Geometric Evaluation, Automated DEM and Orthoimage Generation from Along-Track Stereo ASTER Images

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Abstract-A cloud-free ASTER scene combination covering 61.5km x 63km Zonguldak testfield in the north-west Turkey has been analysed. It comprises the nadir and backward views with a base-to-height ratio of 0.6. The pixel size on the ground is 15m. The bundle orientation was executed with the related module of PCI Geomatica V9.1.4 software package and resulted the 3D geo-positioning to an accuracy of about 14m in planimetry and 13m in height. This level of accuracy can be provided using the number of GCPs up to 14 which are distributed over the scene uniformly. Based on the scene orientation, a DEM of the area has been determined by an automatic image matching and PCI system yielded a DEM with 30m cell size. For the validation of extracted DEM, different groups of GCPs selected over the testfield were utilized. In this analysis, GCPs were located in the raster DEM in according to their planimetric coordinates, then the heights are estimated by the bilinear interpolation of the neighboured grid cells. This was done by the program DEMINT and mean square differences was obtained in the range of 12 to 14m. Moreover, matched DEM was checked against reference DEM based on digitised contour lines from the 1:25000 scale topographic maps using program DEMANAL. The discrepancies between the two DEMs were determined as reference DEM minus matched DEM. Then positive biases resulted which show that matched DEM occurred under the reference DEM. These biases appeared also in the superimposition of contours from two DEMs. Image of DZ discrepancies is displayed as a function of grey values as well and discrepancies is displayed as a function of grey values as well and their planimetric coordinates, then the heights are estimated by the bilinear interpolation of the neighboured grid cells. This was done by the program DEMINT and mean square differences was obtained in the range of ±21-22m. Finally, orthoimage was generated using matched DEM and nadir image component of ASTER stereopair without problem. Planimetric accuracy check of this product was realized using the GCPs and shows no systematic error pattern overall.

I. INTRODUCTION

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is an imaging instrument that is flying on Terra, a satellite launched in December, 1999 as part of NASA’s Earth Observing System (EOS). A Joint US/Japan Science Team was responsible for instrument design, calibration and validation. The primary objective for the ASTER mission is to obtain high spatial resolution images of the Earth in fourteen spectral bands. ASTER consists of three different subsystems: the Visible and Near Infra-Red (VNIR, 15m), the ShortWave Infra-Red (SWIR, 30m), and the Thermal Infra-Red (TIR, 90m). 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 contain three CCD linear arrays (bands 1,2,3N) while the focal plane of the backward telescope has only one (3B). The nadir and backward looking telescope pair has a focal length of 470mm. The two near-infrared spectral bands (0.76-0.86µm), 3N and 3B, generate along-track stereo-pair from a 705km platform altitude with an intersection angle of about 27.7 degrees. In this configuration, 9 seconds are required to acquire a single image and approximately 64 seconds for a stereo-pair. The two ASTER telescopes can be rotated ±24 degrees to provide extensive cross-track pointing capability and 5-day revisit capability. Across-track stereo-imaging with better B/H ratio (close to 1) is theoretically possible. However, due to the high data rate of the three ASTER subimaging systems, only eight minutes of data, are required per orbit and the along-track stereo-imaging is then favoured.

The release of ASTER data has two significant impacts. First, they are available with very small expenses. Second, it provides a new alternative for mapping at medium-to-large scales and for generating DEM. Especially, its along-track data acquisition with across-track stereo, which can then compensate for the weaker stereo geometry.

Up to till now, main emphasis has mainly given to the multispectral image classification using spectral bands of ASTER satellite. Accounts of ASTER stereo-imagery being employed for sensor orientation and DEM extraction are given in [5], [1], [11], [6], [8], [9], [10] and [2]. First four studies deal with the accuracy estimates of ASTER stereo-scenes with simulated data for DEM generation capability of the future planned satellite. Others report on an evaluation of the geo-positioning accuracy and DEM generation and validation from real ASTER data using commercial software packages. All these publications give DEM accuracy between ±7 and 50m, depending on the number of GCPs provided.
In this paper, the authors report on the results of sensor orientation, DEM and orthoimage generation approaches for ASTER stereo-scenes using PCI Geomatica V9.1.4 commercial software package. First, Zonguldak testfield is described, then the application of bundle orientation is explained in detail. This is followed by a discussion of DEM extraction using automatic image correlation. Afterwards, validation tests of matched DEM based on the reference DEM digitized from the 1:25,000 scale topographic maps were given in detail. Finally, orthoimage generation was carried out using the matched DEM and the nadir component of ASTER stereopair in addition to the geometric accuracy test of this product with the help of GCPs using the similarity transformation.

