A Modified Bundle Adjustment Software for SPOT Imagery and Photography: Tradeoff

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Abstract

A major problem for SPOT imagery is its geometric accuracy in relation to aerial photography, especially from the point of view of digital terrain models (DTM) and orthophotography. Computer simulation using a modified bundle software fosters versatility and high accuracy in terms of mirror tilt angles, distribution of ground control points (GCP), etc., and is a feasible and cost-effective analytical tool. This paper presents a tradeoff study of a modified bundle adjustment program for the simulation of SPOT geometry vis-a-vis *conventional photography with regard to precision for various tilt angles, number of GCPs, various positions of control points in different patterns, etc.*

Introduction

Accurate topographic mapping at a scale of 1:25,000 utilizing satellite imagery requires expensive instrumentation such as analytical stereo plotters, digital plotters, etc. Satellite imagery has been widely used for mapping by developing countries such as Sudan, North Yemen, and China (Welch and Pannel, 1982; Kennie and Mathews, 1985; Parry and Perkins, 1987; Hartley, 1988; Bohme, 1989). There are, however, some major problems such as the one encountered in the Sudan experiment in the identification of point and line features such as roads, railways, bridges, settlements, etc., and also in the geometric accuracy of the imagery in relation to conventional aerial photography.

The problems associated with satellite imagery are due mainly to the large orbital height of satellites, though these can be somewhat alleviated in missions such as those of the space shuttle (Doyle, 1985). At an image scale of 1:80,000, one approaches the limit at which many "cultural features" such as settlements, bridges, etc., can be identified. With satellite imagery, we have, in general, much smaller scales and these pose problems in terms of completeness of details, as for instance in Landsat imagery (Kenny and Mathews, 1985). The height information that can be derived from photogrammetric models can be used to form a DTM (Doyle, 1978).

The bundle adjustment method is a flexible analytical tool and a powerful computational technique for coordinating engineering and industrial structures (Granshaw, 1980), and fosters high accuracies economically. The application of the bundle method to multistation photography can provide high, homogeneous precision even without the incorporation of control data. Though the bundle method is mainly associated with multiple photographs and images, as in the case of aerial triangulation, it has been used in the present study in view of its flexibility, even though the study involves only stereopairs. Whereas identification of topographic features is a major problem for SPOT imagery as well as for virtually all other space imagery, the focus of the modified bundle adjustment program is not feature identification, but geometric accuracy of SPOT imagery which is of overriding consideration in deriving a DTM and orthophotography.

The advantage of the present simulation is that parameters such as mirror tilt angle, distribution of ground control points (GCPs), etc., can be readily changed to investigate the fundamental properties of the imagery. Most of the work done by various researchers has been somewhat limited in respect of viewing angle and ground control, and, in many cases, the results have been checked only against existing maps whose intrinsic accuracy itself is in question (Rodriguez *et al.*, 1988; Gugan and Dowman, 1988; Kratky, 1989; Sharpe, 1989; Dowman, 1990; Westin, 1990). Again, the basic idea of this simulation is not merely to test the results of SPOT coordinates derived from different geometric and control configurations, but also to compare SPOT imagery with conventional aerial photography of equivalent characteristics (position, attitude, focal length, etc.) to facilitate proper analysis of the dynamic characteristics of the SPOT imagery, although such photography has not been acquired in practice. The bundle program has been written for conventional photography and, based on this experience, subsequently modified considering the dynamic nature of the SPOT imagery which has inherent complications in view of its non-conformity to single perspectives. The modified bundle adjustment software facilitates cost-effective and optimum geometry of the SPOT imagery and GCP distribution, though it is not intended to be an alternative to topographic mapping using conventional sophisticated and expensive instrumentation.

SPOT imagery is generally capable of accuracies up to 5 m in both planimetry and height, depending on factors such as image quality, base-to-height ratio, identification problems, instrumentation used, control point quality, etc. (Rodriguez *et al.*, 1988). Much work on the geometric accuracy of SPOT imagery has been undertaken as part of the preliminary evaluation program for SPOT (PEPS). Using SPOT imagery in both the Kern DSR-1 analytical plotter and digital plotters, it is re-

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ported that the degradation in quality of the film hardcopy compared to the digital images is striking (Gugan and Dowman, 1988). A number of studies (Ley, 1988; Kratky, 1989; Sharpe, 1989; Westin, 1990) have been made using SPOT imagery for diverse areas such as west Cyprus, Ottawa, Sherbrooke, Grenoble, etc., for various base-to-height ratios, tilt angles, number of ground control points, etc.

