ACCURACY ANALYSIS OF DEMS DERIVED FROM ASTER IMAGERY

J. A. Gonçalves, A. M. Oliveira

Science Faculty – University of Porto, Portugal
jagoncal@fc.up.pt, anamariap@mail.telepac.pt

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ABSTRACT:

ASTER acquires along track stereoscopic imagery, with a spatial resolution of 15 meters. Automatic generation of Digital Elevation Models (DEMs) from these images is a well established process, implemented in many commercial software packages. It can provide relief information for areas with poor coverage of topographic mapping.

This paper presents a study of the accuracy achieved in DEMs extracted from ASTER, for an area in Portugal, using the PCI OrthoEngine software. Images were orientated with ground control points (GCP) obtained from topographic maps. Experiments were carried out in reducing the number of GCPs. A number of 5 or 6 GCPs was always required to orient the images, in order to keep the accuracy achieved with larger numbers of points. It was possible to conclude that more use could have been done of the approximate orientation provided in the image header. A grid of points derived from the sensor position and attitude, estimated by onboard equipment, is given in the image header. The precision of these data was assessed as being better than 100 meters. A significant reduction in GCP requirements would be possible if more use of this information would be done.

The vertical accuracy of the extracted DEMs, assessed with a 8 m DEM grid, produced by a local mapping agency, was of 9 meters in areas of mountains with low vegetation. The percentage of coverage of the DEM is very large, however the automatic filling of gaps, in areas where the stereo-matching failed, degraded the DEM detail and accuracy. A manual edition of gaps, according to user perception of relief forms is more appropriate when deriving DEMs for production and update of topographic map products.

1. INTRODUCTION

1.1 DEMs from optical satellite data

Digital elevation models are important data sources in topographic mapping production, such as contour generation and image ortho-rectification. Terrain analysis in a GIS also requires those types of data, which in general are available from mapping agencies in developed countries. However, large parts of the Earth are not properly mapped in medium scales, such as 1:50,000.

Satellites can provide DEMs for the map production and other applications through different means. Among the optical sensors, across-track stereoscopy has been widely used, for example in the SPOT programme, with SPOT 1 to 4. The two images of a stereopair are acquired pointing the sensor to the same area, with different incidence angles, in different orbits. Time separation between images can range from a few days to months. Cloud coverage makes the acquisition of stereopairs difficult. Different sun illumination conditions, as well as different vegetation growth, produce significant image differences, complicating the automatic stereo matching.

Along-tack stereoscopic image acquisition requires two sensors with different inclinations, observing at the same time. SPOT-5, the most recent satellite of the SPOT programme carries, among other sensors, a system of this type, the High Resolution Stereo (HRS) system (Spotimage, 2002). That is also the case of ASTER which is equipped with two telescopes, both sensible in the range of 0.78-0.86 μm, one pointing in the nadir direction and the other pointing backwards, with an offset angle of 26 degrees. This leads to a base-height ratio of 0.6 (ERSDAC, 2001), which is appropriate for automated extraction techniques in various terrain conditions (Hirano et al., 2003). Time separation is of only 60 seconds. Illumination conditions are very similar allowing for an efficient automatic matching. The two bands are identified as 3N (nadiral) and 3B (backwards). Band 3N is associated with two others. The three bands (1, 2 and 3N) are acquired by Aster VNIR imaging system (ERSDAC, 2001) and have an image size of 4100 by 4200 pixels. Band 3B has 5000 by 5400 pixels.

1.2 Orientation of linear array images

The extraction of DEMs in a well defined cartographic reference system requires that exterior orientation is well known. Ground control points are required in order to determine a set of parameters of a sensor model that express the mathematical relation between ground and image coordinates.

Sensor models for optical sensors, such as SPOT or ASTER, comprise position and attitude parameters. Usually some orbital parameters are considered, in order to describe the sensor position, and 3 absolute attitude parameters (roll, pitch, yaw) at the initial image instant. Together with the orbital perturbation theory and attitude variations measured on board, position and attitude can be calculated for any image line. The sensor model is based on the colinearity equations. Different variations are described by many authors. See for example Kratky (1987), Gugan and Dowman (1988), Westin, (1990) or Toutin (1994). Commercial software packages for mapping from satellite images implement this type of physical sensor models.

