GENERAL DESIGN OF SPACE OPTICAL MAPPING REMOTE SENSING CAMERA

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ABSTRACT:

Surveying and mapping plays an important role in all aspects of economic development, national infrastructure construction and national defence construction. Especially in the overall and strategic level, most of them need to apply geospatial information. Geospatial information acquired through surveying and mapping technology has become an important strategic resource. Because space photography is faster, cheaper and unrestricted by regions and borders, countries around the world are scrambling to develop their own mapping satellites.
In recent years, great breakthrough has been made in the field of on-board optical stereo mapping, many countries have launched satellites with surveying and mapping as the main function, and obtained image data from 1:50000 to 1:10000 scale. This paper describes a design of a stereo surveying and mapping camera system that can achieve 1:10000 scale maps.

1. INTRODUCTION

1.1 Backgrounds

Space-borne stereo mapping camera is mounted on the spacecraft and takes photograph of the surface of the earth far away from the planet. In this way digital surface model can be obtained efficiently at lower costs. Film-based space-borne stereo mapping cameras have been widely used in the past and are applicable for making maps without ground control points. However images cannot be obtained until the spacecraft returns to the ground of the earth. With the development of the charge coupled device (CCD) technology, digital space-borne stereo mapping cameras based on CCD sensors are predominant ways, because the images can be obtained instantly and are Convenient for subsequent image analysis and processing.

1.2 Principal of Space-borne Stereo Mapping Camera

Generally space-borne stereo mapping camera can be classified as one-line-array stereo mapping camera, two-line-array camera and three-line-array stereo mapping camera. Three-line-array stereo mapping camera can reconstruct exterior orientation elements from images and demand less attitude stability of the satellite. As a result three-line-array stereo mapping camera is more likely to realize photogrammetric survey without ground control points. But three-line-array makes the satellite bulky and the structure of the camera has become more complex, the difficulty of technical realization is increased. So with the progress of camera and satellite technology, two-line-array has been gradually applied to the application of mapping without ground control points.

Shown as fig 1 is the diagrammatic sketch of stereo mapping principle for two-line-array CCD camera. The two cameras push and scan the same target at different angles and different times, obtaining a pair of stereo images.

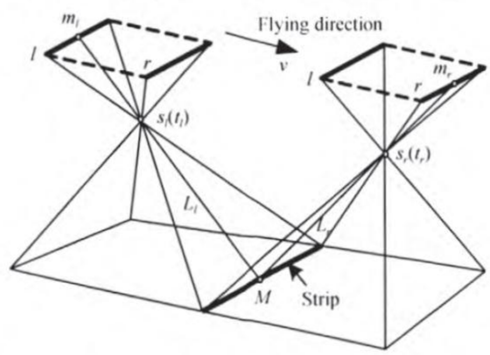

Figure 1. Diagrammatic sketch of stereo mapping principle for two-line-array CCD camera

Continuous image strips are obtained by linear CCD meanwhile the satellite can provide recorded exterior orientation elements of the moment. There is a strict central projection relationship between the scanned image and the photographed object in each line. The front and back images obtained from the same ground position constitute a pair of stereoscopic pictures, and the coordinates of ground object points can be calculated by the forward intersection method. The forward intersection locating model of two-line-array is shown below.

$$\begin{cases} X_m = X_{S1} + NX_1 \\ Y_m = Y_{S1} + \frac{1}{2}\left(NY_1 + N'Y_2 + B_Y\right) \\ Z_m = Z_{S1} + NZ_1 \end{cases} \quad (1)$$

$$\begin{cases} N = \dfrac{B_X Z_2 - B_z X_2}{X_1 Z_2 - X_2 Z_1} \\ N' = \dfrac{B_X Z_1 - B_z X_1}{X_1 Z_2 - X_2 Z_1} \end{cases} \quad (2)$$

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$$\begin{cases} B_X = X_{S2} - X_{S1} \\ B_Y = Y_{S2} - Y_{S1} \\ B_Z = Z_{S2} - Z_{S1} \end{cases} \tag{3}$$

