Precision Processing of High Resolution Satellite Data

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Abstract

Though the data acquired is of high resolution, the system corrected data product (standard product) is limited by the system level accuracy, which is of the order of 2 km. For large-scale mapping and other related applications of high-resolution data, very high product accuracy (better than 10 m) is required. Hence for such kind of applications, the product should be further improved in terms of its geometric quality. This can be only achieved through using a few Ground Control Points (GCPs) along with a proper geometric model relating image points to the corresponding ground points. This paper deals with the algorithms/ approaches developed by Data Products Group at Space Applications Centre for precision correction of high-resolution data obtained in a step and stare mode and imaging is done with multiple strips to cover a single scene. Exercises carried out on two data sets resulted in product accuracies less than 10 m using four control points, which is satisfactory because the source GCPs themselves have around 10 m error. With the kind of accuracies obtained, these products are useful for generation of large-scale base image maps from high-resolution satellite imagery. The product accuracy depends on the GCP distribution and the accuracy of the GCPs used for modeling.

Overview

1. Introduction

High-resolution (approximately 1 m) in along track data can be acquired by a payload using a technique called step and stare. However the across track resolution is dependent on the camera parameters. Increased swath can be achieved by using multiple (four) strips for imaging. Though the data acquired is of high resolution, the system corrected data product (standard product) is limited by the system level accuracy, which is of the order of 2 km. For large-scale mapping and other related applications of high-resolution data, very high product accuracy (better than 10 m) is required. Hence for such kind of applications, the product should be further improved in terms of its geometric quality. This can be only achieved through using few Ground Control Points (GCPs) along with a proper geometric model relating image points to the corresponding ground points. In the present work, an attempt has been made to update the satellite orientation parameters (especially attitude and attitude rate biases) using space resection method on GCP co-ordinates with the help of collinearity conditions. And then this updated orientation is used to generate the geo-referenced products separately for all the strips. Since the orientation is updated, the ground to image relation becomes precise, which in turn leads to a precision product. These products are then evaluated using GCPs for their geometric quality. Validity of this procedure on other data sets of same areas is also tested. This paper gives precision processing methodology in terms of mathematical formulation and evaluation procedures for high-resolution data.

2. Methodology

The precision processing and evaluation procedures have the following four major steps:

1. Identification of GCPs on base image map and on the RAD data;
2. Mathematical modeling using collinearity condition equation and updation of satellite orientation through Space Resection;
3. Generation of Geo referenced products and
4. Product evaluation

2.1 Identification of GCPs: A base image map already generated from IRS-1C/1D data is taken for GCP identification. Accuracy of this base image map is of the order of 10 m, generated using GPS points. Moreover, high-resolution data of this base map area is available for more than two dates, which will be useful for comparison of accuracy for different dates. High contrast feature points are identified first on all four strips of the image and these are taken as GCPs. At least 10 points in each strip are ensured while GCP identification, so that some of these can be used as check points during model evaluation as well as product level evaluation. Corresponding ground coordinates (latitudes and longitudes) for these points are obtained from identifying same features on the IRS1C/1D base image map.

2.2 Mathematical Formulation: A major problem in utilizing linear scanner imagery is to establish a relation between image and object space. Though there are various ways to achieve this, a possible sequence of transformations to establish the view direction using rigorous photogrammetric collinearity condition is developed. This transformation is function of image and ground co-ordinates, satellite orientation (attitude, attitude rates and orbit), payload and mission parameters.

Collinearity Equation

Collinearity equation expresses the fundamental relationship that the perspective center (X_S,Y_S,Y_S) the image point (*f*, -*x*, -*y*) and the object point (X_A,Y_A,Z_A) lie on the straight line (Mitra et.al, 1994). These equations are basic to all procedures in photogrammetry. The basic equation used here is

$$\begin{bmatrix} f \\ -x \\ -y \end{bmatrix} = k * M * \begin{bmatrix} X_A - X_S \\ Y_A - Y_S \\ Z_A - Z_S \end{bmatrix} = k \begin{bmatrix} M1 \\ M2 \\ M3 \end{bmatrix} * \begin{bmatrix} X_A - X_S \\ Y_A - Y_S \\ Z_A - Z_S \end{bmatrix} \quad (1)$$

Where, $[M_1] = [m_{11} \quad m_{12} \quad m_{13}]$,

$[M_2] = [m_{21} \quad m_{22} \quad m_{23}]$,

$[M_3] = [m_{31} \quad m_{32} \quad m_{33}]$,

(f, -x, -y) is the co-ordinate of an image point in focal co-ordinate system (in image space), (X_A, Y_A, Z_A) is the co-ordinate of the object point in geo-centric co-ordinate system and (X_S, Y_S, Z_S) is the co-ordinate of the perspective centre in geo-centric co-ordinate system for a particular line of the image. k is scale factor.

