ORIENTATION OF SPOT STEREOPAIRS BY MEANS OF MATCHING A RELATIVE DEM AND THE SRTM DEM

J. A. Gonçalves [a]

[a] Faculdade Ciências - Universidade Porto,
Rua Campo Alegre 4169-007 Porto, Portugal - jagoncal@fc.up.pt

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ABSTRACT:
This paper presents a methodology to obtain an accurate exterior orientation of SPOT stereopairs using as ground control only the SRTM 3 arc second DEM. The method is based on the extraction of a relative DEM from the stereopair, after a relative orientation. This DEM is then matched to the SRTM DEM by correlation. Small portions of the extracted DEM are adjusted, leading to corrections of the geolocation of the stereopair. A set of ground control points are simulated in order to enter a standard procedure for image orientation. The method was tested with two stereopairs, from Portugal and France. The accuracy of the exterior orientation obtained is similar to what is achieved with GCPs measured in maps of scale 1:25,000. The method can be largely automated and may be useful to make a better use of many thousands of stereopairs available in the SPOT archive, although only for areas with some relief. Another application is the extraction of data to fill SRTM void pixels, especially in mountains.

1. INTRODUCTION

The exterior orientation of optical images, such as SPOT or ASTER, for precise geo-referencing, requires the use of a sensor model and a set of parameters characteristic of a particular image. These exterior orientation parameters describe the sensor position and attitude during the image acquisition and can be determined using ground control points (GCP) or can be derived by navigation equipment on board the satellite. This geo-referencing concept is important since the most relevant mapping applications of satellite data are in remote areas, where GCP collection is difficult. However, although positional parameters can be known with very good accuracy (e.g. DORIS positioning in SPOT-4, or GPS in other sensors) attitude determination has usually an uncertainty of the order of 100 meters. That is the case of SPOT sensors 1 to 4 (CNES, 2000). GCPs are still required to obtain accurate image orientation.

After nearly 20 years of image acquisition by several SPOT sensors, the SPOT image archive contains a few millions of images, many of them composing across-track stereopairs, and covering the whole planet. All of these images are provided with exterior orientation data with geo-location accuracy of the order of 300 meters for SPOT 1 and 2 and better than 100 meters for SPOT 4. The orientation of these images with accuracy similar to their spatial resolution can be done using topographic maps of scale 1:25,000. Since maps of this scale (or even 1:50,000) are not available for most of the planet and field survey may be either very expensive or not possible at all, the potential of the image archive was never fully exploited in terms of positional accuracy.

Global or near global high-resolution data sets, such as ortho-rectified images and Digital Elevation Models (DEMs) have recently become available. They might be a solution to provide the 3D GCPs for orientation of optical satellite images. The Global Land Cover Facility (GLCF, 2005) provides a global data set of Landsat ETM orthorectified colour images, of free access, with 15 meter spatial resolution, resulting from the fusion of multispectral and panchromatic bands. However, both the pixel size and the planimetric accuracy (of around 50 meters) are not appropriate for accurate orientation of SPOT imagery (10 or 5 m pixel spacing). DEMs derived from the Shuttle Radar Topography Mission (SRTM) are also freely available in the form of grids with 3 arc second spacing, covering most of the Earth (56ºS to 60º N). It can provide appropriate heights but not planimetric positioning for individual images.

The development of alternative methods to provide accurate image orientation is important to avoid the need of GCPs. This paper describes a method to improve orientation of stereopairs of SPOT panchromatic images using the SRTM 3 arc second DEM. It is based on the extraction of a relative DEM from a stereopair, for which a relative orientation is previously done. The extracted DEM is then matched to the SRTM in order to bring the DEM (and consequently the relatively oriented images) to the correctly geo-referenced position. Section 3 describes the method in detail.

The matching of DEM surfaces can be done with sub-pixel accuracy. In a previous study carried out by the author (Gonçalves and Morgado, 2005) the matching of a DEM derived from topographic maps and SRTM could be done with a precision of 5 meters, i. e., approximately 1/20 of the SRTM grid spacing.

This technique has the great advantage of allowing for the orientation and ortho-rectification of SPOT stereopairs without any GCP and using only freely available data. The main difficulty in its application occurs when the terrain is flat or the relief is very smooth. The relief is required for the surface matching to work properly.

Two SPOT stereo pairs were used. The first from Portugal, near the city of Porto was acquired in June 1994, by SPOT-2. The second pair is from the south of France, near Marseilles, and was acquired in March and May 1986, by SPOT-1. Figure 1 shows shaded relief images of the SRTM DEM and the boundaries of the images.