II. PCI GEOMATICA V9.1.4 SYSTEM

The mathematical model which underlies and forms the basis of the photogrammetric solutions adopted in this package is based on the work developed by [7] at the Canada centre for remote sensing (CCRS). It follows the three-dimensional approach based on the use of collinearity equations which relates corresponding points in the image space and object space via the perspective centre of the imaging sensor. These equations have been adapted and formulated to suit the geometry of linear array (pushbroom) scanners such as ASTER in which each line of the scanner image has an individual and different perspective centre, instead of the single perspective centre for a whole image which exists with the frame photographs generated by aerial and space cameras.

Besides the need to estimate and reconstruct the 3-D coordinates of the individual perspective centre for each individual line of a linear array image, it is also necessary to take account of the changing attitude of the satellite and its sensor over the time period during which the ASTER image has been acquired. Again, this is achieved through the modelling of the satellite orbital path in space by combining the satellite’s positional and velocity vectors with the changing attitude of the platform to generate exterior orientation parameters for the linear array image. Thus Toutin’s model takes into account both the displacements due to the dynamically changing platform and sensor motion and orientation and those arising from the sensor geometry due to the physical characteristics of the Earth (rotation, curvature, and ground relief) (more details may be found at http://www.pcigeomatics.com).

III. ZONGULDAK TESTFIELD

The test site is Zonguldak and its close vicinity, located in Western Black Sea region of Turkey. It is famous with being one of the main coal mining area in the world. Although losing economical interest, there are several coal mines still active in Zonguldak. Area has a rolling topography, in some parts, with steep and rugged terrain. While partly built city area is located alongside the sea coast, there are some agricultural lands and forests inner regions. The elevation ranges roughly up to 1800m. The Zonguldak ASTER images are acquired on September 25th, 2000. The level 1A data (images, ephemeris and attitude) have been directly downloaded from the NASA web. Only the near-infrared backward and nadir images (3B and 3N) are used in the sensor orientation, DEM and orthoimage generation. These images have a size of 4200x4100 pixels with a pixel resolution of 10 m (15m on the ground) and scale of 1:1,500,000.

Fig. 1 shows the nadir component (3N) of Zonguldak ASTER stereo-pairs with the location of GCPs used in the bundle adjustment. In total, 22 GCPs have been digitized from Turkish 1:25,000 scale topographic maps, and planimetric accuracy of these GCPs can be expected in the range of ±7.5m. Digital image coordinates for GCPs were measured manually using GCPWorks module of PCI system with the sub-pixel point location. Same with many satellite datasets; road crossings and bridges can easily be selected as control points in ASTER scenes. Especially, points on bridges can be determined sharply over the water bodies since both scenes were taken in infrared bands (water bodies do not reflect radiation in infrared channels and appears as black in the satellite image). Moreover, user can grab better contrast for topographic structures (lineaments) and river crossings on the ASTER data, but they were not used as GCPs because of the changes can be expected over these areas by human factors.

IV. GEOMETRIC ACCURACY TESTS

The detailed results from PCI’s satellite orbital modelling of ASTER stereo-pair are shown in Table 1. Several tests were carried out by dividing the ground control points into two groups in different combinations. The first group acted purely as control points while the second group acted purely as independent check points whose coordinates were not used in the adjustment procedure.

![Figure 1. ASTER scene of Zonguldak testfield with GCPs locations.](image-url)
TABLE I

<table>
<thead>
<tr>
<th># Control points / Independent check points</th>
<th>GCPs</th>
<th>ICPs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X - rmse (m)</td>
<td>Y - rmse (m)</td>
</tr>
<tr>
<td>22/0</td>
<td>14.12</td>
<td>13.81</td>
</tr>
<tr>
<td>12/10</td>
<td>12.08</td>
<td>13.98</td>
</tr>
<tr>
<td>11/11</td>
<td>12.02</td>
<td>14.29</td>
</tr>
<tr>
<td>10/12</td>
<td>12.39</td>
<td>14.37</td>
</tr>
<tr>
<td>9/13</td>
<td>13.07</td>
<td>11.12</td>
</tr>
<tr>
<td>8/14</td>
<td>13.56</td>
<td>11.70</td>
</tr>
<tr>
<td>7/15</td>
<td>7.25</td>
<td>12.95</td>
</tr>
<tr>
<td>6/16</td>
<td>5.15</td>
<td>12.23</td>
</tr>
<tr>
<td>5/17</td>
<td>7.60</td>
<td>17.12</td>
</tr>
<tr>
<td>4/18</td>
<td>7.41</td>
<td>17.68</td>
</tr>
</tbody>
</table>

