RECTIFICATION OF SINGLE AND OVERLAPPING FRAMES OF SATELLITE SCANNER DATA

Fidel C. Paderes Jr.
Edward M. Mikhail
School of Civil Engineering
Purdue University
West Lafayette, Indiana 47907, U.S.A.
Commission III - Working Group III-4

ABSTRACT

Rectification of single scanner frames is carried out using a newly developed comprehensive geometric model. The performance of this model is compared to that of the widely used polynomial model, using both synthetic and real data. The effect of the number of control points on rectification accuracy, as well as the effect of control position accuracy both on the image and on the ground are studied. A block adjustment method of rectifying strips of overlapping frames is also implemented using the above geometric model and its performance is compared with single frame rectification.

INTRODUCTION

Satellite scanner data are digital images consisting of pixels. Each pixel has two types of attributes, the first concerns multiple spectral values, and the second is its ground position. The spectral values associated with a pixel, which represent the relative amount of reflected and/or emitted energy from the imaged object are directly measured. The ground position of a pixel, however, can only be computed indirectly from other measured quantities. The process of finding the ground position of pixels is called rectification. In this process, known locations on the ground or its map representation are used as reference. If, on the other hand, the reference is another remote sensing image, then the process is known as registration.

Unlike frame photographs which are essentially area sensing systems, scanner imagery is basically a point sensing system in which the pixels are exposed sequentially. Since the satellite is moving in space, each pixel has its own unique exterior orientation elements which correspond to the satellite position and sensor attitude at the moment a given pixel is sampled. If the exterior orientation elements (i.e. position and orientation) are completely known, the ground position of pixels can be directly computed given either overlapping image data sets, or one image set with some assumptions about the object. Satellite position can be derived from ground tracking data and the sensor attitude can be supplied by measuring instruments on-board the satellite. Unfortunately the accuracy of the resulting exterior orientation elements derived in this manner is not acceptable for quality rectification.

An alternative method of deriving the exterior orientation elements is through the use of ground control points. These are points of known image and ground position. This method can be further classified into two approaches according to the type of model used to relate the image to the ground. The first approach uses interpolative models, such as polynomials, to transform the image to the ground. An important characteristic of this approach is that the orientation elements are not explicitly derived. Because of this, a-priori knowledge of some or all of the exterior orientation elements cannot be exploited during the adjustment. Interpolative models, especially higher order ones, by their nature, require a lot of control points for uniform accuracy.

The second approach, known as the parametric approach, uses mathematical equations which attempt to model the geometric process involved in pixel imaging. In this approach, the exterior orientation elements are explicitly derived. Due to the weak geometry of scanner images, the model parameters are highly correlated, which frequently results in ill-conditioned normal equations during adjustment. This ill-conditioning can be minimized by one or more of the following: (1) a well-designed model; (2) using a-priori information on the exterior orientation elements; (3) solving for sub-groups of parameters in stages; and (4) reducing the number of parameters used in the model.

LITERATURE REVIEW

The earliest approach to rectification of satellite scanner data utilized polynomials as mathematical models. Its reported accuracy was comparable to other methods (Forrest [9], Trinder [22], Bähr [2], Dowman [6]). Because of its simplicity and accuracy, polynomials are still the most commonly used rectification model.

The earliest parametric model for satellite scanner data was an adaptation of models used for aircraft scanner data. This type of model assumed that the satellite orbit is a straight line and that the earth is flat or projected onto a mapping plane (Kratky [12], Konecny [11], Dowman [6]). Only the parameters describing variations in sensor attitude and satellite elevations were recovered.

The next improvement in parametric modelling defined the satellite orbit and position in terms of satellite position and velocity vectors (Caron and Simon [5], Puccinelli [18]). The flat earth assumption was also done away with in favor of the spherical earth (Caron and Simon [5], Bähr [3], Sawada [20]). Then the satellite position was defined in terms of orbital parameters which vary with time (Bähr [3]). Still the resulting models were not stable.

