PRECISE ORIENTATION OF SPOT PANCHROMATIC IMAGES WITH TIE POINTS TO A SAR IMAGE

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ABSTRACT:

The extraction of spatial data from satellite imagery requires that precise sensor models are used to orientate images. This is particularly important with images acquired by linear sensors, such as SPOT, frequently pointed with large incidence angles. Image orientation with pixel accuracy requires that accurate ground control points are used. The acquisition of ground control is especially difficult in remote areas, where satellite images are important data sources for the production and updating of topographic maps.
This paper describes a method for the orientation of SPOT panchromatic images making use of tie points with a SAR image. SAR and SPOT images compose stereo-pairs with a good stereo intersection, from which heights can be derived. For the SAR-SPOT tie-points, approximate heights are derived from parallaxes and can be corrected using altimetric ground control points. The method described makes use of the fact that the SAR image orientation can be derived from the orbit and SAR processing parameters, provided with SAR images, and does not require ground control points.
The paper reports on a study carried out with SPOT and Radarsat images from Portugal. Accuracy assessments were done with digital cartography and field surveyed GPS data. It was possible to conclude that using a SAR image, accurate SPOT image orientation can be achieved requiring only very few altimetric control points.

1. INTRODUCTION

1.1 Satellite image orientation

Satellite images are important data sources for the production and update of topographic maps at medium scales, such as 1:50,000. This is especially important in remote and undeveloped regions. Optical images acquired by linear sensors, such as SPOT, provide significant amounts of topographic detail for that scale (Gugan and Dowman, 1988). Stereopairs, acquired in two different orbits, with variable across-track pointing angles, provide the height data required to plot planimetric detail in 3D and to generate digital elevation models (DEMs). Orthoimages can then be produced and act by themselves as map products or can be used to provide planimetric data. Sub-pixel accuracy can be achieved in the 2D and 3D data extracted from SPOT (Westin, 1990, Gugan and Dowman, 1988).
Both the generation of orthoimages and the extraction of 3D data require that precise sensor models are used (Olander, 1998). Equations must be set up, using sensor specific parameters, to relate ground and image coordinates. For a given sensor, equations can be written according to the physical process of image formation, expressing the position of a point on the image space (x,y) as a function of its ground coordinates (X,Y,Z):

$$\begin{cases} x = f_1\left(X,Y,Z;A_1,...,A_n\right) \\ y = f_2\left(X,Y,Z;A_1,...,A_n\right) \end{cases} \quad (1)$$

Usually the geocentric Cartesian terrestrial System (CTS) is used to exepress ground coordinates. A set of n parameters $\{A_1,\ldots,A_n\}$ that characterize a particular image (the exterior orientation parameters) are also involved in the sensor equations. The knowledge of precise exterior orientation parameters for a given image of a particular sensor is an important requirement in order to fully exploit the resolution of the sensor. Using an appropriate number of ground control points (GCPs) the exterior orientation parameters can be determined, after which the image is said to be oriented. Image orientation is required for the topographic applications of satellite images, such as ortho-rectification and height extraction. In order to maximize the potential of the image resolution, the accuracy of GCPs should be better than the image resolution. In the case of SPOT panchromatic imagery, with a pixel size of 10 m, ground control should be acquired by field survey or from topographic maps at least of scale 1:25,000, to ensure that accuracy.
Remote areas of the world, which are the ones where topographic mapping from satellite images can be more useful, are normally poorly mapped. Field surveys can be extremely expensive or not possible to carry out. In such situations GCPs will not be available with appropriate accuracy to extract spatial data from images to their highest potential.
The requirement of GCPs for image orientation can be overridden if exterior orientation parameters are collected by onboard equipment (direct georeferencing). Positioning systems, such as GPS (Global Positioning System) and DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) can be used to determine satellite trajectory with better accuracy than image resolution. That is the case of SPOT4, positioned by DORIS, with 1 m accuracy (CNES, 2000). The attitude angles of optical sensors, which are also exterior orientation parameters, are determined by navigation equipment but not as accurately as the orbit. Pointing errors on the ground are, in the case of SPOT, of the order of 500 m (CNES, 2000).

