

# SPOT SOFTWARE FOR WILD AVIOLYT BC2 ANALYTICAL PLOTTER

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Operational software has been developed for mapping from SPOT satellite images on the Wild Aviolyt BC2 analytical plotter. The software is designed to reflect as nearly as possible standard BC2 software procedures. The solution of the scanner geometry is based on a rigorous collinearity formulation with the position and tilts varying according to first or second order polynomials. Coordinate transformations will enable the plotting and computation of coordinates in a local projection system. Precision of computation of object coordinates have been shown to be of the order of 5-10m in planimetry and height coordinates depending on the precision of ground control points.

## 1. INTRODUCTION

With the successful launching of SPOT-1 on the 22nd February 1986, the production of topographic maps from space on a operational basis is now a possibility. SPOT acquires high resolution imagery of almost all of earth's surface and on the basis of coverage per single image, its imagery is cheaper than aerial photography. Some of SPOT's characteristics that make it potentially suitable for topographic mapping are:

- i. high resolution,
- ii. attitude stability,
- iii. off nadir viewing, and
- iv. linear array CCD technology.

Exploiting the above characteristics, it is possible to determine the X, Y and Z coordinates of the terrain with a pair of stereo SPOT imagery in a similar manner as used in analytical photogrammetry. However, as the image has a cylindrical perspective relationship, the mathematics of the SPOT images are different from those of conventional photographs. A detail treatment of the mathematical model has been dealt with by Carroll (1987). This paper describes software developed for the measurement of SPOT images on the WILD BC2 analytical stereoplotter. It will detail the mathematical relationships used to compute the spacecraft attitude and position, and hence object point coordinates, the method of satisfying the real-time equations during observation of the terrain, and the results of tests of images observed in the WILD BC2.

As the mathematics developed are based on the projective relationships between the imagery and the terrain at the time of imagery, only those SPOT images that retain these geometric relationships can be used. Currently, only the preprocess level 1A images satisfy this condition. Standard SPOT

panchromatic level 1A images are offered either on Computer Compatible Tape (CCT) or positive film. The positive film has a scale of 1/400,000 with an image size of 150 mm by 150 mm. A standard CCT containing only the ancillary data will also be provided with the positive film images.

Because the mathematics for the SPOT imagery and conventional photography are quite similar, the software developed was designed to be able to process a pair of conventional photography (as in a bundle solution). Extending this capability, a stereo model could also be formed by a SPOT image and a conventional photograph in a combined setup. This step has not been implemented in the software yet.

## 2. BASIC FORMULATION FOR LINEAR ARRAY IMAGERY

The standard photogrammetric collinearity equations are not applicable to linear array push broom imagery. This is because in a linear array image, only one line is imaged at any one instant of exposure. Hence a separate set of collinearity equations exist for each line of the image. Figure 1 shows the image space/object space geometry for a point 'j' for a linear array image. Taking the image x axis to be in the direction parallel to the epipolar plane (as in conventional photogrammetry), it can be noted that the projective relationship exists only in the x-z plane of the image space. Thus the resulting collinearity equations for a line k are given by:

$$F_{xj} = x_j + f \frac{m_{11}(X_j - X_k^c) + m_{12}(Y_j - Y_k^c) + m_{13}(Z_j - Z_k^c)}{m_{31}(X_j - X_k^c) + m_{32}(Y_j - Y_k^c) + m_{33}(Z_j - Z_k^c)} = 0$$

$$F_{yj} = f \frac{m_{21}(X_j - X_k^c) + m_{22}(Y_j - Y_k^c) + m_{23}(Z_j - Z_k^c)}{m_{31}(X_j - X_k^c) + m_{32}(Y_j - Y_k^c) + m_{33}(Z_j - Z_k^c)} = 0$$

where  $X_k^c, Y_k^c, Z_k^c$  are the coordinates of the perspective centre for line k of the image

$f$  is the effective focal length

$m_{11}, m_{12}, \dots, m_{33}$  are the elements of the rotation matrix of the sensor for line k

.... equation (1)

### 2.1 Coordinate System Used

In dealing with satellite imagery, there are several possible coordinate systems which can be selected. The local space rectangular coordinate system has been chosen for the software with the appropriate corrections applied for earth curvature, and the difference between local space rectangular and grid coordinate system (eg UTM). This system is a rectangular coordinate system which coincides with the plan and height movements in the model. The main disadvantage of the local space rectangular coordinates is that the satellite coordinates cannot be accurately defined in this system. This however is not normally a significant problem because the objective of the solution is usually only in accurate ground coordinate determination. The coordinates for the satellite's position in the software developed in this project are used to provide approximations for the solution of ground coordinates rather than to pin-point the location of the satellite at the time of imagery. The local space rectangular coordinate system is thus the best choice for both the solution of the orientation parameters and also for the real-time equations used for plotting.