M is the rotation (orientation) matrix from one co-ordinate system to the other, which is a function of exterior orientation parameters viz., attitude, rates and orbit in addition to look angle.

Transformation matrix M consists of three rotation matrices (Mitra et.al, 1994 & Anon., 1989), look angle, attitude and orbital parameters

$$[\mathrm{M}] = [\mathrm{R_L}] * [\mathrm{R_A}] * [\mathrm{R_O}] \quad (2)$$

As [M] is a time varying component and can be modeled by polynomials in time.

All matrices taking part in [M] are orthogonal in nature

$$-\frac{x}{f} = \left[\frac{M_2.(X_A - X_S)}{M_1.(X_A - X_S)} \right]$$

$$-\frac{y}{f} = \left[\frac{M_3.(X_A - X_S)}{M_1.(X_A - X_S)} \right]$$

$$E_1 = \left(x * [M_1] + f [M_2] \right) \begin{bmatrix} X_A - X_S \\ Y_A - Y_S \\ Z_A - Z_S \end{bmatrix} = 0 \quad (3)$$

$$E_2 = \left(y * [M_1] + f [M_3] \right) \begin{bmatrix} X_A - X_S \\ Y_A - Y_S \\ Z_A - Z_S \end{bmatrix} = 0 \quad (4)$$

E_1 and E_2 (equations 3 & 4) are the modified collinearity equations for the satellite linear array image.

Description of Rotation Matrix M

Continuing through equation $[M] = [R_L] * [R_A] * [R_O]$

[R_L] is look angle matrix transforms from spacecraft body coordinate system to image coordinate system,

[R_A] is attitude matrix transforms from orbital coordinate system to spacecraft body coordinate system,

[R_O] is orbit matrix transforms from geocentric coordinate system to orbital coordinate system.

$[R_A] = [R_{yaw}] * [R_{roll}] * [R_{pitch}]$, Where roll angle is α, pitch angle is β, yaw angle is γ and

For [R_O], position vector ***[r = (x, y, z)]*** and velocity vector [**v**=$(\frac{dx}{dt}, \frac{dy}{dt}, \frac{dz}{dt})$] will be used.

$$[R_O] = \begin{bmatrix} Yaw_1 & Yaw_2 & Yaw_3 \\ Roll_1 & Roll_2 & Roll_3 \\ Pitch_1 & Pitch_2 & Pitch_3 \end{bmatrix}$$, Where Yaw = -r, Pitch=-(r×v), Roll=(r×v×r)

Yaw_1= -x, Yaw_2= -y, Yaw_3= -z,
$Pitch_1$=-$(r \times v)_1$, $Pitch_2$= -$(r \times v)_2$, $Pitch_3$= -$(r \times v)_3$,
$Roll_1$=$(r \times v \times r)_1$, $Roll_2$=$(r \times v \times r)_2$, $Roll_3$=$(r \times v \times r)_3$,

Hence [R_O] matrix can take the form

$$[R_O] = \begin{bmatrix} -x & -y & -z \\ (r \times v \times r)_1 & (r \times v \times r)_2 & (r \times v \times r)_3 \\ -(r \times v)_1 & -(r \times v)_2 & -(r \times v)_3 \end{bmatrix}$$

Space Resection

The term space resection is used for the process of determining the spatial position and orientation of an image based on image coordinate of the ground control point (GCP) appearing in the image. With the help of GCP the exterior orientation of image can be modeled in time varying orbital elements and an additional attitude rotation and sensor look angle rotation is also employed in order to compensate the dynamic motion of the sensor.

Although several space resection procedures are available in literature but the procedure described here is based on collinearity condition and valid for the satellites, whose orbits are similar to the SPOT and IRS series and other near earth sun synchronous remote sensing satellites.

The orientation and compilation of space images are normally carried out in a geocentric ground coordinate system to avoid the distortions due to earth's curvature. The major components of dynamic motion are the satellite motion along the orbit and the rotation of the earth. But in the case of high-resolution data in step and stare mode, attitude and attitude rates are quite large so roll, pitch and yaw and their rates will play a major role in dynamic motion of satellite. Therefore attitude correction/ updation is required instead of adjusting orbital components.