The consequence is that GCPs will always be required in order to precisely orient images with pixel accuracy.

SAR images have a significant advantage over optical images. Due to the image generation process, based on distance measurements, image orientation is independent from sensor attitude angles (Renouard and Perlant, 1993). Provided that an accurate orbit is available, together with precise SAR processing parameters, images are already precisely oriented and GCPs are not required. That is the case of ERS SAR imagery, which have a geo-location accuracy of 10 m (Mohr and Madsen, 2001).

Mixed sensor image pairs, composed by a SAR and an optical image, provide a strong parallax effect from where heights can be determined (Raggam et al., 1994, Toutin, 2000). Provided that precise orientation is known for both images, heights of conjugate points can be determined by applying an intersection algorithm. If only the approximate orientation is known for SPOT then parallaxes will be systematically affected.

The essential point of the methodology proposed here for the improvement of SPOT image orientation is that using altimetric ground control points, the relation between parallaxes and heights can be calibrated, allowing for the determination of heights for a set of SAR-SPOT tie points. Using the precise SAR image orientation and the heights of the tie-points, planimetric coordinates can be calculated, thus transforming the SAR-SPOT tie points into actual GCPs. These GCPs can then be used in the standard SPOT image orientation procedure.

1.2 Study area and available data

The methodology proposed in this paper was tested with a SPOT and a SAR scene of Portugal. The area is mountainous, with a height range of 1000 m.

The SPOT scene is of panchromatic mode, with an incidence angle of 25.5º to west of the trajectory. It was acquired in August 1991, by SPOT1.

A Radarsat image, covering almost all of the area, was available. It is of the standard mode, with a pixel size of 12.5 m and was acquired in August 1997, in the ascending pass of the orbit, with an incidence angle of 44º. Figure 1 represents the location of the two images.

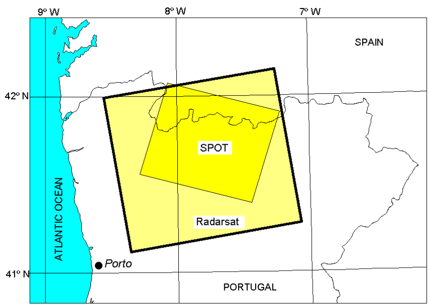


Figure 1 – Location of the Radarsat and SPOT images used

An ERS-2 image of northern Portugal was also available but with a very small overlap with the SPOT image. An ERS SAR image would have been preferable, due to the better geolocation information. For Radarsat, the orbit accuracy is known to be of the order of 100 m (Rufenacht et al, 1997).

The verification of SAR image orientation was done with digital topographic map data. A hydrographic network, digitised from topographic maps of scale 1:25,000, was used. A set of 13 check-points uniformly distributed on the image were surveyed with GPS and used to assess the SPOT image orientation.

2. SPOT IMAGE ORIENTATION

2.1 SPOT 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. Figure 2 represents the image formation process and the sensor coordinate system (*x*,*y*,*z*).

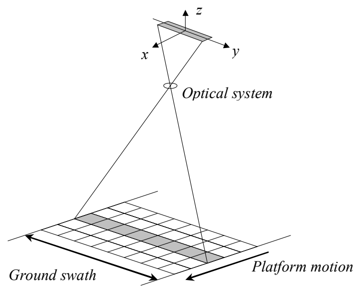


Figure 2 – Image acquisition by a linear array scanner

The relation between ground and image coordinates, in a linear sensor, is established by the co-linearity equations. A detailed description of these equations for SPOT is given by Westin (1990).

The exterior orientation parameters of a SPOT scene describe the satellite trajectory and the sensor attitude, and are all functions of time. Usually only 4 orbital parameters are required, all corresponding to the instant of the first image line (Gugan and Dowman, 1988, Westin, 1990). Their variations in time are predicted by the orbital perturbation theory.

The attitude angles at the time of first image line (roll, ω_0, pitch, φ_0 and yaw, κ_0) are also exterior orientation parameters. Their variations in time can be predicted by the onboard measurements of attitude variation (Westin, 1990). In this case a total of 7 parameters are required to orientate a SPOT scene. Other authors prefer to model the attitude variations in time by linear or quadratic functions, introducing the derivatives of attitude angles as additional orientation parameters. In this case the number of parameters becomes 10 or more.