### 2.2 Orientation Parameters

For linear array imagery a set of collinearity equations can be written for each line of the image with its

own perspective centre and attitude (rotations) as shown in equation 1. Obviously it is impossible to solve for the orientation parameters of every line in the image independently. A solution is to model the orientation parameters for the whole image by polynomials in terms of the y image coordinates. Carroll (1987) recommends that the orientation parameters be modelled with polynomials as follows:

$$X_k^c = X_0^c + X_1^c y_j + X_2^c y_j^2$$

$$Y_k^c = Y_0^c + Y_1^c y_j + Y_2^c y_j^2$$

$$Z_k^c = Z_0^c + Z_1^c y_j + Z_2^c y_j^2$$

$$\omega_k = \omega_0 + \omega_1 y_j$$

$$\phi_k = \phi_0 + \phi_1 y_j$$

$$\kappa_k = \kappa_0 + \kappa_1 y_j$$

where  $X_0^c, Y_0^c, Z_0^c$  are the coordinates for the scan line in the middle of the image

and  $\omega_0, \phi_0, \kappa_0$  are the corresponding rotations

equation (2)

### 2.3 Corrections to Local Space Rectangular Coordinates

As coordinates used for the ground control for mapping and surveying are in the local grid coordinate system (which is based on a curved earth's surface projected onto a map projection surface), there is a need to include in the software the conversion of the local space rectangular coordinates to the local grid coordinates, and vice versa. Two steps are required:

- i. convert the local rectangular coordinates to a local curvilinear coordinates by applying earth curvature correction;
- ii. convert the local curvilinear coordinates to grid coordinates by applying corrections for map projection distortions.

#### 2.3.1 Earth Curvature Corrections

Figure 2 shows the relationship between the local space rectangular coordinate system and the local curvilinear coordinates. Conversion from local space rectangular to local curvilinear coordinates is achieved using the following formulae:

$$\alpha = \arctan[S / (R + Z)]$$

$$H = (R + Z) \sec \alpha - R$$

$$\Delta S = (R + Z) \sin \alpha - R \alpha \quad \dots \text{equation (3)}$$

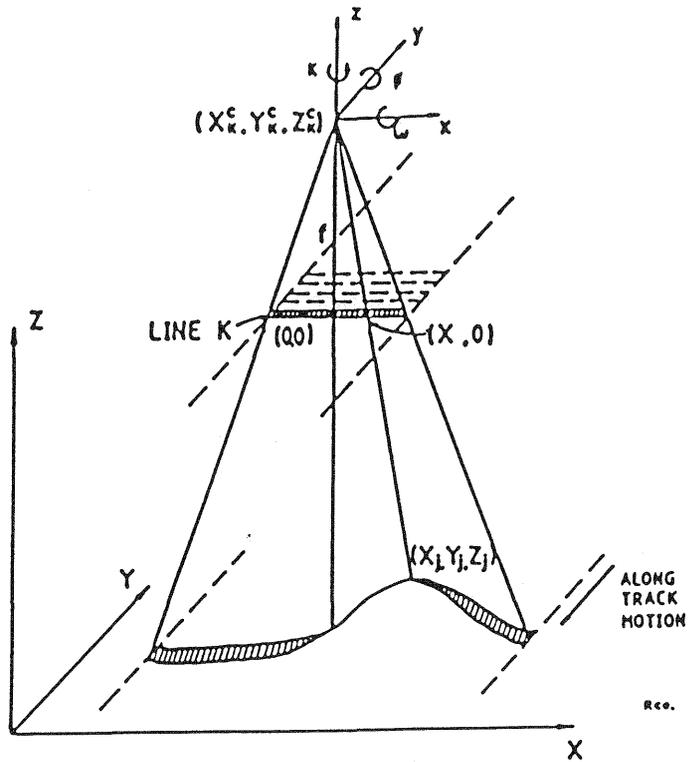


Figure 1. Collinearity Relationship for Linear Array Imagery.