Inspection of the RMSE values for the residual errors at the check points given in Table 1 shows that, obviously, the best result was achieved at the ICPs when more control points have been used in the solution. In the case of all GCPs are used as control points, the RMSE values for the residual errors in planimetry and height were about ±14m and ±13m respectively. For the residual errors of the GCPs, it is clear from the Fig. 2 that the distribution of the errors in random both in extent and direction. When 10 control points used in the solution and 12 independent check points, the RMSE values of the residual errors at check points were found to be ±17.7m in X, ±16.2m in Y and ±13.2m in Z. By increasing the number of check points to 14, the RMSE values of the residual errors at these check points were obtained as ±17.8m, ±22.6m and ±23.4m in X, Y and Z-components respectively. With 15 check points, the RMSE values of the residual errors at the check points were ±26.9m in X, ±40.6m in Y and ±48.3m in Z. Increasing the number of independent check points to 18 and using the rest of the GCPs as control points in the adjustment, the RMSE values of the residual errors at the check points were ±45.0m in X, ±123.7m in Y and ±99.8m in Z.

Inspection of the RMSE for the residual errors at the check points for planimetry and height given in Table 1 and shown graphically in Fig. 3 indicates that the RMSE values of the residual errors lie in the range ±14.1m to ±45m in X, ±13.8m to ±132.7m in Y and ±13.0m to ±103.6m in Z using different combinations of control points and check points which indicates that the accuracy decreases with a decrease in the number of control points. Especially, it is clear from the Fig. 3 that until the solution with 14 check points, accuracy values in each axis are changing smoothly. However, thereafter, abrupt and strong changes occurred in all axes, but more in Y and Z-components.

Figure 2. Vector plot of the residual errors in planimetry (with blue color) and height (in green) at the ground control points.

Figure 3. Graphical representation of the accuracy in planimetry and height at the check points of the ASTER stereo-pair.

V. DEM GENERATION

To extract a DEM from a stereo-pair, it is necessary to match points on the one image with the corresponding points on the other image. For this purpose, PCI system employs an area-based image matching technique and produces the DEM through a comparison of the respective grey values on each of these images. This procedure utilizes a mean normalized cross-correlation matching method with a multi-scale strategy to match the image using the statistics collected in defined windows. Matching is performed by considering the neighbourhood surrounding a given pixel in the left quasi-epipolar image (thus forming a template) and moving this template within a search area on the right epipolar image until a position is reached which gives the best match. The actual matching method employed with PCI software generates correlation coefficients between 0 and 1 for each match 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 sub-pixel accuracy. The difference in location between the center of the template and the best matched pixel position gives the disparity or parallax arising from the terrain relief, from which the absolute elevation value is then computed. This produces a regular grid of elevation values which are extracted to form the DEM. The interval between the points on the grid was 30m for stereo-model tested in this work. Fig. 4 shows the 3-D view of this DEM from Black Sea side.
With extracted DEM, PCI system gives DEM report file which mainly includes elapsed time for extraction process, maximum and minimum elevations for DEM area, DEM cell spacing, elevation residuals for the GCPs used in bundle orientation phase and average, maximum and rmse errors. According to this report file, 2 hours 7 minutes spent for DEM generation with the DEM correlation success rate of 0.51. Finally, rmse error was found to be ±7.2m (less than 0.5 pixel) with the maximum error of 17.6m. This rmse value simply show the accuracy of matching at control points which are always well-defined features.

VI. DEM ANALYSIS

To go further and validate the data quality – more especially in terms of geometric accuracy – of the DEMs extracted from ASTER stereo-pair of Zonguldak testfield, three different tests have been used:

(i) DEM accuracy check by different types of GCPs;
(ii) a comparison of the height values given by the photogrammetrically produced reference maps and the corresponding elevation values given by the matched DEM; and
(iii) Comparison of superimposed contours.

A. DEM Accuracy Check by Different Types of GCPs

Independent accuracy check of matched DEM was first carried out by GCPs measured by GPS survey. For this analysis, program DEMINT from Hannover University was utilized. This program locates the GCPs inside raster DEM in according to their planimetric coordinates and finds their heights by interpolating the neighboured grids. For this, bilinear interpolation based on the neighboured 4 points has been implemented and RMSE-Z was obtained as ±11.98m. Another test was realized by the use of control points located along the road with a certain interval. These points were digitized from the 1:2,000 scale road maps produced by the Highway Department of Turkey. These points were then input to the program DEMINT with their object coordinates for interpolation inside the ASTER DEM. This process resulted in a rmse value for Z as ±13.41m, but these values are influenced by steep slopes, just besides the roads in the mountainous region.

