D. Fritsch, M. Englich & M. Sester, eds, 'IAPRS', Vol. 32/4, ISPRS Commission IV Symposium on GIS - Between Visions and Applications, Stuttgart, Germany.

AN ALTERNATIVE APPROACH TO THE TRIANGULATION OF SPOT IMAGERY

Atsushi Okamoto Kyoto University, Japan
Clive Fraser University of Melbourne, Australia
Susumu Hattori Fukuyama University, Japan
Hiroyuki Hasegawa PASCO Corporation, Japan
Tetsu Ono Kyoto University, Japan

ABSTRACT

Satellite line scanner imagery such as that of SPOT and MOMS-02 is usually analysed via a collinearity equation approach based on projective transformation. This paper discusses the application of an alternative approach to the triangulation of satellite line scanner imagery, namely affine projection. The approach involves an initial transformation of the original perspective line image into an affine projection, which is then followed by a linear transformation from image to object space for stereo geometries (cross-track and along-track). The triangulation phase for the affine image data is in turn in two stages. In the first a preliminary adjustment is performed to determine initial values of the six affine transformation parameters for the selected 'orientation image lines'. The interval of orientation images is about 2,000 lines and the behaviour of the transformation parameters between adjacent orientation images is assumed to be linear. This phase of the process utilises ground control points only. A bundle type triangulation adjustment then follows, in which affine transformation parameters are refined along with the object point triangulation.

Initially, the paper reviews features of the affine projection model with special reference being given to the perspective-to-affine conversion for each image line. The method for acquiring initial values for the bundle adjustment is also discussed, along with ground control considerations. Application of the affine orientation model to a SPOT scene covering the Kobe/Osaka area of Japan is then reported, for both Level-1 and Level-2 cross-track imagery. The results of the triangulation indicate that ground check point accuracies at the level of 6m in planimetry and 7.5m in height can be obtained, for both Level-1 and Level-2 imagery, for ground control configurations of 6 or more well distributed points. The results obtained are very encouraging, especially for the geometrically corrected Level-2 imagery. They illustrate that, in spite of some minor theoretical shortcomings with the formulation of the affine projection model, ground point triangulation accuracies equivalent to and in cases better than alternative approaches based on perspective transformation models can be achieved.

1 INTRODUCTION

A general orientation model for satellite line scanner imagery can be rigorously formulated in terms of a projective transformation (Okamoto et al., 1992). However, due to the very narrow field angle of the imaging device, very high correlations arise between the orientation parameters and the obtained accuracy is thus limited. In order to overcome this shortcoming, an affine transformation approach can be applied for the analysis of satellite line scanner imagery, since affine transformation pertains to parallel projection and so the field angle of the scanner geometrically plays a very limited role.

The general orientation problem of affine line scanner imagery can be discussed along the same lines as that of central perspective line scanner imagery (Okamoto et al., 1992). However, due to our inability to directly acquire affine imagery, we must first convert the central perspective imagery to an affine image in order to apply the proposed orientation theory in a practical manner. This image conversion, however, cannot be carried out rigorously unless the heights of all imaged ground points are available and the orientation parameters of the scanner at the instant of exposure are known. To circumvent this requirement, a method of correcting the image conversion errors has been developed to facilitate practical application of the affine orientation approach for the triangulation of satellite line scanner imagery. The effectiveness of this conversion has previously been demonstrated for SPOT imagery (Okamoto et al., 1996).

In this paper, a general orientation model of affine line scanner imagery, and the central perspective-to-affine image conversion is first briefly described. It is then shown that a method of acquiring initial values of the orientation parameters can be readily constructed using the linearity of the basic affine collinearity equations, when these equations are set up for ground control points only. Moreover, initial values of unknown ground point coordinates can be calculated by employing the obtained initial values for the orientation parameters. These are required for the subsequent bundle adjustment, the model of which will be outlined. The proposed affine model has been applied for the analysis of a SPOT scene covering the Kobe/Osaka area in Japan and the results obtained in this experimental evaluation are discussed.

