correlation with sub-pixel computation of the correlation coefficient maximum in order to produce a disparity map. It is considered as one of the most precise solution [8] and it was chosen and adapted in OrthoEngine^{SE} 3D digital image analysis system of the PCI Geomatics Group using in addition a multi-scale strategy [9]. The number of steps involved in the multi-scale matching varies from five to eight with a maximum resolution reduction of 16. The correlation window size varies from 8 "reduced" pixels at the coarsest resolution to 32 pixels at the full resolution.

The 3-D stereo intersection is performed using the previously computed geometric model to convert the pixel co-ordinates in both images determined in the image matching of the stereo pair to three-dimensional data. Cartographic co-ordinates (planimetry and height) in the user defined map projection system are determined for the measured point with a least-squares intersection process based on the geometric model equations and parameters [6]. The result is an irregular grid in the map projection system, which is transformed to a raw regular DEM and edited with blunder removal and interpolation functions for small mismatched areas (less than 200 pixels).

In addition of these main processing steps some minor pre-processing (radiometric calibration for ASTER) are performed. DEM post-processing (water bodies, glaciers, clouds, shadows, occluded areas) should also be realized depending of data set, study sites and mainly the 3D performance of the system.

RESULTS AND ANALYSIS

Table 1 (right part) gives the general result errors with the standard deviation (STD), the percentage in one STD, the bias, and minimum and maximum errors for the study sites.

1) **IKONOS**: Even if the images were acquired in January snow and icy lakes, there are only 5% of mismatched areas, including 2.5% due to some lakes. The remaining parts of the lakes, where the matching extracted parallaxes, show variations for the lakes elevation of few metres (around 5 m), even in the long shadows generated by the trees due to a sun elevation angle of 19º in January. It confirms that the multi-scale matching well performed with 1-m high-resolution data in semi-rural areas. The remaining 2.5% mismatched areas, located in the northwest slopes of the mountains, are also due to the sun shadow (elevation angle of 19º and azimuth of 166º). The 4.9-m STD obtained with 74% level of confidence is still a good result because the inherent system errors are around 2-3 m [1]. Furthermore, this STD error includes the canopy height and the 5-m error of the topographic checked DEM. Consequently, a more precise (around 2 m) topographic digital surface model (DSM) including the canopy height is needed to verify the accuracy value (5 m or less) of stereo-derived DEMs from IKONOS. Finally, the largest errors, 1% over three STD (15 m), are grouped inside the mismatched areas (easily editable) and in gravel pits where the elevations change during time. More comparisons as a function of the land cover are ongoing at CCRS and will be presented during the Symposium.

2) **ASTER**: The 33-m STD is achieved with an 87% level of confidence, which is a high level of confidence when compared to the two other results (around 73%). It means the error histogram is narrow around the mean value with few large errors. In fact, only 1.3% of the elevation errors is over three standard deviations (101 m). With 0.6 B/H ratio it corresponds to an image matching accuracy of 1.2 pixels, which is consistent with previously mentioned research work [8], because our 87% level of confidence for the STD is much higher than the 68% normally used. The main problems for this data set in the DEM generation are related to the ASTER sensor and the terrain relief. Even with radiometric calibration of the detectors, there was some pixel striping in both images, generating confusion in the matching process. Furthermore, the steep relief generates reflectance variations and shadowing in valleys for the two images, but also occluded areas in the 27.7º backward image for the steepest slopes. In addition to clouds and their shadows, which

frequently occur at the top of the mountains in the Canadian Rockies, all these effects then create large mismatched areas during the image matching process that any automatic interpolation process cannot resolve. Due to their specificity inherent to our challenging site and to not bias the results, the "badly" interpolated mismatched areas were not integrated in Table 1 results.

3) **Landsat-7**: Qualitative evaluation of the DEM shows a little more than 20% of mismatched areas:

- The largest areas (10%) with a size of about 5 by 5 km and more are mainly due to the clouds, haze and their shadows; and
- The smallest areas (12%) with a size of less than 1 by 1 km are mainly due to glaciers, snow and shadow areas.

