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Design concept of geostationary Earth observation segmented telescope and the wavefront management scheme

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ABSTRACT

For crisis management and monitoring, a geostationary Earth observation telescope with large segmented aperture is investigated in JAXA. The preliminary study showed the feasibility of the aperture size of 3.6 m consisted with six primary mirror segments and the fundamental optical design. In order to obtain nearly diffraction limited performance with the optical system in the orbit, the aperture synthesis and wavefront error correction have to be conducted through precise alignment procedure, and therefore the system needs to equip several actuators and sensors dedicatedly designed for the purpose. We constructed the system design through the combination of structural-thermal analysis and optical consideration, and then planned the alignment procedure after launch. Those design concept are planned to be tested in the miniature testbed of segmented optical system under construction. We show the testing equipment and procedure for segment co-phasing and wavefront correction intending in space use.

Keywords: segmented optics, wavefront correction, geostationary orbit, structural-thermal analysis

1. INTRODUCTION

Observing earth from geostationary orbit (GEO) enables us to grasp the overview of unforeseen disasters such as earthquake, volcano eruption, and flood damage instantaneously. The amount and detail of information what we see depends on the resolution of the sensor which is proportional to the numerical aperture of the imager optics. Considering the practical applications for the aforementioned incidents, the sensor has to distinguish the characteristic landscape or artificial structures. The requirement suggests the spatial resolution is expected to be less than 10 meters which means the effective aperture diameter exceeding 3 meters. Such a large aperture is rarely found and hardly achieved by monolithic optical design because of the limitation of production/testing facility and payload.

We are investigating the feasibility of geostationary Earth observation telescope having 3.6 m aperture with segmented optical design [1,2]. Currently, fundamental studies and evaluations of the segment and segment system are being conducted. The planned equipment and its performance can be conceptually inferred from the preceding segmented telescopes such as Keck, SEIMEI [3], and James Webb Space Telescope (JWST). However, since the thermal environment of geostationary orbit is not so stable as the orbit of JWST, the second Lagrangian point, the environmental difference suggests the necessity of a unique system concept.

This paper presents the overview of telescope design and the system concept mainly focusing the optical performance and its management. In Section 2, the concept of mission and the sensor design are presented with the simulation of thermal environment which the satellite is exposed. Section 3 discusses the wavefront management system for the equipment and the procedure. Finally, Section 4 introduces the miniature testbed to conduct the management procedure for future evaluation.

2. MISSION SENSOR

2.1 Mission Concept

As is described in the preceding work [2], the characteristics and benefits of the continuous observation from GEO can be discussed from three aspects: availability, immediacy, and continuity. In terms of ‘availability’, since the GEO satellite can stay its observing area with attitude control, the operating time is free from the constraint which LEO satellites suffer from and that allows on-demand observations to be provided. The ‘immediacy’ represents the low

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latency which is critical performance in an emergency. Learning from the past disasters, in the early stage of the incident, the importance is recognized to grasp the overview of the situation for the prompt decision-making. Observation from GEO, even though the spatial resolution is limited (7-meter in the conceptual study), its high temporal resolution and wide coverage enables (100 x 1000km within 1 hour) to provide valuable information for crisis management. The last feature 'continuity' provides the other uniqueness of the system, such as observing moving objects and producing cloudless mosaic images. Those are functional observations enabled by the multi-frame capturing with station keeping.

Currently, these mission concepts are examined with provisional optical, structural and thermal designs. Further case studies for broader and more complex observations, i.e. combinational use with meteorological satellite or LEO imagers, are also under investigation.

2.2 Optical/Structural Design

Figure 1 shows the optical telescope model handled in this study. Based on a Korsch three mirror anastigmat, the telescope has six hexagonal segmented mirrors that form a 3.6-meter primary mirror together. Each mirror segment is kinematically mounted and controllable in its position by actuators for all axes. With this optical configuration, the spatial resolution at nadir is about 7-meter for the visible region and 100-meter for the thermal infrared [2]. This performance is not very high compared to that of high spatial resolution satellites such as WorldView and Pleiades Neo. However, in considering crisis management and monitoring, it is expected to be sufficiently useful with its high temporal resolution and persistency.

For the stable and well-adjusted observation to be managed, the thermal environment of the orbit should be concerned since the angle of incident of solar ray on the satellite changes throughout the day which promotes the temperature variance both temporally and spatially. The material of mirrors and supporting structures with small CTE (coefficient of thermal expansion), the baffle to isolate/shielding the telescope from the sun light is designed with adaptive temperature control by the heating system. It should be also taken care that the maneuver of satellite is to be planned to prevent the sun light directly shines the telescope optics.