Satellites carry navigation equipment that can estimate the exterior orientation parameters. The image geo-location of

optical satellite images is usually in the order of 100 meters. For example, in the case of SPOT-4, the DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) positioning system provides positions with an accuracy of 1 meter or better (Spotimage, 2002). Therefore the geo-location uncertainty is caused by the absolute attitude. Anyway, a significant reduction is possible in the number of GCPs since only attitude parameters are needed.
Alternative orientation methods are also possible. Dial and Grodecki (2002) describes the orientation of Ikonos imagery (also a linear array sensor) based on adjustments in image space.
Commercial packages that deal with satellite images implement, in general, physical sensor models. That is the case of PCI OrthoEngine, used in the work described in this paper. However, the user does not have control on the parameters considered in the orientation or on the initial approximations.

1.3 DEM generation with commercial software

PCI Orthoengine was used in this work for the image orientation and DEM extraction. The process is very straightforward and can be carried out by unexperienced users. It consists of the following steps (PCI, 2000):
1. Define the coordinate system. Usually, cartographic systems, such as UTM, are used. A local geodetic datum, different from WGS84, can also be chosen. Users can enter their own datum by means of the 3 or 7 parameter transformations.
2. Chose the sensor model to use. A global option can deal with different sensors including optical and SAR. Images are input preferably in their standard distribution format. This allows for the use of the initial orientation parameters, provided in the ancillary data.
3. Enter the GCP data and apply the sensor model. A residual report is output.
4. Generate epipolar images: in this step images are transformed so that parallax effect exists only in *x* direction. In the case of ASTER this step is essentially a rotation of 90 degrees since that, due to the across track stereo mode, disparities occur in *y* direction.
5. Automatic DEM generation: the user defines the pair of epipolar images to use and the process is automatic. The only options respect to DEM spacing and detail and if holes are filled automatically by interpolation. No options exist explicitly related to the matching process, such as window size or acceptable correlation value.
6. DEM geocoding: the initial DEM is in the epipolar image space. This step consists in projecting from image to map space. There is an option to fill gaps, by inerpolation, of holes resulting from the resampling process.

DEM generation from ASTER is a well documented process. Results obtained by several authors refer a vertical accuracy of 10 meters or better, especially in terrain with low vegetation. This study intends to assess, making use of a standard commercial software, how efficient can be the DEM extraction, the vertical accuracy that can be achieved and how small can be the number of ground control points.

2. EXPERIMENTS OF DEM GENERATION

2.1 Data used

Some images of a region in north Portugal, near the city of Porto, were provided by the Japanese Space Agency. One of these images was used for the experiments of DEM generation. Figure 1 shows a map of the region, where bands 3N and 3B are represented. The region has heights ranging from sea level to 1000 meters.
A DEM produced by the Portuguese Army mapping service was used in order to assess the accuracy of heights derived automatically from the images. This DEM, with a spacing of 8 m, was produced by photogrammetric means and is known to have an accuracy better than 2 m. The rectangle of the DEM is shown on the map of figure 1.

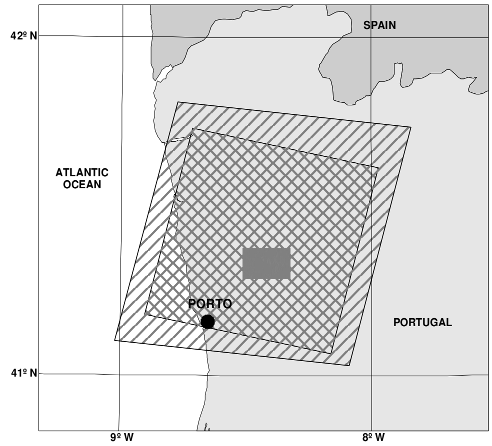
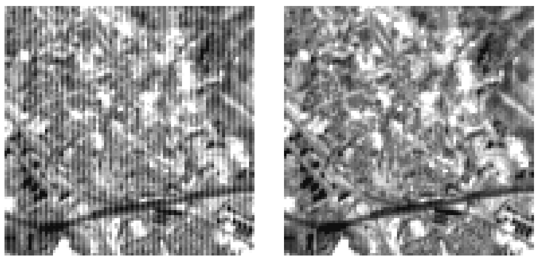


Figure 1. Location of the 3N and 3B images (dashed polygons) and DEM (small grey rectangle).

