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Accuracy Analysis of Space Three-line-array Photogrammetry Based on Forward Intersection

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***Abstract*—Positioning accuracy is one of the greatest concerns in space photogrammetry. A method about positioning accuracy estimation was put forward in this paper, and the error analysis was developed. According to the theory of forward intersection, the model of space photogrammetry based on three-line-array CCD was established， the formulas of precision estimation for three-line-array CCD imagery without ground control points were deduced form the model, and the primary error sources affecting the positioning accuracy of stereophotogrammetry were analyzed. Finally, the precision estimation was done using the simulated data, and the relation between the positioning accuracy and the main error sources which contained attitude angles (pitch, roll, and yaw), photogrammetric base, and focal length were studied in depth, and some technical requirements were put forward based on the analysis introduced in this paper.**

Keywords-photogrammetry; positioning precision; forward intersection; three-line-array CCD

I. INTRODUCTION

Photogrammetry is the practice of determining the geometric properties of objects from photographic images. It is as old as modern photography and can be dated to the mid-nineteenth century. Space photogrammetry is a new subject that developed based on space technology and remote sensing technology. It takes satellite, spaceship, space shuttle and other space vehicles as carrier, use many kinds of sensors to realize remote sensing of earth and other planets on the orbit space, and make use of the information downloaded form the space vehicle in topographic mapping. Space photogrammetry is considered with reference to various aspects of the astronomical-geodetic and cartographic investigation of the solar-system planets[1]. Furthermore, stereophotogrammetry, a more sophisticated technique, involves estimating the three-dimensional coordinates of points on an object. These are determined by measurements made in two or more photographic images taken from different positions. Since the 1980s, three-line-array CCD camera has been advised to stereophotogrammetry. Compared to other data-transmitted digital photogrammetric cameras, such as IKONOS [2], SPNI-2, SPOT 1~4[3], etc., three-line-array CCD camera characterizes by along-track stereo imaging and reconstructing exterior orientation parameters directly from the images acquired by itself. As a result, three-line-array CCD camera is widely valued by space photogrammetry scientists all over the world, as well as China[4]. In 2007, China launched the first lunar exploration satellite-CE-1, and the payload for lunar surface stereo imaging and reconstructing was just a new kind of three-line-array camera.

Positioning accuracy of the points on the object is one of the greatest concerns in space stereophotogrammetry, and the elevation error is an important basis when we discuss the mapping efficacy of the photogrammetry system. So positioning accuracy estimation is a critical point of constructing a photogrammetry system. This paper describes a method for positioning accuracy estimation of space three-line-array photogrammetry. According to the theory of forward intersection, the model of space photogrammetry based on three-line-array CCD was established, the formulas of precision estimation for three-line-array CCD imagery without ground control points were develop form the model, and the primary error sources affecting the positioning accuracy of stereophotogrammetry were analyzed. Finally, the precision estimation was done using the simulated data, and the relation between the positioning accuracy and the main error sources, such as attitude angles (pitch, roll, and yaw), camera station position, photogrammetric base, etc., was studied in depth, and some technical requirements were put forward based on the analysis introduced in this paper.

II. POSITIONING ACCURACY ANALYSIS BASED ON FORWARD INTERSECTION

A. *Photogrammetric Principle of Three-line-array CCD Imagery*

As shown in Fig. 1, the photoelectric scanning imaging part of the three-line-array CCD camera is consist of three linear CCD, which are lay on the focal plane of the photo system. *l, v, r* stand for forward-looking CCD sensor, vertical-looking CCD sensor, and backward-looking CCD sensor respectively. The three linear CCD are parallel to each other, and all of them are vertical to the flight direction. Each linear CCD sweeps the ground with same scanning period but different imaging angle. Therefore, three images of the flight path (Ls, Vs, and Rs) are made which have different perspective centers and overlap with each other.