The present simulation using modified bundle adjustment software attempts to investigate the precision of ground points for real image coordinates measured on hard copy images using inexpensive instruments such as a stereo comparator. A major problem for SPOT imagery is the identification of topographic features for interpretation and selection of the GCPs.

This software is useful for optimization of the number of GCPs, especially for developing countries such as Sudan where extensive topographic mapping has not hitherto been carried out.

Modified Bundle Software

The modified bundle adjustment software, based mainly on Granshaw (1980), focuses not on the identification of topographic features, but on the geometric accuracy of SPOT imagery, and readily facilitates change of parameters such as mirror tilt angle, distribution of control points, etc., to investigate the fundamental properties of the imagery. The photographic simulation has been carried out for a number of GCPs in different patterns and for various tilt angles and compared with that of SPOT. Konecny *et al.* (1987) have described a detailed flow chart for the restitution of the SPOT imagery and also discuss a rigorous method for the geometric processing of the images.

In order to restitute SPOT imagery, analytical instrumentation can be used provided the software is reprogramed to process the imagery, for example, the Kern and Zeiss software (Konecny *et al.*, 1987; Gugan and Dowman, 1988). A promising developement in this connection is the availability of digital stereoplotters such as the Kern DSP-1, and also a number of instruments currently in production such as the Helava 740, Intergraph Imagestation, etc., which will have significant impact on the restitution of SPOT imagery (Bonjour and Newby, 1990; Dowman, 1990; Kennie and Petrie, 1990). For testing the software described in this paper, a Kern DSR-1 analytical stereoplotter has been used as a stereocomparator with the image coordinates measured and used offline. It may be mentioned that, whereas analytical plotters are somewhat expensive for topographic mapping, particularly for developing nations, the modified bundle software is cost-effective from the point of view of investigation of geometric accuracy and GCP configuration, and gaining a better understanding of the relationship between satellite imagery and topography, though it is not an alternative to the analytical plotter.

The bundle adjustment program for photography is based on the collinearity equations and the procedure suggested by Granshaw (1980). These equations have been modified as follows with a slight change in notation:

$$x_i = -f\,\frac{r_{11}(X_i - X_s) + r_{21}(Y_i - Y_s) + r_{31}(Z_i - Z_s)}{r_{13}(X_i - X_s) + r_{23}(Y_i - Y_s) + r_{33}(Z_i - Z_s)} \tag{1}$$

$$y_i = -f\,\frac{r_{12}(X_i - X_s) + r_{22}(Y_i - Y_s) + r_{32}(Z_i - Z_s)}{r_{13}(X_i - X_s) + r_{23}(Y_i - Y_s) + r_{33}(Z_i - Z_s)} \tag{2}$$

where x_i and y_i represent the plate coordinates relative to the origin at the principal point, f is the principal distance, (X_i, Y_i, Z_i) are the ground coordinates of the i^{th} point, (X_s, Y_s, Z_s) are the perspective center coordinates, and r_{ik} are the typical elements of a rotation matrix $\mathbf{R}$ representing the ω, ϕ, κ rotations of the image coordinates with respect to the ground coordinates as follows:

$$\mathbf{R} = \begin{bmatrix} \cos\phi\cos\kappa & -\cos\phi\sin\kappa & \sin\phi \\ \sin\omega\sin\phi\cos\kappa + \cos\omega\sin\kappa & -\sin\omega\sin\phi\sin\kappa + \cos\omega\cos\kappa & -\sin\omega\cos\phi \\ -\cos\omega\sin\phi\cos\kappa + \sin\omega\sin\kappa & \cos\omega\sin\phi\sin\kappa + \sin\omega\cos\kappa & \cos\omega\cos\phi \end{bmatrix} \tag{3}$$

