Comparison of automated digital elevation model extraction results using along-track ASTER and across-track SPOT stereo images♥

Thierry Toutin
Natural Resources Canada
Canada Centre for Remote Sensing
588 Booth Street
Ottawa, Ontario
K1A 0Y7 Canada
Email: thierry.toutin@ccrs.nrcan.gc.ca

Philip Cheng
PCI Geomatics
50 West Wilmot Street
Richmond Hill, Ontario
L4B 1M5 Canada
Email: cheng@pcigeomatics.com

Abstract. A digital elevation model (DEM) can be extracted automatically from stereo satellite images. During the past decade, the most common satellite data used to extract DEM used was the across-track SPOT. Recently, the addition of along-track ASTER data, which can be downloaded freely, provides another attractive alternative to extract DEM data. This work compares the automated DEM extraction results using ASTER stereo pair and SPOT stereo pair, over an area of hilly mountains in Drum Mountain, Utah. The result shows that SPOT produces better DEM results in terms of accuracy and details, if the radiometric variations between the images, taken on subsequent satellite revolutions, are small. Otherwise, ASTER stereo pair is a better choice because of simultaneous along-track acquisition during a single pass. In comparing to the USGS 7.5-minute DEM, the ASTER and the SPOT extracted DEMs have a standard deviation of 11.6m and 4.6m, respectively.

1 Introduction

Producing digital elevation models (DEMs) from satellite data has been a vibrant research and development topic for the last thirty years, beginning with the launch of the first civilian remote sensing satellite. Stereo viewing of images has been the most common method used by the mapping, photogrammetry, and remote sensing communities for elevation modeling[1]. To obtain stereoscopy with images from satellite scanners, two solutions are possible: along-track stereoscopy from the same orbit using fore and aft images, and across-track stereoscopy from two different orbits.

The latter solution has been applied more often since 1980 – first with Landsat from two adjacent orbits, then with SPOT using across-track steering capabilities, and finally with IRS-1 C/D by “rolling” the satellite. In the last several years, the first solution has gained renewed popularity due to the JERS-1’s Optical Sensor (OPS), the German Modular Opto-Electronic Multi-Spectral Stereo Scanner (MOMS), and the ASTER sensor aboard recently launched NASA Terra satellite. Simultaneous along-track stereo-image data, because it is acquired on the same pass, is not affected by the changes in radiometric variations that can occur in across-track stereo-image pairs collected on different satellite passes, possibly during different seasons. On the other hand, across-track stereo-data has

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the advantage of more symmetrical view angles to the ground area of interest as compared to along-track collections where one image might be taken directly beneath the satellite (at nadir) while its stereo companion image might be taken at backward-looking view angle, which is much different.

Since SPOT 1 was launched in 1986 and the subsequent launch of SPOT 2, 3 and 4, SPOT has been the most popular satellite used for stereoscopy and DEM extraction[2]. Thousands of SPOT stereo pairs from around the world have been acquired. SPOT is fitted with a steerable mirror, which enables the instrument to image areas up to 27 degrees east or west relative to the vertical. The pixel resolution of SPOT data is 10-m panchromatic and 20-m multispectral. It can provide an overlapping across-track coverage with base-to-height (B/H) ratio of up to 1.0. The main drawback of using a SPOT stereo pair is the use of multi-date stereo data with radiometric variations due to different dates and seasons or environmental conditions. For example, difficulties have been experienced with orientation and plotting when the individual SPOT images making up the stereo pair have been acquired some months apart, e.g., at the beginning and the end of the rainy season. These result in the very different appearance of vegetation, cultivated areas, and water bodies in the corresponding images, resulting in problems with stereo-viewing and image matching [2]. To our knowledge, no study had addressed this specific problem to quantify the radiometric variations that can be tolerated between the stereo images. Research studies were more focused on image matching algorithms to compensate and accept the variations, such as the normalized or mean normalized cross-correlation [3,4].