Where:
(X_m, Y_m, Z_m)- The coordinate of the ground point in the photogrammetric coordinate system
(X_{S1}, Y_{S1}, Z_{S1}), (X_{S2}, Y_{S2}, Z_{S2})- The coordinate of two camera's photogrammetric centre point in the ground photogrammetric coordinate system, that is, the camera's external orientation elements
N, N_1-Projection coefficients of two image points
Bx, B_Y, B_Z-Three coordinate components of the photogrammetric baseline in the ground photogrammetric coordinate system
(X_1, Y_1, Z_1), (X_2, Y_2, Z_2) - the coordinates of the image point in the image space auxiliary coordinate system, The relationship with the coordinates of image points is shown as the following formula

$$\begin{cases} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = R_1 \begin{bmatrix} x_1 \\ y_1 \\ -f \end{bmatrix} \\ \begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = R_2 \begin{bmatrix} x_2 \\ y_2 \\ -f \end{bmatrix} \end{cases} \tag{4}$$

Where:
(x_1, y_1, -f), (x_2, y_2, -f)- The imaging points coordinates of two cameras
R_1, R_2 - Transformation matrix of image space coordinate system and image space auxiliary coordinate system

In the process of designing surveying and mapping camera, effective design measures can be taken to control the errors according to the influence models of various errors on the geometric accuracy of imaging.

1.3 Developments of Space-borne Stereo Mapping Camera

Typical surveying and mapping satellites in the world such as MOMS of Germany, SPOT-5 & Pleiades of France, ALOS of Japan, CARTOSAT-1/2 series /3 of India and ZY-3 series of China and so on. These satellites have the ability to make 1:50000 to 1:5000 scale topographic maps. And with the dramatic improvement of the attitude maneuver ability of remote sensing satellites, one-line-array detector can also achieve stereoscopic mapping image. Such as IKONOS, WORLDVIEW-1/2/3, GEOEYE-1. With the support of ground control points, 1:10000 or even larger scale topographic maps can be made.

2. SYSTEM DESIGN OF THE CAMERA

Based on the theories above, we propose a kind of high performance surveying camera system. This system uses the stereo push imaging mechanism of one-line-array, so it is equipped with two cameras with basically the same parameters. The camera adopts TMA optical system. The resolution of 0.6m can be achieved by the 6m focal length at 500km orbit, and the coverage width of 40km can be achieved by the 5 °field angle.

The optical mechanical structure made of carbon fibre composite material combined with high-precision temperature control system makes the camera have high stability, which is an essential feature of high-precision mapping camera. Therefore, the camera is particularly suitable for 1:10000 scale satellite stereo mapping. Performances and specifications of the cameras are shown in the following table.

Parameters	Forward camera	Back camera
Focal length	7900 mm	7050 mm
Field of view(FOV)	4°33′	5°20′
Relative aperture(F/D)	1/11	1/11
Pixel size	7μm	7μm
MTF(Static)	0.18	0.18
Resolution	0.5m	0.5 m
Swath	44km	44 km
Distortion	4.8μm	3.2μm
Size	3500 mm×3200 mm×1500 mm	
Weight	1600 kg	

Table 1. Parameters of two cameras

Two cameras are installed on a frame with high stability. One camera points 26 ° in front of the subastral point, the other points 5 °behind the subastral point, and the intersection angle of the two cameras is 31 °.

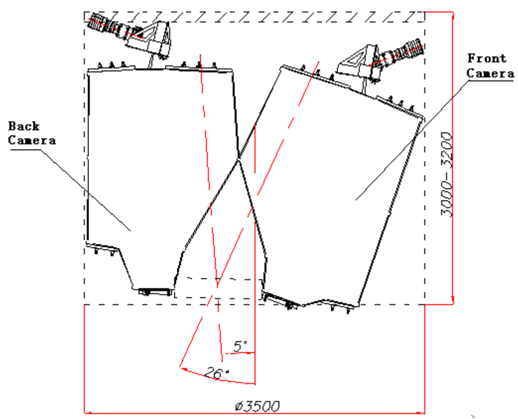

Figure 2. Layout of two-line-array CCD camera

In order to improve the accuracy of determining the exterior orientation elements of the cameras, two star cameras are installed on the camera frame.

3. MEASURES FOR SPACE BORNE SURVEYING & MAPPING CAMERA

The positioning accuracy of mapping satellites is the core and key index for evaluating the performance of Surveying and mapping. At present, it has developed to the precision of the meter level. Therefore, in the design process of Surveying and mapping camera, it is not only necessary to ensure that the image has good MTF, SNR, dynamic range and other basic radiation characteristics, but also need to focus on geometric accuracy and stability.

