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On Orbit Real-time Position and Attitude Metrology of Long focal Length Optical System

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ABSTRACT

The urgent need for the precise, real-time position metrology between the optical components in a modern space camera is becoming more critical with the increased resolution, aperture, focal length, and light-weighted structure. Gravity offload, composite material humidity desorption, temperature cyclical variation with the illumination, and micro-vibration on platform would introduce unpredictable affect to decrease the imaging quality. The solution of the optical system disorders would mainly rely on the ground-based stimulation and on that basis, active optics compensation, which could not be accurate. This influence expands within the opto-mechanical structure complexity. This paper represents an implement solution for position and attitude metrology used for on-orbit real-time measurement. To deal with the contradiction of system accuracy and simplicity, we simplified the system to a measurement model equivalent to 6 degree of freedom Stewart Platform structure. The works on this paper tightly coupled to the accuracy requirement of a long focal length optical system. After carefully compare the systematic requirement and balance the implementation costs, we applied the common-path, multi-channel heterodyne interferometers to accomplish the large-scaled coarse measurement for the step disturbance and small-range fine measurement to sense the ambient vibration. The metrology accuracy analysis and error evaluation indicated an effectiveness of this metrology system, which met the requirement of our given optical system. It was indicated in this paper that the metrology method could be generalized in other optical systems and similar long focal length optical systems in the future.

Key words: absolute distance metrology, heterodyne interferometers, long focal length, Stewart

1. INTRODUCTION

The improved requirements of target resolution and sensitivity promote the development of long focal length optical system to large aperture, reflecting structure with more restrictions on launching envelope and mass, etc. These systems often indicate more sophisticated response to the disturbance during both launch process and on orbit operation, causing the opto-structure deformation, and the image distortion followed. Take a long focal length optical system with the aperture of 1.4 meter and distance between primary mirror and secondary mirror of 1.4 meters as an example. Analyses indicated that there are several factors to cause the displacement of optical components. Firstly, gravity offload. On-ground stimulation indicated a 70um displacement after launch between primary and secondary mirrors and this stimulation result, though carefully calculated, was hardly to verify on orbit. Secondly, composite material humidity desorption. Composite material is widely used in optical systems nowadays to meet the light-weighted requirement. The structure deformation would happen followed by humidity desorption process. This procedure would last for weeks to months, and decreased image quality is followed. Thirdly, temperature cyclical variation with the illumination condition would also introduce structure deformation and affect the image quality. Last but not least, the response of different structure components to micro-vibration from satellite platform would not be ignored. The influence of all the factors above would become more serious with the expanding focal length and increasing resolution in an optical system.

Therefore, to guarantee the image quality, on orbit close-loop optical adjustment is generally seen as a prerequisite in the large aperture system. Generally, there are two sorts of solutions to compensate the deformation. On the one hand, in relatively small aperture systems, open-loop, one-dimensional, passive engineering based adjustment to a signal optical component is popular. For example, the linear focal plane adjustment structures are common on mirrors or focal plane assembles. On the other hand, some close-loop optical adjustment is also introduced to adjust the wavefront variation, among which wavefront sensing is most popular. For the former methods, it have been verified through both on-orbit imaging result and ground-based analysis that, with passive engineering along is not accurate enough to reach the required image quality. For the latter sort, Ref.[1] analysed a situation when the structure limitation happened, enough wavefrount sensors could not be implemented, resulting in a corresponding failure of the focal plane adjustment, and focal plane tilt and field-linear astigmatism could be followed thereafter. Moreover, the two sorts of methods, since the on-orbit real-time data is not acquirable, the adjustment followed the initial design is not able to implied. To accomplish high accuracy fine adjustment, the high-precise position and attitude metrology of optical components could be necessary.