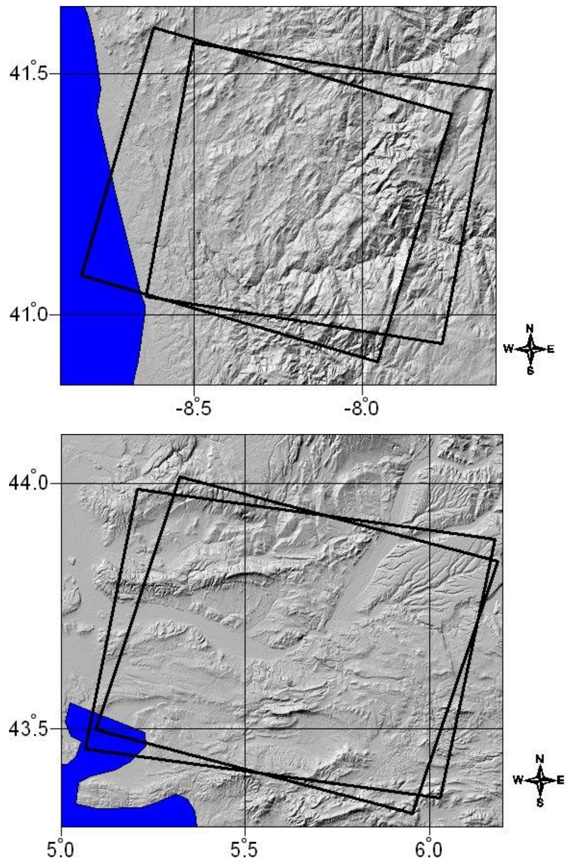


Figure 1 – Location of the images: (a) Portugal, (b) France

2. SPOT IMAGE ORIENTATION

2.1 Spotimage sensor model

Optical line scanners on board of satellites acquire strips of images composed of consecutive image lines. Each line is generated by a central projection, which is represented by the co-linearity equations, as for aerial photography but with the difference that exterior orientation parameters are functions of time. A sensor model establishes a mathematical relation between object space (3D) and image space (2D), for a particular sensor.

Spotimage (2002) provides the rigorous mathematical formulation to establish an image to object projection for SPOT. It uses the ancillary data provided with images in the SPOT standard distribution format. In particular these data includes orbit information, pointing direction angles and attitude variation rates.

For a given image point, with pixel position (P, L), the time of acquisition is calculated from the line coordinate (L). The sensor position (X_S, Y_S, Z_S) is interpolated from the orbit state vectors provided, as well as the unit vector of the pointing direction, (u_x, u_y, u_z). This vector is calculated from the pointing angles (ψ_X, ψ_Y) and from the attitude angles (ω, ϕ, κ), calculated by integration of the attitude variation measurements. Initial values of these angles (ω_0, ϕ_0, κ_0), are not provided with accuracy and can be used as exterior orientation elements, together with some orbit parameters.

The equation of the straight line that originated the image point can be written as (equation 1)

$$(X,Y,Z)=(X_S,Y_S,Z_S)+k(u_x,u_y,u_z) \tag{1}$$

where k is the parameter that expresses the distance along the line. This line can be intersected with a surface model of the Earth in order to determine the corresponding ground coordinates of the point. If the height H (above the reference ellipsoid WGS84) is known, the surface can be an ellipsoid expressed by equation (2):

$$\frac{X^2+Y^2}{(a+H)^2}+\frac{Z^2}{(b+H)^2}=1 \tag{2}$$

where a and b are the semi-axes of the WGS84 ellipsoid. This surface is very close to a constant height surface. The problem is solved in geocentric Cartesian coordinates, (X,Y,Z), which are then converted to geographic coordinates. This image to object projection and its inverse can be expressed in a condensed form by equations (3) and (4) (Olander, 1998):

$$(\lambda,\varphi)=f(P,L,H) \tag{3}$$

$$(P,L)=g(\lambda,\varphi,H) \tag{4}$$

where (φ, λ) are the WGS84 geodetic coordinates of the point observed.

2.2 Commercial software for SPOT orientation

Several commercial software packages exist to deal with optical satellite images from a photogrammetric point of view, i. e. ortho-rectification and 3D data extraction. PCI Orthoengine was used in this work for several operations. It implements Toutin's generic model for the orientation of optical satellite images (Toutin, 1994), based on a rigorous orbital sensor model, like the one described by Spotimage (2002). In particular it uses equations of the form (3) to solve for the exterior orientation by a least squares adjustment to a set of GCP's.

