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Instrument Design of 1.5-m Aperture Solar Optical Telescope for the SOLAR-C Mission

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A 1.5 m aperture optical telescope is planned for the next Japanese solar mission SOLAR-C as one of major three observing instruments. The optical telescope is designed to provide high-angular-resolution investigation of lower atmosphere from the photosphere to the uppermost chromosphere with enhanced spectroscopic and spectro-polarimetric capability covering a wide wavelength region from 280 nm to 1100 nm. The opto-mechanical and -thermal performance of the telescope is crucial to attain high-quality solar observations and we present a study of optical and structural design of the large aperture space solar telescope, together with conceptual design of its accompanying focal plane instruments: wide-band and narrow-band filtergraphs and a spectro-polarimeter for high spatial and temporal observations in the solar photospheric and chromospheric lines useful for sounding physical condition of dynamical phenomena.

Keywords-component; optical telescope; solar space telescope; structural design of telescope

I. INTRODUCTION

As a result of many discoveries on the Sun by Hinode (SOLAR-B) solar observing satellite [1], next Japanese solar space mission, SOLAR-C, is being considered [2]. The SOLAR-C aims at studying small-scale plasma processes and structures in the solar atmosphere for fully understanding of dynamics and magnetic nature of the solar atmosphere. With a large aperture optical telescope planned aboard the SOLAR-C, high spatial and temporal resolution investigation of the solar photosphere and chromosphere is targeted with enhanced spectroscopic and polarimetric (photon collection) capability as compared with Hinode, together with enhanced sensitivity towards both ultra-violet and near infrared wavelengths. The SOLAR-C will be proposed for launch in late-2010s.

The polarimetric sensitivity in the Solar Optical Telescope (SOT) aboard Hinode and existing ground-based telescope is typically ~10^{-3}, which is enough to get polarization signals with photospheric lines but marginal to detect the polarization signals at the chromospheric lines. We need the polarimetric sensitivity of at least 10^{-4} for the the chromospheric lines; we have to collect at least 108 photons when the sensitivity is limited with photon noise. In designing next generation solar space telescope, therefore, it is targeted to attain high polarimetric sensitivity enough to measure polarized spectral lines emanating from the chromosphere. For instance, the He I spectrum line at 1083 nm and Ca II line at 854 nm provide the best magnetic field diagnostic through joint action of the Hanle and Zeeman effect. Those lines have an advantage that simultaneous polarimetric measurements of the photosphere are possible using the nearby photospheric spectral lines.

Other useful spectral lines for SOLAR-C are the Mg II h&k line pair at around 280 nm, because these are sensitive to the temperatures and velocities of fibril structures in the upper chromospheres. Because the lines are not accessible in a ground-based observation and spatial resolution better than 0.05 arcsec can be achieved with 1.5 m class aperture space telescope, the observation of those lines can be a powerful tool for the diagnostics of the dynamics in the high chromosphere.

This paper focuses and presents a conceptual design of the large aperture optical telescope called SUVIT: the Solar Ultra-violet Visible and near IR observing Telescope. The guideline in designing the SUVIT is to take advantage of a heritage from successful space telescope; the SOT aboard Hinode3, 4. Major differences of the SUVIT from the SOT are about three times larger aperture (~1.5 m), which enables to collect one order of magnitude more photons than the SOT, relatively shorter telescope length (2.8 m Gregorian primary-secondary mirror distance), and much wider observing wavelength coverage from UV (280 nm) through near IR (up to 1100 nm).

The SUVIT consists of a few optically separable components; the telescope assembly and an accompanying focal plane package equipped with filtergraphs and a spectrograph. The large aperture is essentially important to attain scientific goals of the SOLAR-C, 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 opto-mechanical and -thermal performance of the instruments is crucial to attain high-quality solar observations. The optical and structural design of the SUVIT telescope assembly and conceptual design of focal plane instruments for the SOLAR-C are given in the following.

II. DESIGN OF TELESCOPE ASSEMBLY

Most large-sized solar telescopes employ Gregorian or combined Gregorian system because of the easiness of telescope thermal design which is crucially important for solar telescope: two field stops can be placed at a primary and a secondary focus to reject unwanted out-of-field solar light to space. Taking this advantage, the baseline optical design of SUVIT telescope assembly adopts the Gregorian system. In addition, the SUVIT is designed to fulfill the following scientific requirements: (1) To resolve at least 0.1 arcsec solar features over a field view of 184×184 arcsec2 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 280 to 1100 nm without frequent focus re-adjustment and to give a well-defined optical interface for accompanying focal plane instruments, and (3) to give negligible instrumental polarization before a polarization modulator or polarization calibration unit for precise polarization measurements.