In the case of SPOT imagery, we have a series of linear arrays each of which can be likened to a one-dimensional photograph. In a panchromatic SPOT image, there will be 6000 perspective centers and 6000 rotation matrices, one for each linear array. The position $S(X_s, Y_s, Z_s)$ of the satellite at a given time can be linearly related to the location $O(X_o, Y_o, Z_o)$ of the satellite corresponding to the central linear array (X_o, Y_o, Z_o). Some researchers (for example, Gugan (1987)) have used second-order polynomials on all exterior orientation parameters, allowing for some degree of nonlinear changes in the satellite's position and attitude as follows:

$$\begin{aligned} X_s &= X_o + a_1 t + b_1 t^2 \\ Y_s &= Y_o + a_2 t + b_2 t^2 \\ Z_s &= Z_o + a_3 t + b_3 t^2 \\ \kappa_s &= \kappa_o + a_4 t + b_4 t^2 \\ \phi_s &= \phi_o + a_5 t + b_5 t^2 \\ \omega_s &= \omega_o + a_6 t + b_6 t^2 \end{aligned} \tag{4}$$

where a_1 to a_6 and b_1 to b_6 are constants to be deter mined and t is the time difference between satellite positions $S(X_s, Y_s, Z_s)$ (positive or negative) and $O(X_o, Y_o, Z_o)$. In these equations, $(\omega_s, \phi_s, \kappa_s)$ and $(\omega_o, \phi_o, \kappa_o)$ represent the image tilt values at the satellite positions S and O, respectively. However, these equations with 18 parameters to be determined do not provide a practical set of parameters, because in a linear array, unlike photography, certain parameters are highly correlated with one another, leading to a very unstable solution reflecting the one-dimensional nature of a linear array. Figure 1 shows the effect of small changes in the six exterior orientation parameters on aerial photography as well as on a linear array. Whereas, in general, these movements cause different effects on aerial photographs, in linear arrays a small change $(d\omega_s)$ in ω_s is indistinguishable from a small change (dY_s) in Y_s; similarly, small changes $(d\phi_s)$ and (dX_s) in ϕ_s and X_s, respectively, can not be differentiated. It is, therefore, necessary to eliminate either ω_s or Y_s and either ϕ_s or X_s from the set of parameters, after which we obtain the following equations with 12 unknown parameters for each image:

$$\begin{aligned} X_s &= X_o + a_1 t + b_1 t^2 \\ Y_s &= Y_o + a_2 t + b_2 t^2 \\ Z_s &= Z_o + a_3 t + b_3 t^2 \\ \kappa_s &= \kappa_o + a_4 t + b_4 t^2 \end{aligned} \tag{5}$$

Any changes in ω_s and ϕ_s should now be automatically accounted for by Y_s and X_s, respectively. The effect of these changes is to replace the rotation matrix $\mathbf{R}$ in Equation 3 by a new matrix given by

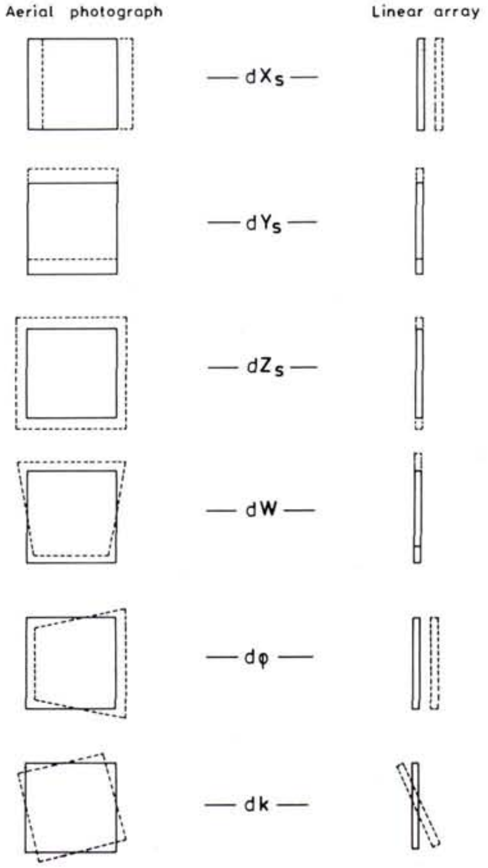


Figure 1. The effect of small changes in parameters for photography and linear array.

$$\mathbf{R} = \begin{bmatrix} \cos(\kappa_o + a_4t + b_4t^2) & \cos\omega\sin(\kappa_o + a_4t + b_4t^2 & \sin\omega\sin(\kappa_o + a_4t + b_4t^2) \\ -\sin(\kappa_o + a_4t + b_4t^2) & \cos\omega\cos(\kappa_o + a_4t + b_4t^2) & \sin\omega\cos(\kappa_o + a_4t + b_4t^2) \\ 0 & -\sin\omega & \cos\omega \end{bmatrix} \tag{6}$$

where κ_o, a_4, and b_4 are to be determined in the solution for a specific mirror tilt angle, ω_t, of the SPOT satellite when the imagery is acquired.