The determination of all the parameters (space resection) requires a number of GCPs greater or equal to half the number of parameters. In order to achieve a strong solution in the least squares adjustment, some redundancy is required.

The number of parameters, and consequently the number of GCPs, can be reduced if an accurate orbit is known, as in the case of SPOT4. Anyway, the precise modelling of sensor attitude always requires the use of accurate GCPs.

Once the precise orientation of a sensor is established, it is possible to do object-to-image projection and image-to-object projections. The latter requires the height of the point above the reference ellipsoid (*H*). The line defined by the sensor equations is intersected with the surface of constant height, which can be approximated by an ellipsoid of semi-axis $a+H$ and $b+H$ (Curlander, 1982):

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

where *a* and *b* are the semi-major axis of the reference ellipsoid. These projections can then be expressed as (Olander, 1998):

$$(col, row) = F(\lambda, \varphi, H) \quad (3)$$

$$(\lambda, \varphi) = G(col, row, H) \quad (4)$$

where (λ, φ, H) are the geodetic coordinates of the point and (col, row) are the pixel column and row position. Similar operations can be done for a SAR image.

2.2 Orientation parameters from the image header

Approximate orbit and attitude parameters can be extracted from the SPOT image header data. The accuracy of these orientation parameters was assessed with the points surveyed in the field using GPS (sub-meter accuracy). Applying the image-to-object projection for these points, errors in longitude and latitude (converted to distances) were found to have the following mean values:

$$\Delta\lambda = 360 \text{ m}$$
$$\Delta\varphi = 594 \text{ m}$$

The methodology proposed significantly improves this figures, using only one altimetric control point.

3. SAR IMAGE ORIENTATION

3.1 SAR sensor model

The relation between ground and image coordinates in a SAR image is given by the Doppler and range equations (Curlander, 1982):

$$\begin{cases} f_{DC} = \dfrac{2}{\lambda} \dfrac{(\boldsymbol{S} - \boldsymbol{P}) \cdot (\dot{\boldsymbol{S}} - \dot{\boldsymbol{P}})}{\|\boldsymbol{S} - \boldsymbol{P}\|} \\ \rho = \|\boldsymbol{S} - \boldsymbol{P}\| \end{cases} \quad (5)$$

where f_{DC} = Doppler shift
λ = Wavelength
ρ = Slant range
$\boldsymbol{S}$, $\dot{\boldsymbol{S}}$ = Satellite position and velocity vectors
$\boldsymbol{P}$, $\dot{\boldsymbol{P}}$ = Imaged point position and velocity vectors

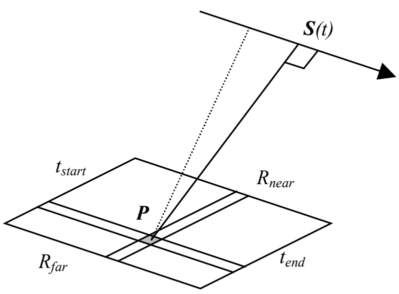


Figure 3 - Point being imaged in a SAR image processed at zero Doppler

The exterior orientation is established by the sensor trajectory, which can be known with high accuracy. From the SAR processing, f_{DC} is known for any point on the image. The projection of a point $\boldsymbol{P}$ onto image space consists of solving equations (5??) in order to determine range (ρ) and time (t). Knowing the start and end time of image acquisition and the near and far range, row and column coordinates can be calculated from t and ρ, respectively. Frequently SAR images are acquired at zero-Doppler (f_{DC}=0). In this case the problem is only to find the instant for which relative position and velocity vectors are perpendicular. Figure 3 represents the search for the instant of perpendicularity.
Orbit data, as well as reference range and time information, required to calculate pixel coordinates of a point on the image space, are extracted from the image header data.