A. Optical Design of Telescope Assembly

To attain the requirements of high spatial resolution and the large number of photons collection capability, we study a 1.5-m class aperture Gregorian5, which can give a theoretical resolution of 0.1 arcsec at 630 nm 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 secondary mirror is to be at least 2.8 m, after preliminary opto-mechanical tradeoff studies within the allowable size of the launcher's nosecone. This short Gregorian demands very small static misalignment tolerances for the primary and secondary mirrors, and hence this makes a structural design of the telescope crucial for high optical performance.

To fulfill the achromatism over the wavelength from 280 nm to 1100nm, collimator unit was designed with all-reflective 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 on-axis three mirror systems which can accommodate the requirements of wide field performance, compactness in size and beam folding to the focal plane instruments which attached a side of the telescope assembly. A design was found in which two of three mirrors are simple spherical and third 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 633 nm5. A baseline optical layout is given in Fig. 1.

The Heat Dump Mirror (HDM) is located at the primary focus and is a 45 deg. flat mirror with a central hole of 344 arcsec. The HDM is designed to reflect more than 90 % of incident solar energy out to space through a heat dump window

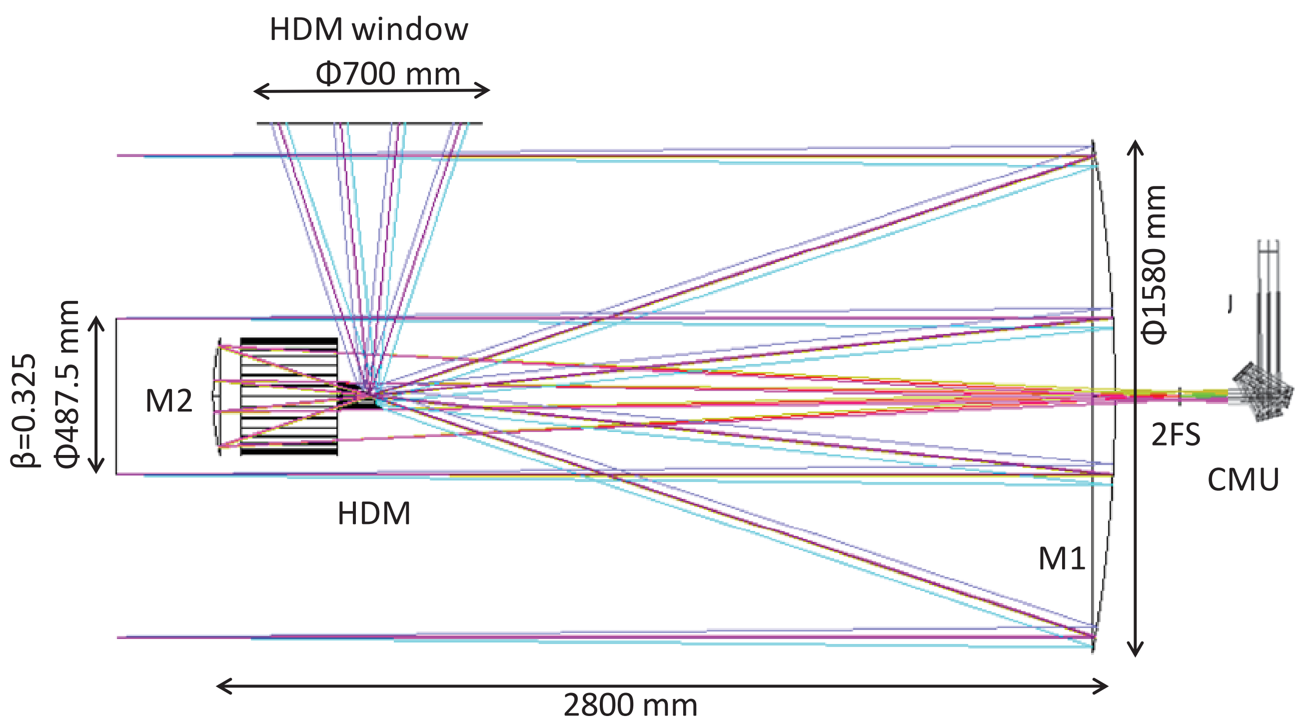
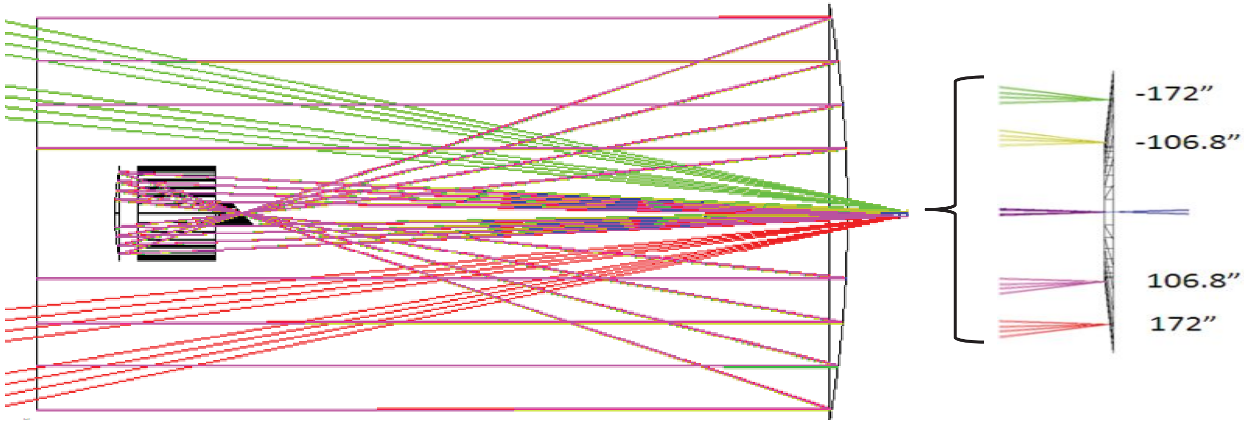


