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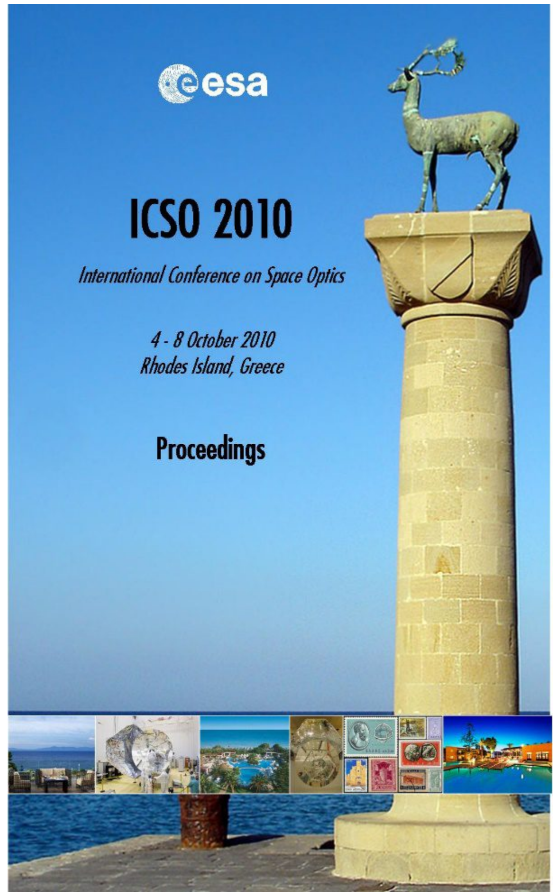


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# OPTICAL AND THERMAL DESIGN OF 1.5-M APERTURE SOLAR UV VISIBLE AND IR OBSERVING TELESCOPE FOR SOLAR-C MISSION

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## I. INTRODUCTION

The next Japanese solar mission, SOLAR-C, which has been envisaged after successful science operation of Hinode (SOLAR-B) mission, is perusing two plans: plan-A and plan-B, and under extensive study from science objectives as well as engineering point of view. The plan-A aims at performing out-of-ecliptic observations for investigating, with helioseismic approach, internal structure and dynamo mechanisms of the Sun. It also explores polar regions where fast solar wind is believed to originate. A baseline orbit for plan-A is a circular orbit of 1 AU distance from the Sun with its inclination at around or greater than 40 degrees. The plan-B aims to study small-scale plasma processes and structures in the solar atmosphere which attract researchers' growing interest, followed by many Hinode discoveries [1], for understanding fully dynamism and magnetic nature of the atmosphere. With plan-B, high-angular-resolution investigation of the entire solar atmosphere (from the photosphere to the corona, including their interface layers, i.e., chromosphere and transition region) is to be performed with enhanced spectroscopic and spectro-polarimetric capability as compared with Hinode, together with enhanced sensitivity towards ultra-violet wavelengths. The orbit of plan-B is either a solar synchronous polar orbit of altitude around 600 km or a geosynchronous orbit to ensure continuous solar observations. After the decision of any one of the two plans, the SOLAR-C will be proposed for launch in mid-2010s.

In this paper, we will present a basic design of one of major planned instrumental payload for the plan-B: the Solar Ultra-violet Visible and near IR observing Telescope (hereafter referred to as SUVIT). The basic concept in designing the SUVIT is to utilize as much as possible a heritage of successful telescope of the Solar Optical Telescope (SOT) aboard Hinode [2]. Major differences of SUVIT from SOT are the three times larger aperture of 1.5 m, which enables to collect one order of magnitude more photons than SOT, relatively shorter telescope length of 2.8 m to accommodate a launcher's nosecone size for possible dual-satellite-launch configuration, and much wider observing wavelength from UV (down to 250 nm) through near IR (up to 1100 nm). The large aperture is essentially important to attain scientific goals of the plan-B, especially for accurate diagnostics of the dynamic solar chromosphere as revealed by Hinode, although this make it difficult to design the telescope because of ten times more solar heat load introduced into the telescope. The SUVIT consists of two optically separable components; the telescope assembly (TA) and an accompanying focal plane package equipped with filtergraphs and spectrographs. Opto-mechanical and -thermal performance of the TA is crucial to attain high-quality solar observations and here we present a status of feasible study in its optical and thermal designing for diffraction-limited performance at visible wavelength in a reasonably wide field of view.