3.1 Optical System with High Stability of Elements of Interiors of Interior Orientation

In order to achieve high-precision stereoscopic mapping, the lens of the mapping camera requires excellent imaging quality and the stability of interior orientation elements.

The off-axis TMA optical system hasn’t obscuration. Through the combination of several mirrors with different curvature shapes, the system is easier to achieve the target of large field of view and high transmission than the coaxial optical system.

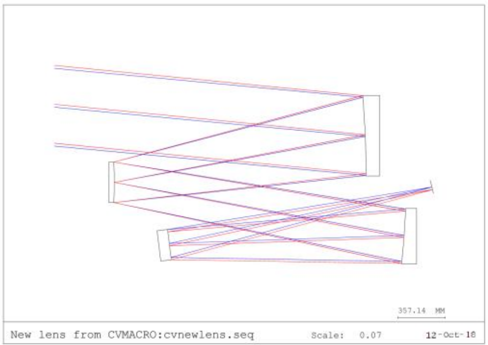

Figure 3. Optical system diagram of the cameras

The calculated results of MTF calculation is shown in figure 4.

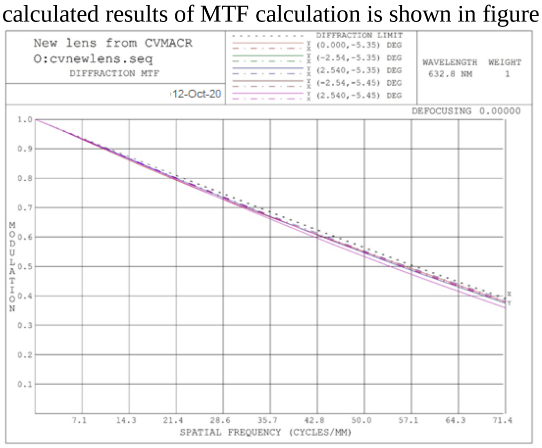

Figure 4. MTF result of the optical system

The image space telecentric system is easier to achieve low distortion than other systems. The calculated results of distortion of the optical system are shown in the table below.

Field angle	Distortion, D X(mm)	Distortion, DY(mm)
0°00' - 5°21'	0	-0.0026
0°30' - 5°21'	-0.0004	-0.0024
0°45' - 5°21'	-0.0006	-0.0021
1°00' - 5°21'	-0.0007	-0.0016
1°15' - 5°21'	-0.0007	-0.0011
1°30' - 5°21'	-0.0005	-0.0003
1°45' - 5°21'	-0.0002	0.0006
2°00' - 5°21'	0.0003	0.0017
2°15' - 5°21'	0.0011	0.003
2°32' - 5°21'	0.0024	0.0048

Table 2. The calculated results of distortion

In order to restrain stray light in the optical system, the baffle plates between the secondary and plane mirrors as well as those between the primary and tertiary mirrors can effectively prevent stray light from entering the focal plane. And because the main light is perpendicular to the surface of the CCD linear array, it is beneficial to reduce the stray light scattering caused by the reflection of the surfaces of the detectors.

Through in-depth study on the thermal stability of optical system, it is found that the image telecentric optical system has better thermal stability of main point and distortion.

3.2 Opt-mechanical Stability Design of Space Optical Mapping Camera

The opt-mechanical structure of the camera is mainly composed of frame and cover. The main frame is most important and crucial component of the camera. The frame provides reliable support to ensure the accuracy of the position between the optical components. Therefore, the frame must be a high stiffness to support the entire optics package with minimal deformation. Meanwhile the structure must be stable when subjected to different thermal environments.

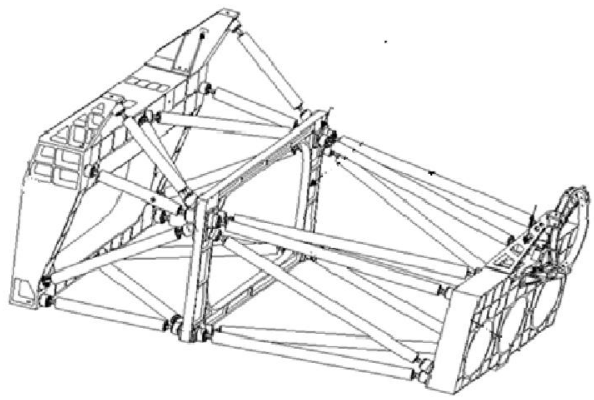

Figure 5. Model of the frame

The key consideration in frame design is to ensure excellent dimensional stability under the condition of temperature alternation. So carbon fibre composite is selected for the frame because of its extremely low coefficient thermal expansion($<10^{-6}K^{-1}$). The frame is constructed of carbon fibre composite tubing. Meanwhile, truss structure is adopted to reduce structure weights. Titanium alloy inlays are machined to provide a repeatable, flat mounting surface to make the interface to the optical elements reliable. The frame is showed on Figure 5. The optical components are attached to the fame.

