

## Assessment of Accuracy of Digital Elevation Model Generation from ASTER Stereo Images by Using Rational Polynomial Coefficients and Toutin's Models

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**Abstract:** This study aims to generate Digital Elevation Model (DEM) by utilizing Rational Polynomial Coefficient (RPC) model (ENVI 4.8) and Toutin's Model (OrthoEngine<sup>SE</sup> of PCI Geomatics 10.3) to determine the suitable model. The along-track stereoimages of Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) sensor with 15 m resolution were used to generate DEM on an area with low and near Mean Sea Level (MSL) elevation in Johor Malaysia. In addition, the area under study was divided into three elevation ranges between 0-100 m (flat), 100-300 m (moderate) and 300-600 m (hilly) to evaluate the DEM accuracy in various terrains. Consequently, the uncorrected DEM of RPC model yielded RMSEz of  $\pm 32.96$  m (0-100 m),  $\pm 23.38$  m (100-300 m) and  $\pm 23.65$  m (300-600 m) while after post-processing the RMSEz decreased to  $\pm 17.69$  m (0-100 m),  $\pm 14.08$  m (100-300 m) and  $\pm 17.77$  m (300-600 m). Overall, the corrected DEM of RPC model reached the expectations with RMSEz of  $\pm 16.49$  m. On the other hand, the DEM of Toutin's model contained many blunders and outliers which indicated the ineffectiveness of Toutin's model for area with low and near MSL elevation. The failure of Toutin's model may mostly be due to the inaccuracy and insufficiency of ASTER ephemeris data for low terrains as well as huge water body in the stereo images.

**Keywords:** ASTER, digital elevation model, ENVI, low elevation, PCI Geomatics, satellite

### INTRODUCTION

Digital Elevation Model (DEM) displays the relief of the earth in digital format at regularly spaced horizontal intervals and is prerequisite for geometric, radiometric and atmospheric corrections of optical and microwave instruments (Toutin, 2008). The absence of accurate DEMs for much of the earth as well as the difficulties of other techniques such as aerial images, terrestrial surveying and GPS, make scientists to use alternative approaches. Therefore, DEMs from satellite stereo images emerged to fill this gap. Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) was launched in December 1999 as the only high spatial resolution instrument on Terra satellite as a cooperative program between National Aeronautics and Space Administration (NASA) and Earth Observing System (EOS) and Japan's Ministry of Economy (Welch *et al.*, 1998; Yamaguchi *et al.*, 1998). ASTER sensor was designed to obtain high spatial resolution, global and local images in 14 spectral bands. ASTER sensor provides the images in 14 Visible and Near-Infrared (VNIR) (15 m), Short-Wave Infrared (SWIR) (30 m) and Thermal Infrared (TIR) (90 m) spectral bands with 60 km swath width. The VNIR subsystem records the stereo images in band 3

(0.78-0.86  $\mu\text{m}$ ) from nominal Terra altitude of 705 km at 15 m resolution. In order to minimize the image distortion, two independent telescopes capture the images in Backward (3B) and Nadir-looking (3N) modes (Yamaguchi *et al.*, 1998) with interval of 60 sec. Also, Along-track stereo images yield a B/H ratio of 0.6 which is suitable for automatic DEM generation. Furthermore, the capability of two telescopes for rotating  $\pm 24^\circ\text{C}$  provides across-track stereo images data with B/H ratio close to one (Toutin, 2008).

Since the availability of ASTER data in March 2000 many scientists have investigated and validated the generated DEM, mostly due to special characteristics of ASTER stereo images, such as world-wide coverage, along-track configuration, high spatial resolution (15 m), easy to access and inexpensive images. These characteristics make ASTER stereo images as significant alternatives for generating DEMs in scientific and commercial applications. Two kinds of studies have been conducted; first the pre-launch or simulation studies and, second the investigations by employing real ASTER data. The first group of studies mostly conducted on mountain areas, showed accuracy between  $\pm 7$  and  $\pm 50$  m for absolute DEM (Arai, 1992; O'Neill and Dowman, 1993; Dowman and Neto, 1994; Giles and Franklin, 1996;

