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HJ-1-A/B OPTICAL SATELLITE IMAGE GEOMETRIC CORRECTION

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Abstract. Small satellite constellation of environment and disaster's monitoring and predicting (shorted for HJ-1) is not a mapping satellite, and its parameters of attitude and orbit cannot satisfy the requirement of geometric correction using strict imaging model. On the other hand, due to the 12000 CCD detectors and large overlay of multispectral payload named CCD carried by HJ-1 satellite, the error caused by CCD distortion cannot be ignored. Aiming at these problems of HJ-1, this paper proposes a strict orbit model algorithm based on Ground Control Point (GCP) and collinear condition equations. Through the robust estimation of parameters, this algorithm can effectively set up imaging geometric model of CCD, and satisfy the requirement of high precision geometric correction.

1. Introduction

HJ-1 is the first constellation specially used for environment and disaster's monitoring and predicting in China, and is the first land observation system of multi-satellites and multi-loads in China[1]. It consists of two small optical satellites (HJ-1A, HJ-1B) and one small Synthetic Aperture Radar (SAR) satellite (HJ-1C). HJ-1A carries two multispectral payloads of large overlay and one super-spectral payload. HJ-1B carries two same multispectral payloads of large overlay as HJ-1A and one infrared payload. HJ-1C carries one SAR. The constellation has achieved the monitoring ability of large area, all time, all weather especially towards environment and disaster.

This paper mainly focuses on the geometric correction model and algorithm of multispectral payload, and its parameters are shown in table 1.

Table 1. Multispectral payload parameters.

Wavelength (μm)	Spectrum section number	Spatial resolution(m)	IFOV(km)
0.45-0.90	4	30	360(one),700(two)

One of the most essential equations of geometric correction is to set up a reasonable remote sensing imaging model, which is the mathematic relation between image coordinate and ground point's geodetic coordinate. Remote sensing imaging model can be divided into two kinds. One is physical model, which considers the physical significance such as the fluctuation of earth's surface, curvature of earth, atmospheric refraction, and camera distortion and so on. The other is universal model, which describes the geometric relation between image point and object point using mathematical function directly.

2. Geometric correction model and algorithm of CCD

2.1. Imaging way of CCD

The imaging way of HJ-1 is linear array push-broom, which acquires the two-dimension image line-by-line with sequential time, as shown in figure 1. where p_k is any image point, x_k is x coordinate in scanning line k, O_k is the projective center of scanning line k, o_k is principal point of scanning line k, l_k is the light ray sent by scanning line k from O_k.

The strict imaging model is the most close to imaging procedure, represented by common collinear condition equation[2]. According to satellite GPS data, attitude and time, through imaging procedure, the relation between image point (l, p) and object point (X, Y, Z) is set up.

2.2. Strict imaging model of CCD

The transformation from image point to object point should be accomplished by coordinate system transformation from navigate coordinate system to orbital coordinate system, and then to ground coordinate system.

- Calculate imaging direction vector $\vec{u}_1$ under navigate coordinate system through imaging angle $(\psi_x)_p$ and $(\psi_y)_p$ on column p, as equation (1)

$$\vec{u}_1 = \frac{\vec{u}_1'}{\|\vec{u}_1'\|}, \quad \vec{u}_1' = \begin{pmatrix} -\tan(\psi_y)_p \\ +\tan(\psi_x)_p \\ -1 \end{pmatrix} \tag{1}$$

- Calculate imaging direction vector $\vec{u}_2$ under orbital coordinate system.

Transform imaging direction vector $\vec{u}_1$ under navigate coordinate system to $\vec{u}_2$ under orbital coordinate system, as equation (2), and the attitude angle of $a_p(t_i), a_r(t_i), a_y(t_i)$ are acquired by the vector cross product of satellite location $\vec{P}(t)$ and velocity vector $\vec{V}(t)$

