

ORIENTATION AND DEM EXTRACTION FROM ALOS-PRISM IMAGES USING THE SRTM-DEM AS GROUND CONTROL

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ABSTRACT:

This paper presents a methodology of image orientation and DEM extraction from ALOS-PRISM stereopairs without the use of GCPs. It uses the approximate geo-location information derived from the sensor navigation instruments and the SRTM-DEM. The method consists in the extraction of a relative DEM, which initially is not correctly geo-referenced. This relative DEM is then matched to the SRTM-DEM, allowing for the determination of positional correction to the image orientation. Although the SRTM-DEM has a much coarser resolution, the positioning accuracy of this matching method was found, in previous work, to be of the order of 5 meters in plan coordinates, using DEM patches of 5 by 5 km. Tests were realized with PRISM images of a relatively mountainous region in Portugal, with heights ranging from sea level to 1400 meters. The horizontal accuracy, assessed with 56 independent check points identified on orthophotos of 0.5 meter resolution, gave an RMSE of 2.7 m and 3.9 m in x and y directions. In terms of vertical accuracy an RMSE of 2.8 meters was found for a total of 45 ICPs measured on a DEM, derived photogrammetrically for mapping scale 1:10,000. The overall accuracy is compatible with the standards for 3D data extraction for 1:25,000 scale mapping, and has the advantage of not requiring any field survey for ground control acquisition.

1. INTRODUCTION

The PRISM sensor on board of Japanese ALOS satellite is fully dedicated to the acquisition of high resolution stereo imagery. It is composed by a triple line scanner, that provides along-track overlapping images with 3 different viewing angles (forward, nadir and backwards). Its high resolution, with a ground sampling distance (GSD) of 2.5 meters, has a good potential for relief mapping with a positional accuracy compatible with scale 1:25,000 (Takaku et al., 2005, Takaku and Tadono, 2007). Topographic mapping at this scale is very important for planning purposes and most of the undeveloped areas in the world are not mapped at any scale better than 1:100,000.

Other optical remote sensing satellite programs have concentrated on relief mapping from stereo images. Missions of this type with a continuous operation and global coverage were SPOT(1-4), ASTER and SPOT-5. SPOT sensors (up to number 4) acquired stereo images in across-track mode, with a GSD of 10 meters and a base-height ratio that could reach 1 (Spotimage, 2004). Since images are acquired in different orbits, with a time separation of a few days or weeks, digital elevation model (DEM) extraction may be difficult due to different tonalities. ASTER and SPOT-5 incorporate along-track sensors fully dedicated to the acquisition of stereo images, allowing for an easier processing in terms of automatic DEM extraction. ASTER, with a spatial resolution of 15 meters allows for a vertical accuracy of up to 8 meters root mean square (RMS) error (Toutin, 2001). The HRS sensor on board of SPOT-5, with a higher spatial resolution and a better base-height ratio allows for an improved vertical accuracy, ranging from 3 to 5 meters (RMSE) depending on terrain type (Baudoin, et al., 2004, Toutin, 2006). ALOS, with an along-track triple sensor, a base-height ratio of 1 and a spatial resolution better than any of the previous stereo sensors is a very promising system for global accurate relief mapping. Other sensors with even higher resolution, such as Ikonos or Quikbird, although achieving a

better accuracy, do not acquire stereo data in a systematic manner.

The other very important remote sensing mission dedicated to relief mapping was the Shuttle Radar Topographic Mission (SRTM), operated by NASA during 11 days in February 2000 (Rodriguez et al., 2006). This is a case of very successful relief data production that provided nearly global mapping (80 % of the land mass) with detailed DEMs. Data in a resolution of 3" (90 m at the Equator) is freely provided for most of the planet (56°S-60°N). These data have a vertical accuracy that proved to be far better than the initially expected (15 m at 90% confidence). Rodriguez et al. (2006) refer final accuracy, at 90% confidence level, of 6.5 m for the vertical component and 9 m for the absolute geolocation.