Figure 1. Optical configuration of SUVIT-Telescope Assembly (TA). Units are in mm. The TA consists of an aplanatic Gregorian; the primary mirror (M1) and the secondary mirror (M2) of effective aperture of 1500 mm, a Collimating Mirror Unit (CMU) behind the primary mirror. In addition, the TA has two 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. The CMU forms an exit pupil of a diameter 60 mm behind it and about which we can place a polarization modulation unit and an active tip-tilt mirror for image stabilization, folding a beam for a focal plane instruments.



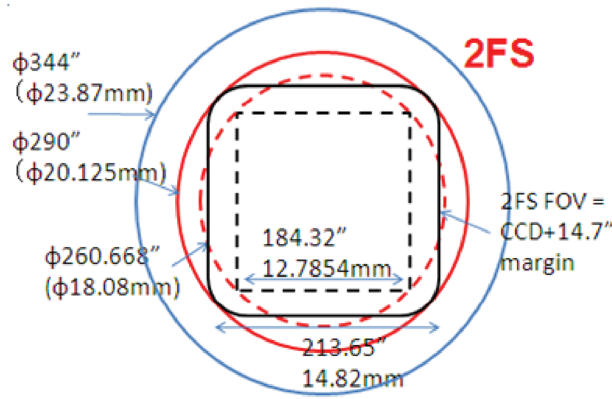


Figure 2. Design of secondary field stop (2FS). The 2FS defines the field of view of 214×214 arcsec^2 and the lights outside this field is designed to be reflected back to the entrance aperture. This gives a flat topped cone mirror of fan angle 176 degrees as shown in upper right panel of the figure.

at the side of TA (Fig. 1). The outer diameter of HDM, which is about twice of the diameter of solar image at the primary focus, determines the maximum offset pointing angle from the Sun center allowable for the spacecraft (about 200 arcsec above the limb). The secondary field stop (2FS) is placed at the Gregorian focus for the purpose of further reduction of energy sent to the following optics. The 2FS defines the field of view of the TA as 214×214 arcsec2, which slightly oversize the area of the detectors in focal plane instruments with a margin of 15 arcsec. The solar light outside this field is designed to be reflected back to the entrance aperture (see Fig. 2). The both mirrors will be made of aluminum alloy and welded by electron beam welding to their support structures of the same material so that the heat absorbed by the mirror can spread over the support structure by thermal conduction and be emitted by large-area radiation. Both mirrors will have high reflectivity coating such as an enhanced silver coating.

