TOPOGRAPHIC MAPPING WITH SPOT IN POLAR REGIONS

Frank Pattyn
Centre for Cartography and Geographic Information Systems
Geografisch Instituut
Vrije Universiteit Brussel
Pleinlaan 2, B-1050 Brussel, Belgium

I.S.P.R.S. Commission IV

ABSTRACT :

A method is presented for the automatic extraction of topography from stereoscopic SPOT images in polar areas. In these regions conventional algorithms fail due to SPOT imaging characteristics and terrain texture. The main difficulties are the large difference in orientation between two images of a stereocouple, the shortage of reference points and the occurrence of high reflectance zones such as snow and ice. The stereo matching procedure is split up in two parts : (i) a geometric correction method in order to register both images in a reference system of quasi-epipolar geometry, using few ground reference points and (ii) an area-based matching technique, based on cross-correlation. In order to reduce the time needed to match corresponding points a multiresolution approach is applied. In the matching procedure also heuristics are incorporated, identifying texture elements such as 'saturated snow', 'snow' and 'shadow'. Matching accuracy over snow areas is further improved by applying selective image enhancement techniques.

The methodology was tested on a stereopair of the Sør Rondane Mountains, Antarctica. Planimetric accuracy lies within the region of 10 to 20m, which is rather low due to the difficulty by which reference points can be identified in the image. The highest matching accuracy was found on medium slopes of rock outcrops and on the ice surface. On the steep slopes and some snow patches accuracy was significantly lower.

KEY WORDS : Image Matching, Photogrammetry, SPOT, Stereoscopic

1. INTRODUCTION

Since the launch of the first SPOT satellite in 1986, digital topographic mapping from space gained more interest as compared to analogue cartography. It became possible to extract automatically and very accurately surface topography so that maps at scales up to 1:50,000 could be produced. The high speed and low cost of production facilitates large scale mapping, not only in developed and industrial zones, but also in developing countries or such remote places on earth, as polar regions. Conventional mapping in the Antarctic, for instance, is very expensive and requires several years of of field work (ground truth collection) and a lot of air surveys, the latter totally dependent on the rapid changing weather conditions. Furthermore, due to the high reflectance of the snow and ice surface it remains very difficult to extract conjugate points with analogue equipment.

Compared to civilised areas at middle latitudes, digital topographic mapping from space in polar regions is hampered by terrain texture and the satellite's imaging characteristics (SPOT HRV). Very few reference points are available and it remains difficult to locate the positions of these reference points accurately in both images of the stereocouple, because no man-made features, such as crossroads and buildings are encountered. High reflectance zones such as snow and ice show a rather small greylevel variance. On some snow surfaces oriented towards the sun, SPOT detectors are saturated (Digital Number=255) and corresponding points cannot be matched. In view of the small greylevel variance it is not possible to extract reliable edges on ice and snow surfaces, so that an area-based matching technique is in order. At high latitudes the prevalent low sun angle accounts for large shadows, further enhanced in mountainous areas. During the winter months images cannot be taken, because of the polar night. The optimal satellite scanning period is therefore restricted to the months June and July in the northern and December and January in the southern hemisphere. Due to SPOT imaging characteristics, a large difference in orientation exists between two images of a stereopair. This difference increases with both increasing viewing angle and latitude, so that at high latitudes epipolar lines are not parallel to the scanline direction. For instance at latitude 70°N, images scanned with a viewing angle of -27° and +27° respectively account for a difference in orientation of 24°.

In this paper, a method is presented in order to derive surface topography from stereoscopic SPOT images, adapted in such a way to overcome above mentioned difficulties. Starting from raw SPOT HRV Level 1A images, satellite auxiliary data and reference points are processed together in order to resample the images into a geodetic raster, thus leaving only relief displacements unaltered (fig.1). Afterwards, matching is performed in order to collect conjugate points from both image planes. The obtained parallax values are converted into elevations through spatial intersection. By introducing *a priori* knowledge concerning surface texture and applying selective image enhancement techniques, the number of 'mismatches' is greatly reduced.