3.2 SAR image orientation using header data

The orbit data and the reference time and range were extracted from the image header. In order to assess their accuracy, 3D digital map data were projected onto image space and superimposed on the images. As map data is in a local map reference system they had to be converted to WGS84.
There are advantages in using linear features instead of check-points. Individual points are difficult to find in SAR images and frequently their location cannot be defined with very good accuracy. Boundaries of water features are very well defined and are an alternative to check SAR image orientation.
In the case of the available ERS-2 image a very good coincidence of river margins could be observed throughout the entire image. Figure 4 represents a portion of the ERS-2 image where the river Douro, in the city of Porto, can be identified and the vector data.
This ERS-2 image is appropriate for the methodology proposed. Unfortunately it has a very small overlap with the SPOT image.

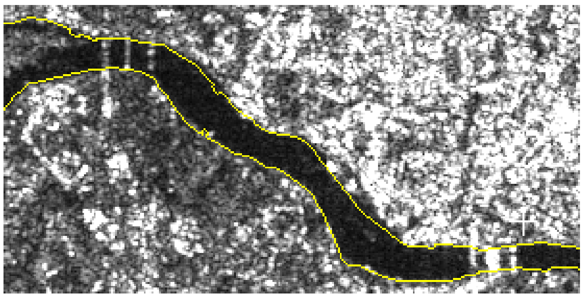


Figure 4 - Portion of an ERS-1 image (300 by 150 pixels) with superimposed vector data corresponding to the river margins, projected onto the image space.

The same procedure was used with the Radarsat image. A systematic shift of the vector data could be clearly detected. Figure 5 represents a portion of the Radarsat image with the superimposed vector data. The displacement was of 5 pixels (approx. 60 m) in range and only 1 pixel in azimuth-time direction.

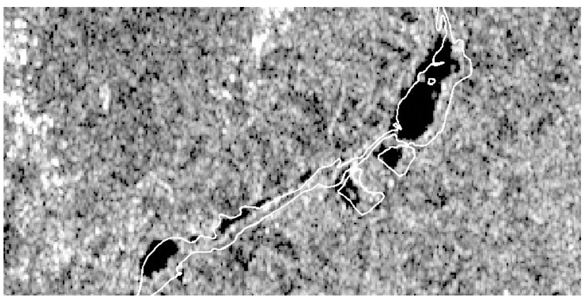


Figure 5 – Portion of the Radarsat image (300 by 150 pixels) with superimposed vector data.

This shift is within the Radarsat standard of image geolocation, which is 100 m (Rufenacht et al., 1997). However, this is not appropriate for the methodology proposed. In order to simulate an accurate SAR image orientation, shifts in range and time were introduced in the object-to-image projection.

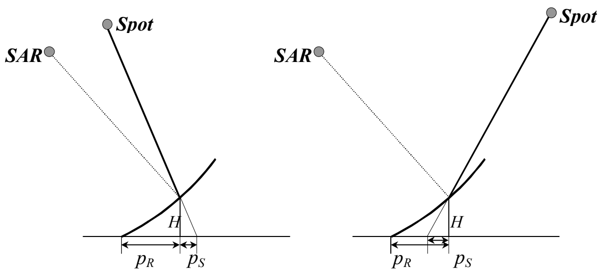
4. INTEGRATION OF SAR AND SPOT MODELS

4.1 SAR-SPOT intersection

Both SAR and SPOT images are significantly affected by the terrain height. Relief displacements (ΔX) of a height h depend on the image incidence angle (α) on the imaged point and are expressed in the following ways:

$$\begin{aligned} \Delta X_{SAR} &= h \cot \alpha_{SAR} \\ \Delta X_{SPOT} &= h \tan \alpha_{SPOT} \end{aligned} \tag{6}$$

A pair composed of a SAR and a SPOT image provides a parallax effect, from which heights can be determined. Three-dimensional coordinates of SAR-SPOT conjugate points can be calculated using the sensor equations. In geometric terms this corresponds to determining the intersection of a straight line and a circle in space. Alternatively, heights can be calculated from parallaxes (Gonçalves, 2001).
SAR-SPOT stereopairs can be acquired with both satellites on the same side relative to the point or on opposite sides. Figure 6 represents these two situations, where a point with height H above a reference datum is being observed. In the first case the two displacements, with respect to the reference datum, occur in opposite directions, resulting in an additive parallax. In the second case the parallax effect is subtractive, corresponding in principle to a less favourable situation for height determination. However, as the main contribution to the parallax comes from the SAR displacement, the accuracy is not significantly affected (Toutin, 2000).