$$\vec{u}_2 = M_p \cdot M_r \cdot M_y \cdot \vec{u}_1 \tag{2}$$

$$M_p = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(a_p(t)) & \sin(a_p(t)) \\ 0 & -\sin(a_p(t)) & \cos(a_p(t)) \end{pmatrix} \quad M_r = \begin{pmatrix} \cos(a_r(t)) & 0 & -\sin(a_r(t)) \\ 0 & 1 & 0 \\ \sin(a_r(t)) & 0 & \cos(a_r(t)) \end{pmatrix} \quad M_y = \begin{pmatrix} \cos(a_y(t)) & -\sin(a_y(t)) & 0 \\ \sin(a_y(t)) & \cos(a_y(t)) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Calculate imaging direction vector $\vec{u}_3$ under ground coordinate system, as equation (3)

$$\vec{u}_3 = \begin{pmatrix} (X_2)_X & (Y_2)_X & (Z_2)_X \\ (X_2)_Y & (Y_2)_Y & (Z_2)_Y \\ (X_2)_Z & (Y_2)_Z & (Z_2)_Z \end{pmatrix} \cdot \vec{u}_2 \tag{3}$$

Where X_2, Y_2, Z_2 is direction vector of 3 coordinate axis under orbital coordinate system.

- Position object point

As shown in figure 2, the intersection point of observation vector u_3 and ground is M, the connect vector between M and the earth's core is $\overline{O_3M}$, so the simultaneous equation is equation (4).

$$\overline{O_3M} = \vec{P}(t) + \mu \times u_3 \Rightarrow \begin{cases} X = X_P + \mu \times (u_3)_X \\ Y = Y_P + \mu \times (u_3)_Y \\ Z = Z_P + \mu \times (u_3)_Z \end{cases} \tag{4}$$

$$\frac{X^2 + Y^2}{A^2} + \frac{Z^2}{B^2} = 1$$

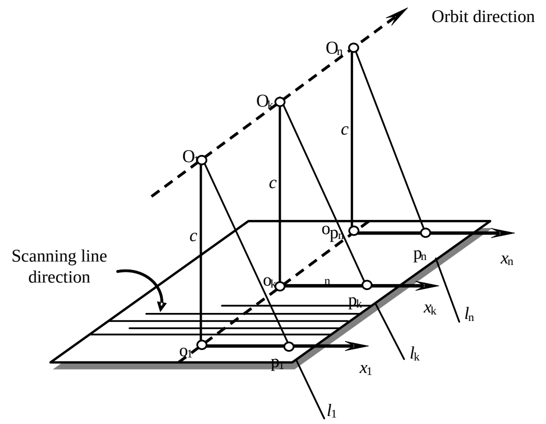

Figure 1. Linear array push-broom

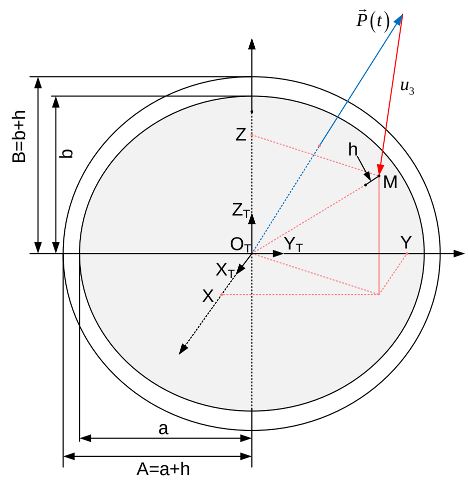

Figure 2. Geometric schematic diagram

Combined with the above several transformation relationship, equation (4) can be transformed as collinear condition equation form as equation (5).

$$u_1 = \begin{pmatrix} -\tan(\psi_y)_p \\ +\tan(\psi_x)_p \\ -1 \end{pmatrix} = \frac{1}{u} R_{21}^{-1}.R_{32}^{-1}.\begin{pmatrix} X - X_P \\ Y - Y_P \\ Z - Z_P \end{pmatrix} \tag{5}$$

The equation (5) expresses the relation between imaging direction vector under navigate coordinate system and observation direction under ground coordinate system. where $(X_P \quad Y_P \quad Z_P)^T$ is the projective center, $(X \quad Y \quad Z)^T$ is object point coordinate, u is projective coefficient. The rotation matrix can be expressed as equation (6).

$$R = R_{21}^{-1}\left[a_r(t), a_p(t), a_y(t)\right] R_{32}^{-1}\left[P(t), V(t)\right] = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \tag{6}$$