2 THE AFFINE ORIENTATION MODEL

The general collinearity equations for the three-dimensional analysis of affine line scanner imagery can be described in the form (Okamoto et al., 1992)

$$0 = X + D_1Y + D_2Z + D_3$$
$$y_a = D_4Y + D_5Z + D_6 \qquad (1)$$

The first expression in Equation 1 denotes the equation of an imaging plane in the XYZ object space coordinate system, whereas the second indicates that an affine relationship is also valid between the line scanner imagery and an image obtained by an orthogonal projection of the object into the Y-Z plane of the object coordinate system, as illustrated in Figure 1.

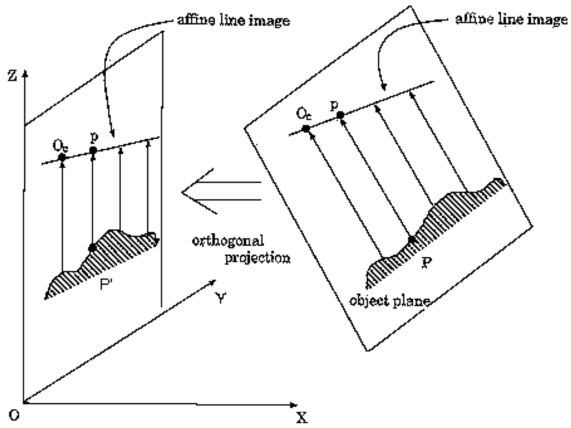

Figure 1: Projective relationship of an affine image.

Further, we can find that the determination of the imaging plane can be performed separately from that of the projective relationship of the affine imagery. This is because the first and second expressions in Equation 1 share no common coefficients.

3 PERSPECTIVE-TO-AFFINE CONVERSION

Let the terrain be flat and let a central perspective line scanner image be taken at an oblique angle ω (see Figure 2). Further, let the image be assumed

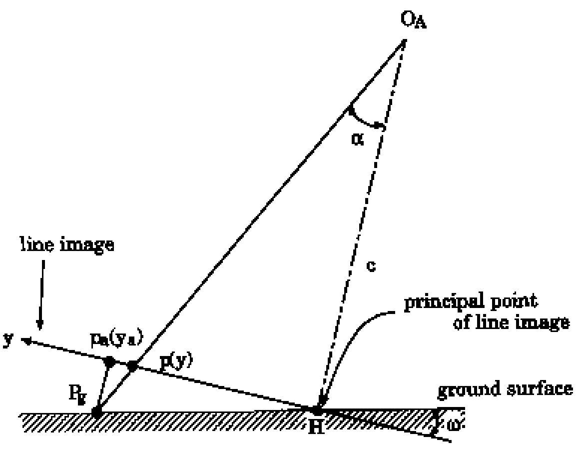

Figure 2: Perspective-to-affine image conversion.

to intersect the terrain at its principal point H. By connecting the projection center O_A and an image point p(y), and extending the line, we can find the object point P_g. The affine image point $p_a(y_a)$ corresponding to the central perspective image point p(y) is then found by drawing the normal to the line image from the object point P_g. The relationship between p(y) and $p_a(y_a)$ is given as follows for a line scanner of principal distance c:

$$y_a = y / (1 - y \tan\omega / c) \qquad (2)$$

At the stage of the perspective-to-affine image conversion using Equation 2, we utilize only the approximations of both the oblique angle ω and the interior orientation parameters of the scanner, and thus an image conversion error can arise. However, under the assumption that the field angle of the scanner is very narrow, this error can be modeled in a linear form and thus be removed automatically in the orientation calculation (Equation 1).

When the terrain is mountainous, the image conversion using Equation 2 yields additional errors due to height differences. If we let ΔZ indicate the height difference from the average ground point height P'_g, and we use α to denote half the field angle of the scanner, the image conversion error Δy due to neglecting the height difference ΔZ can be given in the form

$$\Delta y = \Delta Z \{ \tan(\omega+\alpha) - \tan\omega \}\cos\omega \qquad (3)$$

This is shown in Figure 3. In the case where the field angle of the scanner is 4^o, the oblique angle 30^o and the height difference 1,000m, the image conversion error arising from application of Equation 2 amounts to 20.6m at ground scale.

