

Application of ASTER Satellite in Digital Elevation Model Generation: A Review

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Abstract: Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is an imaging instrument flying on Terra platform. The distinctive specifications of ASTER satellite such as as easy to access, global coverage, cost-effective data and along-track configuration make it as one of the widely used sources of stereo images. Therefore, since the launch of ASTER sensor many studies have been conducted to investigate the accuracy of ASTER-extracted DEM. This study aims to give a review about the characteristics of ASTER instrument as well as the most important studies on the generation and assessment of accuracy of ASTER-extracted DEM.

Keywords: Accuracy, assessment, ASTER, digital elevation model, specifications

INTRODUCTION

A Digital Elevation Model (DEM) is a digital representation of ground surface topography or terrain. It is also widely known as Digital Terrain Model (DTM) (Hirano *et al.*, 2003; Trisakti and Carolita, 2005). There are many methods for obtaining DEM data such as terrestrial surveying, stereo photogrammetry, GPS data and topographic maps. Although, High cost, limited access to the study area, time-consuming procedures and inadequate updating of maps drove scientific researches to new techniques for generating DEM maps. The various applications of DEM and the drawbacks of traditional techniques drastically have increased the significance of using satellite images. In 1986, the SPOT 1 satellite provided the first usable elevation data (Welch and Marko, 1981) for a sizeable portion of the planet's landmass, using two-pass stereoscopic correlation. Later, further data were provided by the European Remote Sensing Satellite (ERS) using the same method, the Shuttle Radar Topography Mission (SRTM) using single-pass SAR and the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instrumentation on the Terra satellite using double-pass stereo pairs (Nikolakopoulos *et al.*, 2006). ASTER is an imaging instrument flying on Terra and is one of the widely used sources of DEM images and data (Toutin, 2002). ASTER stereo data with the specific features such as easy to access, global coverage, inexpensive data can be introduced as substitute source for generating DEM for

research and somewhat business projects. Thus, many studies have been conducted to assess the accuracy of the ASTER DEM. With all the above into consideration, this study aims to give a review about the specifications of ASTER instrument as well as the most significant studies about generating DEM from ASTER stereo images. Also, the results of previous studies are presented to show the most suitable techniques of DEM generation.

ASTER satellite: ASTER is an imaging instrument flying on Terra, a satellite launched in December 1999 as part of NASA's Earth Observing System (EOS). The Terra platform is on a sun-synchronous near-polar quasi-circular orbit with a mean altitude of around 705 km, an orbital inclination of $98.2 \pm 0.15^\circ$ at the equator, an equatorial crossing time at $10:30 \pm 15$ min and an orbit period of 98.9 min with a repeat cycle of 16 days, resulting in 233 revolutions in 16 days with a distance between adjacent orbits of 172 km at the equator (Toutin, 2008) with its 8 min/orbit duty cycle, ASTER can acquire a maximum of around 770 stereo pairs per day and will thus be capable of acquiring the 45000 cloud free digital stereo pairs required to cover the land surface of the Earth below 82°N and 82°S during the 6 year mission (Lang and Welch, 1999). ASTER includes three different subsystems: the Visible and Near Infrared (VNIR), the Shortwave Infrared (SWIR) and the Thermal Infrared (TIR). Table 1 shows the basic characteristics of these subsystems. Details of 14 bands

Table 1: Specifications of ASTER instruments

VNIR	SWIR	TIR
Band 1: 0.52-0.60 μm Nadir looking	Band 4: 1.600-1.700 μm	Band 10: 8.125-8.475 μm
Band 2: 0.63-0.69 μm Nadir looking	Band 5: 2.145-2.185 μm	Band 11: 8.475-8.825 μm
Band 3: 0.76-0.86 μm Nadir looking (3N)	Band 6: 2.185-2.225 μm	Band 12: 8.925-9.275 μm
Band 3: 0.76-0.86 μm Backward looking (3B)	Band 7: 2.235-2.285 μm	Band 13: 10.25-10.95 μm
	Band 8: 2.295-2.365 μm	Band 14: 10.95-11.65 μm
	Band 9: 2.360-2.430 μm	

Table 2: Bands characteristics of ASTER instruments

Characteristics	VNIR	SWIR	TIR
Ground resolution	15 m	30 m	90 m
Data rate (Mbits/sec)	62	23	4.2
Cross-track pointing (deg.)	± 24	± 8.55	± 8.55
Cross-track pointing (km)	± 318	± 116	± 1
Swath width (km)	60	60	60
Detector type	Si	PtSi-Si	HgCdTe
Quantization (bits)	8	8	12

in the visible and infrared spectrum with different spatial resolutions (VNIR at 15 m, SWIR at 30 m, TIR at 90 m) are given in Table 2 (Fujisada, 1994).