## II. OPICAL DESIGN OF SUVIT-TA

Following past designs of large-sized space solar telescopes [2], a basic optical design of SUVIT-TA is determined to be a Gregorian; an axi-symmetric primary and secondary mirror system. Advantage of this design is that field stops can be placed at a primary and a secondary focus to reject unwanted out-of-field solar light to space. With the field stop at the primary, heat load to the secondary mirror and down-stream optics can be much reduced. The SUVIT-TA should fulfill the following scientific and engineering requirements: (1) To resolve at least 0.1 arcsec solar features over a field view of 200×200 arcsec$^2$, provided 4k×4k pixels detector at the focal plane instruments, (2) to have a negligible chromatic aberration with a wide coverage of observation wavelengths from 250 to 1100 nm without frequent focus adjustment and to give a well-defined optical interface with accompanying focal plane instruments, (3) to give negligible instrumental polarization before a polarization modulator or polarization calibration unit for precise polarization measurements, and (4) to accommodate thermal design to reject unwanted solar light from the telescope components as early as possible.

The requirements from high spatial resolution and large photon number collection capability lead to a 1.5-meter telescope aperture, which can give a theoretical resolution of 0.1 arcsec at near-IR wavelengths where accurate polarization measurements can be performed. This aperture size also meets limited capacity of the launcher's payloads (JAXA H-II rocket). The distance between the primary and the secondary mirror of Gregorian was decided to be 2800 mm after considerable opto-mechanical tradeoff studies within the allowable size of the launcher's nosecone (maximum length ~4.3 m for dual-launch configuration). This short Gregorian demands very small static mis-alignment tolerances for the primary and secondary mirrors, on the order of a few tens microns for de-center (< 50 microns) and de-space (< 500 microns) or several arcsec for tilt (< 20 arcsec), and a micron-order de-space short-term stability (< 3 microns) on-orbit during observations. To meet this tolerance, the telescope framework is assumed to be made of a truss of ultra-low-expansion CFRP (Carbon Fiber Reinforced Plastics) pipes in a Graphite Cyanate matrix [2] [3], whose CTE was proven to be smaller than 0.1ppm $K^{-1}$.

To fulfill the above requirements (2) achromatism over the wavelength from 250 nm to 1100nm, collimator unit was designed with all mirror system to be placed behind the primary mirror and to reduce beam size, making an exit pupil of 60 mm diameter to accommodate the clear apertures of the following focal plane instruments. Among all-reflective collimator designs, we selected off-axis three mirror systems (e.g. [4] [5]) which can accommodate the requirements of wide field application, compactness in size and beam folding to the focal plane instruments which attached a side of the TA. With the off-axis system, one mirror can be used as an active tip-tilt mirror for image stabilization which is crucial to attain the diffraction-limited performance. We found a design in which two of three mirrors are simple spherical and one is aspheric the surface figure expressed with Zernike first nine terms, and that is capable to give the diffraction-limited performance when combined with the Gregorian within the field of 200 arcsec diameter in the wavelength longer than 500 nm. It is noted that the afocal beam from the collimator is of benefit to relax the positional tolerance for the focal plane instruments with respect to the TA.