Tokunaga *et al.*, 1996; Welch *et al.*, 1998), while the relative DEM yielded RMSEz of 10-30 m (Lang and Welch, 1999). The second group of studies used the off-the-shelf software such as PCI Geomatica™ OrthoEngine® of PCI Geomatics, Desktop Mapping System (DMS)™ (R-WEL), ERDAS Imagine® OrthoBASE Pro™ (ERDAS), ENVI DEM Extraction Module of ENVI 4.2-4.8 and SilcAst of Sensor Information Laboratory Corp (Hirano *et al.*, 2003; Toutin, 2008). According to Toutin (2008) the Geomatica™ OrthoEngine<sup>SE</sup> of PCI Geomatics is the most used software, which employs the Toutin's model developed at the Canada Centre for Remote Sensing. The Toutin's model showed the vertical accuracy between ±15-25 m depending on the type of terrain of the study site as well as numbers and distribution of applied GCPs (Kaab, 2002; Toutin, 2002; Toutin and Cheng, 2002; Chrysoulakis *et al.*, 2004; Cuartero *et al.*, 2004, 2005a, b; Eckert *et al.*, 2005). However, slightly better results were obtained from ENVI 4.1 (RPC model) and Desktop Mapping System (DMS) which showed the accuracy between ±7 and ±20 m (Hirano *et al.*, 2003; Lee *et al.*, 2008). In comparison to the above software, the absence of specific model for ASTER sensor led to poorer results by OrthoBase Pro module of Erdas Imagine®. The studies yielded the RMSEz of ±34.8 and ±27 m by Cuartero *et al.* (2004) and Trisakti and Carolita (2005) respectively. Finally, the SilcAst (available version 1.10) which is offered by Sensor Information Laboratory Corp from Japan showed the best results with RMSEz of ±6.1 m for relative DEM (Cuartero *et al.*, 2005b).

This study aims to generate the DEM from ASTER stereo images on low and near MSL elevation. The DEMs were produced by using the most used models RPC model (ENVI 4.8) and Toutin's model (OrthoEngine<sup>SE</sup> of PCI Geomatics 10.3). Finally, to evaluate the output DEM as well as finding the best model, comparisons between the Independent Check Points (ICPs) of generated DEMs and topographic maps of the study area are presented.

## STUDY AREA AND DATASETS

The area of study located in Johor state in southern Malaysia (103°16'45.30"E to 103°42'48.46" E to 1°10'12.62"N and 1°47'42.40"N) covers Johor Bahru, Skudai and other small urban and rural districts such as Kulai, Benut, Pekan Nanas, mostly located near the Straits of Malacca. The area comprises flat topography, mainly less than 100 m in urban and clear-cut areas as well as dense tropical forests.

The moderate and hilly terrain restricted to the west of Johor Bahru ranges approximately between 100 to 600 m and more. The land cover of the study site mainly consists of dense oil palm and tropical forests. Johor Bahru is the major city in the south while the other residential and urban areas are sparse in the study area.

The image dataset used was a level 1A ASTER stereo images that were recorded on, July, 14, 2009 with the scene center of 1.47681°N and 103.498°E. The stereo pair consists of 4100 pixels by 4200 lines, covering an area approximately 60 km by 60 km which was delivered in Hierarchical Data Format (HDF). Also, the automatic geometric correction and radiometric calibration are available by utilizing applicable appended coefficients (Toutin, 2002).

The GCPs and check points were extracted from topographic map of the study area. The 1:50000 scale topographic map of the study area was supplied by Universiti Teknologi Malaysia which was digitized by the authors at 20 m grid. The topographic map showed vertical accuracy better than 10 m.

## DEM GENERATION

**ENVI 4.8:** ENVI 4.8 utilizes the RPC model as mathematical model to geo reference and removes the distortions of the stereo images. This model also called, RFM, uses ratios of cubic polynomials to conduct the