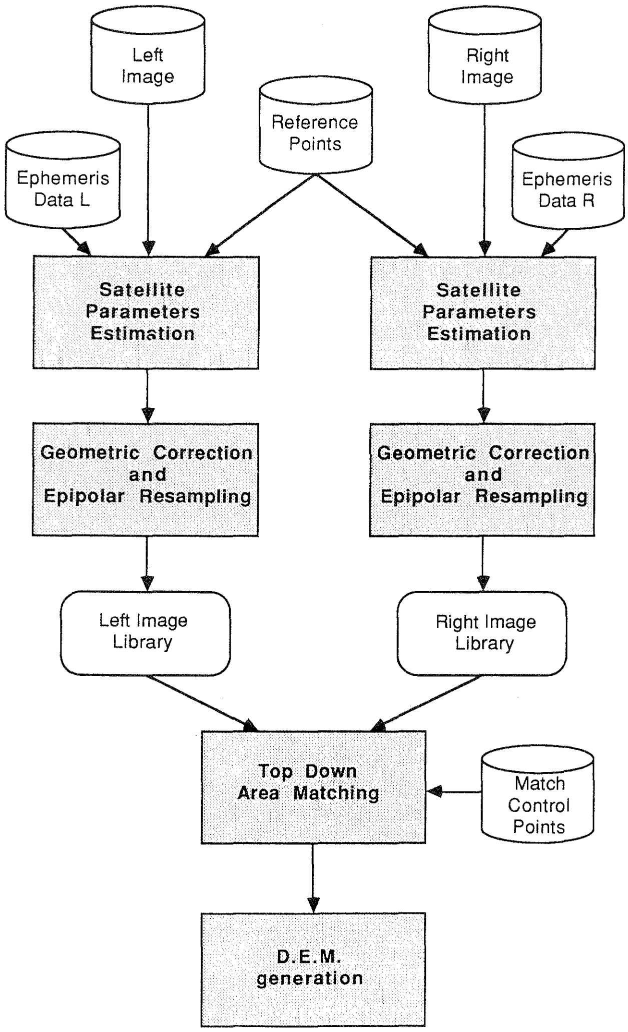

Fig. 1 : Matching Process

2. THE GEOMETRIC CORRECTION MODEL

2.1. SPOT Imaging Characteristics

The SPOT satellite is an earth resource satellite especially designed for cartographic applications. Its sensor package consists of two High Resolution Visible (HRV) imaging instruments. Each HRV is made up of a linear array of Charged Coupled Devices (CCD), i.e. 6000 detectors for the panchromatic mode, accounting for a spatial resolution on the ground of 10m. Images are obtained by using the 'pushbroom' scanning technique, whereby each line is scanned by the CCD-array and successive lines are produced as a result of the satellite's movement along its orbit (Chevrel et al, 1981). As for panchromatic images, lines are scanned at a sample interval of 1.504 milliseconds. Each HRV has a pointable mirror, which allows off-nadir viewing in the cross-track direction over a range of ±27° relative to the vertical.

2.2. Rectification Method

Before the matching algorithm can be applied, both stereoimages should be resampled in a cartographic reference plane (by preference an epipolar registration so that relief displacements are confined to the x-direction). Thereby, all image distortions such as satellite orbit and attitude variations, earth shape and rotation, effects of sensor geometry, panoramic effect, etc. should be removed. A precision rectification of SPOT imagery when only a few reference points are known, requires modelling the satellite motion and attitude in a rigorous way (Pattyn, 1991).

In order to calculate the intersection point of the image vector pointing towards the earth (i.e. vector from the satellite's perspective centre towards a detector in the CCD-array) and the reference ellipsoid, one has to know at any time the position and orientation of the satellite along its orbit and the viewing direction of the CCD-array in the HRV-instrument. The nominal position and orientation of the satellite at moment t is derived from the Ephemeris data, supplied with each SPOT scene. At sample intervals of 1 minute satellite's position and velocity vectors are given in a geocentric reference system. By applying a 7th degree Lagrange interpolation polynomial, satellite position coordinates are generated at equally spaced time intervals of 5 lines within the time span of the acquisition of one scene (i.e. 9 seconds). These points are then described by a second degree polynomial in function of time, which is convenient for scenes smaller than 300 km (Hottier and Albattah, 1990) :

$$\begin{bmatrix} X_s \\ Y_s \\ Z_s \end{bmatrix}_t = a_0 + a_1 t + a_2 t^2 + \begin{bmatrix} \Sigma_1 \\ \Sigma_2 \\ \Sigma_3 \end{bmatrix} \tag{1}$$

with $[X_s\ Y_s\ Z_s]$ the satellite's position and $\Sigma_1\ \Sigma_2\ \Sigma_3$ position errors along its orbit. The three axes defining the nominal orientation of the satellite at moment t are also derived from the Ephemeris position and velocity vectors, forming the orthogonal matrix R_1. Satellite attitude drift rates are measured every 125 ms during image scanning. The relative attitude angles $\Delta\omega\ \Delta\phi\ \Delta\kappa$ are calculated by numerical integration. Since the attitude offset $(\omega_0\ \phi_0\ \kappa_0)$ is not known, rotation angles $\omega\ \phi\ \kappa$ are obtained using reference points in the adjustment phase.

