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Accuracy Improvement of ASTER Stereo Satellite Generated DEM Using Texture Filter

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Abstract The grid DEM (digital elevation model) generation can be from any of a number of sources: for instance, analogue to digital conversion of contour maps followed by application of the TIN model, or direct elevation point modelling via digital photogrammetry applied to airborne images or satellite images. Currently, apart from the deployment of point-clouds from LiDAR data acquisition, the generally favoured approach refers to applications of digital photogrammetry. One of the most important steps in such deployment is the stereo matching process for conjugation point (pixel) establishment: very difficult in modelling any homogenous areas like water cover or forest canopied areas due to the lack of distinct spatial features. As a result, application of automated procedures is sure to generate erroneous elevation values. In this paper, we present and apply a method for improving the quality of stereo DEMs generated via utilization of an entropy texture filter. The filter was applied for extraction of homogenous areas before stereo matching so that a statistical texture filter could then be applied for removing anomalous evaluation values prior to interpolation and accuracy assessment via deployment of a spatial correlation technique. For exemplification, we used a stereo pair of ASTER 1B images.

Keywords ASTER; digital elevation model extraction; stereo matching; texture filter; quality improvement

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Introduction

Sensor orientation, also called image georeferencing, is defined by a transformation between the image coordinates specified in the camera frame and the geodetic (mapping) reference frame. This process requires knowledge of the camera interior and exterior orientation parameters. The interior orientation, i.e., principal point coordinates, focal length and lens geometric distortion characteristics, are provided by the camera calibration procedure. The interior orientation parameters are only concerned with the modelling of the camera projection system, whereas the ex-

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terior orientation parameters directly define the position and the orientation of the camera at the moment of exposure. In photogrammetry, the six exterior orientation parameters (three coordinates of the perspective centre, and three rotation angles known as ω, φ and κ) are determined by using a mathematical model for transformation between object and image spaces, defining correlation between ground control points and their corresponding image representations. This illustrates a traditional approach, where georeferencing is achieved indirectly by adjusting a number of well-defined ground control points and their corresponding image coordinates. In the case of frame imagery, only one set of exterior parameters per image must be determined. However, for sensors such as push-broom line systems or panoramic scanners, perspective geometry varies with the swing angle (panoramic scanners), and with each scan-line (push-broom systems). For these kinds of sensors, the direct georeferencing by means of GPS/INS integrated systems becomes indispensable in order to achieve operationally effective high volume production.

In general, the procedure for DEM generation from stereoscopic views can be summarized as (1) Feature selection in one of the scenes of a stereo-pair: Selected features should correspond to an interesting phenomenon in the scene and/or the object space. (2) Identification of the conjugate feature in the other member of the stereo pair: This problem is known as the matching/correspondence problem within the photogrammetric and computer vision communities. (3) Intersection procedure: Matched points in the stereo-scenes undergo an intersection procedure to produce the ground coordinates of corresponding object points. The intersection process involves the mathematical model relating the scene and ground coordinates and (4) Point densification: High-density elevation data is generated within the area under consideration through an interpolation in-between the derived points in the previous step.[1] The conjugate pixels should represent distinct spatial texture by which they can be distinguished from other pixels. However, in homogeneous areas such as water bodies or forest canopy areas,[2] it is very difficult to find the conjugate pixels due to the lack of distinct spatial textures. Most of the erroneous elevation values in photogrammetrically-derived DEMs are produced in homogeneous areas. However, even when matching points cannot be found, interpolating the elevation values of the conjugate pixels generates the DEM.