B. Structural Design of Telescope Assembly

The framework structure of the telescope assembly (TA) should be light weight but sufficiently robust to support and maintain the optical elements with a required positional accuracy against a violent launch environmental conditions and severe on-orbit thermal conditions without any dedicated alignment mechanisms. The Gregorian telescope requirements demand very small static mis-alignment tolerances for the primary and secondary mirrors, on the order of a few tens microns for de-center and de-space or several arcsec for tilt, and a micron-order de-space short-term stability on-orbit during observations. To meet this requirement, the telescope framework will be made of a truss of ultra-low-expansion CFRP (Carbon Fiber Reinforced Plastics) pipes in a Graphite Cyanate matrix as used in Hinode/SOT4. The CTE was proven to be smaller than 0.1ppm K-1, and the dimensional change due to moisture absorption was measured to be about 30 ppm which is much smaller than conventional epoxy matrix composite pipes. Three CFRP sandwich panels are adhesively bonded with upper and lower truss pipes without any metal junctions to save weight and also avoid differential CTE which may cause unexpected telescope thermal distortion.

A conceptual layout of overall framework structure is shown in Fig. 3. The center panel ring provides the mechanical interface to the spacecraft; The TA is supposed to be mounted on the CFRP-made cylindrical optical bench unit (OBU) to the spacecraft with three quasi-kinematic mounting legs with stress-relief spring structures. The center section is equipped with alignment cubes at the top surface which represent the mechanical and optical axes of the telescope, and are used for co-alignment among other telescopes and spacecraft attitude control system sun-sensors.

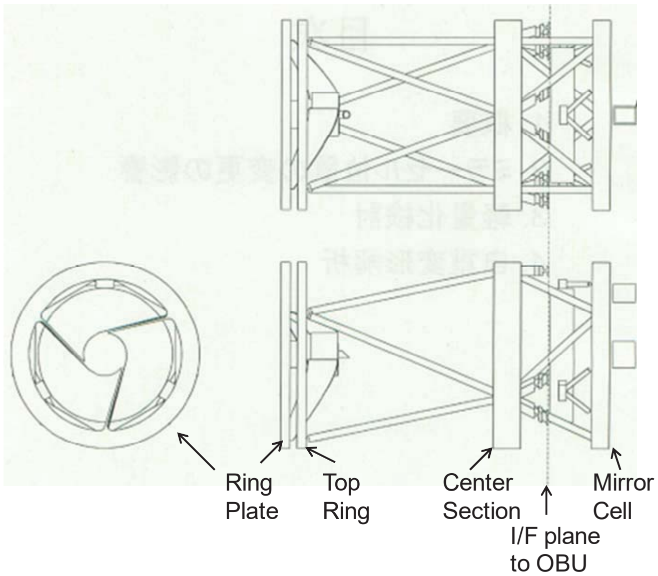


Figure 3. Conceptual layout of framework structure for the SUVIT telescope assembly.

Mounting of the primary mirror (M1) is one of the most critical parts of the TA. The primary mirror, made of light-weighted (90% removed and thus less than 150 kg weight) Zerodur or ULE, is supported by three stress-free mounting mechanisms (flexible bipod) rooted on a CFRP mirror cell, interfaced with three pads bonded on the side of the mirror. The pad interface of the mounting mechanism is torque-free about three axes and also free in the radial direction, thus providing a kinematic mount for the primary mirror. The pad interface thus avoids stresses to the mirror resulting from dimensional errors in machining or temperature change. The only significant surface error of the primary mirror is caused by the difference of CTE between the pads and the mirror substrate, which constrains the best-performance temperature range of the primary mirror; preliminary study of M1 thermal deformation by pads gives sensitive wavefront error (trefoil coma) of 2 nm rms K^{-1}.

The effect of gravity on the surface figure of such a large primary mirror is a critical issue to verify the optical performance of the telescope on-orbit (zero gravity). We carefully studied the effect of mounting positions on the gravity deformation of surface figure and found that the surface figure deformation is sensitive to the height of the mounting point (Fig. 4). Considering that M1 is mounted at three side points and the surface normal is oriented in horizontal direction (horizontal telescope configuration), the minimum surface deformation is about 28 nm rms when the M1 of 110 kg weigh and 200 mm thick light-weight Zerodur is supported at the height 115 mm from the back face. Preliminary study of gravity deformation of both framework structure and mirrors in horizontal test configuration shows overall wavefront error due to gravity within a measurable range of interferometer.