The fact that the SRTM-DEM data are freely available must be taken into account in the planning and exploitation of other remote sensing programs for relief mapping. A project such as ALOS-PRISM does not start from scratch, since for most of the planet the SRTM-DEM exists. An obvious improvement provided by PRISM is the increase of DEM detail due to the much better resolution. An improvement in vertical accuracy is also expected: assuming a parallax uncertainty of 1 pixel, the B/H ratio of 1 leads to a height uncertainty of 2.5 meters. In practical terms due to the presence of blunders in a fully automatic DEM extraction, accuracy may be a bit worse (Gruen et al., 2007), but anyway an improvement with respect to SRTM is expected. In terms of completeness, ALOS DEMs can fill the voids in the SRTM-DEM especially in mountainous areas. Areas of high latitude, not mapped by SRTM, can obviously be observed and mapped by ALOS, although with the limitations of weather conditions.

This study explores a synergy between the existing SRTM-DEM and ALOS PRISM imagery. The first important use of the SRTM-DEM in the processing of an ALOS stereopair is to replace ground control points for the purpose of image

orientation. The methodology is essentially based on extracting a relative DEM from a stereopair, that only went through a relative orientation, and then bring it to a correctly geo-referenced position by matching the SRTM-DEM. This procedure is known to have a planimetric accuracy as good as 1/20th of the SRTM pixel size, i. e. approximately 5 m. This methodology was successfully applied with SPOT and ASTER stereo images, completely avoiding the use of GCPs (Gonçalves, 2006, Gonçalves and Marçal, 2007). In the case of ALOS, image orientation requires the use of GCPs since exterior orientation provided by navigation equipment on board of the satellite have a geo-location uncertainty of some 50 meters (Fraser, 2007). The main interest in DEM extraction from PRISM images is for the remote and poorly mapped areas, in undeveloped countries, where ground control surveys are difficult to carry. The methodology proposed in this paper may overcome this limitation, avoiding any field collection of GCPs.

The second synergistic use of SRTM is in the DEM extraction. The previous knowledge of the terrain form provided by SRTM, in terms of elevation and slope orientation, facilitates the matching procedures, allowing for a faster and more effective automatic DEM extraction.

The test area is a mountainous area in North Portugal, near the city of Porto, with heights ranging from 20 to 1400 meters above sea level.

2. APPROXIMATE SENSOR MODEL

The PRISM images available for this project were of mode 1B2-R, in which images are resampled to a UTM projection. Using approximate sensor position and attitude, images are projected onto the ellipsoid level (Saunier et al., 2007), in the same manner as with other high-resolution imagery, and then projected to UTM. However, in image mode 1B2-R, the image still needs to be rotated to be aligned with UTM axes, so image lines approximately coincide with image lines in the original sensor geometry. An approximate sensor model was developed to deal with these images, not making use of co-linearity equations.

Several aspects of PRISM images, such as the very narrow field of view (2.9°), the fact that a very good initial orientation is known and that terrain height is much smaller than the satellite altitude allow for important approximations by linear relationships.

2.1 Object to image projection for the Nadir image

Sensor model equations establish a projection from object to image space. That will be done stepwise for the 1B2-R images, considering an estimation of relief displacement and additional positional corrections. The sensor model is established for the Nadir image.

Within the image ancillary data, an affine formula is given to convert from image coordinates to UTM and vice-versa (equation 1).

$$\begin{pmatrix} x_0 \\ y_0 \end{pmatrix} = \begin{pmatrix} A_1 & A_2 \\ A_3 & A_4 \end{pmatrix} \begin{pmatrix} E \\ N \end{pmatrix} + \begin{pmatrix} A_5 \\ A_6 \end{pmatrix} \quad (1)$$

where (x_0, y_0) are the predicted image coordinates, (A_1, \dots, A_6) are the given parameters and (E, N) are the UTM coordinates in Km (more precisely the E coordinate does not include the false easting of 500 Km). This relation is not exact due to the relief displacement and due to the inaccuracy of the initial exterior orientation. Figure 1 represents the displacement suffered by an object of height h . This effect can be estimated from equation (2), using the local incidence angle.

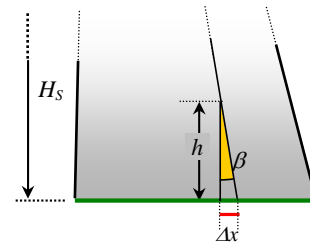


Figure 1. Relief displacement of an object with height h .