$$\begin{aligned} \omega(t) &= \omega_0 + \Delta\omega(t) && \text{(roll)} \\ \phi(t) &= \phi_0 + \Delta\phi(t) && \text{(pitch)} \\ \kappa(t) &= \kappa_0 + \Delta\kappa(t) && \text{(yaw)} \end{aligned} \tag{2}$$

These attitude rotation angles are then used to form the orthogonal matrix R_2.

Assuming a principle distance of 1, a rectangular sensor coordinate system is formed. The components of the viewing vector (i.e. vector from the centre of perspective to a detector in the CCD-array) are derived by linear interpolation between the normalised vectors of the look angles for the detectors at each end of the scanline. These look angles are also supplied with the image and remain constant during the acquisition of one scene (CNES and SPOT IMAGE, 1988). The relationship between the look direction vector [u v w] and three dimensional coordinates on the ground [X Y Z] is then given as :

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \lambda^{-1} R_2 \, R_1 \begin{bmatrix} X - X_s \\ Y - Y_s \\ Z - Z_s \end{bmatrix} \tag{3}$$

with $[X_s\ Y_s\ Z_s]$ the position coordinates of the satellite at moment t and λ a scale factor. Replacing $R_2.R_1$ by M, equation (3) gives rise to two collinearity equations :

$$u = w \, \frac{m_{11}(X - X_s) + m_{12}(Y - Y_s) + m_{13}(Z - Z_s)}{m_{31}(X - X_s) + m_{32}(Y - Y_s) + m_{33}(Z - Z_s)}$$

$$v = w \, \frac{m_{21}(X - X_s) + m_{22}(Y - Y_s) + m_{23}(Z - Z_s)}{m_{31}(X - X_s) + m_{32}(Y - Y_s) + m_{33}(Z - Z_s)} \tag{4}$$

with $m_{11}..m_{33}$ the components of matrix M. Six parameters in the right hand side of (4) remain unknown ($\Sigma_1\ \Sigma_2\ \Sigma_3\ \omega\ \phi\ \kappa$) and are determined accurately in the adjustment phase by applying a general least squares technique using reference points (see Salamonowicz, 1986; Westin, 1990). Once this is done, a relationship between the pixels in the raw image and the cartographic reference plane is established. In order to fulfil somehow the epipolar constraint, an intermediate reference system is introduced, which is the final cartographic plane rotated in such a way that the parallax displacement is more or less confined to the x-direction (fig.2). Leclerc (1989) proposes following method for the calculation of the rotation angle γ:

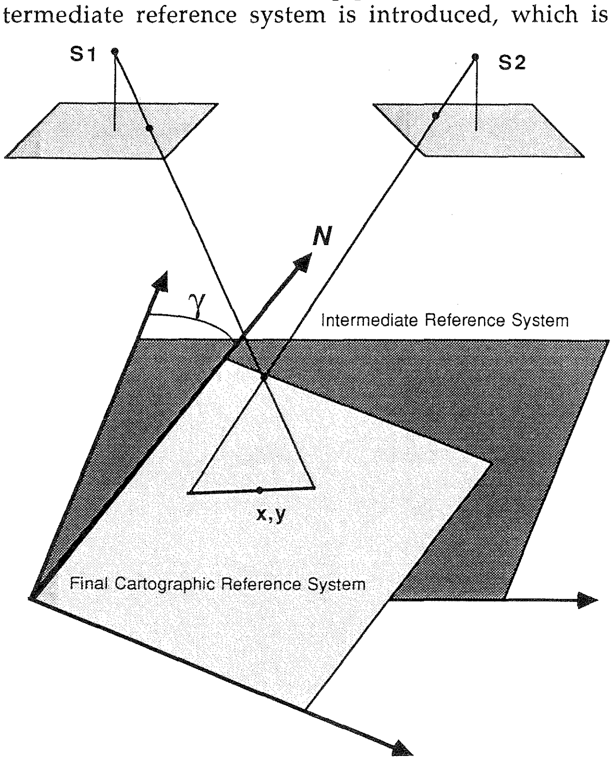

Fig.2 : Parallax Calculation

$$\sin A = \frac{\left| \tan\beta_1 \sin(\gamma_1 - \gamma_2) \right|}{\sqrt{\tan^2\beta_1 + \tan^2\beta_2 - 2 \tan\beta_1 \tan\beta_2 \cos(\gamma_1 - \gamma_2)}}$$