Because each linear array has its own perspective center and has no dimension in the x direction, the x_i coordinate in Equation 1 should be set to zero. Furthermore, because the only estimate we have of the time, t, in Equations 5 is the x coordinate, x_i should replace t. The changes in units will be accounted for by the a and b coefficients in Equation 5. Thus, the collinearity equations for SPOT imagery will now be

$$0 = -f\,\frac{r_{11}(X_i - X_s) + r_{21}(Y_i - Y_s) + r_{31}(Z_i - Z_s)}{r_{13}(X_i - X_s) + r_{23}(Y_i - Y_s) + r_{33}(Z_i - Z_s)} \tag{7}$$

$$y_i = -f\,\frac{r_{12}(X_i - X_s) + r_{22}(Y_i - Y_s) + r_{32}(Z_i - Z_s)}{r_{13}(X_i - X_s) + r_{23}(Y_i - Y_s) + r_{33}(Z_i - Z_s)} \tag{8}$$

where

$$\begin{aligned} X_s &= X_o + a_1x_i + b_1x_i^2 \\ Y_s &= Y_o + a_2x_i + b_2x_i^2 \\ Z_s &= Z_o + a_3x_i + b_3x_i^2 \end{aligned} \tag{9}$$

The r_{jk} are the elements of the following matrix $\mathbf{R}$:

$$\mathbf{R} = \begin{bmatrix} \cos(\kappa_o + a_4x_i + b_4x_j^2) & \cos\omega\sin(\kappa_o + a_4x_i + b_4x_j^2), & \sin\omega\sin(\kappa_o + a_4x_i + b_4x_j^2) \\ -\sin(\kappa_o + a_4x_i + b_4x_j^2) & \cos\omega\cos(\kappa_o + a_4x_i + b_4x_j^2), & \sin\omega\cos(\kappa_o + a_4x_i + b_4x_j^2) \\ 0 & -\sin\omega, & \cos\omega \end{bmatrix} \tag{10}$$

The SPOT collinearity Equations 7 and 8 are linearized using Taylor's theorem. In connection with the simulation of SPOT imagery using this software, the following points are noted:

- Unlike photographic simulations, where exact photocoordinates can be generated directly from Equations 7 and 8 and normally distributed errors added, in the case of SPOT imagery, an x image coordinate does not appear on the left hand side of Equation 7 and must be determined iteratively using Equations 7, 9, and 10. The pseudo code for this process is given in Figure 2.
- During the least-squares solution of the normal equations by Gaussian elimination, partial pivoting has been invoked. During the simulations with photography, partial pivoting has not been used, but in certain SPOT simulations, especially with small mirror tilt angles (and hence a poor base-to-height ratio), instabilities apparent in high numbers of iterations have been noticed and cured by using partial pivoting. This is, perhaps, an indication of the potential weakness of linear array geometry in unfavorable circumstances compared with conventional photography.

```
PROGRAM SPOT.BUNDLE
PROCEDURE SIMULATE {READS DATA}
BEGIN
    READ (ERRORS, REAL POINT COORDINATES, FOCAL LENGTH, HEIGHT)
END;

PROCEDURE IMAGE {CALCULATES IMAGE COORDINATES AND ADDS ERRORS}
BEGIN
    FOR IMAGE = 1 TO 2 DO
    READ ($a_i$, $b_i$, $X_o$, $Y_o$, $Z_o$, W, N}
    FOR POINT = 1 TO N {GCPS + UNKNOWN POINTS}
    CALCULATE (x, y, x + E, y + E) {IMAGE COORDINATES}
END;

PROCEDURE DATA
BEGIN
    READ (INITIAL APPROXIMATIONS)
    CALCULATE (MATRIX: A, $A^T$, $A^TA$, K, $A^TK$)
END;

PROCEDURE GAUSS
BEGIN
    READ ($A^TA$, $A^TK$)
    CALCULATE (MATRIX X)
END;

PROCEDURE TEST
BEGIN
    REPEAT
      PROCEDURE
      DISPLAY RESULTS {PARAMETERS, UNKNOWN POINT COORDINATES}
      DIFFERENCES = RESULTS 2 - RESULTS
      RESULTS 2 = RESULTS
    UNTIL DIFFERENCES < 0.1 OR 0.000005
END;

REAL PROGRAM {USES SUB PROGRAMS}
BEGIN
    SIMULATE; IMAGE; DATA; GAUSS; TEST
    DISPLAY (STANDARD DEVIATIONS OF COORDINATES, DIAGONAL ELEMENTS
    OF $Q_{xx}$ MATRIX COVARIANCES)
END.
```

Figure 2. Pseudo code of the SPOT bundle program.