Next, the orbit was defined in terms of constant orbital parameters. Only the small deviations of the predicted satellite position on this orbit from its actual position were modelled as functions of time. The shape of the orbit was modelled as a circle (Forrest [8], Levine [13], Synder [21]) and as an ellipse (Bähr [3], Sawada [20]). Only Levine, so far, has incorporated in his model all the components of satellite position deviation. Like the others, however, he recovered only the radial or elevation component.

Some authors have recommended that the ellipsoid of revolution be used as the earth model instead of a sphere (Puccinelli [18], Forrest [8], Levine [13], Synder [21]), but so far no formulas in closed form have been derived yet for computation on an elliptical surface. Computation on the earth's ellipsoid involving non-zero elevations require approximations and/or iterations.

A model which assumes that the satellite orbit is an ellipse and that the earth is an ellipsoid of revolution was recently derived (Mikhail and Paderes [17]). Also recently, effective use of a-priori information regarding the sensor attitude, made feasible the bridging of long strips with control at each end only (Friedmann [10]).

SCOPE OF THE INVESTIGATION

We have developed a comprehensive geometric model which minimizes the ill-conditioning of the resulting normal equations during the adjustment (Mikhail and Paderes [17]). The model is based on the photogrammetric collinearity equation and has the following form:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \lambda M \begin{bmatrix} X - X_s \\ Y - Y_s \\ Z - Z_s \end{bmatrix}$$

where:

x, y, z are the coordinates of a given point in the image space. These coordinates are functions of pixel row and column numbers and the internal sensor geometry.

X, Y, Z are the corresponding ground coordinates of the given pixel.

X_s, Y_s, Z_s are the ground coordinates of the satellite position when the given pixel is sampled. These coordinates are the sum of the ideal or predicted satellite position and the deviation of the actual satellite position from the predicted one. The ideal position is a function of orbital parameters and time while the deviations are functions of time (t) only.

t is time which is a function of pixel row and column numbers and the internal sensor geometry.

M is an orthogonal rotation matrix which brings the ground coordinate system into the sensor coordinate system. This is a function of time, sensor attitude, deviation of the satellite position from the ideal, orbital parameters and earth geometry.

λ is a proportional constant which varies from pixel to pixel (i.e. a scale factor).

This model has been extensively tested using simulated data, as reported in Mikhail and Paderes [17]. Five different sets of experiments were performed to study the following factors: (1) the effect of error in parameter estimates on rectification accuracy; (2) the relative performance among four different cases, each a specialization of the extensive model as well as the polynomial model; (3) the effect of different control densities on rectification accuracy; (4) the effect of errors in derived image position on rectification accuracy; and (5) the effect of errors in measured ground position of control points on rectification accuracy.

For the present paper, we used the above model to rectify two frames of real data and corresponding sets of simulated data. Previous conclusions using purely simulated data were generally confirmed. Also, a block adjustment procedure based on the same model was developed to accommodate overlapping images. Block adjustment is worth investigating because it reduces the required number of control points for a given level of rectification accuracy. Some results regarding block adjustment are shown.

EXPERIMENTAL RESULTS

Experiment 1

Two MSS frames taken by Landsat 2 were used in this experiment. The first frame covers Kansas state which is relatively hilly. It has 153 uniformly distributed control points. The second frame principally covers the state of Louisiana which is flat. About 1/3 of this frame on the south-east corner is over the sea. It has 192 well distributed control points, although not as uniformly as in the Kansas frame.