The DEM area (160 km2) has heights ranging from 30 to 600 meters. Although the area is small relative to the image area, its relief is well representative of the whole area.

2.2 Radiometric corrections

Aster images of the level 1A show a stripping effect as can be seen in figure 2. Image (a) shows a sample of 100 by 100 pixels extracted from band 3N.
In order to avoid possible problems in the stereo correlation this effect was corrected. Instead of using a filter, a different approach was implemented. The even and odd columns of the 3N image were extracted and the histograms of these new images were calculated. The two histograms, represented in figure 3, are very similar and differ only by a systematic shift.



(a) (b)

Figure 2. Sample of band 3N of the ASTER image: (a) original image, showing stripping, and (b) after correction.

This shift was found to be of 7 units of greyscale value and it was added to the pixels of the even lines. Figure 2(b) shows the corrected image. In the 3B band the stripping effect was less significant and a correction of only 2 units was applied.
However, experiments of matching images with the radiometric correction did not give any improvement in the matching success or in better accuracy, relatively to the results obtained with the original images.

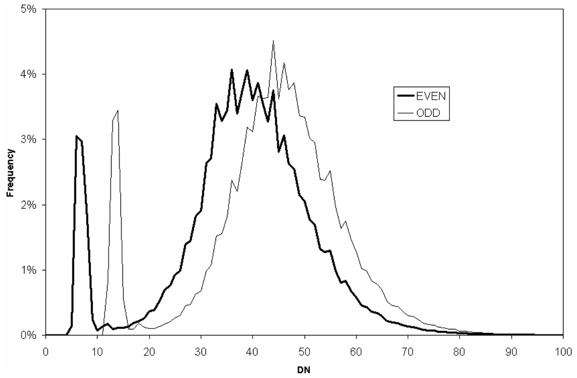


Figure 3. Histograms of even and odd columns of the 3N band

2.3 Image orientation

GCPs were collected from topographic maps of scale 1:25,000. The coordinate system used was the local map projection (Gauss-Krueger) and the local datum (Datum Lisboa). PCI software was configured in order to accept this reference system. Figure 4 shows the location of the points on the 3N image. All points were identified on both images. Heights were interpolated from contours with 10 m contour interval.

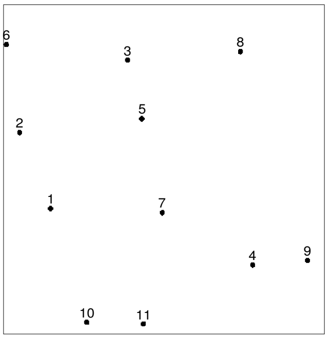


Figure 4. Location of the GCPs on image 3N

The root mean square (RMS) of the residuals after the bundle adjustment in PCI software, of the residuals in these points, in x and y directions, are listed in table 1.

Image	RMS-x	RMS-y
3N	0.81	0.86
3B	0.31	0.62

Table 1. RMS of residuals in image orientation with 11 points

Some experiments of reducing the number of GCPs were carried out. Some points were kept and the others were taken as check points (CP). Keeping the 4 points close to the image corners (6, 8, 9, 10), very small residuals were found but for the 7 check points the RMS were large. Table 2 contains the results obtained for both images on the GCPs and CPs.