$$\gamma = \gamma_2 + A \tag{5}$$

with β_i the incidence angle and γ_i the orientation angle of image i. Both raw stereoimages are resampled in the intermediate cartographic reference system with the above described method, thus leaving only relief displacements unaltered.

3. IMAGE MATCHING TECHNIQUE

The area based matching algorithm is based on a cross-correlation technique and was found to be efficient both in terms of accuracy and computation time. The cross-correlation between an N x M array of pixel greyvalues surrounding pixel i of line j in the target image (fig.3) and an N x M array surrounding pixel i′ of line j′ in the search image is calculated to determine if (i,j) and (i′,j′) are conjugate match points. For T_{ij} and $S_{i'j'}$ defined as the greyvalue for pixel ij and i′j′ in the target and search image respectively, the correlation coefficient is calculated as (e.g. Ungar et al, 1988) :

$$r^2_{ij} = \frac{\sigma^2_{TS}}{\sigma_{TT}\ \sigma_{SS}} \quad \text{with}$$

$$\sigma_{TS} = \sum_{k=-K}^{K} \sum_{l=-L}^{L} \left[T_{i+k,j+l}\ S_{i'+k,j'+l} \right] - (N\,M\,\overline{T}\,\overline{S})$$

$$\sigma_{TT} = \sum_{k=-K}^{K} \sum_{l=-L}^{L} \left[T_{i+k,j+l} \right]^2 - (N\,M\,\overline{T^2})$$

$$\sigma_{SS} = \sum_{k=-K}^{K} \sum_{l=-L}^{L} \left[S_{i'+k,j'+l} \right]^2 - (N\,M\,\overline{S^2}) \tag{6}$$

with $\overline{S}$ and $\overline{T}$ the mean grayvalue of the search and target array respectively.

$K = (N+1)/2$ and $L = (M+1)/2$.

For a target array centred along a particular pixel, a search array seeks a conjugate point by moving over a predefined search space (fig.3). The maximum correlation coefficient of all searches refers to the corresponding point. The overall accuracy is increased by calculating the corresponding points at subpixel accuracy using a suitable interpolation method in the neighbourhood of the maximum (Rosenholm, 1985).

In order to reduce the time needed to match corresponding points, a multiresolution or pyramid hierarchical approach is applied, whereby a sequence of images of the same object is presented at successively reduced resolutions (Li, 1991). First, the image at level k is filtered by a low-pass filter, thereby removing high-frequency noise. This filtered image is afterwards resampled with a reduced sample density to obtain the image at level k+1 (Wong and Hall, 1978). In each step the images are reduced by a factor 2 (fig.4). Once the pyramid is created, matching is performed on the

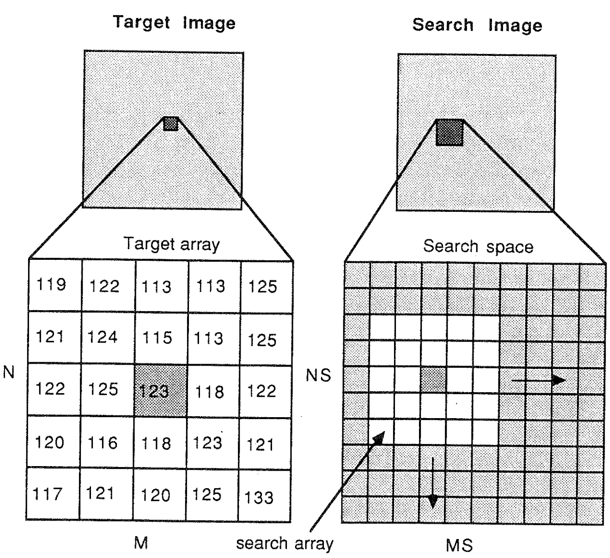

Fig.3 : Detailed view of the Matching Process

coarsest level (highest k-value) according to a regular grid superimposed on the target image. The positions of the matched points then serve as an estimate for the positions on the next level (k-1).