Table 1. Characteristics of geostationary Earth observation telescope.

Aperture diameter	3.6-meter
Size of segmented mirrors	1.3-meter in outer diameter
Field of view (FOV)	100 km x 100 km (0.16 deg x 0.16 deg)
Spatial resolution	7-meter for panchromatic band at nadir 28-meter for multi-band 100-meter for TIR
Altitude	36,000 km

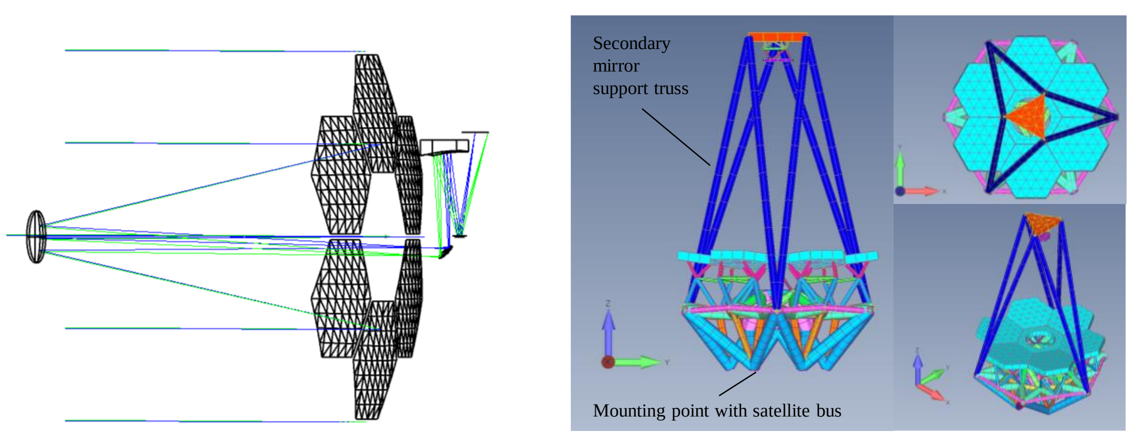

Figure 1. Optical and structural telescope model.

2.3 Structural-Thermal Analysis

To predict the effect of thermal stress on the telescope system, structural-thermal analysis was conducted in preceding to the optical performance analysis. Figure 2 shows the thermal analysis model consists of satellite bus structure, solar array panels, and the telescope optics/structures including baffle. The rotation maneuver of the satellite is planned during night-time to prevent solar ray directly incident to the telescope optics. The heating system inside the baffle manages to keep the temperature of the telescope optics around 23°C via radiance coupling which is the most preferred temperature for the segment mirror made of Cordierite ceramics [4].

Figure 3 shows the obtained temperature distribution around midnight when the temperature difference in the primary mirror segment is maximized during a day. The distribution ranges from 23°C to 27°C for all segments suggesting the thermal control works to keep the optics under targeting condition. The displacement/deformation are analyzed from the temperature analysis. Table 2 shows the relationship between two analyses for each segment. The correlation can be seen for the results, especially between average temperature and displacement (in actual sense, it would come from supporting structure), also between vertical temperature difference and radius of curvature, which is the dominant deformation mode for each mirror. These results coincide with the definition of CTE and the mechanism of the deformation, that is warping is caused by difference of expansion between front and back sides.

From the analysis, the degradation of the optical performance is estimated about either alignment error driven or surface figuring error driven fluctuation. The estimation suggests that the alignment of the primary and secondary mirrors should be maintained with the precision at 10 nm and few micrometers respectively, and deformation of the mirrors should be compensated for.