The corrected image coordinate, x'_0 ,

$$x'_0 = x_0 + \Delta x = x_0 + \frac{h \cdot \tan \beta}{2.5} \quad (2)$$

where h is the terrain elevation, β is the local incidence angle and 2.5 is the pixel size in meters. The tangent of β can be obtained dividing the distance from the point to the ground track by the satellite altitude. Figure 2 represents the image and the ground track in UTM map space. Satellite position and approximate image location given in the ancillary data are enough accurate to calculate the value of β , which is not larger than 3° (in that extreme case the relief displacement would be of 1 pixel for a height of 50 meters).

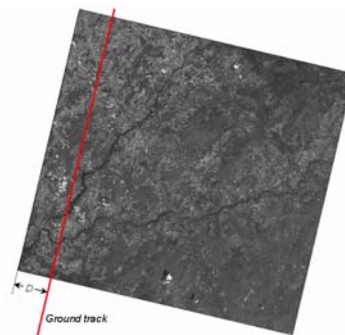


Figure 2. Nadir image and ground track drawn from the ancillary data.

The image coordinates corrected for the height effect will not coincide with the actual position of the point due to the uncertainty in the exterior image orientation, which was used in the processing of 1B2-R images. This effect is essentially a systematic shift, which can be corrected in image space, in the same way as is usually done for Ikonos images (Grodecki and Dial, 2003) and other sensors, by an affine transformation, according to equation (3):

$$\begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} = \begin{pmatrix} B_1 & B_2 \\ B_3 & B_4 \end{pmatrix} \begin{pmatrix} x'_0 \\ y_0 \end{pmatrix} + \begin{pmatrix} B_5 \\ B_6 \end{pmatrix} \quad (3)$$

where $(\Delta x, \Delta y)$ is the shift in image space, x'_0, y_0 are the approximate image coordinates. Parameters B_i , which define the transformation, are determined using some form of ground control. The standard approach is to use conventional GCPs. The alternative method proposed in this paper (section 3) is to use the SRTM-DEM.

The equations presented above do the projection from object space (in UTM coordinates) to image space. They can be easily adapted to do the inverse projection, provided that the terrain height is known. When a DEM is available this becomes an iterative process (Spotimage, 2004)

2.2 Registration of Forwards and Backwards images

Forwards (F) and Backwards (B) images suffer much larger relief effects. The approach followed in the approximate sensor model consists in register these two images to the Nadir image and determine y coordinate displacements, and relate them to heights.

The registration is done by means of the affine formulas that convert from image to UTM coordinates (also provided for images F and B). There is essentially the displacement in y direction, according to terrain elevation. A set of tie points were identified manually in order to assess those differences. Table 1 contains the statistics of the differences in x and y image coordinates, in pixel units.

| | F-N | | B-N | |
|-----------|------------|------------|------------|------------|
| | Δx | Δy | Δx | Δy |
| Minimum | -4.9 | 51.2 | -1.9 | -215.5 |
| Maximum | -2.8 | 271.5 | 0.7 | 56.6 |
| Mean | -3.8 | 134.9 | 0.3 | -77.7 |
| Std. Dev. | 0.48 | 57.0 | 0.56 | 56.6 |

Table 1. Statistics of differences between image coordinates of tie-points between images F and N and B and N.

In the case of the x coordinate there was a systematic shift of a few pixels between Forward and Nadir images. This corresponds to a need of a relative orientation, which in approximate terms can be seen as the shift in x coordinate. With the images in this form it is now simple to determine conjugate points by stereo-matching, with a search space in y direction.

In order to determine heights a calibration of the relation between terrain elevation and y displacement is needed. According to the particular situation of very narrow field of view of the push-broom scanners, the small terrain height relative to the satellite altitude and the small variations in sensor attitude during the acquisition of an image, it can be expected that this relation is approximately linear. Using a set of GCPs it is possible to calibrate this relation.

2.3 Assessment of the sensor model using GCPs

A set of control points were used in order to assess the sensor model and to be used as check points in the methodology

described in section 3. Planimetric coordinates of GCPs were measured on orthophotos of 0.5 m resolution. Elevations were obtained from a 10 m grid DEM, derived photogrammetrically for 1:10,000 scale mapping, with an expected accuracy better than 2 meters.