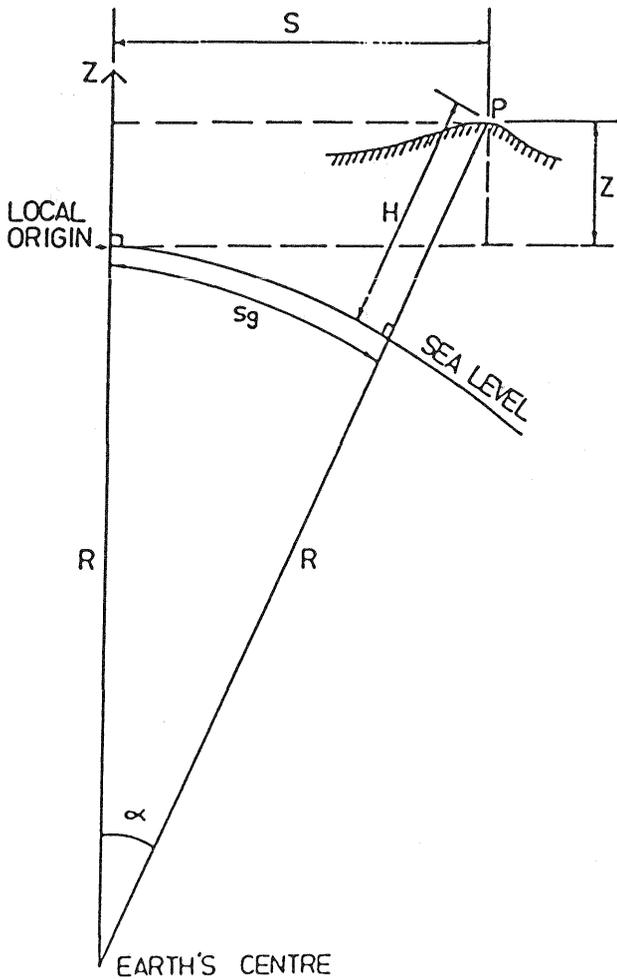


Figure 2. Relationship between Local Space Rectangular and Local Curvilinear Coordinate Systems.

where R is the radius of the earth (e.g. 6371 km), Z is the local space rectangular Z coordinate, H is the local curvilinear height coordinate (which approximates the height above the mean sea level), and S is the distance from the origin of the local system. The trigonometrical functions in equation (3) were expanded into a series and the approximate formulae introduced into the analytical plotter software.

The major correction for earth curvature is in the height. For a distance of about 30 km the correction for height is about 70 m. The planimetric correction is less than 0.5 m for the same distance.

### 2.3.2 Map Projection and Refraction Corrections

Corrections required to convert the local curvilinear coordinates to the grid coordinates are dependent on the map projection used. It is not possible to derive a set of expressions for all map projections and therefore the software must be designed to suit individual users. Currently only UTM projection has been activated for the software.

Due to atmospheric refraction, light rays passing through the atmosphere do not travel in straight lines. However, because of its insignificant effect, there is no requirement to apply correction for atmospheric refraction.

## 2.4 Ephemeris Data

The ephemeris data can be used to compute the coefficients for Xc, Yc Zc and  $\omega$ ,  $\phi$ ,  $\kappa$  polynomials. Two problems must be addressed. Firstly, the polynomials used in the solution are functions of the y image coordinate, in micrometres; thus an expression must be found to relate the satellite's positions to the image distance. Secondly the satellite's coordinates are given in GRS-80 geocentric coordinate system, therefore they have to be converted to the local coordinate system that is used in the solution.

### 2.4.1 Satellite's Position as a Function of Image Distance

Let  $t_0$  be the time at the scene centre. Then with a sampling rate of 1.504 ms (which corresponds to a ground distance of 10 m), the ground distance, D, between the position of the satellite at any time t and its position at  $t_0$ , is given by:

$$D = (t_0 - t) * 10 / 1.504e-3 \text{ m} \quad \text{..... equation (4)}$$

D is positive in the positive direction of y, which is in the opposite direction of satellite's direction of motion. If S is the image scale, the equivalent image distance  $dy$  for the above will therefore be as shown in equation (5) and the coordinates of the satellite given by the ephemeris data can thus be related to the equivalent image distance from the centre of the image.

$$dy = (t_0 - t) * 1e10 * S / 1.504 \quad \text{.....equation (5)}$$

### 2.4.2 Converting GRS-80 Coordinates to Local Coordinates

Conversion from the GRS-80 geocentric coordinates to local space rectangular involves a datum transformation from the GRS-80 to the datum of the local reference ellipsoid, then a transformation to the local space rectangular coordinates. Transformation between the datums of GRS-80 and the local reference ellipsoid, is achieved using the 3 shift parameters, the values of which being given for the commonly used systems around the world in SPOT User Handbook, 1987

### 2.4.3 Computed Exterior Orientation Parameters

Six exterior orientation parameters were computed from the ephemeris data for each scene from the SPOT header data by an auxiliary program provided with the SPOT software. The remaining 3 elements,  $Xc2$ ,  $Yc2$  and  $Zc2$  in equation 2 being the last terms of their corresponding polynomials, remain as unknowns, so that miscellaneous unmodelled perturbations can be accommodated.