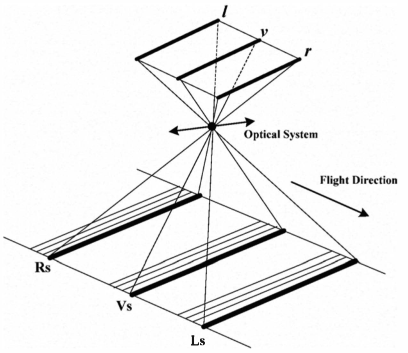

Figure 1. Sketch map of three-line-array CCD camera

Fig. 2 shows the scheme of three-line-array CCD stereophotogrammetry. The exterior orientation parameters at every instantaneous scanning moment are different. One ground point, such as $A(X_A,Y_A,Z_A)$, would be scanned three times successively by the *l*, *v*, and *r*, and the stereo imagery can be reconstructed according to stereophotogrammetry. For the intrinsic camera parameters can be known using camera calibration, the corresponding image points of *A* can be known by image matching method, and the exterior orientation elements can be known by attitude measurement system and orbit measurement system, the ground point *A* can be positioned and its coordinate, that is X_A ,Y_A , and Z_A , can also be obtained according to the stereophotogrammetry.

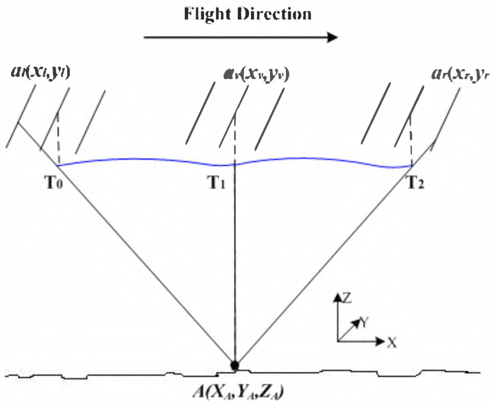

Figure 2. Scheme of three-line-array CCD stereophotogrammetry

B. Positioning Accuracy Analysis Based on Forward Intersection

Fig.3 illustrates the principle of forward intersection. Where $A(X_A,Y_A,Z_A)$ is an arbitrary point on the ground; S_1 and S_2 indicate the camera station of forward-looking CCD sensor and backward-looking CCD sensor respectively; $a_1(x_1,y_1)$ and $a_2(x_2,y_2)$ are corresponding image points of *A*; *B* is photographic baseline.

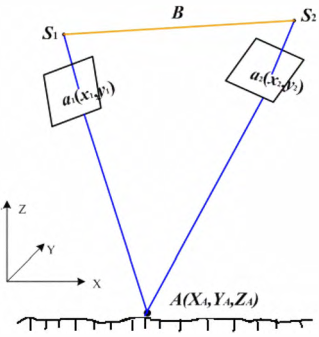

Figure 3. Sketch map of forward intersection

It can be seen that, the coordinates of *A* can be calculated based on the forward intersection as follows:

$$\begin{cases} X_A = X_{S_1} + N_1 \cdot X_1 \\ Y_A = Y_{S_1} + 1/2[N_1 \cdot Y_1 + B_Y + N_2 \cdot Y_2] \\ Z_A = Z_{S_1} + N_1 \cdot Z_1 \end{cases} \tag{1}$$

$$\begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix} = \begin{pmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ y_1 \\ -f \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix} = \begin{pmatrix} a'_1 & a'_2 & a'_3 \\ b'_1 & b'_2 & b'_3 \\ c'_1 & c'_2 & c'_3 \end{pmatrix} \cdot \begin{pmatrix} x_2 \\ y_2 \\ -f \end{pmatrix} \tag{3}$$

$$\begin{cases} N_1 = \dfrac{B_X Z_2 - B_Z X_2}{X_1 Z_2 - X_2 Z_1} \\ N_2 = \dfrac{B_X Z_1 - B_Z X_1}{X_1 Z_2 - X_2 Z_1} \end{cases} \tag{4}$$