As roll angle (α), pitch angle (β) yaw angle (γ) are time varying components, assuming their behavior is linear for a short duration of scene time, they can be written as $\alpha=\alpha_0+\alpha_1 t$, $\beta=\beta_0+\beta_1 t$, $\gamma=\gamma_0+\gamma_1 t$. The exterior orientation parameters $\alpha_0, \alpha_1, \beta_0, \beta_1, \gamma_0, \gamma_1$ can be determined by the collinearity equations 3 and 4.

The direct solution of the above equations (3 and 4) for each GCP is not feasible since they are non linear. The most practical solution is to determine a set of initial values for the unknowns ($\alpha_0, \alpha_1, \beta_0, \beta_1, \gamma_0, \gamma_1$) and linearise the equations by Taylor series expansion (Gopala Krishna, B., *et al*, 1992), which will contain differentials of parameters for each equation and corrections to the initial approximation values. By solving the equations the differential corrections are obtained and these are added to the original approximate values and then the solution of these equations is iterated till they satisfy the collinearity equations to the desired accuracy.

Linearisation of collinearity equations

Assume $A = (\alpha_0, \alpha_1, \beta_0, \beta_1, \gamma_0, \gamma_1)$

Then partial derivatives of E_1 and E_2 with respect to A can be written as

$$\frac{\partial E_1}{\partial A} = \left(x \frac{\partial [M_1]}{\partial A} + f \frac{\partial [M_2]}{\partial A} \right) \begin{bmatrix} X_A - X_S \\ Y_A - Y_S \\ Z_A - Z_S \end{bmatrix} \tag{5}$$

$$\frac{\partial E_2}{\partial A} = \left(y \frac{\partial [M_1]}{\partial A} + f \frac{\partial [M_3]}{\partial A} \right) \begin{bmatrix} X_A - X_S \\ Y_A - Y_S \\ Z_A - Z_S \end{bmatrix} \tag{6}$$

Let $\alpha_0^0, \alpha_1^0, \beta_0^0, \beta_1^0, \gamma_0^0, \gamma_1^0$ are the initial approximation of attitude and rate parameters to be determined and $\Delta\alpha_0$, $\Delta\alpha_1$, $\Delta\beta_0$, $\Delta\beta_1$, $\Delta\gamma_0$, $\Delta\gamma_1$ are the corrections to these initial values, then Taylor series expansion of E_1 is

$$E_1 = E_1^0 + \left(\frac{\partial E_1}{\partial \alpha_0}\right)\Delta\alpha_0 + \left(\frac{\partial E_1}{\partial \alpha_1}\right)\Delta\alpha_1 + \left(\frac{\partial E_1}{\partial \beta_0}\right)\Delta\beta_0 + \left(\frac{\partial E_1}{\partial \beta_1}\right)\Delta\beta_1 + \left(\frac{\partial E_1}{\partial \gamma_0}\right)\Delta\gamma_0 + \left(\frac{\partial E_1}{\partial \gamma_1}\right)\Delta\gamma_1 = 0$$

Where

$E_1 = E_1 (\alpha_0^0+\Delta\alpha_0, \alpha_1^0+\Delta\alpha_1, \beta_0^0+\Delta\beta_0, \beta_1^0+\Delta\beta_1, \gamma_0^0+\Delta\gamma_0, \gamma_1^0+\Delta\gamma_1)$ *and*

$E_1^0 = E_1 (\alpha_0^0, \alpha_1^0, \beta_0^0, \beta_1^0, \gamma_0^0, \gamma_1^0)$

Similar equation can be written for E2.

From equation (3) $E1=0$.
Therefore,

$$\left(\frac{\partial E_1}{\partial \alpha_0}\right)\Delta\alpha_0 + \left(\frac{\partial E_1}{\partial \alpha_1}\right)\Delta\alpha_1 + \left(\frac{\partial E_1}{\partial \beta_0}\right)\Delta\beta_0 + \left(\frac{\partial E_1}{\partial \beta_1}\right)\Delta\beta_1 + \left(\frac{\partial E_1}{\partial \gamma_0}\right)\Delta\gamma_0 + \left(\frac{\partial E_1}{\partial \gamma_1}\right)\Delta\gamma_1 = -E_1^0 \tag{7}$$