The collinear condition equation can be expressed as equation (7).

$$\begin{aligned} &\frac{r_{11}(X - X_P) + r_{12}(Y - Y_p) + r_{13}(Z - Z_p)}{r_{31}(X - X_P) + r_{32}(Y - Y_p) + r_{33}(Z - Z_p)} - \tan(\psi_y)_p = 0 \\ &\frac{r_{21}(X - X_P) + r_{22}(Y - Y_p) + r_{23}(Z - Z_p)}{r_{31}(X - X_P) + r_{32}(Y - Y_p) + r_{33}(Z - Z_p)} + \tan(\psi_x)_p = 0 \end{aligned} \tag{7}$$

2.3. Problems of geometric correction

So far, the known HJ-1's parameters are only orbit and attitude measuring data, focal distance of camera, CCD detectors value, and that is not enough for solution equation (7).

The attitude parameter is usually obtained by Lagrange interpolation or linear interpolation. The geometric location precision is related to sample frequency and measuring precision of attitude and orbit parameters. The higher the sample frequency and measuring precision, the higher the geometric location precision obtained by using attitude and orbit parameters to directly calculate geometric location.

One single CCD camera in one image scene scans 12000 rows, but the number of recording attitude and orbit data is not most than 8. That is to say, CCD image has 30 meters resolution, and attitude and orbit data recorded every 8 second. While the SPOT5 image, which is the representative of strict imaging model based on orbit parameter, has 2.5 meters resolution, and attitude and orbit data recorded every 1/8 second. According to prediction by the resolution and recording interval, the attitude recording precision of SPOT5 is obviously superior to HJ-1 under the same resolution. And the measuring precision of attitude of SPOT5 is also exceeding HJ-1. So the geometric correction error will be very large by using mature strict imaging model through recorded attitude and orbit data of HJ-1.

On the other hand, the 12000 detectors of CCD has used the multiple CCD splicing way. And that will involve CCD splicing error.

2.4. Parameter solution

Based on the above problems, this paper proposes methods of solution of offset angle and exact estimation of attitude and orbit parameters based on GCP.

2.4.1. Solution of offset angle. This paper compensates the system error namely offset angle error based on GCP, as shown in equation (8).

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_{GPS} \\ Y_{GPS} \\ Z_{GPS} \end{pmatrix} + \lambda R_s^m \left(R_c^s \begin{pmatrix} x - x_0 \\ y - y_0 \\ -f \end{pmatrix} + \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix} \right) \tag{8}$$

Where $(X_{GPS} \quad Y_{GPS} \quad Z_{GPS})^T$ is GPS measuring value at imaging time, $(x_0 \quad y_0 \quad -f)^T$ is the inner orientation elements, $(x \quad y)^T$ is the coordinate of image point, $(\Delta X \quad \Delta Y \quad \Delta Z)^T$ is the location error between camera center and GPS center, R_c^s is the circumrotate matrix caused by error of installation angle, R_s^m is the circumrotate matrix caused by 3 angles measured by satellite sensitivity machine.

The equation (8) can be converted to equation (9). Equation (9) can be expressed by $RU = U'$, and solved compensated matrix R by mathematical method. So the installation angle can be obtained by separating R.

$$R_c^s \begin{pmatrix} x - x0 \\ y - y0 \\ -f \end{pmatrix} = \frac{1}{\lambda} (R_s^m)^T \begin{pmatrix} X - X_{GPS} \\ Y - Y_{GPS} \\ Z - Z_{GPS} \end{pmatrix} - \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix} \tag{9}$$

2.4.2. Exact estimation of attitude and orbit based on GCP. Although the attitude's measurement precision of HJ-1 is very low, but its stability is relatively high, that is to say the attitude is relatively stability. So the attitude can be approximately expressed as a certain mathematical model. For this purpose, this paper proposes using a polynomial of certain times based on time to describe orbit parameters, and then using collinear condition equations to describe geometric corresponding relation between image point and object point.