(a) (b)

Figure 6 – Same side (a) and opposite side (b) configurations in a SAR-SPOT stereopair.

The SPOT and Radarsat image used in this work form a same-side stereopair.

4.2 Image registration

As the SPOT and the SAR images have different resolutions, registration is needed in order to measure parallaxes. In this work it was decided to register the SAR image to the SPOT image space using a set of points generated with the image orientation data. A point can be projected from the SPOT image onto the ellipsoid (equation 3) using the approximate orientation parameters and from there onto the SAR image (equation 3, with SAR model). This was done for a set of points on the SPOT image (grid of 7 by 7 points). Figure 7 shows the points in the SPOT and the SAR image.

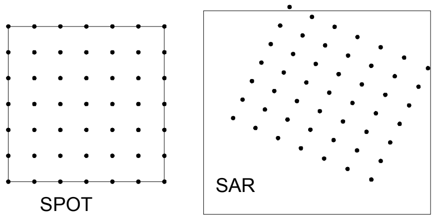
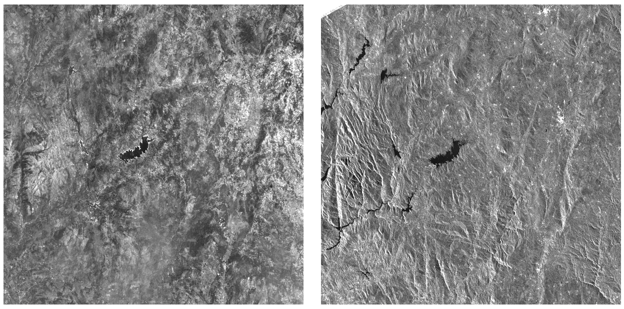


Figure 7 – Location, on both image spaces, of the points used for the registration

A 3rd degree polynomial was then fitted to these points, with residuals smaller than 0.1 pixels in absolute value. This polynomial function (later designated as R) was used in the registration of the SAR image to the SPOT image space. Figure 8 shows the SPOT image (a) and the SAR image registered to the SPOT image space.

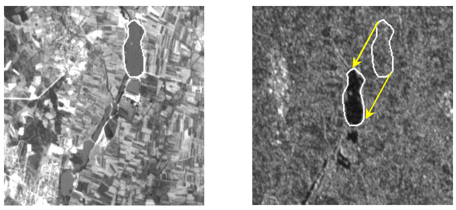


(a) (b)

Figure 8 – Full SPOT image (a) and registered SAR image (b)

4.3 SAR-SPOT tie-point measurement

Tie points had to be measured in the SAR-SPOT pair. Identification of well-defined individual points in the SAR image is extremely difficult, especially because the area does not have large cities or roads. However many polygonal features such as water bodies can be clearly identified on both images. The manual method used to generate tie-points from these features was the following: first the boundary is digitised, in vector format, on the SPOT image. Then, on the SAR image layer, the line is manually moved until matching the corresponding feature on the SAR image. Figure 8 represents the boundaries of a small lake and the vector line digitised on the SPOT image (a) and then dragged on the SAR image (b).



(a) (b)

Figure 9 – Determination of tie-points using area features.

The centroid of the polygon, or even any vertex of the line, can be used as a tie-point. Figure 10 represents the location of the tie-points on the SPOT image. Most of them were derived from lakes, reservoirs or river margins. If original SAR image coordinates are required, the registration function, R, should be used.

