CARTOGRAPHIC APPLICATIONS OF SPOT IMAGERY

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ABSTRACT

Investigations were carried out into the suitability of stereoscopic SPOT imagery for the production of topographic maps as part of the Preliminary Evaluation Programme for SPOT (PEPS). This study shows that, while the accuracy achievable from the imagery is well within 1 : 50000 mapping specifications, the interpretability of the imagery presents some difficulty in mapping at scales as small as 1 : 250000. However, it is possible rectify aerial photography to produce orthophoto maps which meet 1 : 50000 accuracy specifications, using control points and a digital terrain model (DTM) derived from stereoscopic SPOT imagery. This is an effective method of producing orthophoto maps, since it reduces the amount of field work required to provide ground control, and reduces the measurement time of the DTM.

1. INTRODUCTION

This paper documents the results of PEPS Project No 238, entitled "An investigation of SPOT stereoscopic imagery for application to Digital Terrain Models and the production of orthophoto and conventional line maps at medium to large scales in Australia". This project was carried out jointly by the member organizations of the Australian Key Centre in Land Information Studies. These organizations are the Queensland Department of Geographic Information, the Geographical Sciences Department of the University of Queensland, and the Surveying Department of the Queensland Institute of Technology.

2. PURPOSE OF PROJECT

The SPOT satellite, with its 10 metre pixel size, has the highest spatial resolution of any commercial remote sensing satellite to date. This high resolution, coupled with the geometric quality of the images provided by the Charge Coupled Device (CCD) detectors, makes SPOT a potential tool for medium scale topographic mapping. The stereo viewing capability of the satellite enhances this potential.

It is generally accepted that accuracies of the order of 0.5 to 1.0 pixels are obtainable from scanned remote sensing imagery, and that the "smallest resolvable feature" in such imagery must have minimum dimensions of 2 to 2.5 pixels. It was therefore anticipated that positional accuracies of the order of 5 to 10 meters RMS would be achievable in mapping from panchromatic SPOT imagery. This is well within 1 : 50000 mapping specifications. However, in Australian mapping conditions, particularly in sparsely settled areas, small features such as houses, bores, dams and windmills are of great importance, and are shown on maps at scales as small as 1 : 250000. Many of these features are smaller than the "smallest resolvable feature" of SPOT panchromatic imagery with its 10 metre pixels.

The principal purpose of this project was therefore to investigate the combination of stereoscopic SPOT imagery with aerial photography, which has a relatively high resolution, to produce orthophoto maps. It was considered that the planimetric and height information necessary for the rectification of aerial photographs, conventionally obtained from the photography itself, may be able to be obtained more economically using stereoscopic SPOT imagery. The investigation sought to determine the largest scale at which planimetric and height data derived from stereoscopic SPOT imagery could be used to produce orthophoto maps adhering to cartographic accuracy specifications.

In addition, investigations were carried out into the interpretability of panchromatic SPOT imagery, in order to assess its suitability for the production of topographic line maps.

3. PROCEDURE

3.1 INTRODUCTION

The following steps were involved in carrying out the above investigations :

1. Development of a mathematical model to describe the relationship between SPOT image and ground coordinates.
2. Implementation of this model onto an analytical plotter to facilitate the measurement of stereoscopic SPOT imagery.
3. Measurement of a series of check points to assess the accuracy of point coordinate determination.
4. Measurement of a digital terrain model and comparison with known height information to assess the accuracy of terrain height measurement.
5. Application of the results of 3. and 4. to the requirements for orthophoto map production.
6. Production of a line map from SPOT imagery and a comparison with a recent map, to assess the interpretability of the imagery.
7. Investigation of the minimum control point requirement.

The project was carried out using two overlapping panchromatic images including the Brisbane metropolitan area, and extending westwards into relatively rugged, forested terrain up to 750 m above sea level, and southwards into rural areas consisting of both agricultural and grazing areas. A range of both land use and terrain types is therefore represented in the area covered by the images. The two images were acquired 19 days apart in July and August 1986, with view angles of 22.6°L and 25.4°R. The base-height ratio of the two images is 1.05:1. Level 1A film products were used for all of the studies described.