Image	GCPs		CP	
	RMS-x	RMS-y	RMS-x	RMS-y
3N	0.02	0.04	1.78	1.81
3B	0.17	0.71	1.21	3.93

Table 2. RMS of residuals in image orientation with 4 GCPs and RMS of 7 CPs

Some experiments with 3 GCPs only, gave very bad results, in general with RMSs, both on GCPs and CPs, above 10 pixels. After experimenting different combinations of GCPs it was possible to conclude that 3 points are never enough to orientate the image. The minimum would be always 4 points. In order to have some redundancy for the least squares adjustment at least some 5 or 6 will be needed.

Not much is known about internal procedures followed by the software. The requirement of a large number of GCPs is a limitation since the most interesting regions to apply satellite images are those where GCP availability is more difficult.

Some alternatives would be possible, as for example, to fix the orbital data given in the ancillary data and let only attitude to be determined. That would be possible with 3 points only if the initial orientation data is accurate.

Aster images are provided in the HDF format with ancillary data, among which there is a set of simulated GCPs. For a grid of points in image space the equations of projection rays, obtained from the orbital and attitude data, are projected onto the reference ellipsoid. These points are a total of 143 (13 by 11 grid) for the 3N image and 176 (16 by 11) for image 3B, and completely cover the images.

The accuracy of these points depends on the accuracy of the orientation data. In order to assess them they were used to rectify the images using polynomials. Third order polynomials presented residuals with RMS below 0.2 pixels for both images. Once images were rectified on the local mapping system, vector data (from 1:25,000 maps) was overlapped. Figure 5 shows streets in the city of Porto on images 3N and 3B, respectively.

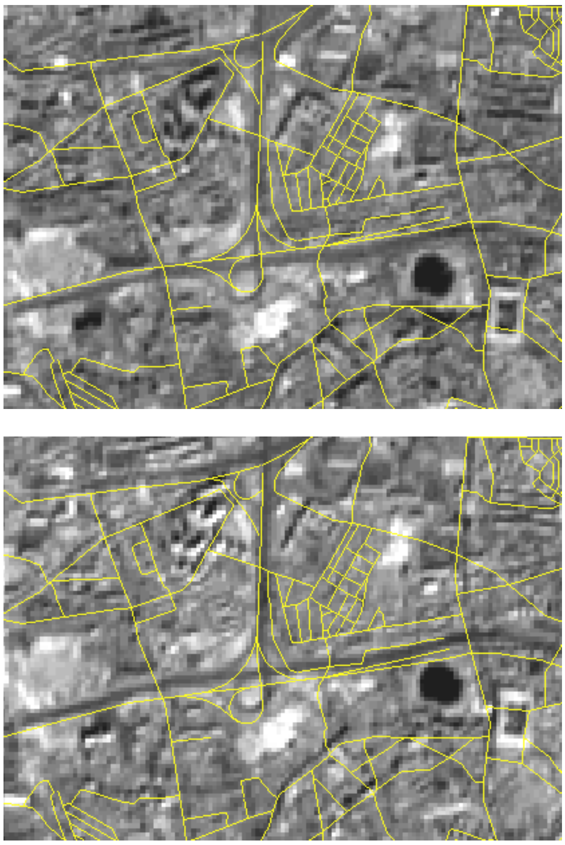


Figure 5. Vector data superimposed on 3N and 3B images rectified with a 3rd degree polynomial.

The lack of coincidence depends on the inaccuracy of the orbit and attitude data and on the height of the area. Height above the ellipsoid in the area of the figure is of 150 meters. It can be observed that the coincidence is better for the 3N image (errors around 35 meters) than for 3B (lack of coincidence around 60 meters, in opposite direction). A larger error is expected for the 3B image due to the larger incidence angle. Among these errors there is a component resulting from the orbit and attitude data, which is only of a few tens of meters.

It would be possible to improve the orientation method, making use of these data, which would require only very few GCPs. A possible alternative would be to apply small corrections in image space by an affine transformation, as described by Dial and Grodecki (2002), for Ikonos.

2.4 DEM extraction and accuracy analysis

Once images are oriented, the epipolar images were generated and the DEM was extracted for the full image using half resolution (30 m spacing). The height range was known to be from 0 to 1000 meters and was given to the matching program.