B. Comparison of the Height Values of Reference DEM Against the ASTER DEM

For the detailed analysis, the matched DEM was checked by a reference DEM based on digitised contour lines from the 1:25,000 scale topographic maps using program DEMANAL which was developed by the Hannover University. Fig. 5(a) and (b) shows the greyvalue-coded forms of reference DEM and matched ASTER DEM. The similarity between two DEMs is quite visible. Firstly, from the frequency distribution of height values of reference DEM it was seen that, the major elevations in the test area are in the range up to nearly 600m above sea level with an average altitude of 299m and a maximal height of 847m. Before DEM check, the accuracy of reference DEM was tested by the control points measured with a GPS survey and RMSE-Z was obtained as ±6.60m. Mean DZ discrepancy was equal to –2.95m. Then, RMS-Z without systematic part was found to be ±5.91m. Height differences showed a dependency upon the terrain inclination and can be expressed with an equation of $\text{RMSE-Z} = 4.7 + 22 \times \tan(\text{slope})$. 

For the separation of forest influence from the DEM generation, image classification result (see Fig. 6) acquired using Landsat TM scene of the experimental area was used in the test. The forest layer can also be respected by the analysis program DEMANAL. In this case, analysis of DEM can be done for forest covered areas and also for the areas without forest. Furthermore, analysis of DEM can be made for the different height levels separately. The frequency distribution of the discrepancies leads to information about specific problems which can be caused by the vegetation heights. Because reference DEM corresponds directly to the surface while generated DEM with image matching refers to the visible surface of the vegetation and to the roofs of buildings. Obvious mismatching can be excluded by a selectable tolerance limit.
The sign of DZ discrepancies determined by the reference DEM minus matched DEM. In this case, there are strong systematic shifts of the matched DEM against the reference DEM, they are reaching up to +12.7m and +16.7 for open and forest areas respectively (see Table 2). These positive shifts confirm that reference DEM above the matched DEM. However, logically, it should be reverse and this is especially the case for the forest areas which can be explained by the influence of the vegetation to the image matching, while the reference DEM has been measured manually setting the floating mark down to the solid ground, even if some trees are available. The shifts are also visible in asymmetric shift of the frequency distribution which resulted a not normally-distributed pattern. RMSE-Z values for forest and open areas are quite close each other, this confirms that the matching performance in open and forest areas are quite equal because of the high contrast of ASTER images taken in near infrared bands. Moreover, changing DZ-limit (70-100m) does not make prominent changes on the final accuracy. Furthermore, the RMSE-Z values of matched DEM obtained as in the range of about 21-22m and worse than a priori Z-accuracy (13-14m) computed on independent check points. The difference is due to the fact that DEM points are rarely easily identifiable unlike well-defined features of ICPs.

**TABLE 2**  
**DISCREPANCIES BETWEEN THE MATCHED DEM AND THE REFERENCE DEM**

<table>
<thead>
<tr>
<th>Area type</th>
<th>RMSE-Z [m]</th>
<th>shift [m]</th>
<th>RMSE-Z without shift [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DZ-limit = 70m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>open area</td>
<td>24.60</td>
<td>12.66</td>
<td>21.10</td>
</tr>
<tr>
<td>forest</td>
<td>26.69</td>
<td>16.59</td>
<td>20.91</td>
</tr>
<tr>
<td>DZ-limit = 100m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>open area</td>
<td>25.34</td>
<td>12.67</td>
<td>21.95</td>
</tr>
<tr>
<td>forest</td>
<td>27.42</td>
<td>16.64</td>
<td>21.80</td>
</tr>
</tbody>
</table>

The height discrepancies were analyzed in a view of the terrain inclination. As can be seen from the Table 3, slope depending component of RMSE-Z are quite small, showing that there is no strong dependency upon the slope.

**TABLE 3**  
**STANDARD DEVIATION OF HEIGHT DEPENDING UPON TERRAIN INCLINATION**

<table>
<thead>
<tr>
<th>Area type</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside forest, DZ up to 70m</td>
<td>[SZ = 23.94 + 2.338 \times \text{TAN(SLOPE)}]</td>
</tr>
<tr>
<td>Inside forest, DZ up to 70m</td>
<td>[SZ = 26.63 + 0.612 \times \text{TAN(SLOPE)}]</td>
</tr>
</tbody>
</table>

**C. Comparison of Superimposed Contours**

In this method, first of all, the contours that have been extracted from the ASTER DEM at an interval of 60m have been loaded into PCI system. Also the contours at the same interval (60m) that have been digitized from the 1:25,000 scale topographic maps were loaded over the first set of contours to form a map with two sets of superimposed contours. These contours will not fit exactly due to the errors that are present in both sets of contours. In the case of the contours from the existing maps, these errors come both from the original compilation of the map that have been digitized and the errors of the measurements made during the digitising procedure itself. Then, of course, errors are present in the contours extracted from the DEM. These derive both from the accuracy of the DEM elevations themselves arising from the matching algorithm that has been used by the system in addition to the morphological nature of the area and the contouring procedure itself.