Where X_{S1}, Y_{S1}, Z_{S1} are coordinates of camera station S_1; B_X, B_Y, B_Z are components of photographic base *B*; X_1, Y_1, Z_1 are coordinates of left image space coordinate system; X_2, Y_2, Z_2 are coordinates of right image space coordinate system; *f* is focal length of CCD; N_1, N_2 are projection coefficient of left photo point a_1 and right photo point a_2; $(a_1 \cdots c_3)$ or $(a'_1 \cdots c'_3)$ is the rotation matrix, and $a_1 \cdots c_3$ or $a'_1 \cdots c'_3$ are defined as (5).

$$\begin{cases} a_1 = \cos\varphi_1 \cos\kappa_1 - \sin\varphi_1 \sin\omega_1 \sin\kappa_1 \\ a_2 = -\cos\varphi_1 \sin\kappa_1 - \sin\varphi_1 \sin\omega_1 \cos\kappa_1 \\ a_3 = -\sin\varphi_1 \cos\omega_1 \\ b_1 = \cos\omega_1 \sin\kappa_1 \\ b_2 = \cos\omega_1 \cos\kappa_1 \\ b_3 = -\sin\omega_1 \\ c_1 = \sin\varphi_1 \cos\kappa_1 + \cos\varphi_1 \sin\omega_1 \sin\kappa_1 \\ c_2 = -\sin\varphi_1 \sin\kappa_1 + \cos\varphi_1 \sin\omega_1 \cos\kappa_1 \\ c_3 = \cos\varphi_1 \cos\omega_1 \end{cases} \tag{5}$$

Where φ_1, ω_1, κ_1, φ_2, ω_2, κ_2 are attitude angles when the CCD imagery was shoot on camera station of S_1 and S_2.

Based on (1), the coordinate error equations are defined as (6).

$$\begin{cases} \delta_{X_A} = \delta_{X_{S1}} + N_1 \cdot \delta_{X_1} + X_1 \cdot \delta_{N_1} \\ \delta_{Y_A} = \delta_{Y_{S1}} + 1/2[\delta_{B_Y} + N_1 \cdot \delta_{Y_1} + Y_1 \cdot \delta_{N_1} + N_2 \cdot \delta_{Y_2} + Y_2 \cdot \delta_{N_2}] \\ \delta_{Z_A} = \delta_{Z_{S1}} + N_1 \cdot \delta_{Z_1} + Z_1 \cdot \delta_{N_1} \end{cases} \tag{6}$$

When the aerocraft flights stably, the imaging mode can be regarded as vertical photography approximately, and the attitude angle is very small, so it is consumed that $\varphi_1=\omega_1=\kappa_1=0$, $\varphi_2=\omega_2=\kappa_2=0$, $B_Z=0$, $B_Y=0$. Depending on the above mentioned contents, the coordinates error formulas can be obtained from (6) as (7).