ASTER is an imaging instrument that is flying on Terra, a satellite launched on 19 December 1999, as part of NASA's earth observing system (EOS). ASTER is the only high-spatial-resolution instrument on the Terra platform. It consists of three different subsystems: visible and near infrared (VNIR) with 15-m resolution, the short-wave infrared (SWIR) with 30-m resolution, and thermal infrared (TIR) with 90-m resolution. The VNIR subsystem consists of two independent telescope assemblies that minimize image distortion in the backward and nadir-looking telescopes. The focal plane of the nadir telescope contains three silicon-charge-coupled detector line arrays (Bands 1, 2, 3N), while the focal plane of the backward telescope has only one (3B). The two near-infrared spectral bands, 3N and 3B, generate along-track stereo image pair with a B/H ratio of 0.6, and an intersection angle of about 27.7 degrees [5].

Besides the stereo geometry and the resolution, the biggest difference between SPOT and ASTER is that ASTER data can be downloaded freely from the web site *http://asterweb.jpl.nasa.gov*. This makes ASTER data very attractive to a lot of users who want to extract DEMs but cannot afford SPOT data. However, there are a few questions that need to be answered. Can ASTER replace SPOT in generating DEMs? How accurate is an ASTER-extracted DEM in comparison to a SPOT-extracted DEM and what are the differences between the DEMs? To our knowledge, these kinds of comparisons are not available. The main objective of this work is to compare automated DEM extraction results using a stereo pair of ASTER data and a stereo pair of SPOT data for the same area using the same ground control points (GCPs). The results were also compared with the USGS 7.5-minute DEM with a grid spacing of 30 m.

2 Study Site and Data Set

The site for this study is of the Drum Mountains, located in west-central Utah, U.S.A. The area is semi-arid with few cultural features and little vegetation. The topography at the study site is 40% steep-and-rugged, and 60% relatively flat, with elevation ranging from roughly 1300 to 2600 m above sea level. A stereo pair of SPOT panchromatic (10-m spacing) level 1A and a stereo pair of ASTER level 1A were acquired for the same area. Level 1A data were chosen because it preserves the geometry of the satellite image for highest accuracy satellite geometric modeling. The SPOT stereo pair (60 by 60 km) was acquired at +12.4- and -15.2-degree viewing angles with the two images taken 30 days apart. The ASTER data (61.5 by 63 km) were acquired from the web site *http://asterweb.jpl.nasa.gov* free of charge. Only the VNIR nadir and backward image (3N and 3B at 15-m spacing) were used in the DEM generation. The radiometric calibration coefficients, which came with the ASTER data, were subsequently applied to both images to remove banding and striping effects.

3 Satellite Geometric Model and Software

A satellite geometry model is needed to determine the correct ground position of a point visible in an image of the earth. It relates 3-D ground positions to the corresponding 2-D image positions. The better the geometric model, the higher the accuracy in DEM extraction and also in image orthorectification. A number of papers have been published on different approaches to satellite geometric modeling [6-12]. Two broad categories of geometric models are usually used: a rigorous model and a simple geometric model. A rigorous model is complex and requires considerable knowledge of both mathematics and image sensor physics; however, it has the advantage of high modeling accuracy, often a fraction of one pixel spacing. A simple geometric model usually involves polynomials, which are easier to understand and do not require knowledge of image sensor physics. However, simple geometric models are less accurate in comparison to rigorous model. A simple geometric model is not recommended unless the image sensor information is not available at all.

In order to get the most accurate results, a rigorous model was needed for this study. A general and high accuracy rigorous model, one that could be applied to both SPOT and ASTER, was needed. Toutin's modeling[13-16] and method developed at the Canada Centre for Remote Sensing (CCRS), Natural Resources Canada, was chosen in this case. This 3-D parametric model is based on principles relating to orbitography, photogrammetry, geodesy, and cartography. The 3-D parametric model reflects the physical reality of the complete viewing geometry and integrates all the distortions generated during the image acquisition as follows:

(1) Distortions due to the platform (position, velocity, and orientation);

(2) Distortions due to the sensor (orientation, integration time, and field of view);
(3) Distortions due to the Earth (geoid, ellipsoid, and relief); and
(4) Deformations due to the cartographic projection (ellipsoid, and cartographic reference).

As a result of this integration, the model equations are simple and straightforward with few unknowns. Each of the unknowns is, in fact, the combination of several correlated variables of the viewing geometry; hence the number of unknowns is reduced to an independent uncorrelated set. The equations are then solved with few ground controls points (GCPs) (minimum three to six for visible and infrared (VIR) and seven for SAR images). Toutin's model has been successfully applied with few GCPs to VIR data (Landsat, SPOT, IRS, MOS, KOMPSAT, and IKONOS), and also to SAR data (ERS, JERS, SIR-C, and RADARSAT). Based on good quality GCPs, the accuracy of Toutin's model was proven to be within one-third of a pixel for medium-resolution VIR images, one to two pixels for high-resolution VIR images, and within one resolution cell for SAR images. Most rigorous models can only be applied to a specific sensor. To our knowledge, Toutin's model is the only satellite geometric model that can be applied to so many different sensors.