A total of 56 GCPs were projected onto image space with correction of relief displacement. Then the correction in image space (affine transformation, equation 3) was determined by least squares adjustment. A mean displacement of 80 meters was needed). Table 2 contains the statistics of the residuals obtained in the planimetric adjustment (image residuals, R_x, R_y , expressed in meters).

Image coordinates were also measured on images F and B, for a total of 45 GCPs (common to the 3 images) and displacements in y direction were calculated. They were plotted against heights and a first degree polynomial was determined by least squares. Table 2 also contains the statistics of the residuals in the linear regression (heights in metres).

| | $R_x (m)$ | $R_y (m)$ | $Rh (m)$ |
|-----------|-----------|-----------|----------|
| Std. Dev. | 1.6 | 1.3 | 2.6 |
| Minimum | -4.6 | -3.6 | -6.3 |
| Maximum | 3.3 | 2.3 | 7.9 |

Table 2. Statistics of the residuals obtained in the horizontal coordinate adjustment and on the calibration of the linear relation between parallax and height.

Figure 3 contains that plot of the y displacements (between F and B images) and heights. The linear relation determined is also in Figure 3.

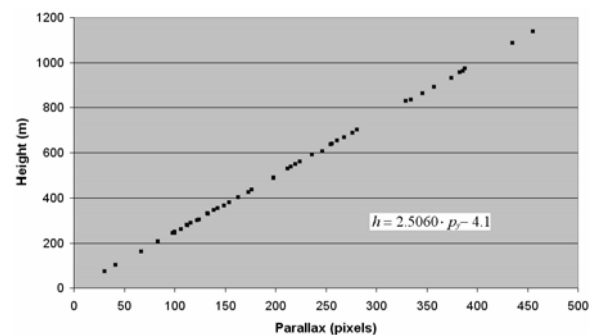


Figure 3. Graphical representation of heights against y -parallaxes, for a total of 45 GCPs

3. ALTERNATIVE ORIENTATION USING SRTM-DEM

3.1 Description of the method

The alternative method proposed makes use of The SRTM-DEM, instead of standard GCPs, in order to correct image orientation. From the image header it is possible to extract information for the correction of relief displacement in the nadir image. It is expected that the adjustment required after that is smaller than 100 m. The steps of the method are described below:

Step 1 - The first step is to identify tie points (TP) on the 3 images. These points should be in areas with good contrast to facilitate the image matching to be done around the TP. They should also be in areas with moderate relief because DEM matching does not work in flat areas.

Step 2 - From the nadir image coordinates it is possible to estimate terrain coordinates, by doing the image to object projection (intersection with the SRTM-DEM). Since the planimetric adjustment required is relatively small (of the order of 1 SRTM pixel), and the relief displacement in the nadir image is small, terrain coordinates only have a systematic shift.

Step 3 - Displacements in y image coordinates between F and B images (the parallax) are calculated. Using the heights estimated in step 2 the linear relationship can be determined by linear regression.

Step 4 - A large number of conjugate points are extracted by stereo-matching around each tie-point (in a rectangle of a few square km). Only very good matches, with high correlation are maintained. Coordinates and heights can now be determined for these conjugate points. A small DEM around the tie-point can be obtained, which is not properly geo-referenced, since images only have a relative orientation.

Step 5 - The fifth step is to determine the displacement required to match these small DEMs to the SRTM-DEM. Once this displacement is determined the tie point will act as GCP, since the local displacement is known.

Step 6 - Displacements in map coordinates are converted to the equivalent in image coordinates. For the set of tie points it is possible to determine the required planimetric adjustment (equation 3).

3.2 Application of the method

A total of 16 TPs, regularly distributed on the N image, were identified and measured on the 3 images. Using the projection from image to object (the SRTM-DEM), approximate coordinates and heights were obtained. The linear relation between parallax (p_y) and height (h) was obtained:

$$h = 2.5130 \cdot p_y - 5.9 \quad (4)$$

with an RMS of residuals of 7.2 m. At this stage heights are determined with some error, however in a large number of TPs, positive and negative errors will tend to be balanced, yielding a reasonable quality calibration.