The matching success was of 98%. The image had a few clouds, where the matching failed. However, some lower clouds were extracted. Figure 6 shows an image of the DEM were clouds can be identified (some not extracted, in black, and the ones extracted, with heights near the maximum, in white). Small gaps were filled by interpolation.

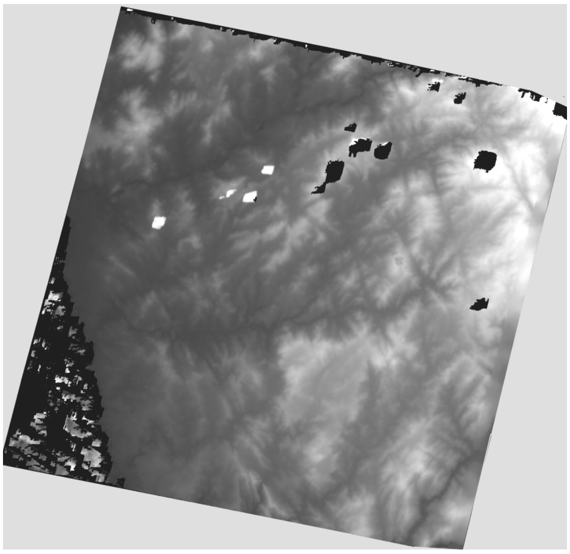
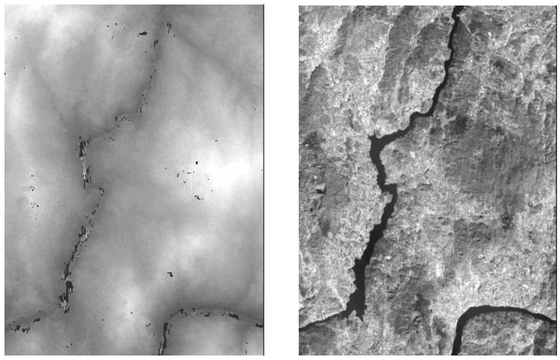


Figure 6. DEM extracted for the whole area.

Failures also occurred in water surfaces, which are very uniform. That is the case of the sea, in the bottom left of the image.

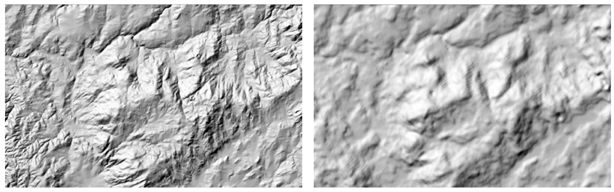
Figure 7 shows the extracted DEM (a), without any interpolation of gaps or smoothing, for a region of approximately 11 by 8 km and the corresponding image (b). There are two rivers in the area where some heights could not be extracted. However, some heights where wrongly extracted. Editing should be done in such areas according to the knowledge of the terrain, in this case a flat water surface.

In order to assess the accuracy of the heights obtained, the extracted DEM was compared with a control DEM, derived from aerial photographs. This DEM covers an area of 16 by 10 km and was produced by the Portuguese Army mapping service. It is known to have an accuracy better than 2 meters. Figure 8 shows shaded relief images of both DEMs.



(a) (b)

Figure 7. DEM extracted (a) for a small area, without any interpolation, and corresponding image (b)



(a) (b)

Figure 8. Shaded relief representations of the control DEM (a) and DEM derived from ASTER (b)

The statistics of the differences between the DEMs are listed in table 3 (all values in meters). Figure 9 shows the histogram of the differences.

Min	-47
Max	69
Mean	4.0
St. Dev.	8.7

Table 2. Statistics of the differences between the two DEMs.

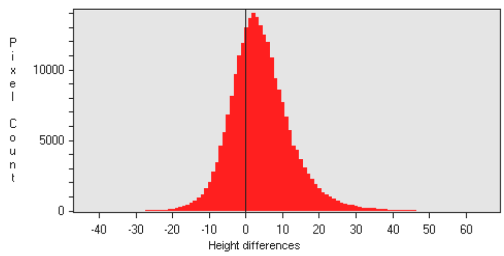


Figure 9. Histogram of the height differences between the extracted DEM and the control DEM

The standard deviation of 8.7 m is a very good result and is according to what is referred by other authors (Toutin and Cheng, 2001, Hirano et al., 2003). There were no clouds or very uniform areas, such as water surfaces, and the area contains essentially hills with low vegetation and agricultural fields, which is the appropriate type of terrain for good results. The accuracy analysis was made with very accurate data but over a small area. More tests should be done, distributed over the whole image, in order to get a more significant figure of the global accuracy.