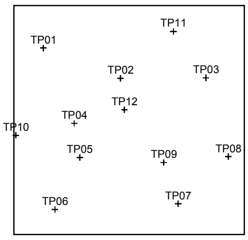


Figure 10 – Distribution of the SAR-SPOT tie points obtained

4.4 Height determination of the SAR-SPOT tie-points

If the SPOT orientation parameters used in the image-to-image registration were exact the two images would coincide for points on the ellipsoid. If the point has a height H above the ellipsoid there will be a parallax in x direction, which relates to height according to equation 7:

$$H = A(x, y) \cdot p_x \quad (7)$$

where (x,y) are the pixel coordinates on the SPOT image and p_x is the x-parallax. Coefficient A is not constant along the overlap area of the images. If only approximate orientation parameters are known for the SPOT image, as is the case when they are derived from the header data, there will be a bias coefficient (equation 8).

$$H = A(x, y) \cdot p_x + B(x, y) \quad (8)$$

The method proposed here is based on the fact that coefficient A can be estimated with very good accuracy only using the SPOT approximate orientation, in the following steps:

1. A given point on the SPOT image is projected from image to ground, with heights 0 and 1000 m. For a height range of this order the planimetric displacement has a linear variation with height.
2. The two points obtained in ground coordinates are projected onto the SAR image space
3. From the SAR image space the two points are brought back to the SPOT image space (points P_1 and P_2)
4. The ratio between the height difference (1000 m) and the difference between x coordinate of points P_1 and P_2, is the coefficient A for that point.

$$A = \frac{H}{x_2 - x_1} \quad (9)$$

Coefficient B must be determined from ground control information. In a first approximation it will be assumed as constant. Knowing the height of one of the tie-points, coefficient B can be determined.
The 12 points extracted corresponded to individual points or water surfaces which are represented in the topographic maps of the area (1:25,000 scale). The heights of 11 of the points could be measured from contours (10 m interval).
Using the height of point 02, which corresponds to a small reservoir, coefficient B was calculated as 362 m. With the calibrated relation, heights were calculated for the other points and compared with map heights, for the remaining 10 points.

Table 1 contains the estimated coefficient A (in meters of height per pixel of parallax), the parallaxes and the corresponding heights calculated by equation 10. Heights measured from maps and the difference between the two heights (dH) are listed for 10 of the points.

Table 1 – Calculation of heights from parallaxes, for the tie-points, and comparison with heights measured from topographic maps.

TP	A (m/pixel)	p_x (pixels)	H (m)	H_{map} (m)	dH (m)
01	8.52	28.2	602	—	—
02	8.70	76.1	1024	1024	—
03	8.93	3.1	390	405	-15
04	8.52	35.0	660	650	10
05	8.49	47.2	763	746	17
06	8.36	4.5	400	386	14
07	8.72	67.5	951	965	-14
08	8.91	53.1	835	855	-20
09	8.72	17.3	513	512	1
10	8.34	30.9	620	616	4
11	8.89	18.6	528	531	-3
12	8.67	63.7	915	916	-1

For the 10 check points, the RMS error is 12 meters. The coordinates of the tie-points in the registered SAR image were converted back to the SAR image space (function R^{-1}). The SAR image-to-object projection was then applied in order to calculate geographic coordinates of the tie-points. These points became GCPs, which were used in the SPOT image resection. The statistics of the residuals obtained in the least squares adjustment, expressed in pixel units, are listed in table 2.

Table 2 - Statistics of the residuals obtained in the SPOT image orientation

	R_x (pixels)	R_y (pixels)
Minimum	-0.07	-1.20
Maximum	0.07	1.32
RMS	0.04	0.70

In order to independently check the accuracy of the image orientation obtained, the GPS points were used as check-points. The statistics of the residuals obtained after projecting the points onto the image are listed in table 3.

Table 3 - Statistics of the residuals found in the check-points

	R_x (pixels)	R_y (pixels)
Standard dev.	1.01	1.25
Mean	0.23	1.06
RMS	1.00	1.60

The RMS of the residuals correspond to approximately 12 m in longitude and 16 m in latitude.
These figures would have been better if actual GCPs could have been used in the SPOT image resection. When analysing the spatial distribution of the errors in the heights determined for the tie-points (table 1), although they are probably close to the best that can be achieved from a SAR-SPOT intersection, it is possible to recognise that they are not randomly distributed. Figure 11 represents the SPOT image space, with the tie-points and arrows in x direction, with sizes proportional to the errors.

It can be seen that negative errors tend to be on the left hand side and positive errors on the right.