Among other facilities the program allows for the determination of residuals in check points, and of stereo GCPs (3D residuals in ground coordinates). These facilities were important in the analysis of the results obtained.

The software was used to automatically extract a DEM from the stereopair, but without a rigorous exterior orientation. Since the program does not include a function to do a relative orientation of the stereopair, this procedure was done externally.

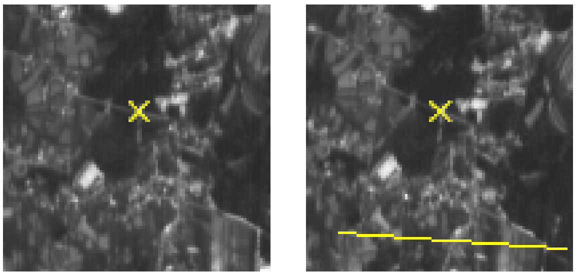
Finally, after the determination of the orientation by the proposed method, the same software was used to ortho-rectify the images.

3. DESCRIPTION OF THE PROPOSED METHOD

The method proposed in this paper is based on a relative orientation of the SPOT stereopair. A DEM is then extracted by conventional stereomatching techniques and then adjusted to the SRTM DEM, bringing the images together to their correct position. The steps of the method are described below and exemplified with the practical application for the stereopair of Portugal. Results are also given for the pair of France.

3.1 Relative orientation

Figure 2 shows small portions (100 by 100 pixels) of the two images of a stereopair, where a tie-point was identified. Using the orientation provided with the image the point was projected onto object space using heights 0 and 1000 m (equation 3) and then onto the right image (equation 4). The line defined for the two extreme heights (epipolar line) is represented on the right image in yellow. A relative orientation is required in order that the line passes on the point.



(a) (b)

Figure 2 – Example of a common point on the left (a) and right (b) images and epipolar line on the right image

It could be noticed that, throughout the image, this displacement is nearly constant. This is essentially due to three reasons:

- The field of view of the images (approx. 4º) is very small, leading to a very similar effect, along the image, of a sensor rotation (even similar to a shift of the sensor)
- The initial approximation of the exterior orientation of both images are very good (errors of some hundreds of meters)
- The height variations of the terrain are much smaller than the distance from the ground to the sensor.

The relative orientation could be achieved by keeping fixed the parameters of one of the images and adjusting the value of attitude angle ϕ_0 (value for first image line) in order to intersect rays for a set of tie-points. Figure 3 shows a total of 30 tie-points obtained manually in a nearly regular grid.

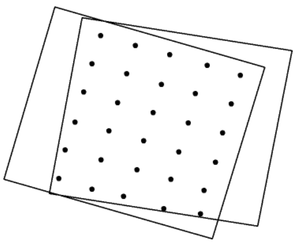


Figure 3 – Tie-points measured for the stereopair of Portugal

The value of ϕ_0 was locally determined for each point. The statistics of the values found was the following:

Minimum:	-120.2”
Maximum:	-113.2”
Mean:	-116.6”
St. Dev.:	+2.0”

Notice that 1” corresponds to a shift of approximately 4 meters, for this stereopair. The mean value was considered and coordinates of the intersection of rays were calculated (in fact for the mean value of ϕ_0 the intersection does not occur and the mid-point of the shortest distance between the two projection rays was considered).

Since the left image was not moved, the coordinates obtained for the tie-points are wrong by a few hundreds of meters. The following step is the extraction of the relative DEM.

3.2 Extraction of the relative DEM

In order to apply the PCI Orthoengine software package for the DEM extraction the coordinates of the tie-points were taken as GCPs and provided to the program to determine the exterior orientation. The root mean square (RMS) of the residuals were 0.18 and 0.23 pixels, in P and L directions.

A DEM could then be derived. The images of Portugal were acquired with 2 days of separation, in very similar conditions, and the DEM extraction was nearly complete. Figure 4 shows a cross-section of the extracted DEM and SRTM. Horizontal and vertical separation can be seen.

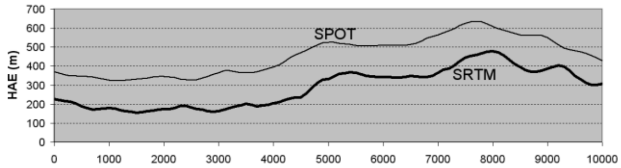


Figure 4 – Profile of the SPOT relative DEM and the SRTM DEM (distance in meters, height above the ellipsoid)

Since the displacement of the DEM from its true position is very small, when compared to the distance to the sensor, there is no scale difference between them. Due to the narrow field of view of the sensor there is no obvious tilt of the extracted DEM. At least locally, around each tie-point it is not detected.