A regular grid of 20 pixel spacing, centred on a TP, covering 5x5 km² was defined on the N image. Conjugate points were obtained on images F and B by stereo-matching. Only those with higher correlations ($\rho > 0.8$) were kept. Heights were determined by equation (4). Figure 4 shows in 3D the points extracted around one of the TPs.

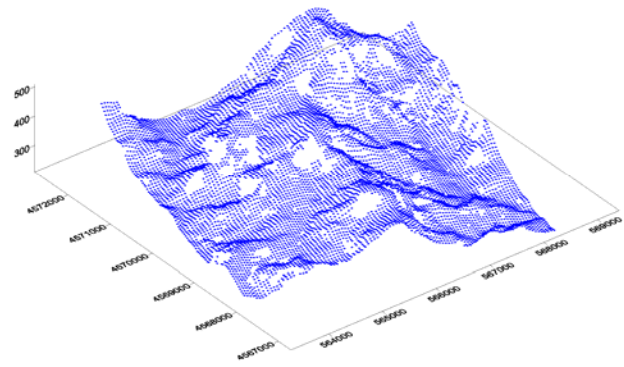


Figure 4. 3D view of points extracted in a rectangle of 25 km².

Figure 5 shows a profile of the SRTM-DEM (line) and the extracted points (dots), along that line. The slight displacement required to make the points fit the line can be detected.

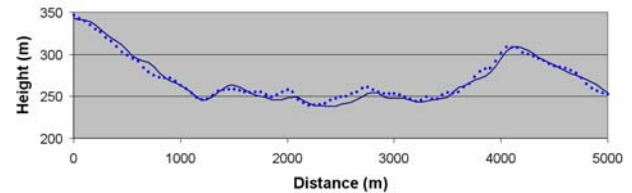


Figure 5. DEM profile and extracted points along that line.

The displacement, with components in easting and northing directions, is determined by matching the SRTM-DEM. Successive shifts (ΔE , ΔN) are applied to the points in order to determine the one that maximises the correlation coefficient between point elevations and SRTM elevations.

The same was done for areas around all the 16 tie points. Displacements in map coordinates were converted to the equivalent in image space. Finally the affine transformation (equation 3) was determined by least squares fit. The formula determined was:

$$\begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} = \begin{pmatrix} -0.000075 & -0.000030 \\ -0.000677 & -0.000079 \end{pmatrix} \begin{pmatrix} x'_0 \\ y_0 \end{pmatrix} + \begin{pmatrix} -8.2 \\ -24.9 \end{pmatrix} \quad (5)$$

with RMS of residuals smaller than 1 pixel in both directions. The precision obtained in the image orientation process is nearly as good as it was when the sensor mode was applied with standard GCPs.

3.3 Assessment with Independent Check Points

This orientation procedure used only SRTM as ground control. The 56 GCP previously used (section 2) will now be taken as independent check points (ICP) in order to assess the quality of the alternative orientation method.

These 56 ICPs were projected from map space to image space, using equation (5) and the corresponding errors in image space were obtained. Using relation (4) parallaxes (F-B) of 45 ICPs were converted to heights and compared to actual point heights. The RMS errors were the following (planimetric error converted to meters):

$$RMSE_x = 2.7 \text{ m}$$

$$RMSE_y = 3.9 \text{ m}$$

$$RMSE_h = 2.8 \text{ m}$$

4. DISCUSSION AND CONCLUSIONS

ALOS-PRISM allows for a positional accuracy and density of information well compatible with mapping scale 1:25,000. The methodology proposed in this paper is capable of doing an image orientation nearly as good as what is achieved with standard GCPs. The main advantage is to avoid any field work for GCP collection. However the method still has to be tested with images of different areas, in different types of terrain in order to be completely validated.

The method was applied to images of mode 1B2-R, which are not in original sensor geometry. This may limit the potential positional accuracy of ALOS-PRISM. Anyway the principle of orientation with a reference DEM surface can also be applied to images of modes 1A or 1B1, in original sensor geometry. In that case a rigorous sensor model would be used, doing adjustments in actual exterior orientation parameters, such as the sensor attitude angles.

A limitation that can be pointed to this methodology of matching elevation data is that it does not work in flat areas. However it still works in areas with relatively small mean slopes, such as 5%.

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