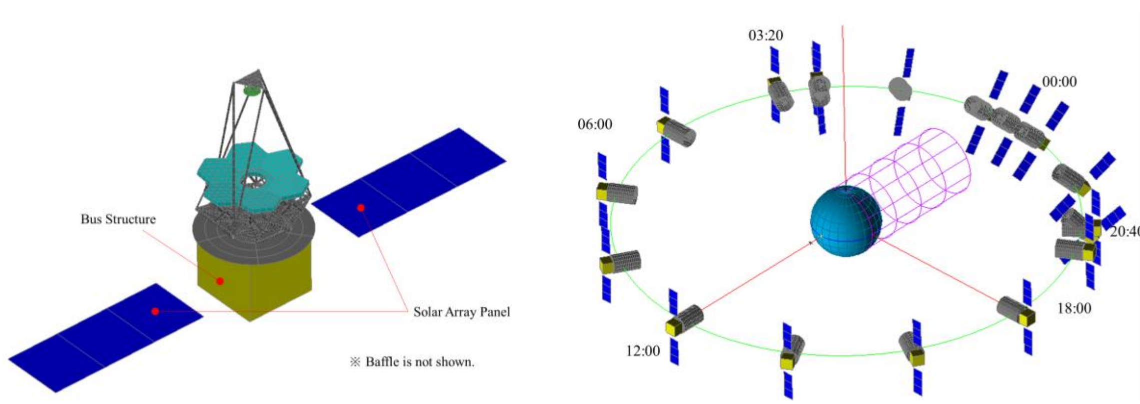

Figure 2. Thermal analysis model (left) and orbital configuration (right).

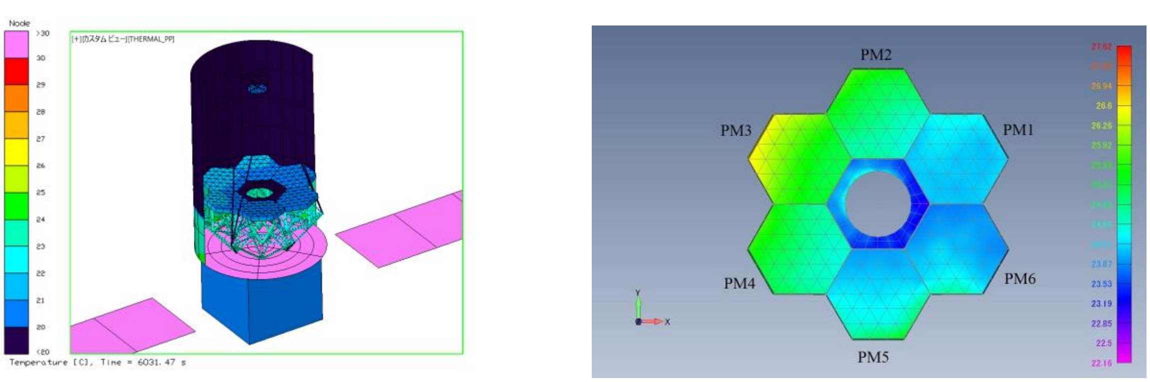

Figure 3. Temperature distribution of the satellite (left) and the primary mirror segments (right).

Table 2. Comparison of analytical results : estimated temperature and deformation.

	Temperature [°C]					Deformation [μm]			
	Front side		Back side		Difference	Piston	Tip	Tilt	RoC
	Ave.	PV	Ave.	PV	Center				
PM1	24.2	**0.4**	23.6	**0.8**	0.50	3.9	-0.18	0.56	-0.010
PM2	25.0	1.3	24.5	1.7	0.55	6.4	-0.58	0.93	-0.006
PM3	**25.7**	1.5	**25.2**	**2.0**	**0.46**	**8.4**	-0.80	0.88	**-0.005**
PM4	25.0	1.2	24.4	1.6	0.60	6.1	-0.65	0.27	-0.009
PM5	24.4	**1.6**	23.6	1.6	**0.80**	3.4	0.00	-0.31	**-0.017**
PM6	**24.1**	1.1	**23.4**	1.4	0.72	**2.8**	-0.85	-0.74	-0.016

3. WAVEFRONT MANAGEMENT SCHEME

3.1 System Equipment

The wavefront management system is designed based on the thermal-structural analysis and optical performance estimation. Figure 4 shows the block diagram of the system. The alignment actuators having six degrees of freedom are implemented to primary and secondary mirrors. The actuator of the secondary mirror takes care of the full aperture aberrations such as global defocus and distortions which is fundamentally equivalent to the equipment of non-segmented telescope optics, whereas the actuators of the primary mirrors are specialized for segment local aberrations and inter-segment misalignment. Since the figuring error of segment mirror is dominated by the radius of curvature (RoC) as is predicted from the thermal-structural analysis, its adjustment functionality is exemplarily prepared. Practically, however, the implementation of RoC actuator is a matter to be examined through the engineering process because the benefit depends on the inter-segment error polarities, whether they are common mode or not. In addition, a deformable mirror is planned to be implemented at exit pupil for active/adaptive control of the optics. These actuators work for wavefront management together with the sensing equipment.

The sensing system consists of the main image sensor for observation and two sub sensors for measuring aberrations. Each sensor is utilized corresponding to the alignment stage and error component respectively. The image sensor and wavefront sensor are supposed to cover various aberrations (tilt, defocus, coma, trefoil, etc.) and provide scene-based wavefront management, whereas the co-phasing sensor is dedicated to the piston errors between segments and designed to work with point source like stars. The investigation and evaluation of several co-phasing sensors are carried out.