Ten cases were run for each frame corresponding to two types of model (collinearity and polynomial) and five types of control configuration. For each case, withheld control points were used as check points. Table 1 shows the results. The collinearity model is superior to the polynomial model when the control points are few especially in hilly terrain such as the Kansas frame. Also, increasing the number of control points beyond 25 has only a marginal effect on rectification accuracy. This confirms in general our previous results using simulated data (Mikhail and Paderes [17]). Two additional cases for each frame were also run where all the control points were exercised in the adjustment. The RMS of the residuals on control points for the Kansas frame were 58.8 and 57.8 m. for the collinearity and polynomial models, respectively. The corresponding values for the Louisiana frame are 61.2 and 60.1 m. These values are the upper bounds of the quality of the data. They are used in the second experiment to determine the precision of the image measurements input into the simulation.

Table 1 RMS Error on Check Points in Meters Using Real Data

Number of Control Points	Kansas		Louisiana	
	Collinearity	Polynomial	Collinearity	Polynomial
10*	68.8	117.1	90.4	96.6
15*	67.9	73.6	72.3	71.7
25	67.6	70.4	69.3	67.3
40	67.9	69.5	66.0	65.4
81/70**	63.8	65.5	68.4	68.4

* When the number of control points is low, the number of parameters in the model is reduced to avoid convergence problems.

** 81 control points for Kansas frame and 70 for Louisiana frame.

Experiment 2

Using our extensive simulation program, the characteristics of the two real image frames were used to produce simulated images which reproduce as closely as possible the real images with respect to control configuration and accuracy. This is done with the full control case, where perfect ground coordinates are calculated from the given image coordinates and exterior orientation parameters. Then the calculated ground position of control points for both frames were perturbed using normal distribution with 15 m. standard deviation in each of the three coordinates. The image positions were perturbed using a combination of normal and uniform distribution. The uniform distribution used for perturbing both frames has a range of -0.5 to +0.5 pixel, and is used to account for round off errors. The normal distribution used for perturbing the Kansas frame has standard deviations of 0.44 pixel in row and 0.40 in column direction. These are the values which when used in the simulation program produced the RMS values given at the end of the preceding section for the full-control case. The corresponding standard deviations for the Louisiana frame were 0.40 pixel in row and 0.64 pixel in column direction. Several sets of simulated data with the described perturbations but with different "seeds" in the random number generator were produced and rectified. Table 2 shows the results of rectification using a representative simulated data set. Comparing Tables 1 and 2, it can be seen that the trends in Table 1 which resulted from rectification of real data are duplicated in Table 2.

Experiment 3

Simulated data using the control configuration of the two real data frames but without perturbations were produced (i.e. perfect data sets). The rectification results using this perfect data set are shown in Table 3. From this table, two significant results can be seen. First, it is possible to recover the correct set of exterior orientation elements using

Table 2 RMS Error on Check Points in Meters Using Simulated Data

Number of Control Points	Kansas		Louisiana	
	Collinearity	Polynomial	Collinearity	Polynomial
10*	84.0	134.4	80.9	89.9
15*	76.9	82.0	78.7	79.6
25	75.4	74.8	72.5	73.8
40	64.6	64.6	65.0	64.8
81/70**	61.9	62.9	60.5	61.0

* When the number of control points is low, the number of parameters in the model is reduced to avoid convergence problems.

** 81 control points for Kansas frame and 70 for Louisiana frame.

Table 3 RMS Error in Check Points in Meters Using Perfect Data

Number of Control Points	Kansas		Louisiana	
	Collinearity	Polynomial	Collinearity	Polynomial
10*	11.8	102.5	10.9	15.4
15*	0.6	13.2	0.3	11.2
25	0.5	10.8	0.3	9.6
40	0.5	10.4	0.3	9.6
81/70**	0.5	9.9	0.3	9.8

* When the number of control points is low, the number of parameters in the model is reduced to avoid convergence problems.

** 81 control points for Kansas frame and 70 for Louisiana frame.

the collinearity model if the data is perfect. Second, and more importantly, it shows that systematic error inherent in the polynomial model is about 10 meters.