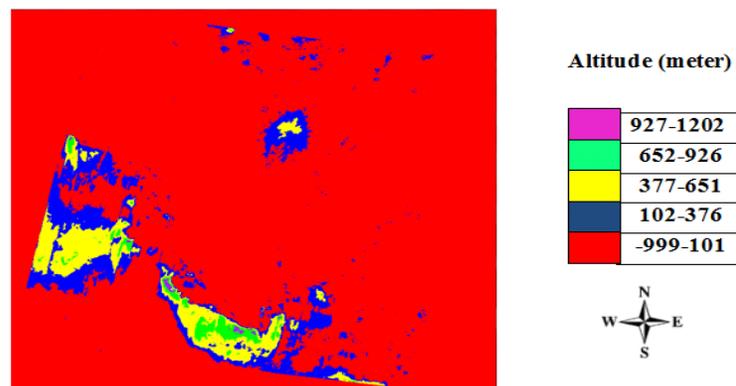


Fig. 1: The uncorrected Digital Elevation Model (DEM) derived from ASTER satellite data of study area, representing elevation in five classes

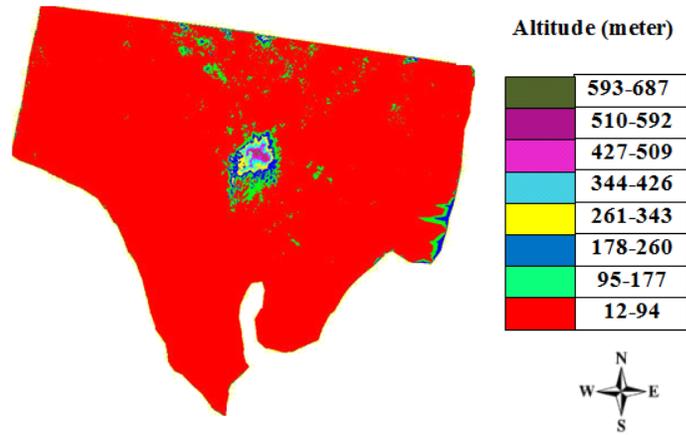


Fig. 2: The corrected Digital Elevation Model (DEM) derived from ASTER satellite data of study area, representing elevation in eight classes

transformation from ground surface coordinates (latitude, longitude, elevation) to image coordinates (line, column) with appended coefficients in an auxiliary file (ENVIDEM, 2009). Although the RPC model can be applied for various sensors such as pushbroom, whiskbroom and SAR systems, the major disadvantages of RPC model are the necessity for sufficient numbers of GCPs as well as high sensitivity to GCPs distribution.

ENVI offers a 9 steps user-friendly extraction DEM wizard to generate ASTER DEM. In our study ASTER stereo images were placed and fitted to UTM coordinate system and WGS84 datum (zone 48N) respectively. In order to perform the RPC model, 53 GCPs which are well distributed and clearly identifiable on both images were collected from the topographic map of the study area. Then, the epipolar images were generated from 26 selected tie points on both stereo images. Finally, moving windows size and minimum correlation of point match were set to 5×5 and 0.75, respectively. Figure 1 shows the uncorrected DEM from RPC model.

In all software and DEM generation technique, there is always a need for post-processing the output DEM, to eliminate void, blunders and filling the mismatched areas. Generally, manual, automatic and interactive techniques are used to edit the output DEM (Toutin, 2002). The specific features of our study area such as dense tropical forests, flat terrain (almost MSL in some areas) as well as cloud cover in the ASTER stereo images led to outliers and mismatched areas in the output DEM. Therefore, first, the automatic interpolation was conducted for areas less than 200 pixels (Toutin, 2002) to replace uncorrected values with good elevation values of the edges of the failed areas. Finally, the constant value +12 was added to remove the remaining negative values. The constant value was determined based on the profile elevation of the mismatched areas. Finally, Fig. 2 shows the corrected

DEM of the study area after implementation of automatic interpolation and removing blunders.

**PCI Geomatics 10.3:** The OrthoEngine<sup>SE</sup> of PCI Geomatics 10.3 uses the Toutin's model to generate DEM for ASTER stereo images. The satellite orbital model, also called Toutin's Model, is a rigorous model developed by Dr. Toutin of the Canada Center for Remote Sensing to compensate for distortions; such as sensor geometry, satellite orbit and attitude variations, earth shape, earth rotation and relief (Toutin and Cheng, 2002). The rigorous model employs the photogrammetric collinearity equations to relate the position of the point on the image to the position of the correspondent point on the ground.

The orbital model shows the accuracy of approximately one-third of a pixel for VIR images when the quality GCPs are used. Although, the Toutin's model is not implemented when there are no orbital parameters, a subset of the original image is used and the image has been geometrically processed.