3.2 MATHEMATICAL MODEL

Mapping from any form of remotely sensed imagery requires that a relationship can be established between image coordinates and ground coordinates. These models consist of two components: a model which describes the sensor geometry, and a model which describes the variation of the position and attitude of the sensor with time. Konecny (1971) showed that modifications can be made to the photogrammetric collinearity equations to model the imaging geometry of a variety of remote sensing systems.

A number of authors have developed such models for the SPOT image - ground coordinate relationship. Of these, Gugan (1987), Konecny et al (1986), Kratky (1987) and Priebbenow and Clerici (1987) use collinearity equations explicitly to model the sensor geometry, while

Guichard (1983) has developed a method in which the collinearity equations are incorporated into a derived mathematical model. The above authors have all used different approaches to model the variation of position and attitude of the sensor during the acquisition of a scene. The method developed by Priebbenow and Clerici (1987) is described below.

Each image line of a SPOT image is acquired virtually instantaneously, and can be considered to be equivalent to a central perspective image, which, in panchromatic mode, covers approximately 60 km by 10 m on the ground. A panchromatic image consists of 6000 of these image lines acquired sequentially. If one assumes that each image consists of an infinite number of one-dimensional image lines, rather than of 6000 discrete lines 1 pixel wide, the collinearity equations given in Equation 1 express the relationship between image and ground coordinates.

$$0 = -f\frac{r_{11}(X - X_0) + r_{12}(Y - Y_0) + r_{13}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)}$$

$$y = -f\frac{r_{21}(X - X_0) + r_{22}(Y - Y_0) + r_{23}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)}$$

$$x = k \cdot t$$

$$\ldots\ldots(1)$$

where

- X, Y, Z are ground coordinates in a cartesian coordinate system
- X_0, Y_0, Z_0 are satellite coordinates in the same coordinate system
- r_{ij} are elements of a rotation matrix expressed in terms of three angles ω, ϕ and κ, which define the angular relationship between the sensor and ground coordinate systems
- f is the focal length of the sensor
- y is the image coordinate measured with respect to the centre of the image line
- X_0, Y_0, Z_0, ω, ϕ and κ vary with time t.
- k is a constant defining the relationship between the x image coordinate and time t.

It is impractical to attempt to derive explicitly the values of the position (X_0, Y_0, Z_0) and attitude (ω, ϕ, κ) parameters for each line using ground control points. Therefore, the variation of the satellite position and attitude with time must be modelled. In choosing a suitable model, three principles were adopted:

1. The model should, as nearly as possible, describe the actual variation of the position of the position and attitude of the sensor with time.

2. The model should be expressed in terms of a minimum number of variable parameters, to minimise the ground control requirement.

3. It should be possible to introduce information known *a priori* about the satellite position and attitude to reduce correlation between the above parameters. This correlation is due to the low ratio of terrain height to satellite altitude, and to the narrow field of view of the sensor (4.118°).

In order to describe the model which was developed, Equation 1 is rewritten in matrix form as:

$$\begin{pmatrix} 0 \\ y \\ -f \end{pmatrix} = \lambda \cdot R3 \cdot R2 \cdot R1 \cdot \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix}$$

$$x = k \cdot t \qquad \ldots\ldots (2)$$

where

- λ is a scale factor.
- ***R1*** is a rotation matrix which transforms the model coordinate system, in which the satellite and ground coordinates are expressed, to the nominal platform coordinate system.
- ***R2*** is a rotation matrix which transforms the nominal platform coordinate system to the actual platform coordinate system. The actual platform coordinate system is defined by the yaw, pitch and roll axes of the platform. The nominal platform coordinate system is that system to which the on-board attitude control system attempts to align the actual platform coordinate system.
- ***R3*** is a rotation matrix which transforms the actual platform coordinate system to the sensor coordinate system.
- The elements of the matrix product ***R3 ·R2 ·R1*** are the elements r_{ij} in Equation 1.