Laser interferometry, with the accuracy of better than micro-meters, is widely accepted as the most accurate metrology existed nowadays. Most of the existed interferometers are based on the Michelson configuration, in which the intrinsic integer ambiguity would limit the measurement range.[2] As a consequence, the interferometry based measurement is separated into two branches named relative metrology and absolute metrology. Relative metrology could sense a displacement within a measurement wavelength. A coherent and continuous measurement could be accomplished through some mechanically assistant method such as guide rail. Absolute metrology is capable to require the real-time displacement without restrictions of either spatial or temporal continuity. By expanding the measure range to a larger one using beat frequency, the accuracy metrology could be accomplished. To the measurement accuracy, it is much easier to reach a higher accuracy in relative metrology than the absolute one, for the absolute metrology often requires multiple wavelengths which are hard to calibrate. Considering the inherent contradiction between long measure range and precise accuracy, therefore, the continuous high accuracy measurement of a specific range inside a grid scale，followed by the continuous measurement inside this range, could also considered as a absolute metrology. The most typical absolute metrology is based on the heterodyne interferometry, in which synthetic wavelengths are introduced to expand the measure range. Multiple-wavelength interferometry (MWI) and frequency-sweeping interferometry(FSI) are two methods can be implemented to absolute measurement. Both methods followed the same synthetic wavelengths generating theory, and different wavelengths variation mechanism. FSI, which provided continuous switching wavelengths by frequency sweeping, is considered to be more feasible to any required measurement range, but with more complicate design and calibrate requirements. Meanwhile, MWI, takes two or more fixed wavelengths to form one or several synthetic wavelengths, could also provide the absolute displacement measurement of finite range.

This paper presents an on orbit position and attitude metrology method of long focal length optical system based on heterodyne interferometer. After the detailed analysis of the optical system, an evaluation system followed the structure of 6 pole Stewart platform was established. With the equivalent of pole structure function and measurement arm in metrology system, the reliable theoretic module and implement method was settled, and the accuracy requirement was provided based on the system. This paper provided a heterodyne interferometry metrology system of multiple wavelengths and common path. The theoretical accuracy and error analyses indicated that this system could meet the metrology requirement of position and attitude in a large aperture system.

2. METROLOGY REQUIRMENT ANALYSIS

We represent a long focal length TMA optical system with the primary mirror diameter of 1400 millimeters, secondary mirror of 320 millimeters, and the distance between primary and secondary mirrors of 1.4 meters. The extra flat mirror was also place near the exit pupil position to shorten the system envelope. To guarantee the image geometry quality, it is required to the whole life cycle, the principal point variation of this system should be less than 2 pixels, line of sight variation less than 0.2 arcsecond correspondingly, the decrease of MTF less than 0.02 and the system defocusing less than 1/4 depth of focus.

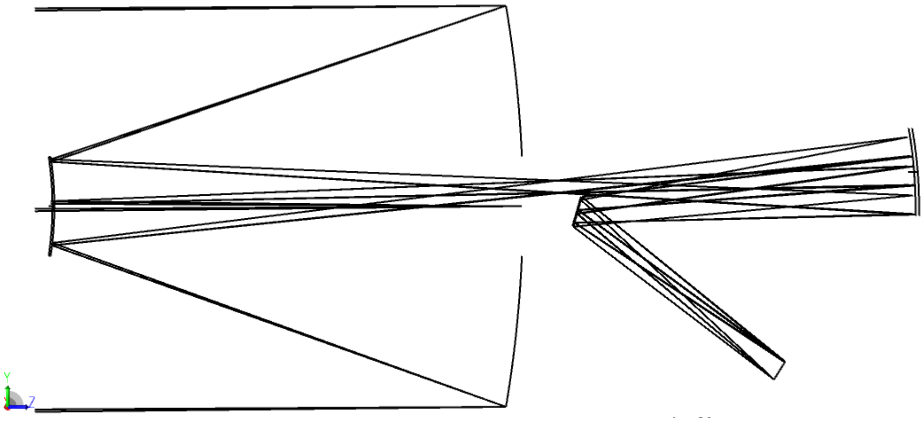

Fig. 1 Ligh Path Diagram of a given system

According to the optical analysis, the displacement of secondary mirror is the most sensitive to the optical system, around 3 to 5 times to that of focal plane assemble. It is also well known that in the optical system evaluation criteria, the acceptable variation range of Line of Sight is most critical. Other criteria, such as MTF, main distance, defocus, etc., are much easier to acquire.