ASTER stereoimaging specifications: The ASTER stereo subsystem is in fact an implementation of the Stereosat-Mapsat concept to acquire global stereo coverage of the land using along-track digital sensors in order to produce global DEMs from principles of photogrammetry (Colvocoresses, 1982). The VNIR subsystem is the only one that provides stereo capability. It consists of two independent telescope assemblies to minimize image distortion in the backward- and nadir-looking telescopes (Yamaguchi *et al.*, 1998). The focal plane of the nadir telescope contains three silicon Charge-Coupled Detector (CCD) line arrays (bands 1, 2 and 3N of Table 1) while the

focal plane of the backward telescope has only one band (3B). The two images, 3N (Nadir looking) and 3B (Backward looking), generate an along-track stereo pairs with a Base-to-Height (B/H) ratio of about 0.6. Since the two telescopes for the VNIR sensor can also be rotated by $\pm 24^\circ$ to provide an extensive cross-track pointing capability and a 5 day revisit capability, across-track multi-date stereo imaging with better stereo geometry and B/H ratios (closer to one) is therefore possible. However, the same-date along-track solution, even with a worse stereo geometry, is preferred to the multi-date across-track solution with a better stereo geometry for the scientific and operational reasons, due to the strong advantages in terms of radiometric variations (Toutin and Cheng, 2002) (Fig. 1).

The ASTER image level-1A is used to produce DEM which contains reconstructed, unprocessed instrument digital data derived from the telemetry streams of the 3 telescopes: Visible Near Infrared (VNIR), Shortwave Infrared (SWIR) and Thermal Infrared (TIR). Data derived from each of these telescopes or sensors are at three different ground resolutions: VNIR at 15 m, SWIR at 30 m and TIR at 90 m. These depacketized, demultiplexed and realigned instrument image data have their geometric correction coefficients and radiometric calibration coefficients calculated and appended but not applied. Level-1A datasets also include corrections for the SWIR parallax and intra- and inter-telescope registration information. ASTER Level-1A data is produced at the Ground Data System (GDS) in Tokyo, Japan and sent to the EROS Data Centre's (EDC) Distributed Active Archive Centre (DAAC) for archiving, distribution and higher-level processing.

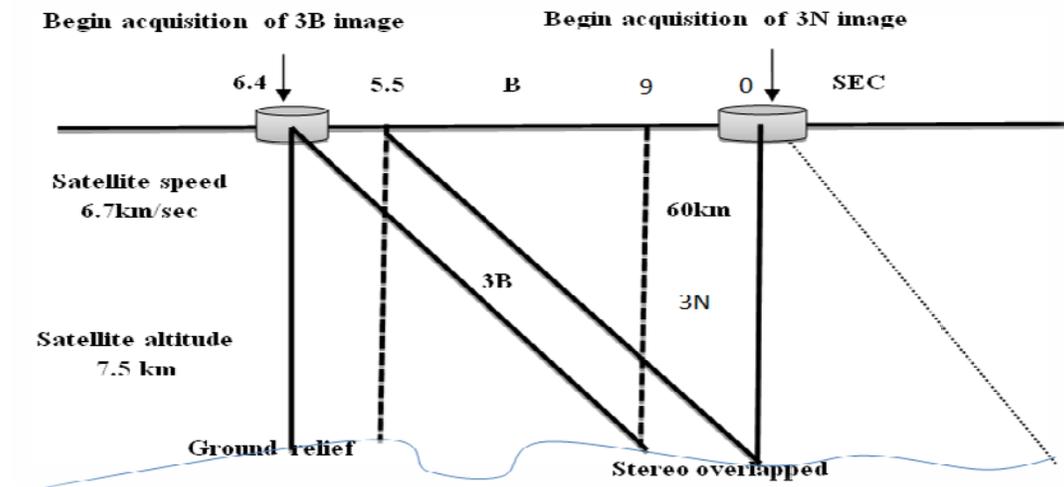


Fig. 1: Configuration of capturing stereo images by ASTER (Toutin, 2002)

