REFOCUSING FOR ON-ORBIT MTF COMPENSATION OF REMOTE SENSING CAMERA

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ABSTRACT:

Refocusing methods are used to compensate optical performance degradation of high resolution satellite camera during on-orbit operation. Due to mechanical vibration during launch and thermal vacuum environment of space where camera is exposed, the alignment of optical system may have error. The focusing error is dominant of misalignment and caused by the de-space error of secondary mirror of catoptric camera, which is most sensitive to vibration and space environment. The high resolution camera of SPOT, Pleiades and KOMPSAT2 have refocusing device to adjust focusing during orbital operation while QuickBird of US does not use on orbit refocusing method. For the Korsch type optical configuration which is preferred for large aperture space remote sensing camera, secondary mirror and folding mirror are available as refocusing element.

KEY WORDS: Refocusing, Focusing Mechanism, Focusing Device, Focusing Error, MTF

1. INTRODUCTION

The design of high resolution optical camera for space application needs critical consideration for opto-mechanical stability at launch environment and space condition of orbit where the camera will be operated. In spite of the stable structure of camera which is designed to have minimum allowable alignment error after launch and exposure in space environment, some high resolution camera system install refocusing device to compensate defocusing alignment which leads to modulation transfer function (MTF) degradation.

The imaging cameras of SPOT series are equipped with refocusing mechanism (Léger, 2003) and the high resolution camera of Pleiades, sub-meter ground resolution camera under developing, uses thermal refocusing device (Lamard, 2004). The multi-spectral camera (MSC) of KOMPSAT 2 can adjust focusing with focusing mechanism of panchromatic and multi-spectral channels in orbital condition (Berger, 2004). The Ball high resolution camera (BHRC 60) of QuickBird satellite which has sub-meter ground sampling distance does not use on-orbit focusing device (Miers, 2001).

This paper reviews the technical properties and trend of focusing device of high resolution space camera from SPOT to MSC. For the MSC detail analysis result is described including thermal and optical analysis. The allowable amount of focussing error and de-space error of two mirror type system are derived and refocusing elements available for Korsch configuration are suggested.

2. FOCUSING ERROR AND OPTICAL PERFORMANCE DEGRADATION

The optical configuration of space camera is very compact, which leads to very high stability requirement. The space error of mirrors in catoptric system is main source of focusing error, image shift along optical axis and blur in focal plan. Even though special materials such as composite which has high thermoelastic stability with good mechanical properties and moisture sensitivity, was selected for structure of camera, the Pleiades camera was required to have focusing function in orbit.

If we consider the optical depth of focus where degradation of optical performance is acceptable, we can estimate allowable focussing error and de-space error of optical system. For the two-mirror system such as Cassegrain configuration, the focusing error is proportion to secondary magnification, square of ratio of system F ratio to that of primary mirror.

The depth of focus and focusing error of optical system is:

$$d_f = \pm 2.44\lambda (f/\#)^2 \quad (1)$$

$$f_e = \pm m^2 s_e \quad (2)$$

where d_f = depth of focus
λ = wave length
$f/\#$ = F ratio of system
f_e = focusing error in optical axis direction
m = secondary magnification
s_e = de-space error of secondary mirror

From equation (1) and (2) it is simply shown that the allowable de-space error of secondary mirror is depend on square of primary mirror's F ratio, and if we consider visual spectral channel with 1.5 to 2.0 F ratio of primary mirror, the allowable de-space error is around +/-4μm ~ +/-6μm. For the compact design, fast primary mirror is preferred while slower is better in point of width of acceptable de-space error. The mechanical and thermal design shall be required to control the de-space error is within allowable range.

3. REFOCUSING OF IMAGING CAMERA OF SPOT SATELLITE (LÉGER, 2003)

As for their predecessors, the high resolution visible (HRV) camera aboard SPOT 1, 2 & 3 and high resolution visible and medium infrared (HRVIR) camera of SPOT 4, the high resolution geometry (HRG) cameras of SPOT 5 are equipped with focusing mechanism. On the ground, the camera is aligned to have best focussing with focusing mechanism in the thermal vacuum condition.