- The possibility of over-parameterization is recognized; just as it is not possible to recover both ω_s and Y_s nor both ϕ_s and X_s, it may also (under certain conditions) not be possible to recover all the parameters of the polynomial form of the satellite movement (a_1, a_2, ..., b_4) due to high correlation between them. This is the same problem that occurs in the bundle adjustment of aerial triangulation where additional parameters intended to model systematic image deformations may be highly correlated, with attendant instabilities, if certain parameters are not rejected (see, for example, Grün (1978)). In the case of SPOT simulations, the program eliminates highly correlated parameters prior to a re-run of the software. The parameters a_3 and b_3 are eliminated by this method. However, the overall results are not affected by the implementation of this technique, as can be seen from Table 1.
- In order to check for consistency with the photographic simulations, the eight parameters a_1, ..., a_4; b_1, ..., b_4 have been set to zero on certain runs.

SPOT Versus Photographic Results: A Tradeoff

Photographic simulation results for convergent tilt angles of 5, 15, and 25 degrees using three to ten GCPs indicate that the height coordinate (*Z*) improves dramatically as the convergent tilt angle increases; thus, the base-to-height ratio also improves, though these tilts do not have a significant effect on the planimetric coordinates (*X* and *Y*), except for marginal degradation in the *Y* coordinates (in the across-track direction), particularly at the highest tilt of 25 degrees.

Table 2 shows the results of the SPOT simulation in relation to those of photography for seven GCPs in four different patterns. It may be mentioned that these patterns are the same as those used by Gugan (1987) who has studied the sensitivity of SPOT geometry for various control point distributions. The results are for actual SPOT imagery and are related to just one stereomodel whose errors may be compounded by the check points relying on the map-derived data, the accuracy of which is a little suspect. It is seen from Table 2 that patterns 2 and 4 result in substantial degradation of SPOT *vis-a-vis* photography in relation to those of patterns 1 and 3. Pattern 4, in particular, has the highest degradation of over 380 percent as compared to all other patterns. The *Z*-coordinate degradation is somewhat less than the planimetric degradation for all the patterns at all the tilt angles. The results of pattern 4, which has no control on any of the linear array in the upper part of the model, explicitly demonstrate that the critical requirement is a good distribution of the GCPs in the along-track direction. Patterns 2 and 3 show that the control points are best located toward the edges of the linear arrays.

The poor accuracy of the pattern 4 results raises the question of possible improvement when one GCP is moved into the area that lacks control in the along-track direction. The GCP identified as A in Table 2 is shifted from the position A.1 to A.2 and then to A.3 as shown in Table 3, for a tilt angle of 15 degrees. It is seen (Table 3) that the precision improves for photography as well as for SPOT for position A.3 with respect to A.1, and the improvement is considerable for SPOT, especially in the *Z*-coordinate in relation to the planimetric coordinates. Furthermore, the degradation of SPOT precision *vis-a-vis* photography substantially reduces in all the coordinates and is dramatic in the Z-coordinate as it gets reduced from 265 percent (for A.1) to 4 percent (for A.3). For the SPOT geometry, there is a precision improvement of about 30 percent in *X*-coordinates and about 60 to 80 percent in the *Y*- and *Z*-coordinates for GCP change from A.1 to A.3. It may be pointed out that the convergence of the *X*-coordinate precision of SPOT toward photogrammetric values (Table 2) requires two points at either side of the upper edge (like pattern 3). The results of the bundle simulation are not of comparable accuracy in relation to the restitution of SPOT imagery using conventional analytical stereoplotters, mainly because of some error sources such as atmospheric refraction, Earth curvature, Earth rotation correction, lens distortion, etc. (Methley, 1986; Mather, 1987), all of which have not been considered in this software.

Table 4 shows the comparison of SPOT accuracies with

TABLE 1. COMPARISON OF PRECISION ESTIMATES WITH AND WITHOUT HIGHLY CORRELATED PARAMETERS IN THE SOLUTION.