## 3. REAL-TIME EQUATIONS

In an analytical stereoplotter special software is required to maintain the stereomodel while allowing an operator to scan. The real-time software operation must be able to compute the transformations between the observed ground points and the corresponding image points at least 60 times/second without overloading the computer's resources.

The collinearity conditions for linear array scanners as described above in equation 1 are not suitable for real-time driving in an analytical plotter since either, the rotation matrices for every scan line must be computed and stored before commencing the real-time software operations or the rotation matrices must be evaluated continuously in the real-time loop. The former approach demands large amounts of storage, about 200 kilobytes for an image and this is impractical both in storage and the time required to compute the matrices. The latter approach is difficult to achieve in the time available in a real-time loop.

The solution adopted involved dividing each image into a number of segments. Each segment is treated as a central projection and the standard collinearity equations are used. The small differences in image coordinates between the computed central perspective projection of the segments and the rigorous collinearity conditions for scanner images can be modelled using a second order polynomial as a function of the image coordinates. Corrections can therefore be applied in real time to the image coordinates of points in the segmented central projections.

Tests have shown this method to give residual differences between coordinates computed in the segmented central perspective equations, and the rigorous collinearity equations of less than 5 micrometres over the whole scene.

## 4. TEST RESULTS AND EVALUATION

### 4.1 Test Images

The test stereo pair of SPOT images consists of scene S1H1861122002053 and S1H1861012235008 over Sydney and its metropolitan area. The former was imaged on the 22nd November 1986 with a 'left' incidence angle of  $30.1^\circ$  and the latter was imaged on the 12th October 1986 with a 'right' incidence angle of  $21.3^\circ$ . The base to height ratio of the pair is thus 0.97.

Table 1 shows some relevant acquisition data for both images (the data are available in the header record of the leader file and the printout of ancillary data supplied with the images).

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Table 1 - Acquisition Data

|                         |                               |                               |
|-------------------------|-------------------------------|-------------------------------|
| Scene                   | S1H1861122002053              | S1H1861012235008              |
| Instrument              | HRV1                          | HRV1                          |
| Spectral Mode           | Panchromatic                  | Panchromatic                  |
| Process Level           | 1A                            | 1A                            |
| Scene Centre            | S 33° 54'36"<br>E 150° 59'46" | S 33° 54'36"<br>E 150° 56'48" |
| Nadir                   | S 33° 12'22"<br>E 146° 32'26" | S 34° 19'43"<br>E 154° 00'46" |
| Scene Orientation Angle | 8.2°                          | 12.1°                         |
| Angle of Incidence      | L 30.1°                       | R 21.3°                       |

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Note : The Scene Orientation Angle is the angle between the centre line of the raw scene and the meridian through the centre of the raw scene; and the Angle of Incidence is the angle between the normal to the reference ellipsoid, passing through the centre of the raw scene, and the instrument look direction for the same point (SPOT Image, 1986)

#### 4.2 Tests on The Solution of Exterior Orientation Parameters and Ground Coordinates

Tests were carried out by KWOH (1988) to evaluate the various solutions of the algorithm prior to incorporating it in the WILD BC2 as follows:

- (i) the minimum number of ground control points required.
- (ii) the effect on the solution without additional ephemeris data
- (iii) as in (ii), but with further corrections for map projection distortions.

Ground coordinates were derived from 1:25,000 maps, and for this test, image coordinates were derived from a VDU display of the digital images. Ground coordinate values had a accuracy of 7.5m and

the image coordinates about 0.5 pixel (equivalent to an accuracy on the ground of 5m). In the initial evaluation, it was found that the minimum number of control points required for the solution with and without the use of ephemeris information was 5 and 7 respectively. Increasing the number of control points from the minimum number generally resulted in significant decreases in all the residuals. However, above 9 control points, the reduction in the residuals was very gradual. It therefore does appear that 9 control points is the minimum number that should be used.