Toutin's model was implemented into the PCI Geomatics' OrthoEngine™ software. In addition to the geometric modeling, the software is able to generate orthorectified satellite images and airphotos, automatic GCP and tie point collections, manual and automatic mosaicing, and can generate DEMs using airphotos, IRS, KOMPSAT, SPOT, IKONOS, ASTER, and RADARSAT stereo pairs. After Toutin's model is computed for a stereo pair of images by using a minimum number of GCPs, a pair of quasi-epipolar images is generated from the images in order to retain elevation parallax in the *X* direction. An automated image-matching procedure is then used to produce the DEM through a comparison of the respective gray values of these images. This procedure utilizes a hierarchical subpixel mean normalized cross-correlation matching method to find the corresponding pixels in the left and right quasi-epipolar images [3]. The actual matching method employed generates correlation coefficients between 0 and 1 for each matched pixel, where 0 represents a total mismatch and 1 represents a perfect match. A second-order surface is then fitted around the maximum correlation coefficients to find the match position to subpixel accuracy. The difference in location between the images gives the disparity, or parallax, arising from the terrain relief, which is then converted to absolute elevation values above the local mean sea level datum using a 3-D space-intersection solution.

4 GCP Collection and Geometric Modelling Results

Differential GPS (DGPS) GCPs with sub-metre accuracy were used in this study. Eight stereo GCPs and six independent check points (ICPs) were collected at the same locations for both ASTER and SPOT stereo pairs. GCPs were collected from within the border of each image and at the high and low elevations points in order to avoid planimetric and elevation extrapolations. ICPs were then collected from inside the areas bounded by the GCPs and were not used in the computation of the geometric model. Table 1 gives the full statistical results over GCPs/ICPs (root mean square and maximum residuals/errors) of the stereo-model computed only with the eight GCPs. From Table 1, the errors are a little larger than the residuals but in the order of GCP plotting accuracy (a little better than one pixel for ASTER and within sub-pixel for SPOT). SPOT has better results because of the better satellite-to-ground target view angles between the two images comprising the stereo image pair. Since the maximum residuals/errors are less than three times the RMS residuals/errors respectively, the geometric model properly describes the stereo-viewing geometry, and is stable and robust for the full stereo model without generating local or systematic errors.

Table 1: Statistical results over GCPs/ICPs, with the root mean square (RMS) and maximum residuals/errors of the stereo-model computed with eight GCPs.

Satellite Sensor	**Residuals/Errors**	**RMS (m)**			**Maximum (m)**		
		X	***Y***	***Z***	***X***	***Y***	***Z***
TERRA ASTER	GCP Residuals	10.7	5.6	8.5	15.9	9.2	14.4
	ICP Errors	15.8	10.5	7.9	22.7	15.7	13.8
SPOT HRV-PLA	GCP Residuals	4.9	3.5	3.2	7.0	4.7	4.2
	ICP Errors	3.5	5.0	3.2	7.3	10.3	4.9

For each stereo pair, the DEM generation that included quasi-epipolar image generation, image matching and filtering, and geocoding took approximately 90 min on a Pentium III 933 MHz computer. Both DEMs were generated at every other pixel with high details and "fill holes and filter" options inside the PCI OrthoEngine software. The generated DEMs were then compared with an USGS 7.5-min DEM (grid spacing at 30 m) obtained from the USGS web site at *http://mapping.usgs.gov*. Only a single USGS DEM for the test site was available from that web site during the study. The USGS 7.5-min DEM was derived either by digitizing USGS 1:24,000 scale quad maps (which gives less accurate results), or by scanning aerial photographs. The old 7.5-min DEM has a rms error of 15 m and a maximum error of 50 m. Most of the 7.5-min DEMs (and all of the new ones) have a rms error of 7.5 m. The accuracy of this USGS DEM was not available from the web site during the study.