Tab.1 Line Of Sight Sensitivity Matrix

item	LOS(″)		item	LOS(″)	
SM	Rotated-x(arcsecond)	Rotated-y(arcsecond))	TM	Rotated-x(arcsecond))	Rotated-y(arcsecond))
dx(1 μm)	0.1025	0	dx(μm)	0.0460	0

dy(1 µm)	0	0.1025	dy(µm)	0	0.0460
dz(1 µm)	0	0	dz(µm)	0	0
dtx(1 arcsec)	0	-0.4295	dtx(sec)	0	0
dty(1 arcsec)	0.4295	0	dty(sec)	0.2662	0
dtz(1 arcsec)	0	0	dtz(sec)	0	0

The variation of LOS is mainly related to the position and attitude of optical components. According to the LOS sensitivity matrix shown in Tab.1, considering the primary mirror as the measuring basis, the displacement of secondary mirror would contribute most to the optical system misalignment. To reach the required accuracy of LOS less than 0.2 arcsecond, the control requirement of the 6 degree of freedom of secondary mirror was provided in Tab.2, together with the measure accuracy requirement followed Shannon’s sampling theorem.

Tab.2 Control requirement and Measure accuracy requirement of Secondary mirror

item	control requirement of SM 6 DOF (″)		measure accuracy requirement of SM 6 DOF (″)	
	x(sec)=0.2	y(sec)=0.2	x(sec)=0.04	y(sec)=0.04
x(µm)	1.9512	0	0.3902	0
y(µm)	0	1.9512	0	0.3902
tx(arcsec)	0	-0.4656	0	-0.0931
ty(arcsec)	0.4656	0	0.0931	0

3. MEASUREMENT MODEL ESTABLISH AND FEASIBILITY ANSLYSIS

3.1 Measurement model establish

Assuming both primary and secondary mirrors are rigid bodies, represented in Fig.3, the 6-DOF precise measurement model of secondary mirror could be established based on a fixed primary mirror, which is equivalent to a 6-pole mechanism named Stewart Platform. The Stewart Platform is a triangular truss structure with 6 poles to link both the moving platform and static platform. The lengths of the 6 poles could uniquely define 6-DOF of the related moving platform reference to the static platform.

Therefore, in this measurement model, we consider the primary mirror as the static platform and the secondary mirror as to the moving platform. The corner-cubes are arranged followed an equilateral triangle to form an ideal Stewart Platform structure to imply a precise position and attitude metrology. The corner-cubes B were placed around the secondary mirror while the truncated corner-cubes A were fixed at the edge of the primary mirror. We defined the optical path difference to be the distance between two corner-cubes on opposite mirrors, equivalent to the optical path difference of the measurement arm and reference arm, so as to measure the distance.[6]