LITERATURE REVIEW

The theoretical accuracy of ASTER DEM is influenced by different parameters, i.e., Ground Control Points (GCPs), Base-to-Height (B/H) ratio and the method of image matching. When GCPs are not available the output DEM is relative and its accuracy is determined by Base-to-Height (B/H) ratio and the method of image matching (Toutin, 2008). In addition, the types of the terrain of the study area, geometric pattern, the accuracy of ephemeris and attitude data are crucial for accuracy of relative DEM. The design specifications of relative DEM of ASTER stereo images released the accuracy of order of 12-25 m or better while the absolute DEM with 4 GCPs shows the accuracy between 7-30 m (Lang and Welch, 1999). In the case of absolute DEM, the accuracy is-governed by the number and distribution of GCPs which are used to either compute the geometric modeling (indirect dereferencing) or to tie the DEM to coordinate system or datum of interest. However, the errors of the GCPs can escalate the propagation of errors in the final DEM. Therefore, the accuracy of the control data should be at least twice more accurate than the expected final DEM. For instance, in order to achieve the 12-25 m accuracy from ASTER absolute DEM, 1:50,000 or smaller scale of topographic maps with at least 10 m accuracy can be used (Toutin, 2008). In order to verify the pre-launch specifications of ASTER DEM (Welch *et al.*, 1998) used the SPOT High Resolution Visible (SPOT-HRV) stereo data to produce the simulation of ASTER stereo data with 15 m resolution. Consequently, the DEM was generated with 30 m resolution. The assessment of accuracy was carried out by comparison between the 63 check points from DEM and United States Geological Survey (USGS) 7.5 min. Therefore, an accuracy of 13 m was obtained. Besides, the same simulations studies have been done on mountainous Japanese and French sites by Arai (1992) and Dowman and Neto (1994), respectively where similar results were achieved. In addition, the along-track stereo data of Japan Earth Resources Satellite Optical Sensor (JERS-1 OPS) was used to produce simulated ASTER stereo data and correspondent DEM. The evaluation of accuracy was conducted by using the check points from 1:25 000 topographic maps which yielded the RMSE of 12 m (Tokunaga *et al.*, 1996). The other parts of the studies are related to the assessment of accuracy of real ASTER stereo images by utilizing different off-the-shelf software. The most used software for generating ASTER DEM is listed as follows (Toutin, 2008):

- GeomaticaTM Ortho Engine^{SE} of PCI Geomatics (www.pcigeomatics.com)
- Ortho Base Pro module of ERDAS Imagine^H and the LPS SP 2 of Leica Geo systems Geospatial Imaging (www.gis.leica-geosystems.com)

- ENVI DEM Extraction Module of ENVI 4.7 (www.rsinc.com)
- Desktop Mapping System (DMS)TM of R-WEL (www.rwel.com)
- Aster^{DTM} module. (<http://www.envi.com.br/asterdtm>)

According to the literatures, Ortho Engine of PCI Geomatica which employed the Toutin's model is the most favorite software (Kaab, 2002; Toutin, 2002; Chrysoulakis *et al.*, 2004; Cuartero *et al.*, 2004, 2005a; Eckert *et al.*, 2005). Toutin's model is a rigorous model developed by Dr. Toutin at the Canada Center for Remote Sensing to compensate for distortions; such as sensor geometry, satellite orbit, attitude variations, earth shape, rotation and relief. However, the model cannot be applied when only a portion of image is used, the image has been geometrically corrected or there is no ephemeris data. The Ortho Engine tool offers the generation of either absolute or relative DEM. The extracted DEM by using the PCI Geomatica mostly gave the accuracy of ± 15 and $\pm 15-25$ m in horizontal and vertical direction, respectively which are dependent on the relief of the study area, number and distribution of applied GCPs.

In comparison to PCI Geomatica the ERDAS Imagine showed weaker results. The most important problem is the absence of specific model for processing ASTER level 1A stereo data. The above problem was verified by Cuartero *et al.* (2004) by generating DEM from 55 stereo data in which the results showed the RMSEz of ± 34.8 m. Besides, Trisakti and Carolita (2005) achieved somewhat better results (± 27 m). In order to solve this problem, the LPS SP 2 in Leica Geosystems Geospatial Imaging was presented by ERDAS but the same results were achieved by using ASTER Level 1A stereo images (Cuartero *et al.*, 2005a).

Apart from above software, ENVI is one the most used software which employs the RPC model to generate the ASTER DEM. A 9-steps user-friendly wizard is offered to produce the DEM. The software allows stepping forward and backward as well as collecting the tie points manually or automatically. ENVI 4.1 was used to produce DEM with 15×15 m resample spacing in a 43 km long and 50 km wide area from ASTER level1B images by Lee *et al.* (2008) in Geyeongsagbukdos (Korea). Finally the accuracy was estimated by using comparing transects from elaborated DEM and referenced digital topographic maps of 1:25000 scales. The Results indicated that RMSE in elevation between ± 7 and ± 20 m could be achieved.

Desktop Mapping System (DMS) is popular software in mapping. Hirano *et al.* (2003) assessed the accuracy of ASTER DEM for four study sites on Japan, Chile and USA by using DMS. The accuracy of the DEMs were evaluated by comparing the Z-values

(check points) from DEMs and corresponding points from topographic maps. Results indicated that a Root-Mean-Square Error (RMSE) in elevation between ± 7 and ± 15 m can be achieved with ASTER stereo image data of good quality.