The FPA layout design is represented in figure 6. 8 TDI CCD sensors are used in FPA. However, not all of them are on the same plane: 4 of the sensors are irradiated directly and 4 irradiated by reflected light which allows the image to be acquired in the same field simultaneously.

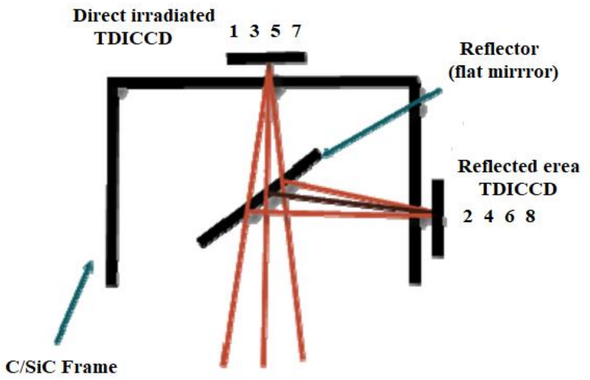

Figure 6. Diagram CCD layout focal plane

Novel carbon fibre reinforced silicon carbon(C/SiC) is used in the focal plane frame, which is a composite ceramic material based on reinforcements of carbon fibres and matrices of silicon carbide. Compared with frequently-used materials, it has excellent comprehensive properties: high stiffness, high thermal conductivity and low CTE, shown as in table 3.

Parameter	E (Gpa)	ρ (g/cm^3)	α (10^{-6}K^{-1})	K (W/mK)
C/SiC	>100	2~2.7	1~2	100
Zerodur	91	2.53	0.05	1.64
Invar	100	8	0.5~3	10
TC-4	210	4.6	8.9	15.2
SiC	380	3.1	4.7	185

Table 3. Properties of frequently-used materials

3.3 High precision temperature control design

Although the optical structure of the camera adopts carbon fibre composite material with high thermal stability, the camera's temperature still needs to be controlled within a critical range due to the large size of the camera structure, especially when the electronic components of the focal plane emit a lot of heat. If no effective cooling measures are taken, the temperature fluctuation of the focal surface structure will be remarkable, thus affect the geometric accuracy of the image. According to the stability analysis results, the specific temperature control requirements for every parts of the camera are as follows:

- Temperature of lens: 20℃ ±1℃
- Temperature of focal plane frame: 20℃ ±1℃
- Temperature of focal plane circuit box: 10℃ ±2℃
- Temperature of CCD: 5℃~25℃

In order to achieve the high precision temperature control requirements, a combination of active and passive thermal control design is adopted.

1) The lens and focal plane of the camera are covered with multi-layer insulating materials, and 21 heating loops and temperature measuring loops are used to compensate for the heating of the camera;
2) The focus circuit works intermittently, so when starting up, focal plane circuit box is connected to the dedicated cooling plate by a grooved heat pipe for heat dissipation, and when shutting down, the heating circuits are used To compensate the heat;
3) In order to meet the CCD temperature control requirement of ±2℃ during the whole life cycle in orbit, a kind of temperature controlling loop heat pipe with the ceramic porous wick is adopted.

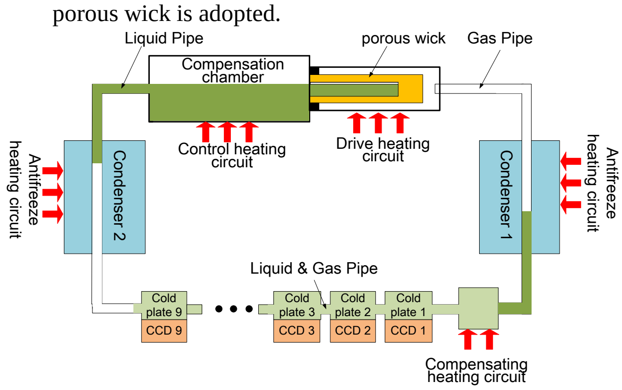

Figure 7. The component schematic diagram of the temperature controlling loop heat pipe