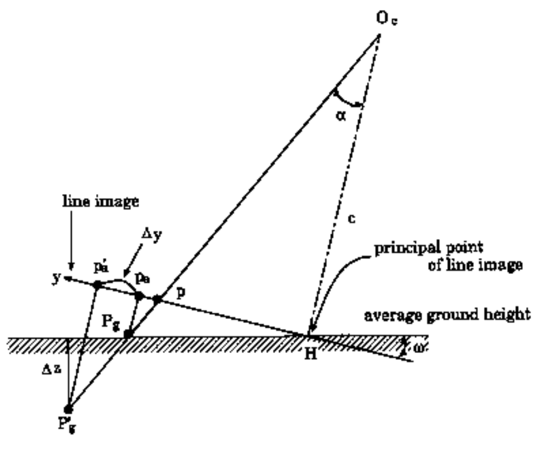

Figure 3: Image error from height differences.

A correction method for this image conversion error is as follows:

1) The orientation calculation using Equation 1 is first carried out under the assumption that the terrain is flat. The approximate height of each ground point is then obtained and the height difference from the average terrain height is calculated.
2) The image conversion error Δy is removed by changing the principal distance for each ground

point, as illustrated in Figure 4, according to the expression

$$\Delta c = \Delta Z/\cos\omega, \quad c' = c + \Delta c, \quad y' = y\, c'/c$$
$$y'_a = y'/(1 - y' \tan\omega / c') \qquad (4)$$

3) The orientation calculation using Equation 1 is repeated with the corrected affine image coordinate y'_a.

4 BUNDLE TRIANGULATION ADJUSTMENT

4.1 Acquisition of Initial Values

The general collinearity model (Equation 1) of affine line scanner imagery is linear with respect to the orientation parameters if the observation equations are set up for ground control points only. Thus, initial values for the orientation parameters can in principle be obtained by solving these linear equations. In the case of analysing line scanner imagery such as SPOT, however, geometric weaknesses may need to be first overcome by employing orbital constraint information. Here, we assume that the interior orientation parameters of the scanner (the principal distance and the principal point coordinate), as well as the oblique angle at the instant of exposure and the flying height, are given quite accurately. This is because these parameters are also required for the perspective-to-affine image conversion.

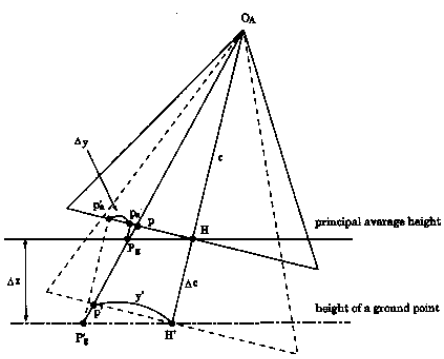

Figure 4: Correction of image conversion error.

In order to calculate the first approximations of the orientation parameters D_i (i=1,…,6) of Equation 1 for cross-track line scanner imagery, the XYZ reference coordinate system is selected as right-handed Cartesian with its origin at the center of the area to be mapped and with its X-axis towards north. The flying direction of the satellite can be roughly assumed to be parallel to the X-axis and the stereopairs are recorded at an oblique angle ω from different orbits. Further, the imaging plane of the line scanner is assumed to be almost vertical. The first approximations A_i of the orientation parameters of the scanner can then be obtained:

$$A_1 = 0, \quad A_2 = 0,$$
$$A_3 = -gw\,(lno - 1)\,S + Dx\,S/2, \quad A_4 = \cos\omega, \qquad (5)$$
$$A_5 = \sin\omega, \quad A_6 = -(Y_o \cos\omega + Z_o \sin\omega)S$$

Here, S is the image scale, lno the line number, gw the ground width of the line scan, Zo the satellite altitude, Yo the Y-coordinate of the flight course and Dx the extent of the area in the flight direction.

Assignment of appropriate weights to the approximations calculated by means of Equation 5 can overcome instability in the solution for the initial values of the orientation parameters for a stereopair of imagery. Initial values of the ground point coordinates required for the bundle adjustment can be calculated by solving the four linear equations for each point using a least-squares approach.