In summary, the optics of SUVIT-TA consists of the Gregorian with the collimating mirror unit (CMU) behind the primary mirror and two field stops; one is a heat dump mirror (HDM) at a focus of the primary mirror and the other is a secondary field stop (2FS) at the Gregorian focus. Besides the above-mentioned requirements, practical requirements given below finally determined the optical parameters of TA: (1) The Gregorian should be aplanatic (both spherical and coma aberration free) to give better image quality over the specified wide field of view. (2) An entrance pupil was positioned 300 mm in front of the secondary mirror vertex. (3) The HDM outer diameter is about twice of diameter of the solar image at the primary focus so that it allows an offset pointing of the telescope for solar limb observations up to ~200 arcsec off the limb. (4) The HDM has a through hole passing the beams of field of view 300 arcsec diameter and it should not vignette any beams reflected back from the secondary mirror with a clear margin of at least 1 mm. Derived optical parameters are given in Table I and the optical layout of TA is shown in Fig. 1.

## III. THERMAL DESIGN OF SUVIT-TA

About 2 kW of solar light is inevitably impinged onto the primary mirror at the bottom of the SUVIT-TA during solar observations from its 1.5-meter diameter entrance aperture. A thermal design to dump such a large heat load to space and maintain critical optical and structure components to within allowable temperature ranges with small temperature fluctuation is critically important to realize a high-performance solar telescope. From this viewpoint, the coating design of optical components is critical, which should limit solar light absorption to a minimum, giving high throughput in the observation wavelengths. In this sense, a silver-based reflective coating is desirable although it has a problem of very poor reflectivity in the wavelengths below 350 nm.

Based on the predicted orbit of SOLAR-C plan-B, extreme cases were defined and studied for thermal design; 'hot case' (solar disk center observation in the hottest orbit with absorption assumed by 5 % increase toward the end of life). The basic concept of the SUVIT-TA thermal design (see Fig. 2) follows Hinode SOT-OTA [2] and is summarized as follows:

1) Most incident energy coming inside the TA is reflected back by the primary mirror and dumped out to space by the HDM at the primary focus through the heat dump window opened at the side of the TA.
2) A sunshade and upper half of a telescope shield tube work as a thermal radiator. The sunshade has an optical solar reflector facing the Sun to keep it cold, while the upper area of the shield tube, not covered by multi-layer insulation (MLI), is covered with a silverized teflon sheet; a good IR radiator.
3) Solar heat absorbed by the primary mirror is radiatively transmitted to a telescope lower tube from its side and from a bottom cooling plate just beneath the primary mirror. The bottom cooling plate consists of a gold-plated aluminum honeycomb sandwich panel and radiatively absorbs the heat of the mirror from its back face.
4) Solar heat absorbed by the secondary mirror is radiatively transmitted to the radiators from its back side.
5) Heat absorbed by the 2FS, CMU and generated by their electronic components is conductively transferred to a mirror cell and also emitted out through their housings, and is finally radiatively transmitted to the lower tube.
6) Heat of the HDM is conductively transferred to the cylindrical structure supporting the HDM and outer spiders, and then radiatively transferred to the shield tube, the radiator and space through the heat dump window.