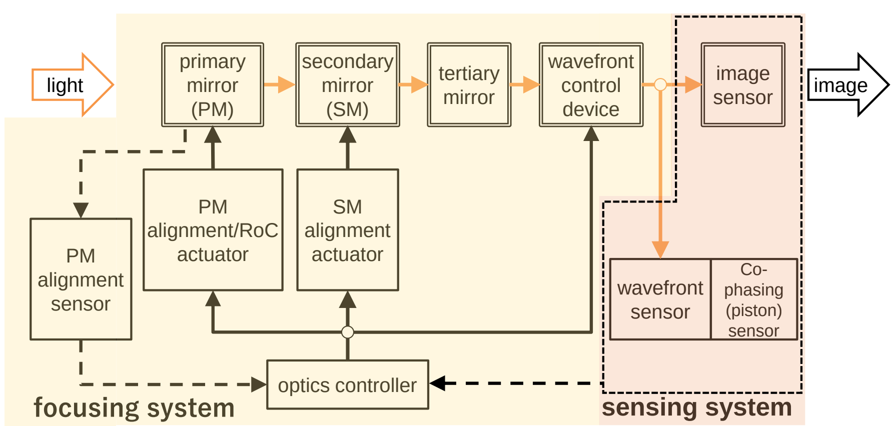

Figure 4. Block diagram of wavefront management system

3.2 Alignment Procedure

The alignment procedure is preliminary described supposing the initial alignment of the telescope in the orbit. By using stars as target, point spread function (PSF) of the optics is optimized. Under the initial condition, the images generated by six mirror segments are neither stacked together nor well focused. The image sensor observes six separated images for every stars in the field of view, therefore the first step of the alignment procedure is:

1. Adjust global focusing of secondary mirror and tip-tilt of primary mirrors so that six segment images are distinguished.

The following steps are conducted in preparation for aperture synthesis:

2. Eliminate large piston error from each segment by the defocus-PSF relationship
3. Perform segment tip-tilt adjustment, which makes six images being stacked

After the above steps, the segmented optics is aligned to form a single overlapped image although that is not synthesized yet due to the imperfection of piston-tip-tilt (PTT) adjustment. The successive procedure compensates the PTT errors, primarily pistons, so that aperture synthesis of the segments is achieved.

4. Compensate piston errors from the measurement of the co-phasing sensor (coarse phasing). The optics is managed into the aperture synthesis condition.
5. Reduce residual errors including figuring errors by wavefront sensor (fine phasing)
6. Complete adjustment through optimization process

Once the alignment procedure is completed, the fluctuation in the orbit is mainly dominated by baking and thermal stress except for the unexpected incident likes debris attack. Since the last two steps work with general scene images, as long as the induced errors are small and gradual, the optical performance would be maintained during earth observation.

4. TESTING PLAN

4.1 Miniature Testbed

For the partially evaluation of the adjustment procedure, small segmented optical testbed is under construction. The optics is based on spherical three segmented mirrors which relay incident light from the pinhole to the imager optics. Two of three segmented mirrors are mounted on the piezo stages which enables precise actuation of the segments. Currently, imager optics consists of two sensors: the main image sensor and the cross-fringe co-phasing sensor [5].