Fig. 3: Output DEM by using toutin's model (PCI geomatics)

In order to generate DEM, the earth model and datum were set to UTM (zone 48N) and WGS84 respectively. The OrthoEngine<sup>SE</sup> applied of geometric processing for 3N and 3B images individually. Although 4 GCPs are theoretically adequate to compute the stereo model, a larger number (53) were used to achieve an overestimation to improve the least square adjustment to reduce the errors of map and plotting errors. In addition, 26 tie points were extracted to enhance the fitting of images to ground coordinate system and fitting of overlapping images to each other. Unfortunately, the output DEM contained many blunders and outliers which were impossible to perform the post-processing and removing the uncorrected values (Fig. 3).

**RESULTS AND DISCUSSION**

**Pre-processing accuracy of DEM of RPC model:** The output DEM is an accumulation of different automatic and manual processing steps, such as collecting and importing GCPs/Tie points, geometrical processing, image matching and editing the final DEM. Therefore, the accuracy of each step affects the ultimate accuracy of DEM. The first results of this study are associated with the computation of RPC model and y-parallax which result in geo referencing the stereo images and generating the epipolar images respectively. As previously mentioned, a total of 53 GCPs were extracted from topographic map of the study area to perform the geo referencing process. Therefore, the difference between predicted map coordinates and the GCP map coordinates showed errors  $\leq \pm 4$  m in X, Y and Z directions which are less than half an ASTER pixel and indicated the high accuracy of geo referencing performance. Subsequently, in order to generate the epipolar images, the maximum allowed y-parallax is 10 pixels, ideally close to zero or less than 2 pixels (ENVIDEM, 2009), the y-parallax value equal to 0.55 was achieved for the 26 tie points of the study area which was quite acceptable to generate epipolar images.

**Accuracy of corrected and uncorrected DEM of RPC model:** In order to evaluate the sensitivity of ASTER

DEM to different terrains, our study area was divided into three elevation ranges. First, 0-100 m which was considered as flat area, second, 100-300 m as moderate area and finally, 300 m to more than 600 m as hilly area. Thus, 15, 20 and 20 Independent Check Points (ICPs) which were surrounded by the GCPs, were not used in the stereo-model, selected from flat, moderate and hilly areas respectively. Besides, the accuracy of uncorrected DEM (DEM1) and corrected DEM (DEM2) were evaluated to validate the automatic interpolation and removing of blunders.

The first results are related to the RMSEz obtained as well as the main statistics of DEM1. The results of DEM1 showed the RMSEz of  $\pm 32.96$ ,  $\pm 23.38$  and  $\pm 23.65$  for the flat, moderate and hilly areas respectively. The RMSEz obtained shows presented the increase of accuracy between flat and moderate areas of approximately  $\pm 10$  m, while the hilly area gave almost the same accuracy. However, there was a small decrease  $\pm 0.27$  in the accuracy of hilly area. The increase of accuracy between flat and moderate area showed the efficiency of ASTER DEM for high elevations. However, almost the same RMSEz in moderate and hilly terrains is mainly due to cloud cover in the high terrains. Finally, the RMSEz of  $\pm 26.43$  was achieved for whole DEM1 which shows the need of further corrections.

The second results are related to the evaluation of accuracy of corrected DEM (DEM2). As previously mentioned, the automatic interpolation and removing of blunders technique were performed to improve the accuracy of DEM1. The RMSEz achieved, showed higher accuracy in comparison to DEM1, with the RMSEz of  $\pm 17.69$ ,  $\pm 14.08$  and  $\pm 17.77$  m acquired for flat, moderate and hilly areas respectively.

On the whole, the RMSEz of  $\pm 16.49$  m was achieved for the DEM2 which shows the effectiveness of correction procedures with almost  $\pm 10$  m of increase in accuracy. The comparisons between the main statistics of DEM1 and DEM2 are summarized in Table 1.