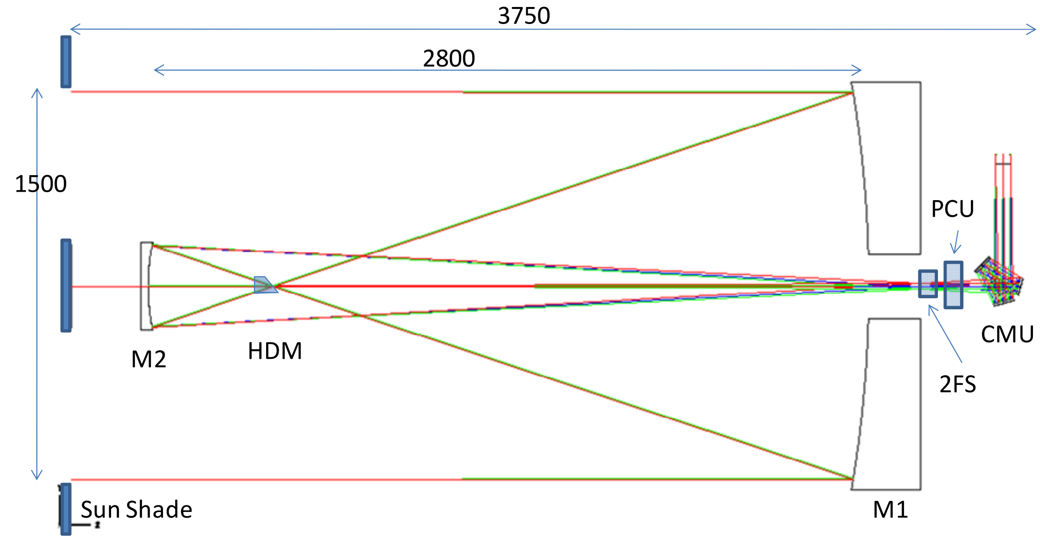


**Fig. 1.** Optical configuration of SUVIT-TA. Units are in mm. The TA consists of an aplanatic Gregorian; the primary mirror (M1) and the secondary mirror (M2) of effective aperture of 1500 mm, a Polarization Calibration Unit (PCU), a Collimating Mirror Unit (CMU) behind the primary mirror whose last mirror can be an active tip-tilt mirror for image stabilization. In addition, the TA has two field stops between the primary and secondary mirrors; one is a heat dump mirror (HDM) at the focus of the primary mirror and the other is a secondary field stop (2FS) at the Gregorian focus.

7) The heat of the lower tube and the shield tube is radiatively emitted directly to the 3K temperature of space through the entrance pupil and indirectly via the radiator of the sunshade and upper shield tube.
8) The TA is thermally insulated from the spacecraft; The TA is physically connected to an optical bench unit (OBU) only by mounting legs of low-thermally conductive titanium and is radiatively de-coupled from the OBU by MLI covering the lower tube and a bottom cover.

Predicted temperatures of on-orbit SUVIT-TA optical components are given in Table II for hot case of solar synchronous polar orbit and geosynchronous orbit with nominal and modified thermal designs. The nominal design is simply a scaled-up model of Hinode SOT-OTA and we found it gives unacceptably high temperatures both for the primary mirror and HDM, especially in the case of polar orbit. Therefore, we studied several modified designs indicated in Table II to lower those temperatures. It turned out, however, that those modifications cannot lower the temperature of primary mirror to the acceptable ones below 50 ℃ when the coating is Al+$MgF_2$ which is the most probable for the UV observations down to 250 nm. To lower the temperature further, more drastic modifications are necessary, in which additional radiator or heat dump system efficiently transfer heat from the primary is accommodated; e.g. change the bottom or side of OBU to a radiator. Some case study indicates that about 100 W of heat from the primary should be dumped to lower the temperature to 50 ℃.

| | |
|---|---|
| Entrance pupil diameter (mm) | 1500 |
| M1-M2 distance (mm) | 2800 |
| M1 outer diameter (mm) | 1580 |
| clear aperture | 1513 |
| radius (focal) | 4629.34 (2314.67) |
| conic const. | -0.990927 |
| M2 outer diameter (mm) | 340 |
| clear aperture | 320.5 |
| radius (focal) | 835.494 (417.747) |
| conic const. | -0.548155 |
| HDM outer diameter (mm) | 48.37 |
| Focal length of Collimator (mm) | 572.3 |
| Exit pupil diameter (mm) | 60 |