3.4 High Precision Time Synchronization Design and Calibration

When the high precision surveying camera is on orbit and CCD linear array push-broom imaging, the error of several milliseconds of the camera imaging time and the satellite time may produce several meters of positioning error, thus reducing the positioning accuracy of the surveying and mapping image. Therefore, in order to meet the high time precision requirements of the mapping task, the high precision time synchronization design must be considered in the design of the surveying camera system and the high precision test must be carried out in the test phases, so that we can ensure strict synchronization between camera and satellite time in the push-broom imaging.

As shown in figure 8, the satellite uses GPS receiver as the reference clock source to provide high precision hardware second pulse signal. By utilizing the whole-second characteristic of GPS signal, the receiver can produce a second pulse signal with an accuracy of 1 microsecond at every whole-second moment of normal operation. At the same time, the GPS time of the second pulse is also broadcasted through the bus communication. When the camera enters the imaging mode, each information source related to the mapping task, including the mapping camera, star sensor, and the gyroscope, takes the GPS second pulse signal as the time benchmark, generates their respective high precision time standard, and finally ensures the precise synchronization between the time standard of the relevant information and the time of the GPS (the synchronization precision is better than 20 us). The imaging time of each line can be accurately calculated by the mapping camera and marked in the auxiliary data of the corresponding image line.

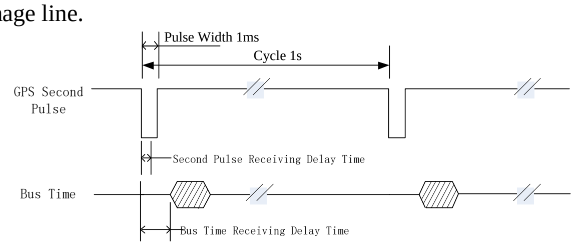

Figure 8. Diagram of time calibration relationship for space-borne mapping camera

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3.5 High Precession Geometric Calibration for Mapping Camera

High precision geometric calibration of surveying and mapping camera is the key factor to ensure high precision positioning of mapping satellites. Therefore, it is necessary to calibrate the geometric elements of the two-line-array mapping camera by using the collimator and the high precision two-dimensional rotating platform, and the geometric elements include the interior orientation elements, the distortion of the lens, the intersection angle between the forward and backward cameras, and the parallaxes of the CCD line. For the scale of l:10000 scale mapping, the calibration accuracy of the main point position of the surveying camera is better than 0.1 pixel, the calibration precision of the principal distance is better than 20 μm, and the calibration accuracy of the camera intersection angle is better than 0.2 ".

For large scale and high-precision mapping camera systems, the influence of gravity on the calibration of internal orientation elements can't be ignored. The average value of the results achieved by reverse the camera can reduce the influence of gravity. Therefore, in the design process of the interior orientation elements test table, the feasibility of the overall reversal test of the camera should be considered, and the optical axis direction between the camera and the star camera should be considered, and the position of the collimators should be designed reasonably, so as to ensure the efficient and accurate measurement of the geometric elements.

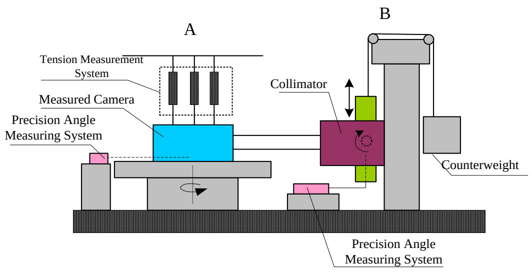

Figure 9. Diagram of the interior orientation elements test with gravity compensation

In addition, most of the surveying and mapping satellites can use the ground high-resolution geometric calibration field for on-orbit image geometric calibration and high-level imaging product accuracy verification. After the satellite was launched, the system error can be calibrated according to the ground control point information of the image. Then the attitude optimal calculation is carried out by using the star sensor, the original data of the gyroscope and the star map data to realize the high precision measurement of the satellite attitude. The coordinates of 18 field control points were measured on the ground by the ZY-3 satellite. The precision is better than 0.1m and the precision of image point measurement is better than 0.5 pixels. Using 4 control points, the high precision digital orthophoto image is generated, and the other 14 control points are used as checkpoints to obtain the calibration value of the exterior orientation elements of the satellite, so that we can evaluate the plane precision and the elevation precision of the satellite by using ground control point. The test results of ZY-3 satellite show that the positioning accuracy of the satellite without control points is about 10 pixels, and the plane and elevation accuracy calibrated with the control points are better than 0.5 pixels, the effect is significant.