The matching algorithm is further enriched by introducing *a priori* knowledge (heuristics) : (i) at each level, the parallax displacement cannot exceed a predefined value, according to the maximum terrain height and the angle of incidence of the image. (ii) In view of the epipolar constraint there exists a maximum disparity in the y-direction (which increases with both viewing angle and latitude). (iii) If the position of a new matching on the image plane k-1 lies to far from the estimated value of level k, matching is rejected. (iv) Since improper matches can occur on snow surfaces (saturation) and shadows (dependent on the elevation and angle of incidence of the sun), each of these texture classes are identified on the basis of the mean and variance of the greyvalues in the target array. According to their matching accuracy they will be rejected or not.

Once matching is performed at the highest level (k=1), parallactic displacements are converted into heights through spatial resection. Corresponding points are transformed to the final cartographic reference system and an accurate position is calculated by finding the midpoint of the parallax of the projecting rays (fig.2).

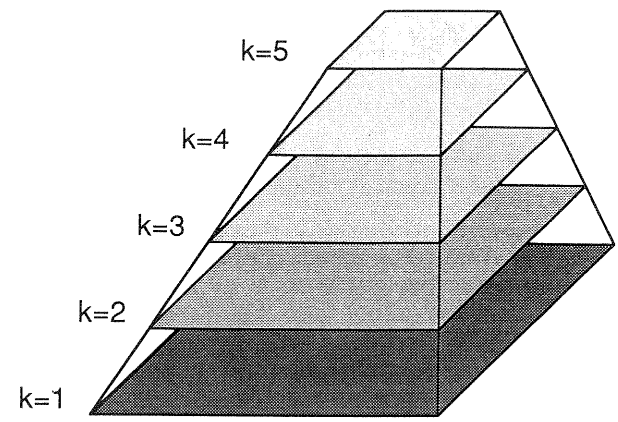

Fig. 4 : Multiresolution Image Library

4. EXPERIMENTAL RESULTS

4.1. Data Acquisition

A set of two panchromatic stereoimages covering the central part of the Sør Rondane Mountains (72°S, 25°E), Dronning Maud Land, Antarctica were obtained (table 1). This mountain range, situated 200 km south of the Princess Ragnhild Coast, belongs to a series of mountains surrounding the East Antarctic continent. Eight geodetic points were used as reference points for the geometric correction model. From a topographic map at scale 1:50,000 of the same region 28 control points were collected.

Date	G.R.S.	Scene centre	view angle
20.02.91	151/690	71°54'S / 25°57'E	22.9E
24.01.91	152/690	71°50'S / 25°10'E	18.1W

Table 1: Sør Rondane scene specifications

Both images are of good radiometric quality, since no clouds occur and a B/H ratio of 0.75 only favourites the matching accuracy. A higher B/H ratio for polar images is not advisable, because this would hamper the epipolar registration. Due to the late acquisition date and the steep relief of the mountain range (heights between 1000 and 2500 m.a.s.l.) shadows become indeed very large. Since both images are scanned a month apart the areal extent of shadowed areas also differs. A higher detector saturation was noticed on the east-looking scene.

4.2. Model Accuracy

In order to test the accuracy of the geometric correction model, the stereoimages were geocoded using the reference points. Parallaxes were calculated for the control points, from which three dimensional coordinates were obtained and afterwards compared with the original coordinates. The results of the accuracy test is shown in table 2.

# control points	R.M.S.E. X [m]	Y [m]	Z [m]
28	18.34	11.53	14.94

Table 2 : Model accuracy for the Sør Rondane images

The low overall accuracy is mainly caused by the difficulty by which reference and control points could be identified in the images. The control points on the images were taken on the contact surface between rock outcrops and ice/snow surfaces, which was done very accurately. However, the contact line between rock and snow on the topographic maps at scale 1:50,000 is so strongly generalised, that geographic coordinates could not be identified properly.

At the moment we are in the possession of a SPOT stereocouple of the northwestern part of Corsica. These images will be used for further analysis of the planimetric accuracy, once enough reliable ground control is available.