The motion of a satellite in orbit can be considered to be smooth and predictable, especially over the short period of time, 9.024 s, in which one SPOT scene is acquired. The orbit of a satellite can be described in terms of 6 osculating parameters, such as those adopted by Guichard (1983) : $(\rho, I, \Omega, w, e_x, e_y)$. Each of these parameters varies with time, under the influence of numerous perturbing forces. Guichard (1983) showed that only the perturbing effect of the V_{20} term of the earth's spherical harmonic disturbing function is significant over the period of acquisition of 10 contiguous SPOT scenes.

The motion of the satellite can be adequately described at any time during the acquisition of an image in terms of the values of these parameters at an initial time prior to the commencement of image acquisition. This is done by numerically integrating the parameters from their initial values. Approximate values for these six parameters can be obtained from the ephemeris data which is provided with the images. It has been found to be sufficient to regard the values thus calculated for e_x and e_y as known values, and to treat the remaining four parameters, at the initial time, as unknown parameters, for which values are calculated using ground control.

The variation of the satellite attitude with time can be described by the product of the three rotation matrices ***R1, R2*** and ***R3*** defined above. The matrix ***R3*** is a function of the satellite position, and can thus be described in terms of the four position parameters (ρ, I, Ω, w). The matrix ***R1*** is constant for any scene, and is derived from the detector look angles provided with the imagery.

The matrix ***R2,*** which describes the variation of the satellite orientation from its nominal orientation, can in part be defined using the yaw, pitch and roll attitude velocity measurements which are also provided with the imagery. These values can be integrated to describe the variation of the yaw, pitch and roll angles with time. If ***R3*** is expressed in terms of three angles ω_s, ϕ_s and κ_s, each of which varies with time, then the matrix ***R3*** can be calculated at any time from the angles given in Equation 3.

$$\omega_s(t) = \omega_0 + roll(t)$$
$$\phi_s(t) = \phi_0 + \phi_1 \, . \, t + \phi_2 \, . \, t^2 - pitch(t)$$
$$\kappa_s(t) = \kappa_0 + yaw(t)$$

..... (3)

The variation of the attitude of the satellite (ω, ϕ, κ) can therefore be described using the five attitude parameters $(\omega_0, \phi_0, \phi_1, \phi_2, \kappa_0)$ in Equation 3 and the six osculating orbital parameters described above, together with the given values for the detector look angles and the attitude velocity measurements.

A least squares solution for the nine unknown parameters defining the variation of the parameters $X_0, Y_0, Z_0, \omega, \phi$ and κ in Equation 1 with time can be achieved with a minimum of five ground control points.

3.3 IMPLEMENTATION ON ANALYTICAL PLOTTER

A photogrammetric analytical plotter provides the facility for the stereoscopic viewing and measurement of film images. Measurement of the images is achieved by the calculation of image coordinates from ground coordinates entered by the operator, given that the values of the parameters defining the relationship between these two sets of coordinates have been determined. This calculation is carried out by a real-time program which operates at frequencies of the order of 50 Hz.

Analytical plotters are used primarily for the measurement of frame camera images. The real time program calculates the relationship between image and ground coordinates according to central perspective geometry. However, the imaging geometry of the SPOT satellite is significantly different to that of frame cameras, as described in the previous section. It is therefore necessary to modify the calculation carried out by the real time program if one wishes to measure SPOT imagery using the analytical plotter.

The calculation of the relationship between SPOT image coordinates and ground coordinates, expressed in a map projection, is relatively complex compared to the same calculation for frame camera imagery, due both to the different imaging geometry and to the large area covered by each image. In order to ensure smooth image movement, and a fast response to movements entered by the operator, an approximating method, based on the use of a correction grid, as proposed by de Masson d'Autume (1979), was therefore used in the implementation of the above mathematical model on the Zeiss Planicomp C100 analytical plotter.

The method involves the following steps:

1. A pseudo model is established in the Planicomp. The parameters of this model are selected so that the image ground relationship approximates that of the SPOT stereo pair.

2. For a grid of ground points, both SPOT image coordinates and pseudo image coordinates are calculated off-line, and the differences stored in a file.