4. OPTICAL PERFORMANCE EVALUATION BY MECHANICAL INTEGRATION ANALISIS

Opto-mechanical thermal integration analysis is an effective method in optical instrument design and analysis, and it can evaluate the optical and mechanical properties of the instrument at low cost. The integration analysis model is a system level model established by using different discipline tools. The model includes various models related to system performance and their interactions, including thermal load model, mechanical model and optical model. In this paper, Sigfit software is used to build the simulation and analysis process of optical mechanical thermal integration

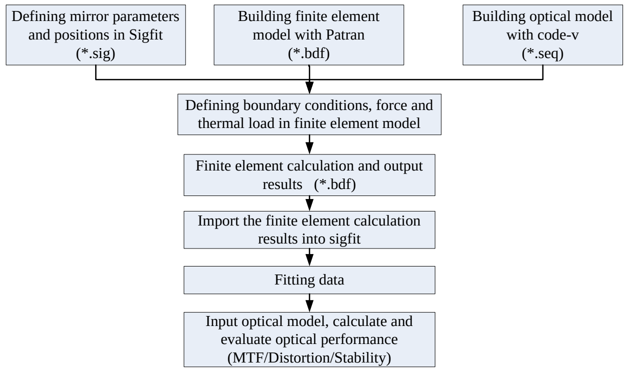

Figure 10. Flow chart of integrated optical-mechanical-thermal analysis

Take the forward camera as example, the opto-mechanical integration analysis is carried out. As shown in Figure 11, the finite element model has about 720000 nodes and 440000 elements. 4 kinds of load condition were calculated:

Load 1: 1g gravity load in Y direction;
Load 2: Thermal deformation at 4℃;
Load 3: Thermal deformation at 4 ℃ temperature Z gradient;
Load 4: Thermal deformation at 4℃ temperature Y gradient.

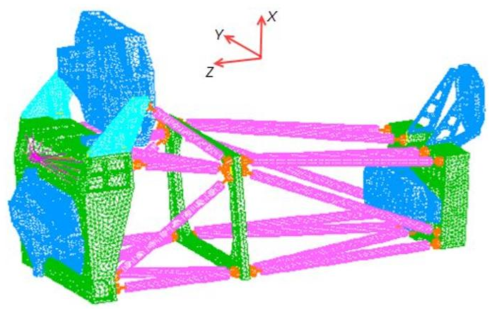

Figure 11. Finite element model of camera

The results of analysis are shown as table 4.

State	MTF	Distortion	Pointing	Focal
Design values	0.37	4.8	0	7900
Load 1:	0.36	4.9	x: 2.4″ y: 8.2″	7900.79
Load 2:	0.35	5.4	x: -0.9″ y: 1.7″	7901.31
Load 3:	0.36	5.1	x: -0.6″ y: 1.3″	7901.17

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Load 4:	0.36	5.2	x: -0.5″ y: 2.2″	7901.04

Table 4. The result of opto-mechanical analysis

The results show that the optical performances of the camera (especially distortion and focus) are stable. Under the condition of load 1, the change of pointing direction is close to 10 seconds, but which only occurs in the weightlessness when the satellite was launched to orbit, so it can be calibrated by the camera in orbit Geometric calibration.

5. CONCLUSIONS

In view of the characteristics of high geometric accuracy and high stability requirements of Surveying and mapping, this paper takes well-directed design measures in optical system design, optical structure design, and thermal control design and time synchronization accuracy calibration. According the results of analysis, the camera has high geometric accuracy and stability, and was applicable for 1:10000 scale surveying and mapping.

By the way, the target analysis must be carried out focus on the joint error analysis with satellite, so that the configuration of the system can be optimized and multi-source data can be properly collocated and used correctly. It can not only improve the precision of the mapping, but also reduce the difficulty of the design of the satellite. Therefore, it is necessary to construct the quantitative analysis and evaluation model of the overall image chain geometric accuracy and the joint error correction method of multiple data sources for the construction of a business system with large scale, high reliability and high processing precision. This will be the focus of our follow-up research work.

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