4.3. Matching Accuracy

The matching accuracy is the percentage of correctly matched points compared to the total amount of matches performed. Matched points are evaluated on the basis of the correlation coefficient and the heuristic

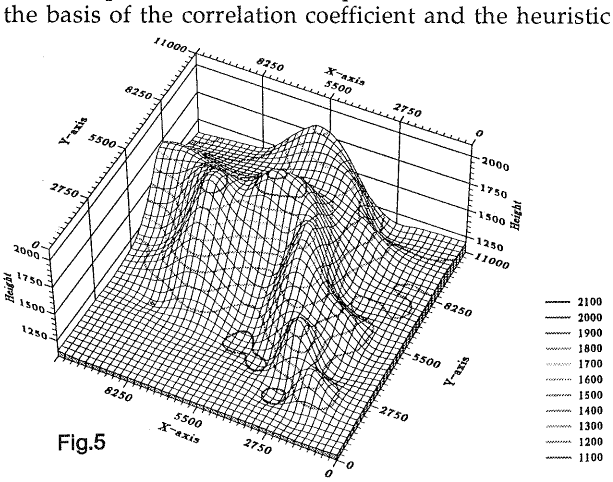

Fig.5

knowledge (see 4). For the Antarctic scenes, matching accuracy did not exceed 60%, both because of the steep relief and therefore large shadows and a higher detector saturation for the east-looking image. Also, only a few matched points were accepted (on the base of the aforementioned criteria) on the ice and snow surface. In order to improve the matching accuracy over high reflectance zones, selective image enhancement techniques (high pass filters and contrast stretching) on the glacierised surface were applied, resulting in a far much better performance (accuracy of 70-80%). However, on saturated snow patches matching still remains impossible.

Fig.5 displays a generalised DEM of the Menipa region (rock outcrop in the Sør Rondane surrounded by several glaciers) obtained from stereo-matching from SPOT. Heights range from 1100 m (flat glacier surface in front) to 2100 m. Preliminary matching tests could not distinguish corresponding points on the glacier surface, due to the low contrast. However, selective enhancement improved results a lot.

5. CONCLUSIONS

A method is presented in order to derive surface topography from stereoscopic SPOT images in polar regions. Despite the low precision by which reference points could be identified in the images, the overall accuracy still allows the production of topographic maps at scales between 1:100,000 and 1:50,000. More accurate ground control should allow for higher precision and therefore larger scale mapping. Matching accuracy and computation efficiency were improved by adding constraints to the matching algorithm concerning geometric characteristics and terrain texture and implying selective image enhancement techniques.

Results obtained this far prove that topographic mapping from space is undeniable the solution for an efficient production of medium to large scale topographic maps in remote (polar) areas.

6. ACKNOWLEDGEMENTS

This research is part of the "Belgian Scientific Research Programme on Remote Sensing by Satellite - phase two" (Services of the Prime Minister - Science Policy Office).

7. REFERENCES

Chevrel, M., M. Courtois and G. Weill, 1981. The SPOT Satellite Remote Sensing Mission. Photogrammetric Engineering and Remote Sensing, 47(8): 1163-1171.

CNES and SPOT IMAGE, 1988. SPOT's User Handbook, Vol.1: Reference Manual. CNES and SPOT IMAGE (Eds.).

Hottier, P. and M. Albattah, 1990. SPOT et la Photogrammétrie Analitique : Solution de Quelques Problèmes. Bulletin SFPT, 117(1): 10-23.

Leclerc, A., 1989. Le Système CARTOSPOT. CISM Journal ACSGC, 43(2): 111-120.

Li, M., 1991. Hierarchical Multipoint Matching. Photogrammetric Engineering and Remote Sensing, 57(8): 1039-1047.

Pattyn, F., 1991. The Geocoding of SPOT Imagery in Raster-Based Geographical Information Systems. In: Proceedings of the second European Conference on Geographical Information Systems EGIS'91, Brussels, Belgium, April 2-5, 1991, pp. 841-46.

Rosenholm, D., 1985. Digital Matching of Simulated SPOT Images. Fotogrammetriska Meddelanden, 2(50): 1-76.

Salamonowicz, P.H., 1986. Satellite Orientation and Position for Geometric Correction of Scanner Imagery. Photogrammetric Engineering and Remote Sensing, 52(4): 491-499.

Ungar, S.G., C.J. Merry, R. Irish, H.L. McKim and M.S. Miller, 1988. Extraction of Topography from Side-Looking Satellite Systems - A Case Study with SPOT Simulation Data. Remote Sensing of Environment, 26: 51-73.

Westin, T., 1990. Precision Rectification of SPOT Imagery. Photogrammetric Engineering and Remote Sensing, 56(2): 247-253.

Wong, R.Y. and E.L. Hall, 1978. Sequential Hierarchical Scene Matching. IEEE Transactions on Computers, C27(4): 359-366.