The satellite location and attitude at the imaging time can be expressed as equation (10). Where $(Xs_i, Ys_i, Zs_i, \varphi_i, \omega_i, \kappa_i)$ is the exterior orientation elements of row i, $(Xs_0, Ys_0, Zs_0, \varphi_0, \omega_0, \kappa_0)$ is the exterior orientation elements of the starting row.

$$\begin{aligned} Xs_i &= Xs_0 + a_0 t + a_1 t^2 + a_2 t^3 + \cdots\cdots \\ Ys_i &= Ys_0 + b_0 t + b_1 t^2 + b_2 t^3 + \cdots\cdots \\ Zs_i &= Zs_0 + c_0 t + c_1 t^2 + c_2 t^3 + \cdots\cdots \\ \varphi_i &= \varphi_0 + d_0 t + d_1 t^2 + d_2 t^3 + \cdots\cdots \\ \omega_i &= \omega_0 + e_0 t + e_1 t^2 + e_2 t^3 + \cdots\cdots \\ \kappa_i &= \kappa_0 + f_0 t + f_1 t^2 + f_2 t^3 + \cdots\cdots \end{aligned} \tag{10}$$

According to photogrammetry principle, a collinear condition equation is used to express the geometric relationship between object point and image point, as shown in equation (11).

$$\begin{cases} x - x_0 - \Delta x = -f\dfrac{\overline{X}}{\overline{Z}} \\ y - y_0 - \Delta y = -f\dfrac{\overline{Y}}{\overline{Z}} \end{cases}, \text{ where } \begin{array}{l} \overline{X} = a_{i1}(X - Xs_i) + b_{i1}(Y - Ys_i) + c_{i1}(Z - Zs_i) \\ \overline{Y} = a_{i2}(X - Xs_i) + b_{i2}(Y - Ys_i) + c_{i2}(Z - Zs_i) \\ \overline{Z} = a_{i3}(X - Xs_i) + b_{i3}(Y - Ys_i) + c_{i3}(Z - Zs_i) \end{array} \tag{11}$$

Where $(\Delta x, \Delta y)$ is the offset value of image point caused by CCD distortion, $(X_{S_i}, Y_{S_i}, Z_{S_i})$ is the object space coordinate of corresponding projection center point of row i, a_{ij}, b_{ij} and $c_{ij}(i, j = 1,2,3)$ are the 9 orientation cosines of exterior orientation elements.

Error equation after linearizing collinear condition equation is shown in equation (12). LS and ridge estimator method is used to solve attitude and orbit parameters to be estimated.

$$V = At + BX - L \tag{12}$$

where $V = \begin{pmatrix} v_x & v_y \end{pmatrix}^T$, $L = \begin{pmatrix} x - x_0 & y - y_0 \end{pmatrix}^T$

$$A = \begin{pmatrix} \dfrac{\partial x}{\partial X_s} & \dfrac{\partial x}{\partial Y_s} & \dfrac{\partial x}{\partial Z_s} & \dfrac{\partial x}{\partial \phi} & \dfrac{\partial x}{\partial \omega} & \dfrac{\partial x}{\partial \kappa} \\ \dfrac{\partial y}{\partial X_s} & \dfrac{\partial y}{\partial Y_s} & \dfrac{\partial y}{\partial Z_s} & \dfrac{\partial y}{\partial \phi} & \dfrac{\partial y}{\partial \omega} & \dfrac{\partial y}{\partial \kappa} \end{pmatrix}, \quad B = \begin{pmatrix} \dfrac{\partial x}{\partial X} & \dfrac{\partial x}{\partial Y} & \dfrac{\partial x}{\partial Z} \\ \dfrac{\partial y}{\partial X} & \dfrac{\partial y}{\partial Y} & \dfrac{\partial y}{\partial Z} \end{pmatrix}$$

$$t = \begin{pmatrix} \Delta X_s & \Delta Y_s & \Delta Z_s & \Delta\phi & \Delta\omega & \Delta\kappa \end{pmatrix}^T, \quad X = \begin{pmatrix} \Delta X & \Delta Y & \Delta Z \end{pmatrix}^T$$

3. Experimental verification

One image of different terrain, different geomorphology is picked to do the experiment.

3.1. GCP's automatic selection

GCP is automatically selected by using the GCP's library and matching algorithm[3]. In this experiment, the distribution of GCP is shown in figure 3.