Experiment 4

A block of 9 frames in 3 adjacent orbits and 3 frames per orbit were simulated. The center of the block is approximately at 58.5°N latitude. The frames have about 60% sidelap between orbits and 15% overlap along each orbit. There are 454 control points at a grid enterval of 20 km, and 453 check points also at a grid interval of 20 km. The check point grid is displaced by 10 km in both easting and northing with the result that each control point is surrounded by 4 check points and vice versa. The ground position of both sets of points were perturbed by 15 m standard deviation in each of the three coordinate directions using the normal distribution. The image position of both sets were also perturbed using a combination of uniform and normal distribution. The uniform distribution has a range of -0.5 to +0.5 pixel. The normal distribution has a standard deviation of 0.5 pixel in both row and column direction. Five cases of block adjustment were run with different control configuration. Table 4 shows the number of control and check points for each frame and for the whole block for each of the 5 cases. It also shows the number of tie points in the block for all cases. A tie point is any point common to two or more image frames which has known image positions but unknown ground position and is included in the block adjustment. In this experiment, the ground elevation of tie points were constrained to its a-priori value. This is necessary because it was previously shown that elevations cannot be recovered with sufficient accuracy using block adjustment techniques for aircraft scanner data (McGlone and Mikhail [16]) and aircraft scanner imagery has a much stronger geometry compared to satellite scanner imagery.

Table 4 Control and Check Point Distribution for Block Adjustment

Cases / Frames	Number of Control Points					Number of Check Points
	1	2	3	4	5	
1	11	15	27	45	91	90
2	9	13	24	39	91	89
3	9	13	26	41	88	87
4	11	15	25	45	89	86
5	11	15	26	42	89	86
6	10	14	26	41	90	86
7	10	14	25	42	88	88
8	10	15	26	44	89	87
9	11	16	26	42	85	88
Block*	42/224	66/212	125/180	214/134	454/0	453

* control points/tie points

Table 5 shows a relative comparison of RMS errors on check points on a frame by frame basis between block adjustment and single frame rectification for all five cases. The case where the parameters are perfectly known is included as a reference. It clearly shows that tie points, which are much more readily available (and less expensive) than control points, have a beneficial effect on rectification accuracy especially when control points are few. This improvement in accuracy is essentially due to tie points because block adjustment without tie points is equivalent to single frame rectification.

Table 5 A Comparison of Check Point RMS Error in Meters Between Block Adjustment and Single Frame Rectification*

Frames \ Cases	1**	2**	3	4	5***	Perfect Parameters
1	93/-	79/92	66/76	67/70	66/66	65
2	77/-	76/-	68/79	74/80	69/69	62
3	117/-	100/-	73/81	80/79	79/79	68
4	87/-	77/98	65/73	67/66	65/65	63
5	76/-	74/142	67/73	70/72	68/68	64
6	79/-	74/142	63/69	69/70	63/63	62
7	113/-	70/85	65/72	65/68	65/65	59
8	92/-	97/-	64/81	69/76	68/68	60
9	83/-	72/82	65/78	67/69	68/68	62
Ave.	90.8/-	79.9/-	66.2/75.8	69.8/72.2	67.9/67.9	62.8

* Block adjustment with tie points/single frame rectification.

** Single frame rectification did not converge because of few control points (no model parameter reduction is exercised in this case).

*** Block adjustment for case 5 is the same as single frame rectification because there are no tie points.

CONCLUSIONS

The developed model performed as designed on both real and simulated data. The block adjustment procedure based on this model was successful. Tie points improved rectification accuracy especially when the control points are few. Some of the previous results based on purely simulated data were confirmed. One such result is that the collinearity equation is superior to polynomials when the control points are few. Another is about the maximum number of control points, where control points in excess of 25 has only marginal effect on rectification accuracy. Although not covered in the present paper, it was previously shown that rectification is more sensitive to image position errors than to ground position errors of control points and that uncertainty in attitude estimates is the main source of error in system corrected images.

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