Average Diagonal Elements of Q_{xx} Matrix	5° Mirror Tilt		15° Mirror Tilt	
	With Correlation	Without Correlation	With Correlation	Without Correlation
X	9.82	9.82	9.82	9.81
Y	10.10	9.85	10.19	9.92
Z	112.70	109.95	37.96	36.95

TABLE 2. DEGRADATION OF SPOT PRECISION RESULTS COMPARED WITH PHOTOGRAPHY WITH THE SAME TILT AND GROUND CONTROL POINT DISTRIBUTION.

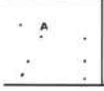
Control Point Locations	Pattern	Tilt Angle (Degrees)	Degradation of SPOT Results Compared with Photography (%)		
			X	*Y*	*Z*
	1	5	9.6	5.5	4.3
		15	10.6	4.7	4.6
		25	10.7	4.7	4.6
	2	5	105.2	8.4	0.4
		15	100.8	3.2	2.6
		25	100.6	3.0	2.6
	3	5	6.7	4.8	4.1
		15	7.6	4.4	4.2
		25	7.2	4.3	3.2
	4	5	412.8	296.3	261.4
		15	385.9	269.7	264.6
		25	382.5	268.5	266.4

TABLE 3. COMPARISON OF PHOTOGRAPHY AND SPOT VARIANCE-COVARIANCE PRECISION RESULTS IN MOVING POINT A FOR TILT ANGLE OF 15 DEGREES. (THE PERCENTAGE DEGRADATION OF SPOT COMPARED WITH PHOTOGRAPHY IS ALSO SHOWN).

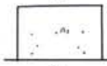
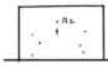
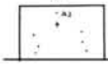
Position of Point A	Photography Precision (metres)			SPOT Precision (metres) & Degradation (% in brackets)		
	X	Y	Z	X	Y	Z
1 	11.54	11.99	45.22	56.07 (386)	42.33 (270)	164.85 (265)
2 	10.43	10.80	40.45	38.56 (270)	12.97 (20)	48.24 (19)
3 	9.87	10.22	38.15	38.37 (289)	10.71 (5)	39.84 (4)

TABLE 4. COMPARISON OF SPOT ACCURACIES (VARIANCE-COVARIANCE INDICATORS) WITH PHOTOGRAPHY OF EQUIVALENT GEOMETRY.

Number of Ground Control Points	Tilt Angle (Degrees)	Planimetry			Height		
		Photos (m)	SPOT (m)	Degradation (%)	Photos (m)	SPOT (m)	Degradation (%)
6	5	9.82	12.21	24.3	111.56	131.42	17.5
	15	9.78	12.26	25.4	37.17	44.23	19.0
	25	10.10	12.63	25.0	22.73	27.06	19.0
10	5	9.47	9.83	3.8	105.56	109.95	4.2
	15	9.46	9.88	4.4	35.85	37.02	3.3
	25	9.76	10.20	4.5	21.96	22.67	4.4

photography of equivalent geometry for mirror tilt angles af 5, 15, and 25 degrees and for six and ten GCPs. It is seen that, for the case of photography, an increase in the number of GCPs from six to ten results in only a marginal improvement in accuracy, for instance, by 0.3 percent in planimetry and 5.4 percent in height coordinates for a tilt angle of 5 degrees. This is in line with expectations, confirming the geometric stability of central perspective photography. For the SPOT geometry, the corresponding improvement in accuracy is 19.5 percent and 16.34 percent, respectively, for a tilt of 5 degrees; and 19.24 percent and 16.22 percent, respectively, for a tilt angle of 25 degrees. Figure 3 shows precision as a function of the number of GCPs for the cases of photography and SPOT for a tilt angle of 15 degrees. The degradation of SPOT in relation to photography is substantially less at 3.8 percent for ten GCPs as compared to 24.3 percent for three GCPs for planimetry, necessitating the need for an increased number of GCPs for enhanced SPOT precision, subject to the distribution of control points. It is seen that the height coordinate (Z) improves dramatically (from 131.42 m to 27.06 m) for SPOT as the mirror tilt angle increases from 5 to 25 degrees; thus, the base-to-height ratio also improves. A similar trend is also evident for photography. Figure 4 is a plot of the SPOT and photographic precision (for planimetric and height coordinates) versus mirror tilt angle for ten GCPs. It may be noted that there is only marginal degradation in precision for SPOT as well as photography as the tilt angle increases. An increase in the number of control points from six to ten results in much greater improvement in overall precision for SPOT than photography (Figure. 3). For example, at a mirror tilt angle of 15 degrees, when the GCPs are increased to ten from six, the photographic solution improves by only 3.3 percent in planimetry and 3.6 percent in height, whereas the corresponding figures for SPOT are 19.4 percent and 16.4 percent, respectively, suggesting that dynamic SPOT imagery benefits far more from increased ground control than does conventional photography with rigid geometry. The variance-covariance indicators shown in Table 4 also suggest that