4.2 'Bundle' Adjustment

In the bundle-type adjustment of a stereopair of satellite line scanner imagery, the general collinearity equations (Equation 1) are first linearised with respect to the orientation parameters D_i and the XYZ object space coordinates in the form

$$0 = fxo + A_Y\,\Delta D_1 + A_Z \Delta D_2 + \Delta D_3 + \Delta X + A_1\,\Delta Y + A_2\,\Delta Z$$
$$y_a = fyo + A_Y\,\Delta D_4 + A_Z \Delta D_5 + \Delta D_6 + A_4\,\Delta Y + A_5\,\Delta Z \qquad (6)$$

where

$$D_i = A_i + \Delta D_i$$
$$X = A_X + \Delta X, \quad Y = A_Y + \Delta Y, \quad Z = A_Z + \Delta Z$$

The collection of Equations 6 for all the orientation points of the stereopair leads to a system of linear observation equations

$$\mathbf{B}\,\Delta\mathbf{x} = \mathbf{c} \qquad (7)$$

in which **B** is the coefficient matrix, $\Delta\mathbf{x}$ the vector of corrections to unknowns, and **c** the vector of constants. As in the conventional bundle adjustment, object space control is used to overcome the rank defect of **B** and the solution $\Delta\mathbf{x}$ is obtained via a least-squares approach.

5 APPLICATION TO SPOT IMAGERY

5.1 Kobe/Osaka Test Field

In order to investigate the geometrical characteristics of the proposed affine model, an experiment was conducted within the Kobe/Osaka SPOT testfield. This test field is covered by large cities in the south and by mountains with an elevation range of 850m in the north. The extent of the area in the flight line direction is about 25km, while the width (in the scanning direction) is 40km. One of the primary requirements for the SPOT image test was the availability of image-identifiable ground control and check points which could be accurately surveyed. These points were first selected as ground features which were visible in both the stereopair of SPOT imagery and in aerial photography at a scale of 1:17,000. Ground coordinates had been obtained from the aerial photography through aerial triangulation to an accuracy of 30cm in planimetry and 60cm in height.

D. Fritsch, M. Englich & M. Sester, eds, 'IAPRS', Vol. 32/4, ISPRS Commission IV Symposium on GIS - Between Visions and Applications, Stuttgart, Germany.

In order to achieve triangulation accuracies at the 5-10m level, sub-pixel image mensuration precision was required. The image identification on the SPOT images was carried out by overlaying the digitized aerial photographs upon the area under consideration. Image coordinate observations were then made monoscopically in units of 1/4 pixel. About 150 well distributed image-identifiable ground control and check points were thus established.

5.2 Level-1 and Level-2 SPOT Imagery

Rigorous approaches to triangulation of cross-track satellite line scanner imagery can, in general, be applied to geometrically uncorrected Level-1 SPOT imagery only (Ebner et al., 1992; Fraser and Shao, 1996). However, the process of producing Level-2 images from the original imagery is analogous to the perspective-to-affine image conversion process discussed previously, as is illustrated in Figure-5. Therefore, the proposed affine model was applied to both the Level-1 and Level-2 stereo SPOT scenes.

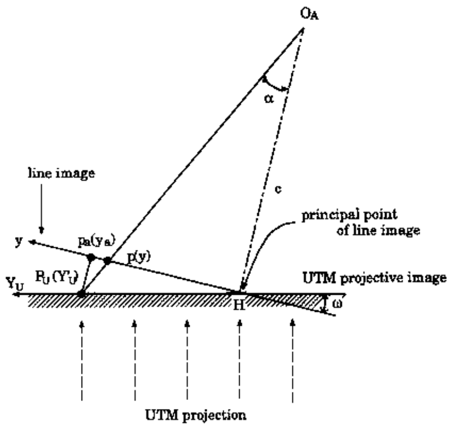

Figure 5: Geometry of Level-2 imagery.