Since the small and large mismatched areas are specific to this cloudy and mountainous site, the evaluation of automatically interpolated elevations in the mismatched areas was only performed for these areas: a STD (73% level of confidence) of 233 m with maximum errors of 700 m were computed. These large errors are related to mountain summits, which were truncated in the interpolation. It proves than such mismatched areas have to be visually edited by high-performance 3D tools because any automatic interpolation process will never "reconstruct" the mountains of this study site. Unfortunately, few remote sensing systems offer such capabilities but only automatic interpolation. Consequently, the quantitative comparison of the stereo-extracted DEM with the topographic DEM is only computed for the area excluding the mismatched areas: a STD of 101 m with largest errors of 460 m. Considering a B/H ratio of 0.15, 101-m elevation accuracy corresponds to one pixel (15 m) accuracy (73%) in the image matching, which is consistent with the previous different image matching evaluations [8].

CONCLUSIONS

Largely extrapolated on results from scanned aerial photos, IKONOS stereo-images demonstrated a potential for creating DEMs with about 2-m vertical accuracy. However, real stereo-images are different from simulation and air photos: e.g., off-nadir collection and sun elevation angles generate occluded and shadow areas, respectively. First results on a semi-rural area with real stereo-data confirm more and less these prognostics with an elevation error of 4.9 m and 15 m with 74% and 99% level of confidence, respectively. The larger errors are due to sun shadow areas in northwest slopes of the mountains and to gravel pits with time-varying elevations. Good matching results were obtained over snowy and icy areas (elevation variation of flat surfaces around 5 m) and rural cities.

With the medium resolution images (15 m), along-track stereo with ASTER and adjacent-orbit stereo with Landsat 7 ETM^+, the results on stereo-extracted DEM are consistent with most of the previous results using different stereo VIR images depending of the B/H ratio. A matching accuracy of one pixels is achieved, which results in an elevation accuracy of 33 m and 101 m for ASTER (B/H=0.6) and Landsat 7 ETM^+ (B/H=0.15) respectively, but with a higher level of confidence for ASTER (87% versus 74%). The major problems in these challenging study sites in the Canadian Rocky Mountains are related to the steep relief (cast shadow and occluded areas) and to the quasi-permanent clouds with their shadows, generally in the mountains.

These accuracies can be consistently achieved if the automatic DEM are manually edited with performing 3D capability. Work still need to be carried out to evaluate the possibility for integrating in the post-processing some existing cartographic data, such as buildings in urban areas or hydrographic features and canopy heights in rural areas.

ACKNOWLEDGMENTS

The author thanks Dr. Philip Cheng of PCI for the $OrthoEngine^{SE}$ adaptations and also Mr. R. Chénier of Consultants TGIS inc. and Mr. Thomas Gründemann of the Technische Universität Dresden for the data acquisition and processing. The topographic data over the Quebec site are a courtesy of the Ministère des Ressources naturelles du Québec, Canada.

REFERENCES

[1] Space Imaging Web Site, *http://www.spaceimaging.com/*, 2001.

[2] Y. Yamaguchi, A. Kahle, H. Tsu, T. Kawakami and M. Pniel, "Overview of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)," *IEEE Trans. Geoscience and Remote Sensing*, 36(4):1062-1071, July 1998.

[3] R. Simard and R. Slaney, "Digital terrain model and image integration for geologic interpretation," *Proceedings of the Fifth Thematic Conference on Remote Sensing for Exploration Geology, Reno, Nevada, U.S.A., September 29 - October 2,* pp. 49-60.

[4] Th. Toutin, "DEM generation with a photogrammetric approach: examples with VIR and SAR images," *EARSeL J. Advances in Remote Sensing*, 4(2):110-117, March 1995.

[5] Th. Toutin, "Multi-source data fusion with an integrated and unified geometric modeling," *EARSeL J. Advances in Remote Sensing*, 4(2): 118-129, March 1995.

[6] Th. Toutin and Ph. Cheng, "Demystification of IKONOS," *EOM*, 9(7): 17-21, July 2000.

[7] Ph. Cheng and Th. Toutin, "Unlocking the potential of Landsat 7 data," *EOM*, 9(2): 28-30, February 2000.

[8] E. Gülch, "Results of test on image matching of ISPRS WG III/4," *ISPRS Journal of Photogrammetry and Remote Sensing*, 46(1): 1-18, February 1991.

[9] PCI Geomatics Group, "$OrthoEngine^{SE}$ 3D," *Reference Manual, Version 7.0*, 2001.