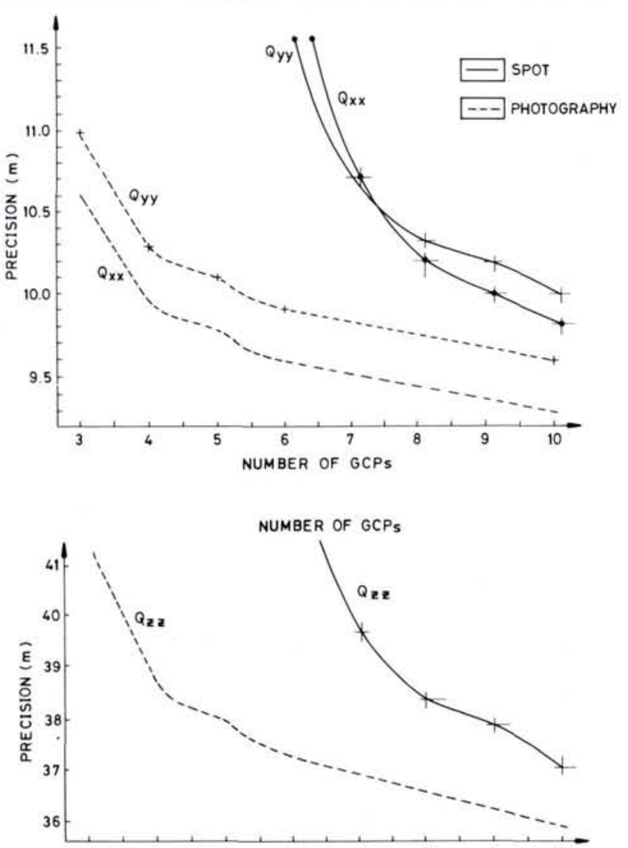


Figure 3. Change in precision with different number of GCPs with a tilt of 15 degrees (SPOT and photography).

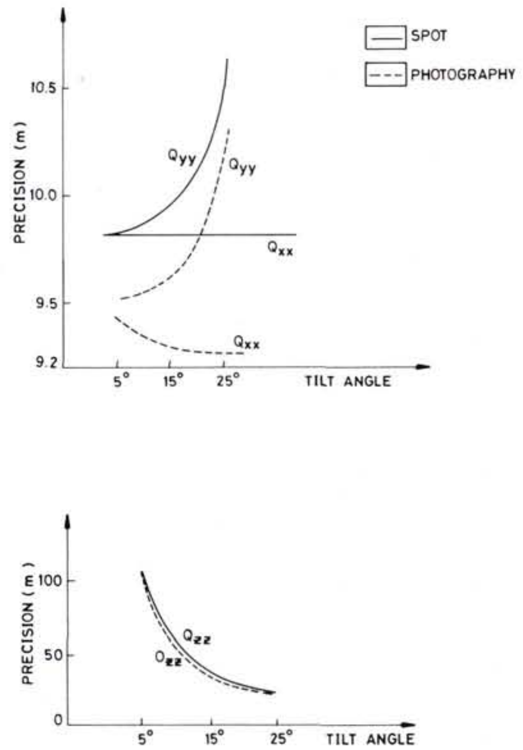


Figure 4. SPOT and photographic precision versus mirror tilt angle for ten GCPs. $\mathbf{Q}_{xx}$ and $\mathbf{Q}_{yy}$: planimetric coordinates $\mathbf{Q}_{zz}$: height

SPOT images are around 25 percent less accurate than those of photography for six GCPs while the degradation is only around 4.2 percent when the GCPs are increased to ten. Figure 5 shows the variance-covariance precision for different GCP positions for a tilt angle of 15 degrees.