The focusing method uses the two cameras simultaneously viewing the same target. The focus of one camera is left fixed and is used as reference while the refocusing mechanism of the other camera is varied around its initial position.

For each couple of scenes, the ratio of the Fourier transforms is calculated and the best focus is selected to have maximum of this spectrum ratio, which varies as a near parabolic curves. In case of HRG camera, +/-8 steps, very small defocus about 9.5μm, of focus mechanism is moved first around initial position to test the focus mechanism without reaching large defocusing values. If there is no vertex in the curve, the vertex position is extrapolated from the measurement. To increase accuracy, the focus mechanism can be operated with sufficient walk to overpass the best focus.

Currently other methods such as artificial neural network method which use no reference image are studied for the future satellite.

4. THERMAL REFOCUSING DEVICE OF PLEIADES(LAMARD, 2004)

The high resolution (HR) camera of Pleiades camera used Korsch type configuration which consists of three aspheric mirrors to take wide field of view. The secondary mirror of the HR camera has adjustment function on orbit along optical axis and the thermal refocusing device installed in secondary mirror offers possibility for re-align the optics during flight.

The focusing device has 33.5μm displacement capability along optical axis with stability of ± 0.8μm focusing and ± 5urad tilting. The temperature controlling of an aluminium ring located between mirror and structure in figure 2 provides possibility of adjustment of secondary mirror position along optical axis direction.

5. REFOCUSING MECHANISM OF MSC (BERGER, M., 2004)

The MSC has two spectral channels for visual and near infrared wave length range, panchromatic and multi-spectral channels. Two channels share catoptric mirror but they have their own lens group to extend field of view.

The panchromatic channel's first and second folding mirror assembly in figure 1 can move along optical axis with stepper motor. The folding mirrors are flat and it can only adjust focusing without any optical aberration. For the multi-spectral channel a doublet lens in figure 2 with stepper motor is focusing mechanism.

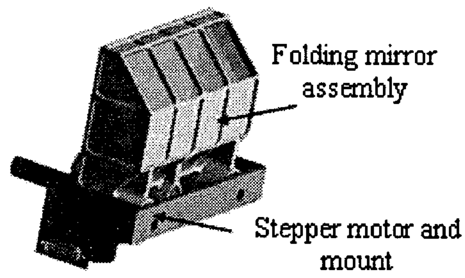

Figure 1. Refocusing mechanism of MSC panchromatic channel

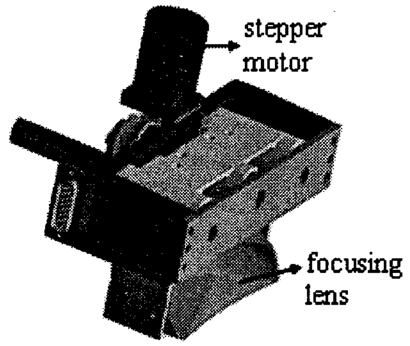

Figure 2. Refocusing mechanism of MSC multi-spectral channel

5.1 Thermal Analysis

Hot and cold thermal condition was calculated as table 1. The extreme temperature condition was +40°C and 0°C, but the possibility of extreme condition is very low.

Table 1. Hot and cold thermal condition of MSC

Parameters	Hot	Cold
Spacecraft temperature	20°C	5°C
Solar flux	1419 W/m^2	1286 W/m^2
Albedo	0.35	0.3
Planet IR	249 W/m^2	227W/m^2
Altitude	70°S ~ 70°N	

5.2 Mechanical Analysis

According to the worst case analysis result the peak-to-peak de-space of two mirrors is in the range of 6.9μm.

The distance between the centers of seasonal orbit is 3.4μm.