3.2. Precision evaluation

After the algorithm process, the residual error result of GCP is calculated as shown in table 2. Some check points are selected to further check the correction result. The distribution of check point is shown in figure 4, and they are also uniformly distributed. And the error evaluation result of check point is also shown in table 2. From table 2, it shows that after the algorithm process, the residual error of GCP and the error of check point in two-dimension are about 3 pixels. And it is proof that the algorithm can be used to effectively geometric correct the CCD image.

Table 2. The error evaluation result of GCP and check point.(unit:pixel)

RMS	X RMS	Y RMS	Two-dimension RMS
residual error of GCP	2.50	1.69	3.02
error of check point	2.72	1.71	3.21

4. Conclusion and prospect

According to HJ-1's multispectral payload characteristics of large overlay, large distortion and low precision of attitude and orbit parameters, this paper especially proposes a robust solution algorithm of satellite orbit model parameter based on GCP. In the area of cloudless or partly cloudy, on the condition that the GCPs are reasonably distributed and the number is enough, this algorithm can solve the attitude and orbit parameters in high-precision, set up strict imaging model, realize high-precision ortho-rectification, and efficiently improve the precision of image geometric correction.

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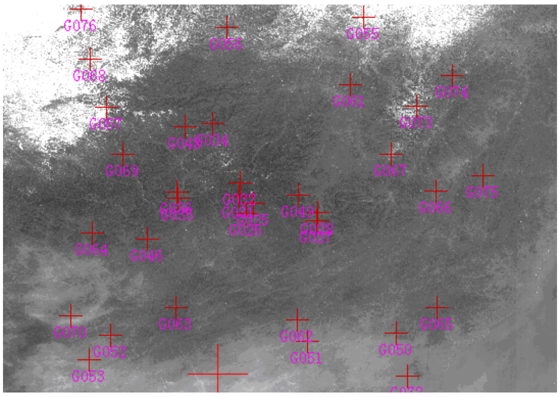

Figure 3. GCP's distribution.

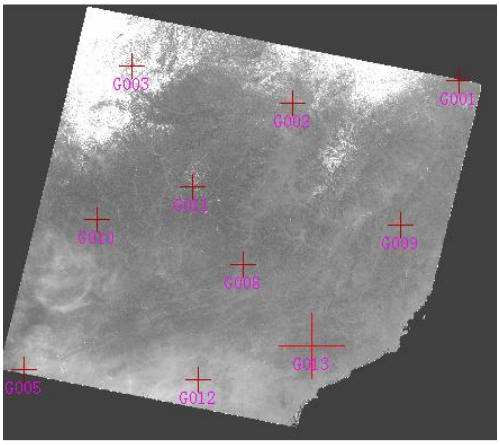

Figure 4. Check point's distribution.

Based on the research and development of the above algorithm, NDRCC has developed a remote sensing image geometric correction system[3]. This system is designed to fine rectify and ortho-rectify image data of multi-spectral, infrared and super-spectral carried by HJ-1A and HJ-1B from level one and level two image into level three and level four image. It offers the automatic, semiautomatic, alternating correction process methods. It includes GCP image selection subsystem, GCP image retrieval selection subsystem, GCP image managerial subsystem, remote sensing correction subsystem and etc. And it provides the image process of geographical coding level facing to disaster reduction application.

The system operates well in NDRCC. Aiming at especially big disaster emergence events, it done the geometric correction process quickly and provided first hand of remote sensing data for disaster emergency, and won the time to make sure the disaster relief work is fast and effective[4].

At the same time, based on this system, NDRCC has made HJ-1's optical mosaic image of the whole China, and made base map of nationwide disaster characteristic parameters. Along with the accumulation of this work, it will push forward the process, analysis and application of time sequence products of disaster characteristic parameter of remote sensing image, advance the remote sensing image application transformation from disaster monitoring and assessment to disaster early warming, and promote the disaster reduction application's potential and ability of remote sensing image.

HJ-1C has launched successful in November 2012. It is hopeful to further set up GCP image library and correction system based on SAR image, and prefect the data process and application ability of the whole HJ-1 constellation.

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