Two cross sections, one in direction east-west and the other north-south, were plotted for both DEMs (figure 10). It can be seen that in some slopes the ASTER DEM tends to be above the actual terrain.

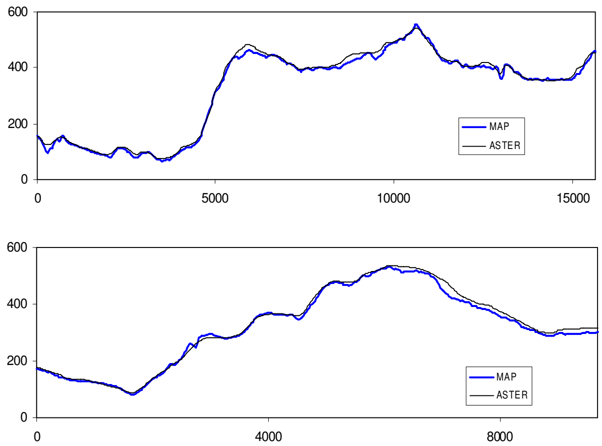


Figure 10. Cross sections of the DEMs (east-west and north-south)

3. CONCLUSIONS

Aster provides a simple and effective method of DEM generation. The percentage of success is very large, due to the simultaneous acquisition of stereo data. The success of automatic stereo-matching is only limited in uniform areas such as water surfaces. However, in those cases editing is very simple.

DEM production is possible in remote areas that require medium scale topographic mapping. The typical vertical accuracy around 10 meters can easily be achieved using standard software packages.

However, these packages require relatively large numbers of GCPs, in order to obtain properly geo-referenced DEMs. This may be a limitation due to the difficulty in GCP acquisition. A better use would be possible from position and attitude data provided with images. These data provides a very good a priori geo-location of images, with errors of few tens of meters. Simplifications in the sensor model for image orientation may be possible, requiring less ground control and keeping the same accuracy standards in DEM geo-referencing.

References from Journals:

Gugan, D. and I. Dowman, 1988. Topographic mapping from SPOT imagery. *Photogrammetric Engineering and Remote Sensing*, 54 (10): 1409-1414.

Hirano, A., R. Welch, H. Lang, 2003. Mapping from ASTER stereo image data: DEM validation and accuracy assessment. *ISPRS Journal of Photogrammetry and Remote Sensing*, 57(2003), pp. 356-370.

Kratky, V., 1989. On-line aspects of stereophotogrammetric processing of SPOT images. *Photogrammetric Engineering and Remote Sensing*, 55(3): 311-316.

Toutin, T., Cheng, P, 2001. DEM Generation with ASTER Stereo Data. *Earth Observation Magazine*, June 2001.

Westin, T., 1990. “Precision rectification of SPOT imagery”. *Photogrammetric Engineering and Remote Sensing*, 56(2): 247-253.

References from Other Literature:

Dial, G., J. Grodecki, 2002. Block adjustment with rational polynomial camera models. ACSM-ASPRS 2002 Annual Conference Proceedings. Washington, D.C., USA, April 19-26 2002.

ERSDAC, 2001. ASTER user guide – Level 1 Data Products Version 3.1. Earth Remote Sensing Data Analysis Centre.

PCI, 2000. OrthoEngine V7.0 – User Manual.

Spotimage, 2002. Spot Satellite Geometry Handbook (document S-NT-73-12-SI), Spotimage, 15-01-2002.

Toutin, 1994. Multisource data integration with an integrated and unified image geometric modelling. *Sensors and environmental applications (Proceedings of the 14th EARSel Symposium)*. 33 (2): 500-504.

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