Therefore, in order that accuracy be improved, it is necessary to generate the most densely-distributed conjugate pixel array as possible. Many studies for improvement of stereo matching techniques for DEM quality can be cited. The epipolar geometry for utilizing matching techniques (http://www.enge.ucl.ac.be/EARSEL/workshops/3D-RS/start.htm) and a novel stereo matching algorithm use wavelets to obtain a dense disparity model for DEM generation from complex SPOT stereo image pairs.[3] Such methods deploy only the brightness values of the imagery to calculate the statistical similarity of candidate pixels. A statistical filter was used to remove the anomalous elevation values in a SPOT Image data set and found that the number of erroneous elevation values produced was significantly less than without application of such a filter.[4] In this present study, such a filter was used (in pre-processing) not only to reduce the number of erroneous values but also to experiment with scope for determining the optimum sizes and parameters of the texture filter for use with the 15 m spatial resolution of ASTER stereo imagery.

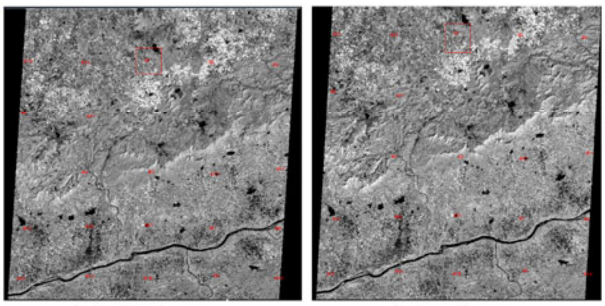
1 Data used

Fig.1 displays the stereo pair of ASTER level 1B imagery covering many lakes and homogeneous terrain (forest) used in this study. The ASTER sensor is designed to provide image data in 14 visible, near-infrared, short wavelength infrared and thermal infrared spectral bands (Table 1). Stereo image (acquired using both nadir and aft-looking telescopes) data are recorded only in Band 3, which is the near-infrared wavelength range from 0.78 to 0.86 μm. From the nominal Terra altitude of 705 km, the "pushbroom" linear array sensor covers a 60-km-wide ground track at a 15 m spatial resolution. There is an approximately 60 s interval between the time the nadir telescope passes over a ground location and the aft telescope records the same location on the ground track of the satellite. Images generated from the nadir and aft telescopes yield a B/H ratio of 0.6, which is close to ideal for a variety of terrain conditions for generating DEMs by deployment of automated techniques.[5] A major advantage of the along-track mode of data acquisition (as compared to cross-track) is that the images forming the stereo pairs are acquired a few seconds (rather than days) apart and so they refer to uniform environmental and lighting conditions. Thus, the resulting stereo pairs are of consistent quality that are recognised as being well suited for DEM generation by automated stereo correlation techniques.[6-8]

Table 1 Technical specification of ASTER sensor and Terra satellite orbital parameters

Technical specifications	Terra ASTER stereo
Band in visible/near-infrared	3
Band in short wavelength infrared	5
Band in thermal infrared	6
Stereo capability	Yes, Bands 3N (nadir) and 3B (aft-looking), 0.78-0.86 μm
Stereo imaging geometry	Along-track
Base-to-height (B/H) ratio	0.6
Pixel size	15 m
Scene coverage	60 km × 60 km
Orbital path	Near-polar Sun-synchronous
Orbital altitude	705 km
Orbital inclination	98.20
Repeat cycle	16 days

Source: Akira *et al*., 2003.



(a) Right image (b) Left image

Fig.1 ASTER panchromatic images. Red dot shows control points (25GCPs) over the image

2 Preprocessing of ASTER stereo imagery

A total of 25 ground control points (GCPs) were selected on each of the ASTER level 1B members of the stereo pair. These GCPs referred to topomap were used in the exterior orientation process to define the position and angular orientation of the ASTER sensor when the images were captured.