Furthermore, Aster DTM module, developed by SulSoft who are the exclusive ENVI distributors in Brazil, is a new add-on module to ENVI, which allows DEMs to be quickly created only from ASTER level 1A and 1B stereo pairs (www.envi.com.br/asterdtm/english/). Therefore, both absolute and relative DEMs can be generated. Aster DTM converts the stereo images into a pair of quasi-epipolar images that have a pixel displacement in the satellite flight direction proportional to the pixel elevation. A cross-correlation method is then used to evaluate this displacement and transform it into elevation values. An existing DEM can be added in the process to fill in areas where the correlation values are too low. Automatic detection of water bodies was recently added and water pixels forming large water bodies (lake, reservoirs, sea, etc.) are now automatically assigned the mean elevation value of the borderline (Toutin, 2008). Studies which have been conducted by Cuartero *et al.* (2005b) yielded an error of almost 17 m with 90% level of confidence by utilizing Aster DTM module.

In addition to the above studies which specifically covered the assessment of accuracy of ASTER-extracted DEM, there are other studies which investigated the application of ASTER DEM in geosciences. ASTER images were used to produce DEM of Taranaki volcano in North Island of New Zealand by Stevens *et al.* (2004). In order to determine the relative offset between each pixel and the same pixel on the earth, the nadir and aft images were compared manually. Consequently, an iterative, 4-step approach for matching method was used. Rough offset between the nadir and aft views (bands 3N and 3B) for each pixel was calculated and then refined and fine-tuned. This was achieved by selecting tie-points common in both images, generating a polynomial (usually of degree 1) to relate nadir coordinates to aft coordinates and resample the aft scene in nadir space based on this polynomial. A frequency domain cross-correlation was then used to estimate the offset between images at each pixel using a roving kernel, or window of pixels, starting with a kernel of 16×16 pixels. The cross-Correlation (Corr) of a kernel in the nadir (n) and the aft (a) is given by the relation Eq. (1):

$$\text{Corr}(n, a) = \text{IFFT}(NA^*) \quad (1)$$

where,

N & A : The two-dimensional Fourier transforms of n and a

* : The complex conjugate of the transform

IFFT : The Inverse Fast Fourier Transform

The maximum value in the resulting Corr (n, a) array is the maximum correlation and the location within the array provides the offset between aft and nadir images at the Kernel location. The kernel size was then decreased successively to 8×16 pixels, 8×8 and 4×8 . Each time the kernel size was reduced, the offset was updated by combining the offset and the lag from the new correlation. Inspection of the offset array reveals a significant number of spikes or high frequency noise, which was reduced using a median filter (which preserves correlation peaks). After the 8×8 kernel stage, the final offset is an integer value. In the final operation, the kernel size is reduced to 4 samples by 8 lines and a polynomial interpolation on the resulting correlation matrix provides a fractional value for the lag position. This is the final match position. The relative Height (ΔH) of a feature on the landscape is then derived by the relationship Eq. (2):

$$\Delta H = \Delta X / \phi \quad (2)$$

where,

ΔX : The parallax or final match offset

ϕ : The intersection angle

As the image matching method used a ‘kernel’ operation, the exact parallax at any point was not calculated, but instead an average parallax for the kernel was derived and the resulting calculated values of height were essentially smoothed. Besides, ASTER DEMs of Taranaki volcano were dereferenced initially to geographic map coordinates using the supplied ASTER header data and then refined using known survey trig points identifiable in the false color composite imagery derived from bands 1, 2 and 3N of the nadir image.

Comparison of the ASTER DEMs with Land Information New Zealand (LINZ) digitized data and with surface features in the georeferenced TOPSAR DEMs indicated that the ASTER data were georeferenced to within subpixel accuracy (< 15 m) by this method. The trig points were also used to refine the vertical scaling of the ASTER DEMs interactively, as well as using the assumption that the coastline has zero elevation, in the case of the DEM of Taranaki.

CONCLUSION

The various applications of DEM and the drawbacks of traditional techniques drastically have increased the significance of using satellite images. Remote sensing has become an essential and universal tool to produce DEM and 3D images in many areas. The special characteristics of ASTER stereo images such as world-wide coverage, along-track configuration and easy access make them valuable for DEM generation for various applications. Therefore, since the launch of

ASTER sensor many studies have been conducted to investigate the accuracy of ASTER-extracted DEM. The studies can be divided into two groups; first the pre-launch or simulated studies which showed the expected accuracy of ASTER DEM between ± 7 and ± 20 m; second the studies with real ASTER stereo data. Most of the studies with the real ASTER stereo images have been carried out on mountainous areas by utilizing various software such as PCI Geomatica, ERDAS and ENVI. The results showed the accuracy is depended on the employed software, type of the terrain and numbers and distribution of GCPs in the case of absolute DEM.

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