The solutions using ephemeris information were superior to those without the use ephemeris information. This was evidenced from the generally lower residuals in the computed coordinates and lower standard deviations of the computed exterior orientation parameters throughout the test. Furthermore, solutions using ephemeris information converge more quickly, requiring 3-4 iterations compared to 6 - 7 iterations for solution without ephemeris information.

The accuracy (rmse) obtainable from this set of test data estimated from the mean rms of the residuals at its check points, from solutions with 10 to 19 control points is shown in Table 2, and is consistent with the accuracy of the original data. The rms errors also compare favourably with those obtained by Konecny et al (1986), who reported values of 10.9m, 13.7m and 6.5m for the rms errors of X, Y and Z coordinates respectively from a solution with 18 control points. The ground control and check points used in Konecny's evaluation were also obtained from existing 1:25,000 maps.

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TABLE 2

Estimated Rmse of Solution with Test Data (m)

|                        | E    | Y    | H   |
|------------------------|------|------|-----|
| Without Ephemeris Data | 11.4 | 11.1 | 7.7 |
| With Ephemeris Data    | 10.4 | 10.3 | 6.6 |

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These rms errors were however significantly larger than those obtained by the French Institut Geographique National (IGN), who reported values of 4.6m, 4.4m and 5.3m in X, Y and Z respectively, with scenes at maximum satellite look angles (CNES, 1987). This lower accuracy (larger rms errors) can be attributed to the inherent errors of the test data used in this project being of the same order as the rms error of the solution, thus degrading the accuracy of the solutions significantly.

#### 4.3 Tests on The WILD BC2

Having implemented the bundle solution and the software for the real-time equation, analogue images from the above described scenes were printed and observed on the WILD BC2. Printing was achieved on an image writer with a 50 micrometre pixel size covering an image area of 4000 x 4000 pixels, which was the maximum size which could be stored by the computer during the writing operation. Ground control coordinates were derived from 1:25,000 maps and also 1:4,000 orthophotomaps with accuracies of 12.5 m and 2m respectively in planimetry, and 4m and 2m in height. Forty control points were observed for orientation and approximately 80 check points were also observed in the WILD BC2 using the 2 sets of control data. Ephemeris data was used as a basis for the orientation computation. Results of the orientation are shown in Table 3

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TABLE 3

Residuals from Tests in WILD BC2 (m)

|                                     | E   | Y   | H   | position vector |
|-------------------------------------|-----|-----|-----|-----------------|
| Orientation using<br>1:25,000 data  | 9   | 9   | 1   | 11              |
| Check points using<br>1:25,000 data | 11  | 9   | 3.5 | 14              |
| Orientation using<br>1:4,000 data   | 4.7 | 6.8 | 1.0 | 8.2             |

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Residual y-parallaxes from the orientation were 20 micrometres (equivalent to 4m on the ground). Pointing precisions were tested by repetitive observations on well-defined points giving the following results:

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TABLE 4

Pointing Precision on SPOT Images (m)

| E | N | H |
|---|---|---|
| 2 | 2 | 1 |

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The accuracies given in Table 3 agree with those shown earlier in this paper but those based on the 1:4,000 orthophoto data approach accuracies obtained by IGN. Height coordinate accuracies are even lower than those obtained by IGN being 1m and 3.5 m for the orientation and check points respectively. The precisions of pointing are very high and perhaps indicate the base level that could be approached with the solution if higher accuracy control could be obtained. Overall, the accuracies demonstrate the extremely high geometric accuracies achieved with stereo SPOT images and indicate that SPOT images could result in data with position accuracies compatible with 1:25,000 mapping or smaller.

## 5 CONCLUSIONS

(i) The software developed to measure SPOT images on the WILD BC2, has been shown to achieve high accuracies in the orientation based on control point measurement. The accuracies match the accuracy of the ground control points of 5 to 7 m in planimetry and as little as 1m in height. These accuracies would be suitable for mapping at scales of 1:25,000 and smaller.

(ii) The approach to the solution of scanner data of approximating the variations in the orientation parameters by polynomials has proved successful. The inclusion of ephemeris data in the solution improves its rate of convergence and should always be included in the solution since it is available in the image file header data.

(iii) The real-time equations have been computed by dividing the images into a number of segments which are assumed to behave as central projections, and applying corrections for the distortions introduced by this step. Accuracy of this approach is better than 5 micrometres and well within the

accuracy of the solution.

(iv) This software package is recommended for any organisation wishing to carry out mapping from SPOT images. The solution is effective and produces high accuracy mapping data.

## REFERENCES

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