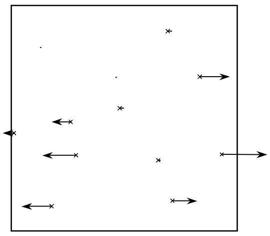


Figure 11 – Height errors represented as arrows in *x* direction

This error pattern suggests that coefficient B in equation (8), which was assumed in a first approach as a constant, should be considered as a function of the *x* image coordinate:

$$B(x, y) = B_0 + B_1 x \tag{10}$$

There are two coefficients to determine, which require that heights of at least 2 tie-points are known. These 2 points should have some separation in *x* direction in order to determine B1 with some accuracy. If more heights are known all should be used in a least-squares adjustment.
There is a theoretical explanation for equation (10). SPOT parameters extracted from the header are not exact, which explain the systematic errors in parallaxes. Errors in the orbit elements have a constant effect in the image location on the ground. However that is not the case with errors in attitude angles, in particular the roll angle. The SPOT sensor has a field of view of 4º. When projecting from image to ground, the effect of an error in roll is variable from the left to right side if the image. As the field of view is small there is an approximately linear relation between the image coordinate and the error on the ground coordinates. The points used in the image registration have variable errors, affecting parallaxes with a shift that varies linearly with *x* image coordinate. It is then possible to slightly improve the model for height determination.

5. DISCUSSION AND CONCLUSIONS

It was possible to verify that a SAR image can help in improving the orientation of a SPOT image, requiring as little as one height control point. Heights of SAR-SPOT tie-points could be determined from parallaxes. These heights were found to have a RMS error of 12 m when compared with map heights. The tie-points were transformed into GCPs, which allowed for the SPOT image resection with accuracy a bit larger than one pixel.
An essential requirement is that an accurate SAR image orientation must be known, which was not the case of the Radarsat image used. For practical reasons the Radarsat image orientation was improved. This improvement required ground control, which is against the principle of trying to use as little ground control as possible. The actual application of this methodology would require an ERS SAR image.
Serious difficulties can be found when looking for tie-points in the SAR image. However, as water surfaces are clearly identified on the SAR image, their boundaries could be used to look for their conjugates on the SPOT image. Relatively accurate tie-points can be obtained in this way provided that the shape of the features does not change from one image to the other. That might be the case with reservoirs due to changes in water levels. Provided that some stable features, common to both images, exist tie-points can be obtained.
The ground control data required is only altimetric. It is much simpler to obtain the height of a lake, for example, than precise planimetric coordinates of a point.
The methodology proposed, although not completely eliminating ground control, strongly reduces it. It may be useful in order to simplify the process of topographic mapping from images of remote regions.

REFERENCES

CNES, 2000. SPOT4 internet web pages: http://spot4. cnes.fr/spot4_gb/index.htm (visited on 20-09-2001).

Curlander, J., 1982. "Location of Space borne SAR Imagery". *IEEE Transactions on Geoscience and Remote Sensing*. 20 (3): 359-364.

Gonçalves, J., 2001, "Integration of SAR and SPOT data for topographic mapping". *Ph.D. Thesis, University of London*. 246 pages.

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

Mohr J., and S. Madsen, 2001. "Geomtric calibration of ERS satellite SAR images ". *IEEE Transactions on Geoscience and Remote Sensing*, 39 (40) 842-850.

Olander, N., 1998. "Modelling Spaceborne and Airborne Sensors in Software". *International Archives of Photogrammetry and Remote Sensing*. 32(2): 223-228

Renouard, L. and F. Perlant, 1993. "Geocoding SPOT products with ERS-1 geometry". *Proceedings of the Second ERS-1, Space at the Service of the Environment*, Hamburg: 653-658.

Raggam, J., A. Almer, and D. Strobl, 1994. "A combination of SAR and optical line scanner imagery for stereoscopic extraction of 3-D data". *ISPRS Journal of Photogrammetry and Remote Sensing*. 49 (4): 11-21.

Toutin, T., 2000. "Stereo-mapping with SPOT-P and ERS-1 SAR images". *International Journal of Remote Sensing*, 21 (8): 1657-1674.

Rufenacht, H., R. Proulx, and P. Cefola, 1997. "Improvement of RADARSAT image localization". *In* Geomatics in the Era of Radarsat; Directorate of Geographical Operations, Canadian National Defense; CD-ROM.

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

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