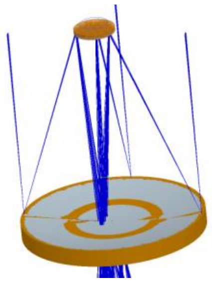

Fig.3 Primary and Secondary Mirror Structure

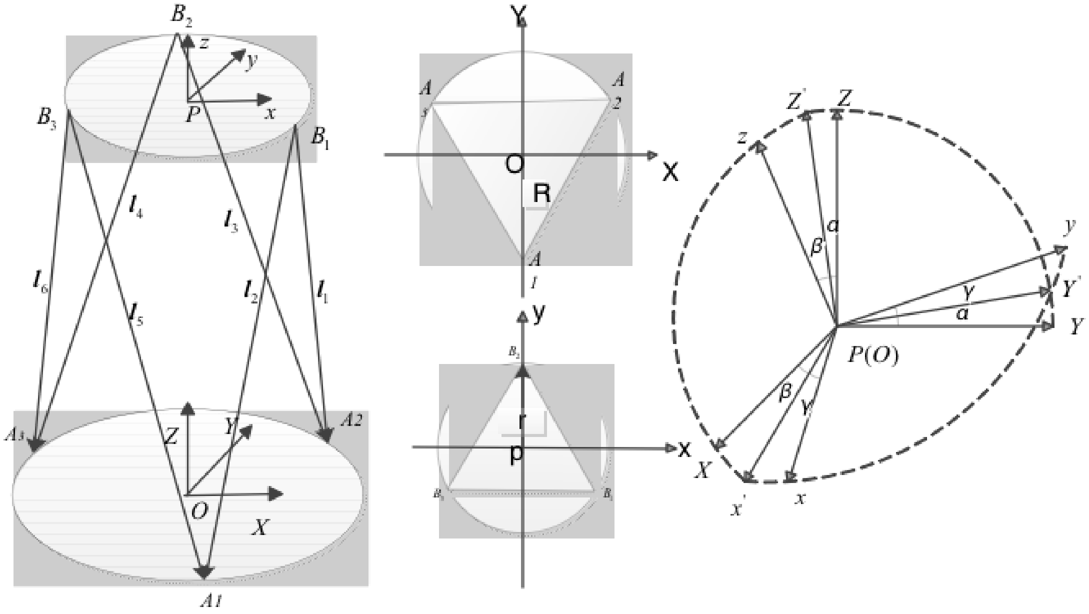

Fig.4 Attitude Transformation by Eular Angles

Followed by the Stewart structure and coordinate transformation, the unit position and attitude variation corresponding to the pole length change could be calculated, shown in Tab.3. To meet the position and attitude measurement accuracy provided in Tab.2, the pole length metrology accuracy was provided, shown in Tab.4.

Tab.3 Unit Position and Attitude Variation Corresponding to the Pole Length Change

	dL1/μm	dL2/μm	dL3/μm	dL4/μm	dL5/μm	dL6/μm
x/1μm	-0.4033	0.2797	0.1236	0.1236	0.2797	-0.4033
Y/1μm	0.0901	-0.3042	-0.3943	0.3943	0.3042	-0.0901
z/1μm	0.9106	0.9106	0.9106	0.9106	0.9106	0.9106

tx/1”	0.6117	0.6117	0	0	-0.6117	-0.6117
ty/1”	-0.3532	-0.3532	0.7064	0.7064	-0.3532	-0.3532
tz/1”	0.3059	-0.3059	0.3059	-0.3059	0.3059	-0.3059

Tab. 4 Pole Length Metrology Accuracy Requirement

	Position and attitude accuracy(nm)	Metrology accuracy requirement(nm)
x(μm)	0.3902	48.2
y(μm)	0.3902	35.2
tx(arcsec)	0.0931	56.9
ty(arcsec)	0.0931	32.9

Therefore, the metrology accuracy of less than 32.9 nano-meters was the measurement requirement.

4. METROLOGY SYSTEM DESIGN

4.1 Structure of metrology system

The system parameters are chosen followed by the variation range of the optical system. In the optical design, it was indicated that the initial pole length was less than 2 meters. The thermal and stress stimulation indicated the maximum variation of less than 1 centimeters with the accuracy of no less than 32.9 nano-meters., provided in the chapter above.

Based on the requirement, a metrology system based on MFI to required the absolute distance was provided. This system followed the well-established MFI structure, which is Michelson configuration system with the ability to pursue the absolute measurement in finite range.

In the Michelson systems, OPD is acquired from the difference of a reference arm and a measure arm, represented in the form of phase difference, followed the function of $L = \frac{\emptyset}{2\pi}\lambda$. However, since the fringe pattern is periodic by 2π, $0 \leq \emptyset < 2\pi$, therefore, the distance L is measured as followed:

$$L = \frac{N+\emptyset}{2\pi}\lambda \tag{1}$$

in which N is an undetermined integer, which is defined as integer ambiguity.

To reduce the influence of integer ambiguity and expand the measurement range, the well-established heterodyne interferometry technology was introduced with the synthetic wavelength λ_{synth} defined as:

$$\lambda_{synth} = \frac{c}{f_2-f_1} = \frac{c}{\Delta f} = \frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1} \tag{2}$$

The measurement system was reproduced from Ref.[3-5], in which two laser sources, frequency-offset-locked to a frequency difference of 15GHz. Two acousto-optic modulators(AOM1, AOM2) were used as the frequency switch, providing a synthetic wavelength of 2cm for coarse measurement. The followed fine stage heterodyne interferometers were established with the frequency difference of 100kHz. System schematic diagram was provided in Fig.5.