The procedure for stereo DEM generation is the process of exterior orientation. Exterior orientation defines the position and angular orientation of the sensor that captured an image. The variables defining the position and orientation of an image are referred to as the elements of the exterior orientation. In the case of ASTER imagery, we have a series of linear arrays each of which can be likened to a one-dimensional photograph. The position (X_t, Y_t, Z_t) of the satellite at a given time t can be linearly related to the location (X_o, Y_o, Z_o) of the satellite corresponding to the central linear array. The image tilt values (ω_t, φ_t, κ_t) at a given time t also can be linearly related to the image tilt angle (ω_o, φ_o, κ_o) of the central linear array. Once the elements of the exterior orientation are determined, a position value can be calculated from the conjugate pixel's image coordinate. In order to be found as conjugate pixels, the pixels should have distinct spatial texture to be distinguished from other pixels.[9] However, in the homogeneous areas such as water covered or forest canopied areas, it is very difficult to find the conjugate pixels due to the lack of distinct spatial texture. Most of the erroneous elevation values in the stereo DEM are produced in those homogeneous areas.

To generate densely distributed elevation values, the threshold value of similarity needs to be set at a low a value as possible. However, if too low, erroneous conjugate pixels are selected and anomalous elevation values appear in the DEM. In this study, it is proposed to use texture information of input image in order to exclude very homogeneous areas from being a candidate for participation in the stereo matching process. Through careful examination of various texture filters, an entropy filter of kernel size 5 by 5 was found to be most appropriate for extracting a homogeneous area from ASTER panchromatic image. Gong *et al*.[10] showed that the same effect was observed on the SPOT image used in their study. The 5 by 5 kernel size entropy filtered result is shown in Fig.2. By applying histogram threshold, the binary image shown in Fig.3 can be generated. The black colour coded areas shown are those homogeneous areas where the automated stereo matching process should not be applied.

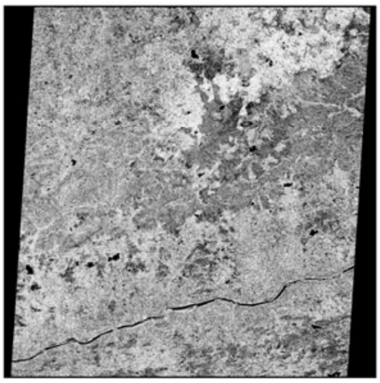


Fig.2 The 5×5 entropy filter image of study area

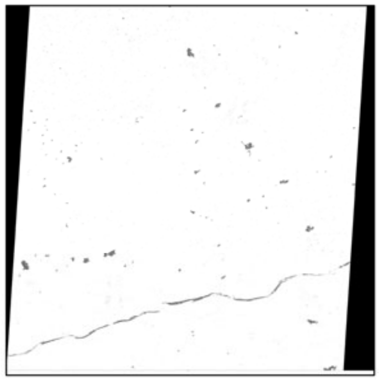


Fig.3 Histogram applied on entropy filter image (Fig.2)

3 Results and discussion

The stereo matching process mostly influences the accuracy of DEMs generated from stereo pairs of satellite images. In this study, the area based (as opposed to the feature-based) matching method was used. The kernel size for stereo matching was 15 by 11 and the normalized cross correlation coefficient was used as a measure for similarity between the candidate pixels. Fig. 5 shows elevation values generated by deployment of a correlation threshold value of 0.5. Stereo matching failures are shown as black coloured pixels. Even though elevation values are produced for most of the study area, a lot of anomalous elevation values were produced, especially over the water-covered area.

The statistical filter was applied to remove the above anomalous values. It calculates the mean values m and standard deviation values of the pixels surrounding the central pixel within a given kernel. If the value for the central pixel is larger than $m + a*s$ as smaller than $m-a*s$, (where "a" is a variable that determines the extension of the filtering effects) the elevation values of the central pixel is removed and regarded as a point where stereo matching failed. If values are less than b, the elevation value of the central pixel is removed.[4] Beyond the several texture measures defined, the entropy texture measures were chosen regarding their applicability in homogenous areas, and calculated for each co-occurrence matrix

$$\mathrm{ENT} = \sum_{i=0}^{n-1}\sum_{j=0}^{n-1} f(i,j)\log[f(i,j)] \tag{1}$$

where i, j are the coordinates in the co-occurrence matrix space; $f(i, j)$ is the co-occurrence matrix value at the coordinates i, j; n is the dimension of the co-occurrence matrix. The entropy is high for fine-textured objects and low for coarse-textured objects (water, tree and grass classes). They also highlight the object (water bodies) outlines (characterized by high values).