3. Stereoscopic measurement of the SPOT images is carried out by allowing the real time program to calculate pseudo image coordinates according to central perspective geometry. Corrections are added to the calculated pseudo image coordinates by an interpolation program which uses the pre-calculated values from Step 2.

The use of this method enables the 50 Hz frequency of the real time program to be maintained, and gives a smooth and 'instantaneous' response to movements entered by the operator.

3.4 ACCURACY OF POINT COORDINATE DETERMINATION

An experiment was carried out to determine the accuracy with which the ground coordinates of well defined points could be determined from the measurement of stereoscopic SPOT imagery. A set of 210 points which could be seen both in the SPOT images and in existing controlled aerial photography over the area was selected. The ground coordinates of these points were then measured from the photography and the image coordinates from the SPOT imagery, with a classification of 'good', 'average' or 'poor' being given to each point by the operator. The majority of points were intersections of linear features such as roads and tracks.

Initial calculations were carried out to identify erroneous points. Due to the fact that the aerial photography was acquired in 1971, many changes had occurred in the area covered by the imagery. This was suspected to be the cause of a number of points having residuals in the 20 - 30 m range, compared to a RMS residual value of 6 m. Points with residuals larger than 20 m were therefore rejected. A number of these were obvious mis-identifications. 22 of the original points were rejected.

A set of 27 of these points, well distributed in the images, was selected as control. Only those points which had been classified as good or average were used. A calculation of the parameters defining the relationship between image and ground coordinates, as described above, was carried out using these control points. The coordinates of the remaining 161 points were then calculated using the SPOT image coordinate measurements. For all 188 points, the differences between the ground coordinates derived from the SPOT images and from the photography were calculated. The RMS residuals in Easting, Northing and planimetry were 4.2 m, 4.0 m and 6.2 m respectively. The RMS residual in height was 3.1 m.

3.5 DIGITAL TERRAIN MODELLING

The aim of this experiment was to determine the accuracy of a digital terrain model (DTM) measured from SPOT imagery. Profiles covering the area of one 1 : 25000 map sheet were measured at 100 m intervals. Using the DTM package HIFI, a 25 m grid was interpolated from these measurements.

The controlled aerial photography used for the previous experiment was also used to derive the data against which the SPOT-derived DTM was compared. A grid of heights at 50 m spacing was measured over the same area. The estimated standard error of these heights is 1.0 m. Again, this data was interpolated to a 25 m grid using HIFI.

The accuracy of the SPOT-derived DTM was assessed by calculating the height differences between the two data sets for every point in the interpolated grid. The RMS height error derived from these differences is 5.4 m, consisting of a mean datum shift of -3.2 m, and a standard deviation from this mean of 4.3 m.

3.6 SUITABILITY FOR ORTHOPHOTO PRODUCTION

Based on the results of the above experiments, it is possible to make an estimate of the accuracies achievable in rectifying aerial photography using planimetric and height information derived from SPOT imagery. A number of factors contribute to the accuracy of the final orthophoto map. For the case of rectification of 1 : 40000 wide angle (f = 152 mm) photography in an analytical orthoprojector the mean square error (MSE) of the orthophoto map can be estimated as :

$$\sigma^2_M = \sigma^2_C + \sigma^2_O + \frac{r^2}{f^2} (\sigma^2_{HC} + \sigma^2_{DTM} + \sigma^2_I) \qquad \ldots\ldots (4)$$

where

- σ^2_M is the MSE of the orthophoto map.
- σ^2_C is the planimetric MSE of the control points (38.44 m^2).
- σ^2_O is the MSE of the absolute orientation of the photography in the orthoprojector. The measurement precision is assumed to be 0.01 mm in x and in y. Thus this value is 0.32 m^2 ($= 0.01 * \sqrt{2} * 40)^2$.
- r^2 is the mean square distance from the nadir of all points in the photograph, assuming vertical photography with 60% forward and 20% side lap. (5735 mm^2).
- σ^2_{HC} is the MSE of the height control points (9.61 m^2).
- σ^2_{DTM} is the MSE of the DTM (29.2 m^2).
- σ^2_I is the MSE of height interpolation, which is a function of the ruggedness of the terrain and of the slit width of the orthoprojector (excluded from this calculation).