Assuming a system with reference arm of L_0 and measurement arm of $L = L0 + 2d$, respectively. The distance d indicated the displacement between reference mirror and measurement mirror, in which d was doubled by the round trip. Therefore, the phase difference between reference signal and measurement signal could be indicated as:

$$\varnothing = \varnothing_1 - \varnothing_2 = \frac{2\pi f_0 L}{c} - \frac{2\pi f_0 L_0}{c} \approx \frac{4\pi}{c} f_0 d \qquad (3)$$

The differential for both sides of this equation indicated the phase change during measurement as followed:

$$\Delta\varnothing = \frac{4\pi}{c} d \Delta f_0 + \frac{4\pi}{c} f_0 \Delta d \qquad (4)$$

The system schematic diagram was shown in Fig.5.

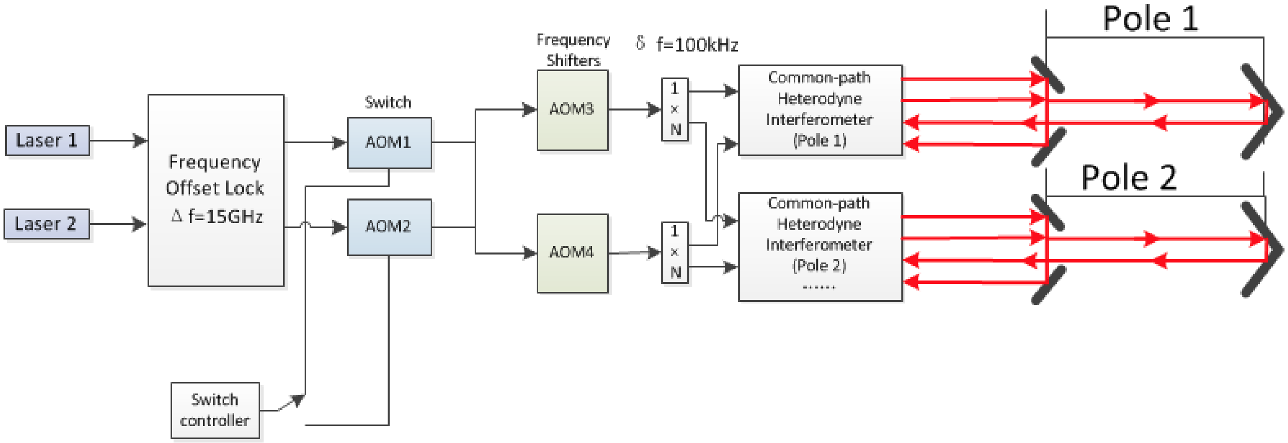

Fig. 5 Dual-frequency Heterodyne Interferometry with common path design

It is shown that the first term of Equ.(4) indicated the absolute distance while the second term indicated the disturbance because of environment. The measurement process of the second term could be similar to the ordinary phase meter. With the software fringe counting and the corresponding ADC circuit, the measurement accuracy of 1/1000 would not hard to accomplished. Chosen a Nd:YAG laser of 1.319μm, the accuracy of less than 10 nano-meters could be accomplished.

4.2 Error analysis

The error analysis based on the related system indicated in related heterodyne system indicated the systemic error of several nano-meters, normally in the three aspects: (1) random errors; (2) systematic errors; and (3) environment errors. [7]

The random errors indicated the detector noise, photo noise, amplifier noise, phase meter noise, etc. for our system design on the switch frequency of 1kHz, the typical values of these noise were around tens of pm to less than 1nm.

The systematic errors included cyclic errors and diffraction errors. Both are nonlinear. Cyclic error can be caused by polarization leakage, optical cross-talk in the heterodyne source, electrical cross-talk between reference channels, and other system implementations. This error should be controlled by design in an interferometer system, i.e. pm magnitude. Diffraction error is another error contribute to the inaccuracy. It could be controlled by introduce a reference arm.

The environment errors are mainly due to temperature fluctuations and vibration. By the common-path design of the system, the disturbance could be reduced.

5 SUMMERY AND FUTURE WORKS

In this paper, we present a reasonable solution for the on-orbit position and attitude metrology of the long focal length optical system. Taken accounts of both the simplicity and accuracy, a metrology system to accomplish absolute measurement within a finite range was provided. This system based on a double frequency, double heterodyne interferometer structure with a common path design. Followed by the measurement requirement, the measurement accuracy and error analysis indicated that the system could accomplish the position and attitude metrology of a required accuracy. We provided a modelling method used in the main optical components in the optical system. With a proper measurement model establishment, this method could be expanded to other optical systems and other related long focal length optical systems.

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