The program uses the focal length value of 1.082 m for SPOT as well as photography to maintain identical conditions. The program resorts to both fictitious and real GCP values, the latter derived from topographic maps of Dorset area of England at 1:25,000 scale. For the actual GCP measurement, the DSR-1 analytical stereoplotter with Kern SPOT software has been used. The ten selected GCPs have their National Grid planimetric coordinates and heights determined from the Ordnance Survey 1:25,000-scale maps. These coordinates are then converted to the geocentric coordinate system used by the Kern SPOT software. The orientation of the SPOT model is achieved using these coordinates. The measured stereo image coordinates of the selected control points of the Dorset area serve as input to the modified bundle software.

The fictitious GCP Cartesian coordinates are used as input to the modified bundle program to compute the corresponding stereo image coordinates to facilitate more realistic estimation, considering the measurement and human errors. The precision results of this study are based on the fictitious image coordinates. These results, though fairly reliable and accurate, are yet approximate in relation to map values. This program uses a rectangular Cartesian coordinate system, and thus the *Z*-coordinate has to be converted to height by taking into account Earth curvature. Again, the program relies on the mirror tilt angles provided for the imagery, and considers these tilts as fixed values without corrections because of high correlation between ω_s (being eliminated in the program) and Ys (satellite coordinate). The software chooses to keep ω_s constant and allows changes in Y_s. Clearly, this program does not allow for large variations in ω_s, though small variations are accounted for in terms of the Y_s correction. Further research on the subject is in progress at the Marmara Research Center using software based on artificial intelligence and GIS.

Conclusion

The modified bundle adjustment software has facilitated a comparative study of SPOT geometry versus conventional photography in respect of precision for various tilt angles and a diverse number and positions of GCPs in different patterns. Whereas, for the case of photography, an increase in the number of GCPs results only in a marginal improvement in accuracy, there is substantial improvement for the SPOT geometry. The precision of the height coordinate improves dramatically for SPOT imagery as the mirror tilt angle increases, say, from 5 to 25 degrees; thus, the base-to-height ratio also improves. A similar trend is evident for the photographic case. There is only marginal degradation in precision for SPOT imagery as well as photography as the tilt angle increases. The SPOT images are around 25 percent less accurate than those of photography for six GCPs while the degradation reduces to 4.2 percent for ten GCPs. Patterns 2 and 4 result in substantial degradation of SPOT *vis-a-vis* photography in relation to those of patterns 1 and 3. The modified software has explicitly demonstrated that the critical requirement is a good distribution of the GCPs in the along-track direction for this particular geometric model. Other geometric models for SPOT perform well with only two to three GCPs in a strip of multiple scenes. The precision improves for photography as well as SPOT when the GCP position is moved from A.1 to A.3, and the improvement is considerable for SPOT, particularly along the *Z*-coordinate.

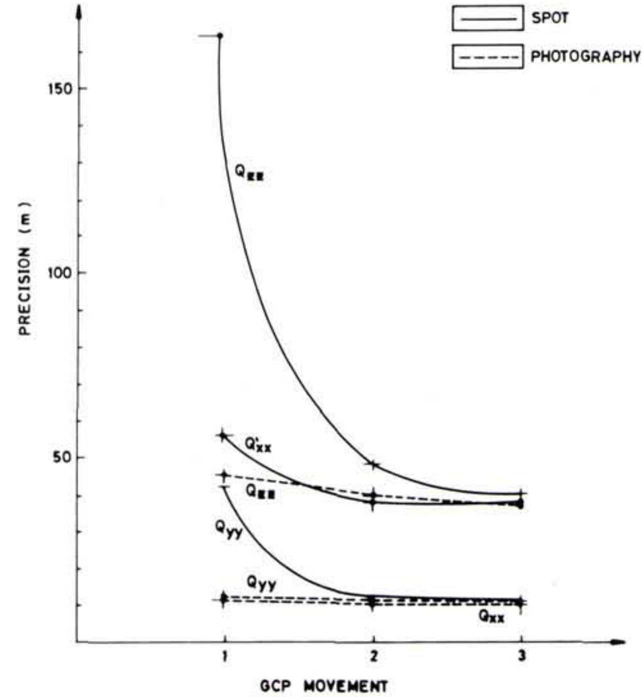


Figure 5. Results (variance-covariance precision for different GCP positions for 15 degrees tilt) of moving point A (for SPOT and photography).

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