Thus σ_M = 6.95 m.

Topographic mapping accuracy specifications generally state that the limit within which 90% of all points must lie is 0.5 mm at map scale, which at 1 : 25000 is 12.5 m, and at 1 : 50000 is 25 m. This 90% limit is equivalent to 1.645 σ_M, which for the above case is 11.4 m. Thus, it is possible to rectify aerial photography to produce orthophoto maps meeting map accuracy specifications at 1 : 50000, using control and height information derived from stereo SPOT imagery. Considering that σ^2_I has been excluded from the calculation of σ_M, and that there may be other possible error sources, the suitability for 1 : 25000 orthophoto mapping is marginal.

The 60 km square area covered by a SPOT image would be covered by approximately 128 models of 1 : 40000 photography. The provision of adequate ground control for such a block of photography would involve the establishment of approximately 12 planimetric and height points, and an additional 12 height points. The establishment of this control by field methods would involve significantly more work than that required to measure the 6 to 8 planimetric and height points required for a SPOT stereo pair. The measurement of the DTM would involve significantly more work using the photography than using the SPOT imagery, due both to the scale difference between the two types of imagery and the difference in the number of models involved.

3.7 LINE MAP PRODUCTION USING SPOT IMAGERY

A topographic line map over the area covered by a 1 : 25000 map was produced from the SPOT imagery. The sites selected for this experiment were chosen because the existing 1 : 25000 topographic maps covering the areas had recently been revised, allowing them to be used as a basis for comparison, and because the areas included a variety of terrain and land use types.

The mapping, which was carried out using the Zeiss Planicomp, was done in two stages. Firstly, the operator measured all detail which he could see in the area, without input from any other source. As part of this stage, a contour plot, with a 20 m interval, was also produced. Secondly, a "field" check was carried out using the existing 1 : 25000 topographic map. With the knowledge of the existence of features which were not located in the first stage, the known location of every such feature was inspected in the imagery. These features were then plotted if they could be seen.

Table 1 shows some of the results of this exercise. A number of broad categories of cultural features are shown, with the percentage of each of these features located at each stage of the process.

3.8 CONTROL REQUIREMENTS

An investigation into the minimum control point requirement was carried out. The 188 points used as control and check points in the earlier experiments were also used for this exercise. From the set of 27 control points, different numbers of points were selected as control, and the parameters describing the relationship between image and ground coordinates were calculated. Using these parameters, the coordinates of the 188 points were calculated from their image coordinates.

The results showed that, when more than four control points were used, the RMS planimetric and height residuals calculated for the check points were almost independent of the number of control points. However, when less than four control points were used, these RMS values increased considerably. When a low number of control points is used, these RMS values can be improved significantly by including measurements of the image coordinates of a number of additional parallex points distributed over the image.

FEATURE CLASS	% PLOTTED and IDENTIFIED	% PLOTTED and NOT IDENTIFIED	% PLOTTED AFTER 'FIELD' CHECK	% NOT PLOTTED	TOTAL ON MAP
Sealed Road	68	11	6	15	46.7 km
Unsealed Road	42	25	11	22	41.7 km
Track	9	15	14	62	82.4 km
Urban Road	65	0	5	30	11.9 km
Railway	0	78	3	19	17.9 km
Power Line	100	0	0	0	12.4 km
Fence	13	1	0	86	345.5 km
Dam	1	4	16	79	469
Building	30	0	8	62	554

Table 1. Percentages of various classes of features within a 1 : 25000 map area which were located in the SPOT image at different stages of the line mapping exercise.

4. CONCLUSIONS

The series of experiments described above was intended to investigate cartographic applications of SPOT imagery. The high geometric accuracy of the imagery is sufficient to meet 1 : 50000 topographic mapping specifications. However, the image interpretability has limitations at this scale. The proposed method of combining the geometric accuracy of SPOT with the relatively high resolution of aerial photography is capable of producing 1 : 50000 orthophoto maps which meet standard mapping specifications. This method is potentially more economical than current methods used for orthophoto map production.

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