Similarly for E2,

$$\left(\frac{\partial E_2}{\partial \alpha_0}\right)\Delta\alpha_0 + \left(\frac{\partial E_2}{\partial \alpha_1}\right)\Delta\alpha_1 + \left(\frac{\partial E_2}{\partial \beta_0}\right)\Delta\beta_0 + \left(\frac{\partial E_2}{\partial \beta_1}\right)\Delta\beta_1 + \left(\frac{\partial E_2}{\partial \gamma_0}\right)\Delta\gamma_0 + \left(\frac{\partial E_2}{\partial \gamma_1}\right)\Delta\gamma_1 = -E_2^0 \tag{8}$$

The partial derivatives of E_1 and E_2, w.r.t. to parameters $(\alpha_0, \alpha_1, \beta_0, \beta_1, \gamma_0, \gamma_1)$ can be defined in the terms of partial derivatives of M w.r.t. the same parameters.

The partial derivatives of E_1 i.e. $(\partial E_1/\partial\alpha_0)$, $(\partial E_1/\partial\alpha_1)$, $(\partial E_1/\partial\beta_0)$, $(\partial E_1/\partial\beta_1)$, $(\partial E_1/\partial\gamma_0)$, $(\partial E_1/\partial\gamma_1)$ and of E_2 i.e. $(\partial E_2/\partial\alpha_0)$, $(\partial E_2/\partial\alpha_1)$, $(\partial E_2/\partial\beta_0)$, $(\partial E_2/\partial\beta_1)$, $(\partial E_2/\partial\gamma_0)$, $(\partial E_2/\partial\gamma_1)$ and the terms E_1 and E_2 can be computed by substituting the approximate values of $\alpha_0, \alpha_1, \beta_0, \beta_1, \gamma_0, \gamma_1$ *in* equations formulated above. For each control point a pair of collinearity equations can be formulated and get two observation equations 7 and 8. So, we need at least three control points for six attitude parameters. This system of equations is solved simultaneously and the corrections for the six unknown parameters $\Delta\alpha_0, \Delta\alpha_1, \Delta\beta_0, \Delta\beta_1, \Delta\gamma_0, \Delta\gamma_1$ are obtained. Then these corrections are added to the initial approximations and revised values of parameters are computed as follows.

$$\alpha_0^1=\alpha_0^0+\Delta\alpha_0,\ \alpha_1^1=\alpha_1^0+\Delta\alpha_1, \quad (9)$$

$$\beta_0^1=\beta_0^0+\Delta\beta_0,\ \beta_1^1=\beta_1^0+\Delta\beta_1, \quad (10)$$

$$\gamma_0^1=\gamma_0^0+\Delta\gamma_0,\ \gamma_1^1=\gamma_1^0+\Delta\gamma_1 \quad (11)$$

The revised values are considered as new approximations of the parameters and the procedure is repeated until the magnitude of corrections of all parameters are insignificant or reached a predefined values (10^{-5} deg for attitude and 10^{-7} deg for rates) or predefined number of iterations (twenty). If more than three control points are available they give more than six observation equations. Solutions are obtained using least square method in this case.

Input required for the resection process

1. Ephemeris information i.e. state vector [position – (X, Y, Z), velocity-(dX/dt, dY/dt, dZ/dt)] of the satellite at a regular interval from ancillary file
2. Mission/payload parameters
3. Coordinates of ground control points (GCPs) Through one GCP a pair of collinearity equations can be formulated, so two parameters can be estimated through one GCP.
4. Image coordinates corresponding to the same GCPs

Output will be the updated parameters of attitude (roll, pitch, yaw) and attitude rate biases, in the form of updated OAT. Space resection is done using individual set of GCPs for each strip. Thus four updated OATs are obtained for four individual strips. And four individual products are generated for evaluation. Image to ground and ground to image transformation used for computation and evaluation are same as given in (Gopala Krishna, B., *et al*, 1992).

2.3 Generating Geo-referenced image: Main crux of generating a geometrically corrected product is the establishment of a relationship between the output grid and input image. The available software for geometric correction of high resolution data is used for product generation. This software needs input as ancillary data in the form of OAT and corresponding image data after radiometric correction. This software basically contains GRIDGEN and RESAMPLING modules. The output space is divided in to a number of regular grid points for which input co-ordinate is calculated using output to input transformation. Then the gray value for each output point is computed by the resampling the input image. Using this software two products per strip are generated. One with using the system level OAT and other one with corresponding updated OAT.