**Pre-processing accuracy of Toutin’s model:** The pre-processing for generating ASTER-extracted DEM by

Table 1: Main statistics of uncorrected DEM (DEM1), corrected DEM (DEM 2) generated from RPC model (ENVI 4.8)

Generated DEM	Statistics			
	Min	Max	Mean	SD
DEM 1	- 999	1300	241.54	479.54
After automatic interpolation	- 4	671	119.12	122.21
DEM 2 (automatic interpolation + removing outliers)	12	687	135.12	122.21

Table 2: Main statistics of DEM from Toutin’s model, almost 96% of the DEM is covered with failed values (-100)

Number of pixels	23912549.000	Minimum value	-100.0000
Number of pixels with data value of -100 (failed value)	23454133.000	median value	-100.0000
Mean value	-94.596	standard deviation	45.6683
Maximum value	636.000	number of pixel with maximum value	4.0000
Percentage of failed value	98%	percentage of maximum value	<1%

utilizing Toutin's model includes geometrical correction, quasi-epipolar image generation and image matching (Toutin and Cheng, 2002). The results of geometrical correction which has been done individually for each stereo image gave the RMS of 0.87 pixels (53 GCPs) and 0.88 pixels (53 GCPs) for 3N and 3B images respectively. Finally, in order to perform bundle adjustment and generate quasi-epipolar images 26 well-distributed tie points were selected in each stereo image. Consequently, the residuals between 0.150 and 1.402 pixels were achieved.

**DEM accuracy of Toutin's model:** Despite the satisfactory pre-processing results the visual assessment of the DEM generated from Toutin's model showed that the DEM contained many outliers and incorrect values.

Table 2 lists the main statistics extracted from Toutin's model of DEM. In the Table 2 almost 98% of DEM includes data value equal to -100 (failed values) which represents the value for the points that were not either computed or extracted from the stereo images by using Toutin's model.

**Comparison of models:** The comparison between the output DEM from RPC and Toutin's model proved the better accuracy and effectiveness of RPC model in an area with mostly low and near MSL elevation. The RMSEz of corrected DEM in different terrains and the whole DEM of RPC model were within the ASTER design specifications (Lang and Welch, 1999) as well as previous work by utilizing ENVI 4.1 (Lee *et al.*, 2008). In addition, the increase of accuracy in both DEM1 and DEM2 between the flat and moderate areas showed the efficiency of ASTER DEM for high elevations especially more than 100 m. Nevertheless, there is a reduction in the accuracy obtained between moderate and hilly areas especially in the DEM1 which is due to first, the cloud cover in the high elevation of the study area and second, the adding of constant value in order to remove the blunders which escalated the error propagation in the high elevation. On the other hand, despite the satisfying pre-processing results of ASTER DEM by utilizing the Toutin's model, the output DEM was full of failed values. The failure of Toutin's model may be due to insensitivity of ASTER for MSL terrain as well as using the ephemeris data as the core data in Toutin's model which can produce incorrect values. However, further studies need to be done.

## CONCLUSION

The Advanced Space borne Thermal Emission and Reflection radiometer (ASTER) is the only multispectral high resolution sensor on the Terra platform which captures along-track stereo images with the Base-to-High (B/H) ratio of 0.6. The stereo images are recorded in near-infrared wavelength region (band 3) in Nadir (3N) and aft-looking (3B) mode. In this study, the DEM was

produced by using RPC model (ENVI 4.8) and Toutin's Model (PCI Geomatics10.3). In total, 53 Ground Control Points (GCPs) from topographic map of the study area were used to compute the RPC model with ENVI.

The results of uncorrected DEM of RPC model showed the RMSEz of  $\pm 32.96$ ,  $\pm 23.38$  and  $\pm 23.65$  for different terrains between 0-100, 100-300 and 300-600 m respectively. Applying the automatic interpolation as well as adding the constant value improved the accuracy to RMSEz of  $\pm 15.27$  m,  $\pm 14.0$  and  $\pm 17.77$  for the respective terrains. Overall, the output DEM of RPC model yielded the RMSEz of  $\pm 16.49$  which was within the design specifications and met the expectations. In order to, generate the DEM by using Toutin's model, also, 53 GCPs were used for 3N (nadir looking) and 3B (backward looking) images. The DEM of Toutin's model contained many outliers and blunders which showed the inefficiency of Toutin's model for areas with low and near MSL elevation. The failure of Toutin's model is mostly due to the low sensitivity of ASTER stereo images for low and near MSL elevation. Also, it indicates that the ephemeris data of ASTER is not sufficient and accurate enough to generate DEM for low elevation areas.

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