Because only one USGS DEM was available, only the areas covered by the USGS DEM were used for comparison. Both ASTER and SPOT DEMs were resampled at 30-m spacing (the same spacing as the USGS DEM). Figures 1, 2, and 3 show the USGS DEM, ASTER-extracted DEM, and SPOT-extracted DEM, respectively. As seen from the figures, the ASTER DEM (Fig. 2) lacks the detail of the reference USGS DEM (Fig. 1) or the SPOT extracted-DEM (Fig. 3). This is mainly due to the higher resolution and better stereo viewing geometry (left and right looking symmetry) of the SPOT sensor stereo image pair.

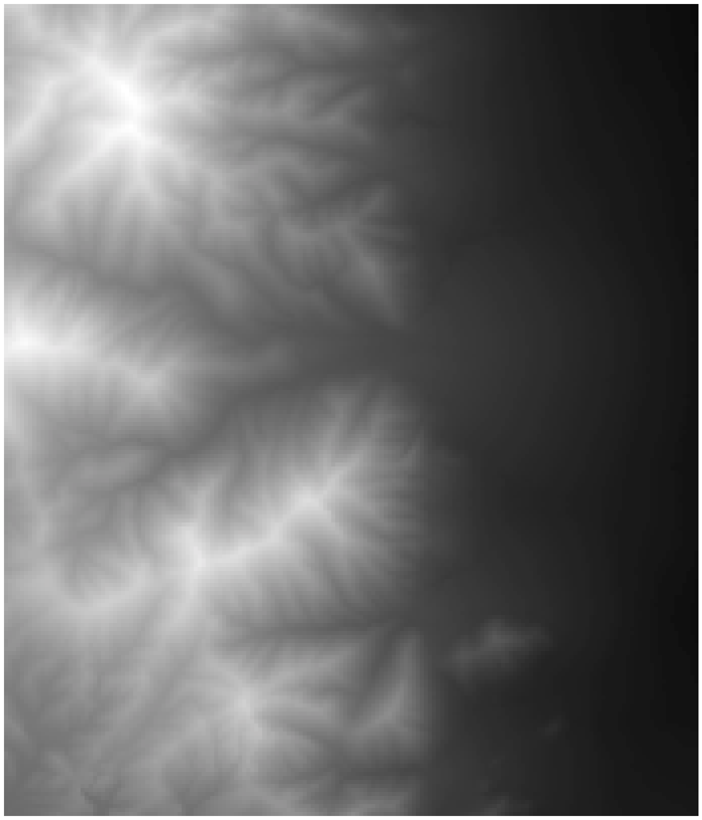

Figure 1: A USGS 7.5m DEM at 30-m spacing

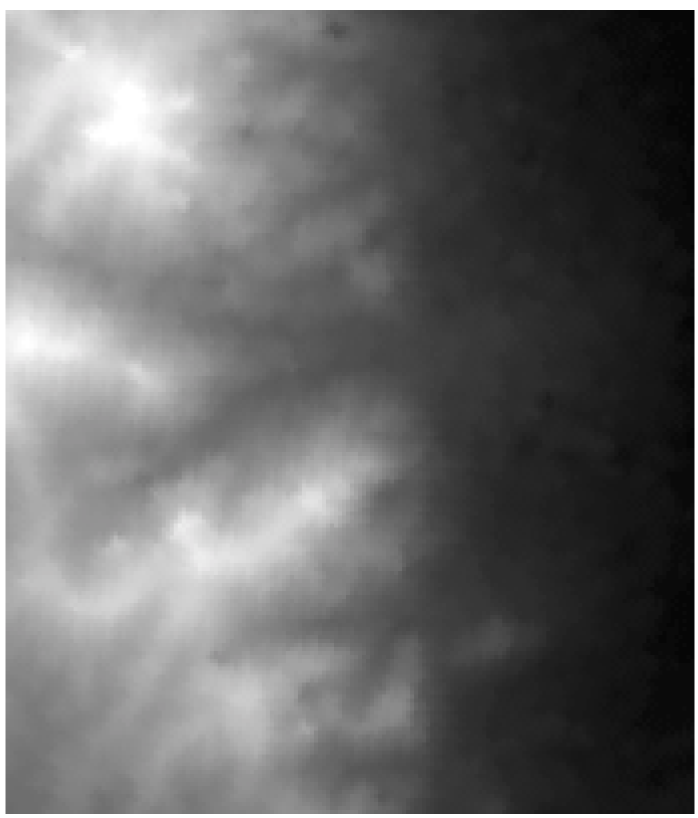

Figure 2: An ASTER-extracted DEM at 30-m spacing

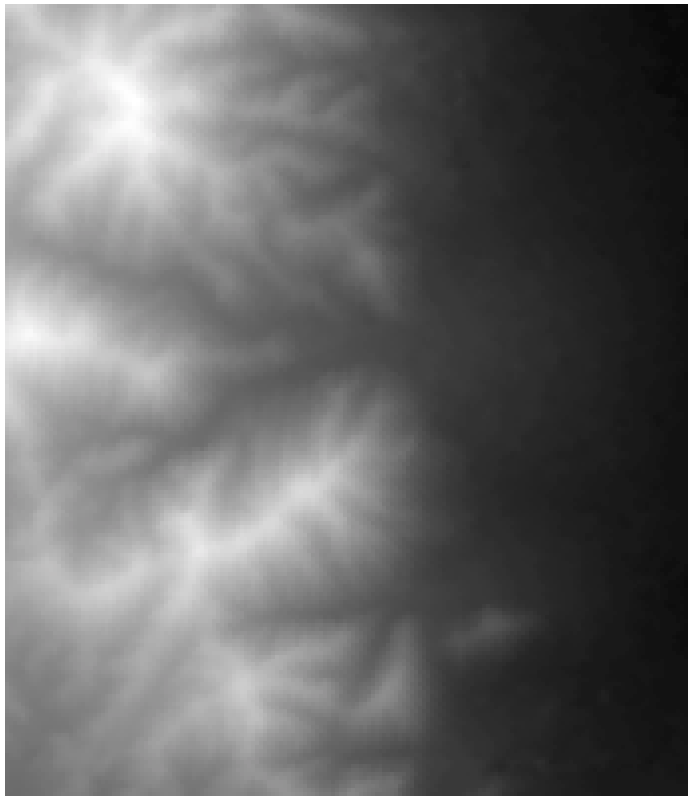

Figure 3: A SPOT-extracted DEM at 30-m spacing

A total of 140,000 elevation points were used to compare the results. Table 2 shows a summary of the differences between the ASTER-extracted DEM and the USGS DEM, and the SPOT-extracted DEM and the USGS DEM.

Table 2: Differences between the ASTER-extracted DEM and the USGS DEM, and the SPOT-extracted DEM and the USGS DEM.

Satellite	**Within 5m**	**Within 10m**	**Within 15m**	**Within 20m**	**Mean Diff. (m)**	**Min. Diff. (m)**	**Max Diff. (m)**	**Standard Deviation (m)**
ASTER /USGS	55%	82%	89%	92%	1.8	-99	135	11.6
SPOT/ USGS	59%	92%	98%	99%	3.4	-31	41	4.6