3. Evaluation

High-resolution data for two dates is chosen for the exercises. Image to ground transformation (Srivastava, P. K., Medha Alurkar, 1997) using collinearity condition is applied and ground coordinates are estimated corresponding to the image coordinates for each GCP before and after resection. The actual ground coordinates and computed ground coordinates are compared and the residual errors are obtained.

In product level accuracy verification, GCPs are re-identified on the final product and their ground co-ordinates are estimated with respect to corner co-ordinates of the product. Corner co-ordinates are re-computed during geometric correction process. The estimated ground co-ordinates are then compared with the actual GCP co-ordinates to get the residual errors. This gives the product level accuracy.

4. Results

Results are given in Tables 1, 2, 3 and 4. Table-1 gives model level accuracy for data set 1 for pre and post resection. It can be observed that the residual errors before resection are ~1.7 km and these errors are reduced to less than 10 m after resection as expected. Table-2 gives the product level accuracies for data set 1 with respect to tickmarks (corner co-ordinates of the product) and they are comparable to model level error of Table -1. The difference between the errors at model and final product (minor in nature) can be attributed to the factors like manual GCP identification etc. Errors at model and product level are matching within 5 m after resection. Table-3 gives model level error for data set 2. For this data set product level results are not available. Table-4 gives the residual errors on GCPs in all four strips using single updated OAT (strip2 OAT in this case).

Data Set 1 results are shown in Tables 1, 2 and 4 while those of Data Set 2 are shown in Table 3.

Table 1: Residual error on GCPs at model level for data set 1

Pre resection:

	Mean_error (km)		Std. Dev.	
	Scan	**Pixel**	**Scan**	**Pixel**
Strip1	1.671	2.154	27	45
Strip2	1.769	1.757	33	54
Strip3	1.949	1.411	23	41
Strip4	1.767	1.763	25	33

Post resection:

	Mean_error (m)		Std. Dev.	
	Scan	**Pixel**	**Scan**	**Pixel**
Strip1	0.1	0.0	1.4	1.8
Strip2	0.1	0.0	2.0	1.8
Strip3	0.1	0.0	0.4	4.1
Strip4	0.1	0.0	3.3	4.6

Table 2: Residual error on GCPs at Precision Product level for data set 1

Using Pre resection parameters:

	Mean_error (km)		Std. Dev.	
	Scan	**Pixel**	**Scan**	**Pixel**
Strip1	1.759	1.739	24.63	44.81
Strip2	1.773	1.757	32.59	53.05
Strip3	1.761	1.743	27.82	39.53
Strip4	1.768	1.747	25.68	32.84

Using Post resection parameters:

	Mean_error (m)		Std. Dev.	
	Scan	**Pixel**	**Scan**	**Pixel**
Strip1	5.375	2.875	4.74	6.69
Strip2	20.05	1.02	10.65	2.56
Strip3	4.67	2.65	4.49	3.54
Strip4	4.16	4.29	5.77	8.07

Table 3: Residual error on GCPs at model level for data set 2

***Pre resection*:**

	Mean_error (m)		Std. Dev.	
	Scan	**Pixel**	**Scan**	**Pixel**
Strip1	233	-98	50	25
Strip2	144	-53	172	64
Strip3	218	-104	82	55
Strip4	211	-98	102	50

Post resection:

	Mean_error (m)		Std. Dev.	
	Scan	**Pixel**	**Scan**	**Pixel**
Strip1	0.0002	0.0018	0.9	3.4
Strip2	0.0210	-0.016	6.6	2.7
Strip3	0.0010	-0.001	1.1	3.7
Strip4	-0.003	0.001	2.5	6.0

Table 4: Residual error on GCPs of all four strips at model level using updated OAT of Strip2 for data set 1

	Mean_error (m)		**Std. Dev.**	
	Scan	**Pixel**	**Scan**	**Pixel**
Strip1	11	12	13	8
Strip2	-1	0	3	3
Strip3	-5	-3	6	8
Strip4	-1	-2	13	10

5. Conclusions

- Product accuracies less than 10 m can be achieved using four control points.
- OAT generated from one strip can lead to maximum 13 m error at other strips at the model level as well as final product level.
- These products are useful for base image map generation as the accuracies are significantly improved.
- Model and product level accuracies are matching within 5 m, which ensures the consistency of the model.
- The biases updated are not to be treated as true biases but they are pseudo values having coupling with other parameters.
- The model/product level accuracies depend upon the GCP distribution and the accuracy of the GCPs used for modeling

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