5.3 Behaviour of Orientation Parameters

The behaviour of the exterior orientation parameters of the scanner along the flight path has been considered in detail by a number of researchers and many functional models describing this behaviour have been proposed. Of these, we have employed the model formulated by Hofmann (1986), where the orientation parameters of the scanner are determined for orientation image lines at selected, regular intervals. The variations in the orientation parameters between adjacent 'orientation images', which are here spaced at intervals of 2000 lines, are assumed to be linear.

5.4 Outlier Testing

An outlier test (the Danish method) was first conducted to 'clean' the measured image coordinate data. However, outliers invariably could not be detected and localised very effectively. This was due to the fact that in the orientation determination for cross-track stereo imagery, residuals in the scanning direction become, in principle, almost zero due to the coplanarity condition of the corresponding rays in the Y-Z plane of the reference coordinate system. A future solution to this problem for steerable scanners would be to utilise 3-fold stereo, though even here there remain limitations in localising the observational errors.

In this research work, outliers, mainly comprising identification errors, were detected by an outlier test which considered all the ground check points, used effectively as control points. The resulting image coordinates having residuals larger than 3σ were flagged for rejection. In the orientation analysis of Level-1 SPOT imagery, which had originally 128 check points, some 10 observations were rejected. For the Level-2 imagery, on the other hand, 12 points out of 154 were regarded as having associated image measurements which were outliers.

5.5 Discussion of Triangulation Results

Shown in Tables 1 and 2 are the triangulation results for SPOT Level-1 and Level-2 imagery of the Kobe/Osaka testfield. From these tables, which indicate an attained external accuracy level of 5-8m in the ground point triangulation process, some notable characteristics can be reported:

1) The internal precision of image coordinate measurements is quite difficult to accurately quantify in the orientation calculation. In the outlier tests using all the check points, standard error values attained were 7.1μm for Level-1 imagery and 8.1μm for Level-2. However, the estimated standard errors in the bundle adjustment were 5μm for the former and 4.5μm for the latter, because residuals in the scanning direction vanish in the orientation analysis of the stereopair of line scanner images.
2) Orbital information can be very effectively employed to improve the stability of the solution. The analysis of stereo SPOT imagery can proceed with as few as 4 ground control points at the corners of the area under consideration. However, the orientation/ triangulation requires at least 6 ground control points when the assumption is invoked that the co-planarity condition of corresponding rays does not alone provide orientation parameters.
3) The behaviour of the orientation parameters of the scanner along the flight path can be modeled in a linear form so long as the extent of the area is not too great. In our case the extent was 25km. Increasing the number of orientation image lines can be expected to weaken geometry.
4) If we assume that the standard errors obtained in the outlier testing give the most realistic estimates of precision, then the affine model is shown to produce accuracies close to the optimum level expected from SPOT triangulation, namely ground point accuracies in the range of 5-8m.

From the triangulation of geometrically uncorrected Level-1 SPOT imagery, the following characteristics have been noted:

1. The Kobe/Osaka area analyzed in this research was rather mountainous. The maximum height

D. Fritsch, M. Englich & M. Sester, eds, 'IAPRS', Vol. 32/4, ISPRS Commission IV Symposium on GIS - Between Visions and Applications, Stuttgart, Germany.

difference amounted to 850m. Therefore, the image conversion errors were corrected by repeating (iterating) the orientation calculation twice. This resulted in accuracies being obtained to the optimum level anticipated, thus showing that the proposed method is mathematically sound.

2. In the perspective-to-affine image conversion, the errors of the exterior and interior orientation parameters of the scanner were neglected. The resulting image conversion errors were nevertheless compensated for due to the scanner's very narrow field angle.

The following features were noteworthy in the triangulation results of Level-2 imagery:

1. The proposed affine model can also be employed for the orientation analysis of geometrically pre-corrected satellite imagery which no longer constitutes a perspective projection.
2. The planimetric accuracy was slightly lower with Level-2 imagery than with Level-1 data. This means that the image conversion into a UTM projection deviated slightly from the affine image transformation of the original imagery.

6 CONCLUSIONS

In this paper an orientation model for the triangulation of satellite line scanner imagery based on affine transformation has been described. In order to apply the proposed method in a practical situation, a conversion from the original central perspective imagery to an affine projection is required. The means of carrying out this conversion has also been presented and the associated treatment of conversion errors considered.