$$\begin{cases} \delta_{X_A} = \delta_{X_{S1}} + \frac{x_1}{b_x}\delta_{B_x} + \frac{x_1 x_2}{b_x f}\delta_{B_z} + \frac{B_x x_2}{b_x^{\ 2}}\delta_{x_1} + \frac{B_x x_1}{b_x^{\ 2}}\delta_{x_2} + \frac{B_x x_2 (x_1^2 - f^2)}{f b_x^{\ 2}}\delta_{\varphi_1} \\ \quad + \frac{B_x x_1 (x_1 x_2 - f^2)}{f b_x^{\ 2}}\delta_{\varphi_2} - \frac{B_x x_1 x_2 y_1}{f b_x^{\ 2}}\delta_{\omega_1} + \frac{B_x x_1 x_2 y_2}{f b_x^{\ 2}}\delta_{\omega_2} + \frac{B_x x_2 y_1}{b_x^{\ 2}}\delta_{k_1} - \frac{B_x x_1 y_2}{b_x^{\ 2}}\delta_{k_2} \\ \delta_{Y_A} = \delta_{Y_{S1}} + \frac{y_1}{b_x}\delta_{B_x} + \frac{1}{2}\delta_{B_y} + \frac{y_1(x_1 + x_2)}{2 b_x f}\delta_{B_z} + \frac{1}{2}\frac{B_x}{b_x}\delta_{y_1} + \frac{1}{2}\frac{B_x}{b_x}\delta_{y_2} - \frac{B_x y_1 f}{b_x^{\ 2}}\delta_{\varphi_1} + \frac{B_x y_2 x_1 x_2}{b_x^{\ 2}}\delta_{\varphi_2} \\ \quad + \frac{1}{2}\left[\frac{B_x f}{b_x} - \frac{B_x (x_1 + x_2) y_1^{\ 2}}{f b_x^{\ 2}}\right]\delta_{\omega_1} + \frac{1}{2}\left[\frac{B_x y_2^{\ 2}(x_1 + x_2)}{f b_x^{\ 2}} + \frac{B_x f}{b_x}\right]\delta_{\omega_2} + \frac{2 B_x y_1^{\ 2} - B_x x_1 x_2 + B_x x_1^2}{2 b_x^{\ 2}}\delta_{k_1} \\ \quad + \frac{-2 B_x y_2^{\ 2} - B_x x_1 x_2 + B x_2^2}{2 b_x^{\ 2}}\delta_{k_2} + \frac{B_x y_2 x_1}{2 f b_x^{\ 2}}\delta_f \\ \delta_{Z_A} = \delta_{Z_{S1}} + \frac{f}{b_x}\delta_{B_x} + \frac{x_2}{b_x}\delta_{B_z} + \frac{B_x f}{b_x^{\ 2}}\delta_{x_1} - \frac{B_x f}{b_x^{\ 2}}\delta_{x_2} + \frac{B_x x_1^{\ 2} + 2 B_x x_1 x_2 + B_x f^2}{b_x^{\ 2}}\delta_{\varphi_1} - \frac{B_x (x_1 x_2 - f^2)}{b_x^{\ 2}}\delta_{\varphi_2} \\ \quad + \frac{B_x y_1 x_2}{b_x^{\ 2}}\delta_{\omega_1} - \frac{B_x y_2 x_2}{b_x^{\ 2}}\delta_{\omega_2} - \frac{B_x y_1 f}{b_x^{\ 2}}\delta_{k_1} + \frac{B_x y_2 f}{b_x^{\ 2}}\delta_{k_2} + \frac{B_x}{b_x}\delta_f \end{cases} \tag{7}$$

III. ANALYSIS OF MAJOR ERROR SOURCES

From (7), it can be seen that the error sources of stereophotogrammetry include attitude error, image point coordinate error, camera station position error and baseline error, camera focal length error.

A. *Attitude Angle Error*

Attitude angle error is the major factor of photogrammetric positioning accuracy. In the three attitude angles (pitch, roll, and yaw), pitch angle has the most obvious impact on the positioning accuracy and elevation accuracy. This conclusion will also be reflected in subsequent experiments.

At present, the aircraft attitude sensors on board are mainly star tracker, gyro, infrared earth sensors, RF sensors, magnetic meter, etc.. Compared to the other attitude sensor, the star sensor can provide a higher pointing accuracy, three-axis attitude information as well as omnidirectional attitude information. It also can meet the requirement of extrasolar deep space exploration, and the output attitude is real-time direct measurement relative to the inertial coordinate system without a slow drift. Currently, the star tracker has been widely used in various earth orbit satellites.

The attitude determination accuracy of star sensor is mainly affected by the following factors: field range, imager noise, the optical axis pointing accuracy, angle measurement accuracy between the star tracker and the camera axis. Now, the typical attitude determination accuracy range of the star sensor is 0.004°~0.3°.In order to improve the accuracy of attitude determination, we can use integrated attitude determination system which combines high-precision star tracker, gyro, and GPS. Japanese ALOS satellite adopts integrated attitude determination system based on three high-precision star sensor, inertia gyro and the high-precision ADS(angular displacement sensor), through integrated attitude determination algorithms, to make the onboard attitude determination accuracy of 1.08″and post-processing accuracy of 0.72″[5].