This statistical texture filter was applied iteratively with changing the kernel size from 17 by 17 to 5 by 5. Out of the full ASTER image selected subset scene which contains a water cover area for testing elevation-extraction methods. Fig. 4 (a) shows the pattern of elevation values generated by applying a correlation threshold value of 0.5. Red and pinkish colour-coded pixels are where the stereo matching failed. The failures are seen to be more prevalent for water covered areas. To remove these anomalous elevation values,

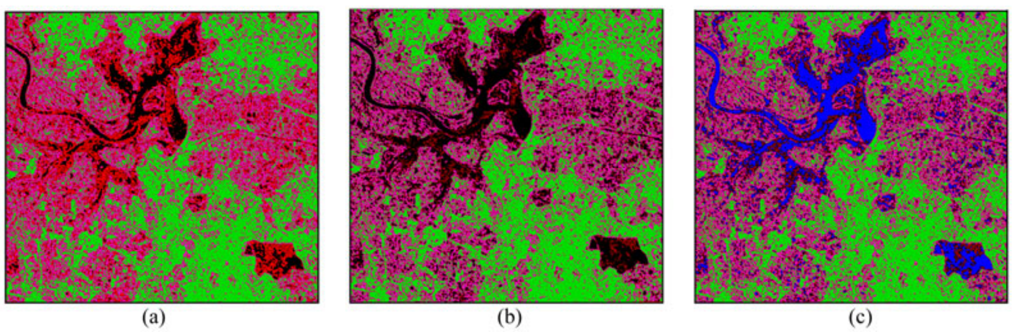


Fig.4 Image subset of surrounding water-body area (Threshold values is 0.5)

a statistical texture filter was applied on Fig.4 (a), resulting in the patterns shown in Fig.4 (b). Most of the anomalous elevation values are seen to have been removed. The final DEM was generated by interpolating (a Krigging method used) among the elevation values in Fig.4 (b) to produce the pattern shown in Fig. 4(c). This DEM was at 15 m resolution, the same as the source data (the ASTER stereo image).

The correlation threshold value is changed to 0.7, and the image is shown in Fig. 5. It is clear that there are fewer points of anomalous elevation values compared with the results shown in Fig. 4(a) (generated by using the similarity threshold value of 0.5). The anomalous elevation values exist not only within the water-covered area but also outside it. Such anomalous elevation values should be removed before applying interpolation. Fig.5 (b) shows the modelled elevation pattern after the statistical filter has been applied. Fig.5 (c) shows DEM values generated by interpolation among the elevation patterns displayed in Fig.5 (b). Most of the anomalous elevation values (reddish colour) in the final generated DEM shown in Fig 4 (c) and Fig 5 (c) have been removed but still some values exist in the water body area.

Apparently, the stereo matching process has failed in application across the water body area because the terrain homogeneity disabled the interpolation such that anomalous values appear in the output DEM. To overcome this problem an entropy filter was utilized (Fig.5(a)). For the homogenous area extracted by entropy filtering, a user defined elevation value was assigned as elevation values instead of being determined from stereo matching. Fig.6 shows the stereo matching results that emerged from application of threshold values of 0.5. Fig.6 (b) shows the elevation values obtained by the proposed method. The final DEM generated is shown in Fig.6(c). For comparison purposes, an orthorectified image is shown in Fig.6(a).