The following step is to correct the position of the extracted DEM by surface matching to the SRTM DEM.

3.3 DEM to DEM matching and generation of simulated GCPs

The matching to the SRTM DEM intends to determine the planimetric shift of the relative DEM that gives the maximum correlation factor between the two height sets. Once that horizontal alignment is done, the mean vertical difference is calculated. The 3D shift is applied to the initial ground coordinates of the tie-points. This procedure transforms the tie-points in actual GCPs that can be incorporated in the standard image orientation procedure of the PCI software.

It was decided not to do the matching globally, for all the DEM area, since different shifts may be required locally. For a given tie-point a set of points around it, up to a distance of 4 km, were taken from the extracted DEM.

For that set of points (n) we have their heights, Z', and the heights interpolated from SRTM, Z''. The correlation coefficient is calculated according to the formula:

$$\rho = \frac{\sum_{i=1}^{n}\left(Z_i^{'} - \overline{Z}^{'}\right)\cdot\left(Z_i^{''} - \overline{Z}^{''}\right)}{\sqrt{\sum_{i=1}^{n}\left(Z_i^{'} - \overline{Z}^{'}\right)^2 \cdot \sum_{i=1}^{n}\left(Z_i^{''} - \overline{Z}^{''}\right)^2}} \qquad (5)$$

where Z'_i and Z''_I are the mean values of the two height data sets.

A set of shifts were applied to the SPOT DEM points, in a longitude, latitude grid. Variations from -20 to 20 arc-seconds, with step of 1 second were tested. For each shift the correlation was calculated. Figure 5 represents a plot of the correlation function. A maximum is observed, that can be more accurately calculated using a grid of smaller step around it. In general, correlation factors where very high, above 0.99.

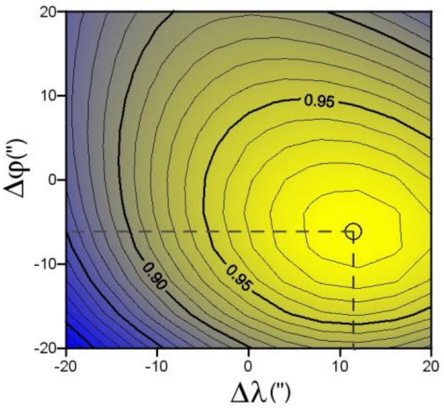


Figure 5 – Correlation as a function of shifts applied in longitude (Δλ)and latitude (φ), in seconds.

After the planimetric shift is determined the vertical shift is the mean of the height differences. Since the coordinates obtained for the tie-points had heights above the ellipsoid and the SRTM DEM has heights above the geoid, the local geoid-ellipsoid separation was considered.
The statistics of the shifts found for the 30 points are listed in table 1.

Table 1 – Statistics of the shifts found for the 30 tie-points

	Δλ (")	Δφ (")	H (m)
Minimum	8.72	-6.85	-121
Maximum	12.22	-5.81	-82
Mean	11.39	-6.37	-103
Std. Dev.	0.62	0.27	11

Variations from point to point are relatively large, meaning that corrections must be applied locally.

These corrections were applied to the initial coordinates of the tie-points and then entered in PCI for the final absolute orientation of the images. This process led to residuals with RMS of 0.50 and 0.70 pixels, respectively in P and L directions. These values are relatively small, similar to what is obtained with GCPs measured on topo maps of scale 1:25,000. Although this means the coordinates derived by this process for the tie-points have a good consistency, conclusions about the accuracy can only be taken with external check points. That assessment was done and is described in the following section.

The full methodology was applied to the stereopair of south France. A total of 36 tie points were measured. The intermediate results were the following:

Relative orientation $\phi_0 = -0.06372$ degrees

EO with relative coordinates $RMS_P = 0.38$ pix

$RMS_L = 0.46$ pix

A potential difficulty was found in this case. The DEM extraction was not very efficient because there was a time difference of nearly 2 months between the images. Vegetation differences made the matching work rather poorly, with many failures in the DEM (a total of 17% of failures). Figure 6 shows the holes in the DEM in white.