B. *Camera Station and Baseline Error*

Camera station position of the aircraft is mainly obtained by GPS satellite orbit positioning technology. There are many factors which affect the positioning accuracy, such as satellite clock error, ephemeris error, the error induced by ionospheric refraction, tropospheric refraction, and multipath effect, etc.. In the case of satellite photogrammetry without ground control point, the measurement accuracy of camera station position has a direct impact on the absolute positioning accuracy. At the same time, when we use the data of camera station position to calculate the baseline, relative positioning accuracy will be effected indirectly because of the camera station position error having effects on the photographic scale. The baseline error can bring the changes of model scale directly, and as result the positioning accuracy is influenced.

Today, measurement-based GPS receiver is used in stereophotogrammetry to obtain a high positioning accuracy. Positional accuracy of existing GPS receiver can reach 10 m, and after post-processing the positioning accuracy can be improved to 5m. In order to further improve the positioning accuracy of satellite orbit, as well as the baseline measurement accuracy, we can use multiple GPS receivers, or dual-frequency GPS receiver[6] [7]. Dual-frequency GPS receiver can eliminate the ionosphere signal delay effects and can be used in long distance, such as several thousand kilometers, precision positioning. By using carrier phase differential positioning method to process the signals downloaded form dual-frequency GPS receiver, Japan's ALOS satellite can meet the positioning accuracy of 0.51m (3σ)[5]. At present, GPS dual-frequency receiver which positioning accuracy is up to centimeter level has also been successfully developed, which can significantly improve the positioning accuracy of stereophotography.

C. *Interior Orientation Elements Error*

In order to make high-precision stereophotography a reality, calibration must be done for the camera interior orientation elements (that is focal length and principal point location). Nowadays, in the laboratory conditions, the focal length error is less than 20μm, and the principal point position error is less than 0.3 pixel by high-precision test instrument of the inner orientation elements.

IV. POSITIONING ACCURACY ESTIMATION

Supposed that, the basic photogrammetric parameters of space three-line array CCD camera are:

Orbital altitude: 200Km; pixel size: 14μm × 14μm; face up to the camera focal length: $f = 25$mm; optical axis angle between before (after) to the camera and face up to the camera: 20 °.

Put the above conditions and the point coordinates into (7), we will get the mean square error formula of ground point A as (8).

$$\begin{cases} m_{X_A}^2 = m_{X_{S1}}^2 + 2.423957m_{B_x}^2 + 4.808969m_{B_z}^2 + 803.8979m_x^2 + 26670.72m_\varphi^2 + 888.8816m_\omega^2 + 822.9913m_k^2 \\ m_{Y_A}^2 = m_{Y_{S1}}^2 + 6.329477\times10^{-3}m_{B_x}^2 + 0.250000m_{B_y}^2 + 8.126327\times10^{-3}m_{B_z}^2 + 44.85174m_y^2 \\ \qquad + 2.386523\times10^5 m_\varphi^2 + 2.373334m_\omega^2 + 3.188193\times10^4 m_k^2 + 0.1073298m_f^2 \\ m_{Z_A}^2 = m_{Z_{S1}}^2 + 3.295357m_{B_x}^2 + 6.537769m_{B_z}^2 + 591.2099m_x^2 + 2.702027\times10^6 m_\varphi^2 + 1208.430m_\omega^2 \\ \qquad + 609.1082m_k^2 + 89.70347m_f^2 \end{cases} \tag{8}$$

To analyze the degree that different error sources effect on the positioning accuracy, three maps were given as follows.