5.3 Optical Analysis

The figure 3 and 4 show MTF degradation of MSC panchromatic and multi-spectral channels as a function of de-space error between primary and secondary mirror.

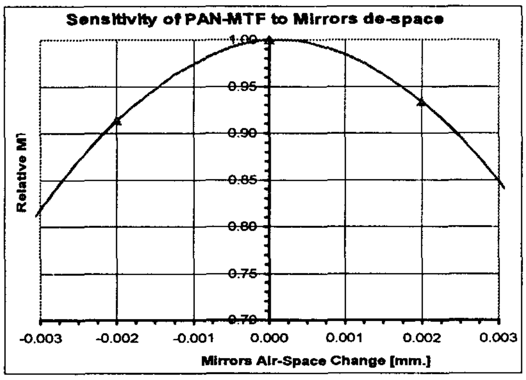

Figure 3. Mirror de-space error and MTF degradation of MSC panchromatic channel

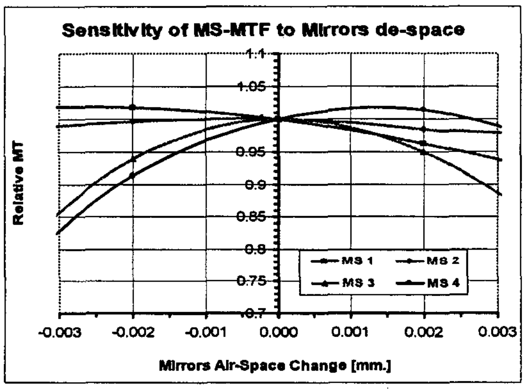

Figure 4. Mirror de-space error and MTF degradation of MSC multi-spectral channel

In case that seasonal refocusing is performed, the MTF degradation is small and acceptable. If no seasonal refocusing is carried out, the maximum degradation will be larger but still image quality is not bad.

6. DISCUSSION AND CONCLUSION

The launch environment and thermal vacuum condition of space cause de-focus error of high resolution space camera. The de-space error of secondary mirror in large aperture catoptric system is most sensitive to mechanical and space environment. The compact design which use fast primary mirror is more sensitive to environment than that use slow primary mirror.

Recently most sub-meter resolution camera use catoptric system, which consist of larger aspheric mirror with some flat mirror to fold beam path for compactness. Korsch type, three aspheric mirrors with obscuration, is preferred for optical configuration. In Korsch type, the secondary mirror can be selected for focusing mechanism like Pleiades and also fold mirror (the fold mirror 2 in figure 5) may available.

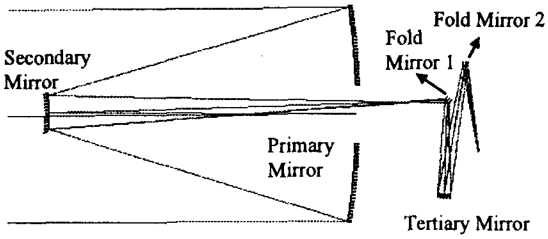

Figure 5. Korsch type configuration with two fold mirror

If we use secondary mirror as defocusing part it is easy to control focus error with small amount of displacement of secondary mirror because focus error is proportion to square of secondary magnification, which also means accurate control of focusing mechanism is required. In the case of flat fold mirror, the optical path change by the moving of fold mirror (optical path change is twice of physical moving) induces same amount of focusing error, which means minimum 100μm moving range is required to control focusing error within 200μm. The control accuracy of fold mirror position is not critical.

Generally the European high resolution satellite camera, from SPOT to Pleiades, equipped focusing device. The SPOT series used two cameras to find best focusing and the Pleiades has thermal focusing device. The QuickBird which is one of the most advanced space camera does not have on-orbit refocusing function while Pleiades and MSC have refocusing device. According to QuickBird design concept, if the camera structure provides very high stability there is no need for focusing mechanism. In case of MSC there is on-orbit refocusing function even though the analysis result shows the imaging performance without refocusing is acceptable.

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