Part of these error values includes the error from the USGS DEM. In most cases, the values of the SPOT-extracted DEM are closer to the USGS DEM than the ASTER. 98% of the SPOT-extracted DEM is within 15-m difference when comparing to the USGS DEM, while the ASTER-extracted DEM has only 89% of the values within 15-m difference when comparing to USGS DEM. This is mainly due to the strong stereo-viewing geometry of the SPOT data and its resolution. However, it should be noted that

DEM extraction using SPOT images may not always produce the best results because of the multidate imagery, which could cause errors especially for areas with different seasons between the stereo pair. In this study, the area has very little vegetation and hence it did not affect the SPOT results, even though the SPOT images used were taken 30 days apart.

5 Conclusions

Automated DEM extraction using across-track SPOT satellite was a popular choice over the past 15 years. The addition of along-track ASTER provides an alternative for the user to extract DEM data. ASTER data can be downloaded freely from the web site, which makes ASTER data very affordable and therefore very attractive. This study has shown that if there is little radiometric or "homogeneous" variations between the stereo images, which can be acceptable by using mean normalized cross-correlation method, across-track stereo SPOT is the better choice to extract DEM due to a better resolution and stereo geometry when compared to along-track stereo ASTER. Stronger geometry compensates for weaker radiometry. The SPOT DEM, as compared to the USGS DEM, offers higher accuracy and more details in comparison to the ASTER DEM under these restricted conditions of little radiometric variations between imageres used as the stereo image pair.

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