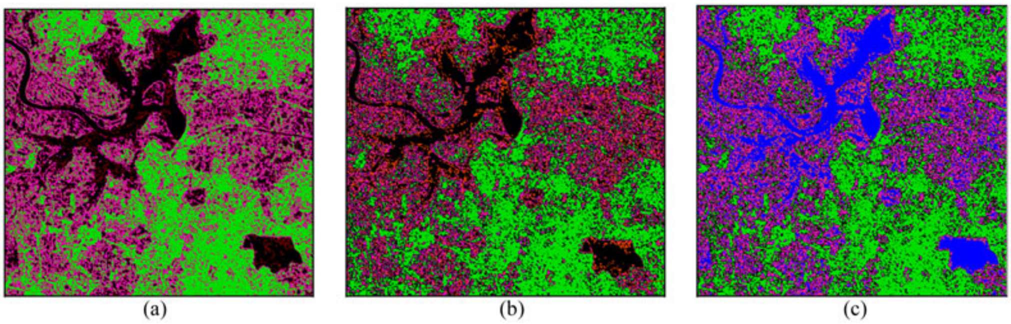


Fig.5 Image subset of surrounding water-body area (Threshold values is 0.7)

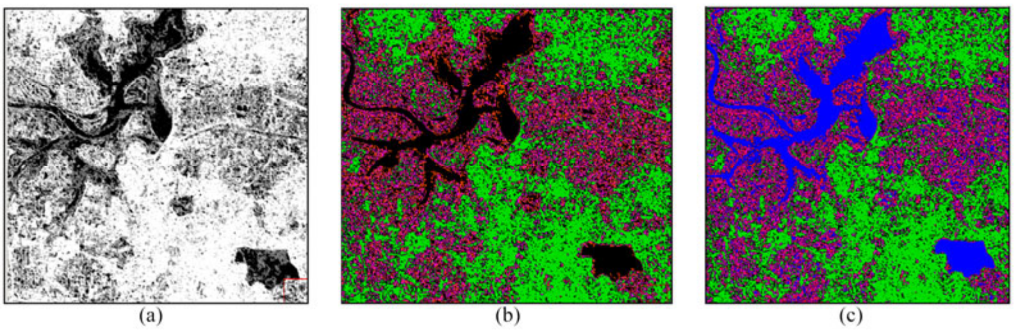


Fig.6 Stereo matching results that emerged from application of threshold values of 0.5

Accuracy assessment was performed by using a spatial correlation technique. The correlation was more than 99% in both of the threshold 0.5 and 0.7 texture filter DEMs (Table 2). For both results, positive correlation was observed but minimum error is found as 29.2 m in the DEM of 0.7 threshold texture filter. Most of the changes observed referred to homogenous areas such as water bodies and forest areas.

Table 2 Correlation and regression coefficients between statistical texture filter DEMs and orthorectified DEM (Fig.6(c))

	Correlation Coef.	Regression line $y=Ax+B$	
		A	B
DEM_thrsld 0.5	0.9972311	0.94	61.54
DEM_thrsld 0.7	0.9962372	0.96	29.21

4 Conclusion

This method is used and examined for improving the quality of ASTER stereo pair generated DEMs. The proposed method uses the entropy filter to extract homogeneous areas such as water cover. For stereo matching purposes, the entropy filter result was used to exclude the homogeneous area from interpolation. Also, statistical texture filter was used to remove anomalous elevation before interpolation. The experiment on ASTER data reported here found that the application of the statistical texture filter reduced the erroneous elevation values in the application of automated conjugate point selection during the application of digital photogrammetry for DEM generation. Deployment of the entropy texture filter allowed the large homogenous area where the most erroneous elevation values were produced in stereo matching process to be identified for extraction from the automated analysis. Thus, problematic photogrammetrically-derived DEM quality can be improved with deployment of a texture filter and, later, an entropy filter during analysis. The optimum window size and related parameters for the texture filter will no doubt vary from image type to image type, not to mention terrain type to terrain type. Benefits may be derived from including the approach explored here in future process paths.

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