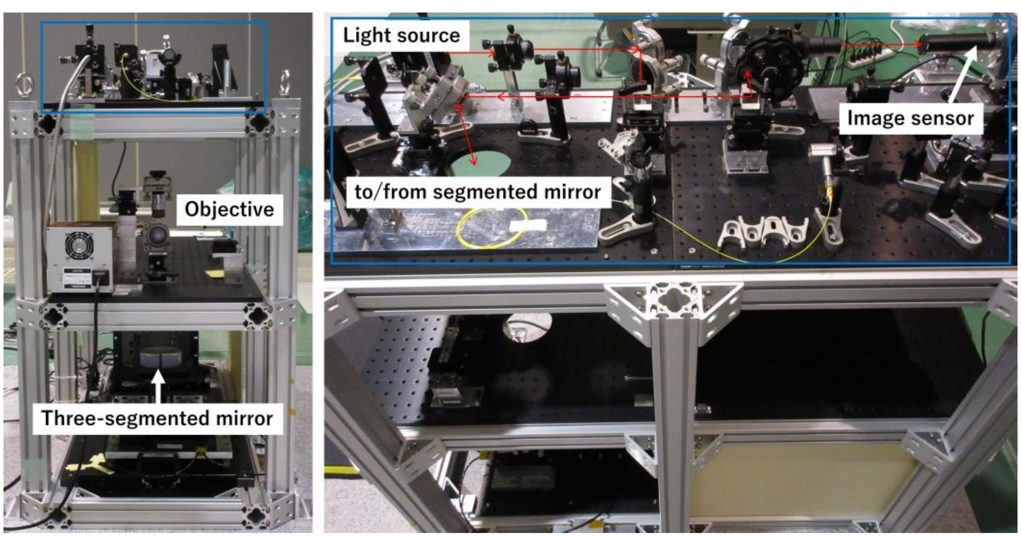

Figure 5. Miniature testbed for testing alignment procedure.

4.2 Preliminary Testing

Preliminary alignment test is performed on the testbed by adjusting the PTTs of two mirror segments. Since the wavefront sensor, deformable mirror and secondary mirror are not installed to the testbed, the conducted sequences do not cover all the alignment procedure described in Sec. 3. The 1st, 2nd and 5th steps are omitted because the corresponding actuator and sensor are not implemented. Those steps are independently examined by simulation, study of active/adaptive optics [6], or heritage-based investigation. The discontinuity of alignment sequence caused by skipping the 5th step is avoided by designing the co-phasing sensor to be short ranged and high resolution. Figure 6 shows the images obtained before and after stacking the segment images (a and b) and final optimized PSF (c). The optimization of the adjustment was performed by stochastic parallel gradient descent (SPGD) algorithm [7, 8].

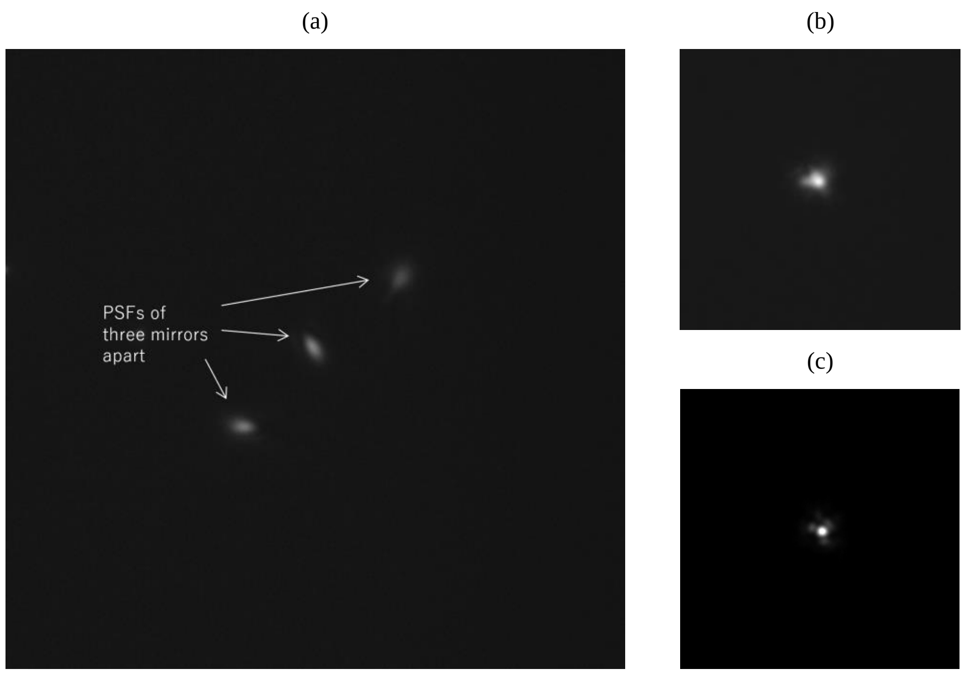

Figure 6. Obtained image before and after phasing. (a) unstacked three PSFs before tip-tilt adjustment (b) stacked and unsynthesized PSF (c) after completed PTT optimization

5. SUMMARY

This paper reported the system concept of the geostationary Earth observation telescope having 3.6-meter segmented aperture. In combination with optical, structural, and thermal designs through their performance analysis, the perspective of wavefront error in the orbit and the correction strategy was investigated. The management system was provisionary designed including the equipment and adjustment procedure. The procedure is planned to be tested in the miniature testbed in the ground. The preliminary testing was performed with a part of the alignment scheme under the three-segment configuration. From the results, we obtained the perspective that the wavefront management system could work providing the sufficient dynamic range, precision, and response of the actuators. The temporal variation of thermal environment is also the issue investigated in progress.

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