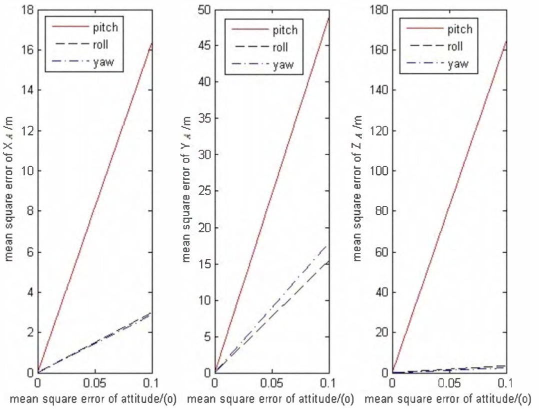

Figure 4. Effect of attitude error for positioning accuracy

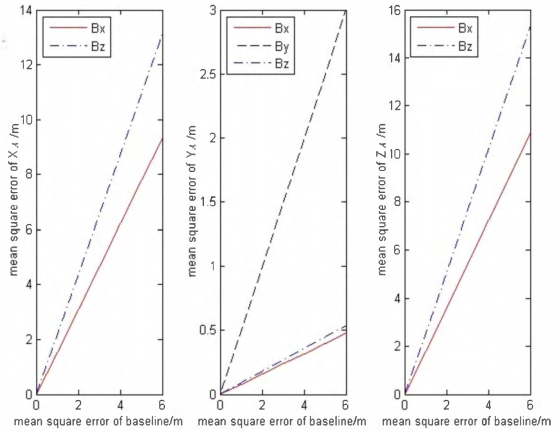

Figure 5. Effect of baseline error for positioning accuracy

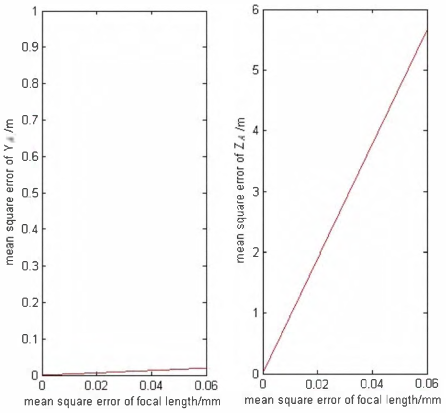

Figure 6. Effect of focal length for positioning accuracy

From the figures above, some important conclusions can be drawn as bellow:

- From Fig.4 it can be seen that, attitude errors have a great effect on the positioning accuracy, and among the three attitude angles, the pitch angle has the greatest impact on the plane positioning accuracy as well as the elevation accuracy;
- From Fig.5, we can see that the photogrammetric base has a big effect on the positioning accuracy, and the positioning error is as big as the baseline error;
- From Fig.6 it can be seen that the focal length error has a big effect only on the elevation positioning error, and has almost no effect on the plane positioning accuracy.

In addition, for the error concerned with imagery measuring is 0.3 pixels at present, according to (8) the positioning error is so small that can be ignored. Therefore, improving the measurement accuracy of camera station and baseline is the key to improve positioning precision, and high precision calibration system of inner orientation elements should be established so as to improve the positioning accuracy especially the elevation accuracy.

V. CONCLUSION

Space photogrammetric precision error model for three-line-array CCD imagery on the basis of forward intersection theory was deduced in this paper, and positioning precision estimation was calculated using simulated data. It can be seen that, in the case of space photogrammetry without ground control points, the primary precision contains attitude angle error, camera station and baseline error, and camera focal length error. Among these error sources, attitude angle error affects the elevation positioning precision most. In order to meet the requirements of mapping the topographic map at the scale of 1:50,000 depending on no ground control point, the elevation error should be less than 6m, and as a result the attitude stability must reach the level of 10^{-6}(°)/s. But until now the attitude determination accuracy of high precision star tracker is 2″, and the elevation error brought in is bigger than 6m. Furthermore, to a great extent the accuracy of a star tracker is affected by field angle size, focal length, magnitude detectable, etc., and consequently the practical accuracy of the star tracker is less than its marked accuracy, so the elevation positioning accuracy of 6m depending on space photogrammetry without ground control points can not be satisfied even using the highest precision star tracker. To meet the demands of space photogrammetry, and reduce the requirements of attitude determination accuracy, some methods are put forward to solve this problem. For example, we can use a new kind of camera, which developed form the traditional three-line-array CCD camera, and we also can use forward-looking imagery, vertical-looking imagery, and backward-looking imagery instead of forward-looking and backward-looking imagery for photogrammetric adjustment. After all, at present realizing high positioning precision space stereophotogrammetry without ground control points and under lower attitude positioning stability is still a great challenge for us.

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