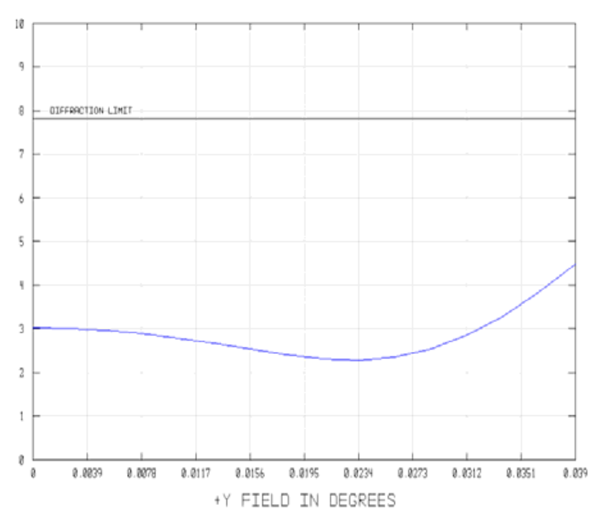


**Table I.** Optical parameters of SUVIT-TA. The figure in the right-hand gives rms spot radius (micron) of the TA as a function of field angle, indicating high optical performance over the 200×200 arcsec$^2$ FOV.

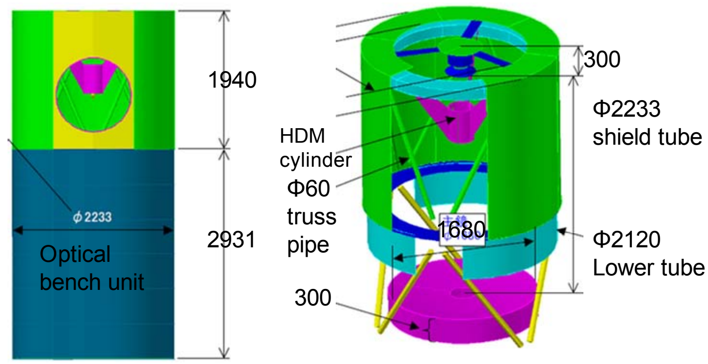


**Fig. 2.** Thermal design of SUVIT-TA

IV. SUMMARY

Short telescope design for 1.5 m aperture Gregorian was presented with the compact design of off-axis three-mirror collimator unit to accommodate a launcher's nosecone size, wide observing wavelength coverage from UV (down to 250 nm) through near IR (up to 1100 nm), and 0.1 arcsec resolution in the field of 200 arcsec diameter. Thermal design of the large aperture telescope is critically important to realize a high-performance solar telescope. Using thermal model similar to the successful Hinode 0.5-m aperture solar telescope, critical points of heat dump scheme from the primary mirror and heat dump mirror at the primary focus were identified with some possible solutions.

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| T (degC) | Polar orbit nominal | Geosync orbit nominal | Polar orbit with Mod-1 | Polar orbit with Mod-1 and Mod-2 | Polar orbit with Mod-1 and Mod-2 and Mod-3 | Polar +Mod-1 α+0.05@ M1&M2 | Geosync +Mod-1 α+0.05@ M1&M2 |
|---|---|---|---|---|---|---|---|
| M1 surface | 61 | 49 | 52 | 52 | 52 | 80 | 70 |
| M2 Surface | -2~ -7 | -24 | -12 ~ -8 | -12 ~ -8 | -12 ~ -7 | 0~4 | -17~ -16 |
| HDM surface | 109~111 | 100 | 103~104 | 77~78 | 60~61 | 63~64 | 51 |
| CMU | 34 ~37 | 22~24 | 24~ 27 | 24~27 | 24~26 | 41 | 29 |

**Table II.** Predicted temperatures of on-orbit SUVIT-TA optical components for hot case of solar synchronous polar orbit (polar) and geosynchronous orbit (geosync) with nominal and modified thermal designs. The nominal design consists of the shield tube whose upper half is a radiator and solar light absorption coefficient $\alpha$ for M1 and M2 of 0.116 (5 % increase of protected silver coating or nominal Al+$MgF_2$ coating). Mod-1 is the case modified from the nominal so that all area of the shield tube works as a radiator. Mod-2 is the case the conductivity of HDM inner spider artificially increases by twice of the nominal. The length of HDM supporting cylinder is artificially enlarged by 33 % in Mod-3. The right-most two columns are the case for $\alpha$ of 5 % degraded Al+$MgF_2$ coating which is most probable for the observation in UV.