Through tests of the proposed affine model with SPOT imagery taken over the Kobe/Osaka area, various interesting characteristics of the method have been clarified:

1) The affine model can be applied not only for Level-1 SPOT imagery but also for geometrically corrected Level-2 imagery.
2) The acquisition of initial values of both the orientation parameters and the ground point coordinates can be readily performed by utilizing the linearity of the basic equations.
3) In spite of some theoretical shortcomings of the perspective-to-affine image conversion, the affine model can provide ground point triangulation accuracies equivalent to and in cases better than conventional central perspective models.

Further, through the results of simulation tests, this method has been revealed to be applicable to the triangulation of along-track stereo imagery, with even higher accuracies being anticipated in this case. Also, from the fact that the narrower the field angle of the scanner, the more accurate the perspective-to-affine image conversion, the affine model is expected to be quite applicable to for the orientation/triangulation of forthcoming 1m high resolution satellite imagery.

Table 1. Triangulation Results for Level-1 SPOT Imagery.

GCP	NOIL	EEINI			AIECH		AEECH	
		σ_{XY} [m]	σ_Z [m]	σ_o [μm]	σ_{XY} [m]	σ_Z [m]	σ_{XY} [m]	σ_Z [m]
4	2	8.2	10.4	5.1	4.3	11.9	5.7	7.5
6	2	7.7	10.2	5.0	3.8	10.7	5.4	8.0
9	2	6.3	9.1	5.1	3.6	9.9	5.1	6.9
9	3	8.4	10.3	5.1	4.0	11.2	5.3	7.6

GCP - number of ground control points
NOIL - number of orientation image lines
EEINI - external errors of initial values of check point coordinates
σ_o - standard error of measured image coordinates
AIECH - average internal error at check points (GCPs not included)
AEECH - average external error at check points (GCPs not included)

Table 2. Triangulation Results for Level-2 SPOT Imagery.

GCP	NOIL	EEINI			AIECH		AEECH	
		σ_{XY} [m]	σ_Z [m]	σ_o [μm]	σ_{XY} [m]	σ_Z [m]	σ_{XY} [m]	σ_Z [m]
4	2	9.9	8.2	4.3	3.6	10.0	7.3	8.4
6	2	8.8	6.8	4.5	3.3	9.5	6.7	7.5
9	2	6.9	6.5	4.6	3.1	8.7	6.5	6.9
9	3	8.1	7.5	4.6	3.6	10.0	6.5	7.5

D. Fritsch, M. Englich & M. Sester, eds, 'IAPRS', Vol. 32/4, ISPRS Commission IV Symposium on GIS - Between Visions and Applications, Stuttgart, Germany.

7 REFERENCES

Ebner, H., Kornus, W. and Ohlhof, T., 1992. A simulation Study on Point Determination for the MOMS-02/D2 Space Project Using an Extended Functional Model. *International Archives of Photogrammetry and Remote Sensing*, 29(B4): 458-464.

Fraser, C.S. and Shao, J., 1996. Exterior Orientation Determination of MOMS-02 Three-Line Imagery: Experiences with the Australian Testfield Data. *International Archives of Photogrammetry and Remote Sensing*, 31(B3): 207-214.

Hofmann, O., 1986. Dynamische Photogram-metrie. *Bildmessung und Luftbildwesen*, 54(5): 105-121.

Okamoto, A., Akamatsu, S. and Hasegawa. H., 1992. Orientation Theory for Satellite CCD Line-Scanner Imagery of Mountainous Terrain. *International Archives of Photo-grammetry and Remote Sensing*, 29(B2): 205-209.

Okamoto, A., Akamatsu, S. and Hasegawa. H., 1992. Orientation Theory for Satellite CCD Line-Scanner Imagery of Hilly Terrain. *International Archives of Photogrammetry and Remote Sensing*, 29(B2): 217-222.

Okamoto, A., Hattori, S., Hasegawa. H. and Ono. T., 1996. Orientation and Free Network Theory of Satellite CCD Line-Scanner Imagery. *International Archives of Photo- grammetry and Remote Sensing*, 31(B3): 604-610.