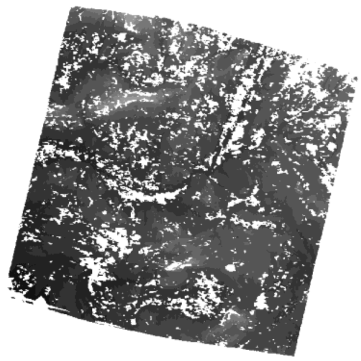


Figure 6 – Representation of the extracted DEM. Failure areas are represented in white

Anyway the process was applied and the corrections could be determined. In the final image orientation, residuals in two of the points were very large (order of 10 pixels). These points certainly had errors in the correction by the DEM matching. The large redundancy of points allowed for the detection and elimination of erroneous points. The final residuals, obtained with the remaining points, where much smaller, below 1 pixel. After eliminating the two points with very large residuals the following was obtained.

EO with corrected coordinates $RMS_P = 0.68$ pix

$RMS_L = 0.70$ pix

4. QUALITY ASSESSMENT OF THE ORIENTATION

4.1 Validation of the image orientation with check-points

A set of 26 well defined points were identified on the image and on the topographic maps of the area in Portugal. Map coordinates were converted to WGS84 geodetic coordinates and projected onto the image space. The statistics of the residuals (differences between calculated and measured pixel coordinates) were obtained and are presented in table 2

Table 2 – Statistics of the residuals obtained on a set of 26 independent check points

	Left Image		*Right image*	
	P (pix)	L (pix)	P (pix)	L (pix)
Minimum	-0.77	-1.90	-0.56	-1.17
Maximum	1.53	1.03	2.31	1.81
Mean	0.27	-0.03	0.54	0.01
Std. Dev.	0.64	0.65	0.68	0.64
RMS	0.69	0.63	0.86	0.63

A mean value close to zero indicates that there aren't systematic trends. The RMS of the residuals is smaller than 1 pixel (10 meters), being similar to what normally is achieved with measurements made on maps of scale 1:25,000.

4.2 Validation by analysis of ortho-images

The final analysis was carried by comparison of ortho-images. Both images of the pair were rectified using the SRTM DEM. Eventual systematic orientation errors of the stereopair would cause a disagreement with the SRTM DEM heights. When an image has systematic orientation errors, in hilly terrain, pixels are displaced due to significantly wrong heights, causing obvious distortions. Due to the different look angles of the images that compose the stereopair, planimetric errors occur in opposite directions. Large discrepancies would occur between the two ortho-images.

Both images of each stereopair were rectified and overlapped. The coincidence is in general very good, with discrepancies normally not larger than 2 pixels. In the case of the test area in France no ground control was available and only this method could be used as a quality control.

In the case of the images of Portugal some of the topo maps were geo-referenced. In a qualitative inspection of the map and the ortho-image, the overall coincidence between features is also very good.

5. DISCUSSION AND CONCLUSIONS

The methodology described was efficient and rigorous in the orientation of stereopairs of SPOT images. From the two tests carried out, the accuracy was at the level of the image spatial resolution (10 meters in this case) and is similar to the accuracy that can be achieved with GCPs measured from topographic maps. The method does not use any conventional GCPs and SRTM has a nearly global coverage, making it applicable in many remote locations of the Earth.

Accurate image orientation and ortho-rectification of many thousands of stereopairs available in the large image archive of SPOT data may become possible. Stereopairs can be ortho-rectified and provide further rigorous ground control for the rectification of other single, panchromatic or multispectral images. This is an exploitation of old SPOT images, in terms of positional accuracy, that certainly was not done with most of them. The method is also possible to implement in a largely automatic manner: tie-points can be automatically extracted by matching; the image orientation and the DEM to DEM matching also don't need user intervention.

However, the method has a few limitations. The most obvious is that it will work only in areas with some relief. That was the case of the two test areas but does not occur in many places of the planet. Further studies of this methodology should consider a characterization of what minimum relief is required for the method to work.

Another limitation, which is well known for the SPOT stereoscopy, occurs when the time separation between images is large. DEM extraction may be very incomplete due to different image tonalities. That was felt in the case of the images from France, but, although there were 17 percent failures, the detail of the relief extracted was sufficient for the DEM to DEM matching.

Another possible application of this methodology would be the filling of void pixels in SRTM DEMs. In steep or poorly imaged areas, SRTM shows some relatively large groups of void pixels that cannot be reliably filled by interpolation. Heights obtained from the SPOT DEM extraction can be used, after the proper image orientation, to fill those voids.

The method is promising and more tests, in diverse conditions, would be important to validate it for further applications.

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