In Fig. 7, DZ discrepancies between two DEMs are shown as a function of grey values. While dark black color is indicating the highest minus DZ residuals, bright white represents the positive DZ values. As can be seen from this figure, there are some dark and white spots occurred as a result of matching failure. However, high DZ discrepancies always follow the topography and appear mainly at the ridges. Figure which shows difference DEM, gives the exact similarity to the topography of the testfield and this confirms that there is a translation between matched and reference DEM that was also shown as positive bias values in the previous section.

**VII. ORTHOIMAGE GENERATION AND VALIDATION**

For the area to be covered by an orthoimage, a suitable digital elevation model (DEM) providing the XYZ coordinate values for all the DEM points must be available. For this purpose, the elevation derived from the prior image matching of the ASTER images – which were arranged in a regular grid – were available to represent the terrain. From these points, an elevation value can be derived for each pixel of the orthoimage. Obviously any errors in elevation will create planimetric errors in the orthoimage. Therefore the accuracy of the elevation model has a great influence on the accuracy of the final orthoimage. Either one (i.e. the nadir or the backward scene) of the original uncorrected images can be transformed into an orthoimage. The correct positions in the digital image are found according to the photogrammetric projection equations using the parameters of the exterior orientation together with the elevation data. Once the orthorectification process has been completed, it is also necessary to find the corresponding grey value for each pixel in the orthoimage. The relevant value is found through a suitable interpolation or resampling carried out using the grey values of the pixels adjacent to each particular orthoimage pixel.

![Figure 7. Image of DZ discrepancies between matched and reference DEM.](Image)
Using the related module of PCI system, stereo-model covering the test area has been used to create orthoimage utilizing the DEM with elevation values created at 30m intervals. In the input to this program, the particular digital elevation channel that is to be used must be specified. In addition to this, the database input file must be specified; this file should contain the imagery and the relevant exterior orientation segments (in this experiment, nadir image component was used). Also the output file should be specified; if not, the program will create a new image database and will geocode it such that the orthorectified image will be fitted to the ground control points with the same resolution as the original uncorrected image. The database file name that contains the DEM data should also be specified, together with the resampling method that is to be used.

Based on the authors’s experience, one can say that the quality of the final corrected output image and the time required in its calculation is highly dependent on the resampling method chosen. This program offers three of the more popular resampling methods: nearest neighbour, bilinear interpolation, and cubic convolution. For the production of the orthoimages in this study, the cubic convolution method has been used. This method uses the weighted average of sixteen surrounding pixels in the uncorrected image to give the DN (i.e. grey level) value of the new pixel in the corrected image. It seems to provide a slightly sharper image than the bilinear method.

Regarding the geometric accuracy of the final orthoimage, a check was carried out by measuring quite independently on the orthoimage the position of 22 GCPs lying within the area of main test scene. These points have been measured using the PCI system and the transformation and comparison of the main test scene. These points have been measured using check was carried out by measuring quite independently on.

The resulting RMSE values were ±14.43m in X and ±11.29m of the GCPs was done using the similarity transformation. The PCI system and the transformation and comparison of the contents (Jacobsen et al., 1998). That means, based on a pixel size of 15m, maps in the scale range of 1:200,000 can be created. However, if the mapping accuracy shall be 0.2mm, a horizontal accuracy of ±40m is required and this is guaranteed by ASTER images. With a base-to-height-ratio of 0.6, rmse value in Z of approximately ±13m could be reached. Based on ASTER scenes, with the use of automatic image matching, DEM with 30m grid cell was generated. The comparison of matched DEM against the reference DEM based on digitised contour lines from the 1:25000 scale topographic maps was carried out and resulted in positive systematic biases between two DEMs. When these systematic shifts taken out, RMSE-Z was obtained in the range of ±21-22m for both open and forest areas. Moreover, superimposed contours from two DEMs show the shifts more clearly and image representation of discrepancies point out that the highest DZ values are located at the ridges. Orthoimage generation was completed successfully and its accuracy check with GCPs shows the errors are in random pattern both in extent and direction.

**REFERENCES**


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