The secondary mirror (M2), which is also made of Zerodur or ULE and light-weighted to about 10 kg weigh, is supported by a Stewart mechanism (hexapod) aimed at the misalignment correction; de-center, tilt, and defocus, in ground testing and orbit as well. The secondary mirror unit is mounted on the central disk of a ring plate which is tangentially supported with

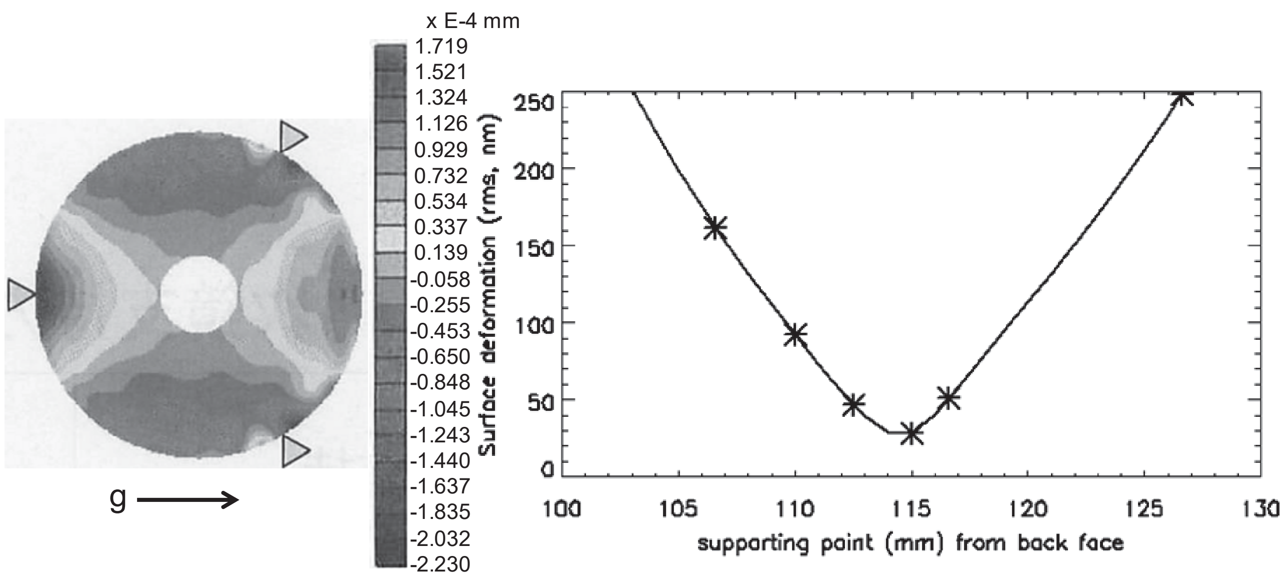


Figure 4. M1 surface figure deformation due to gravity in the case that M1 is mounted at three side points and the surface normal is oriented in horizontal direction (left panel). As the plot in the right panel shows, the surface figure deformation is sensitive to the height of the mounting point, where the symbol indicates calculated points and the curve is their interpolation. The minimum surface deformation is about 28 nm rms when the M1 of 110 kg weigh and 200 mm thick light-weight Zerodur is supported at the height 115 mm from the back face.

three spiders from an outer ring (see Fig. 3). This tangential support works to prevent the M2 from de-spacing causing frequent de-focus error in case of thermal deformation of spider.

The HDM unit is also supported by the ring plate via three tangential mounting spiders like M2 unit. The mounting points at the ring plate have a titanium-made mechanism for de-center and tilt adjustment of HDM unit with respect to M2 and HDM. The HDM has through hole through which the HDM can be properly aligned with the M2 vertex. The ring plate is connected to the CFRP top panel ring via three positional and tilt adjustment mechanisms, with which optical alignment of the secondary mirror, de-center, de-space (focus), and tilt adjustment with respect to the primary mirror can be performed.

The frame structure is covered by a shield tube for the upper half and a lower tube for the lower half for the purpose of protecting critical components from molecular and particle contamination, as well as reducing stray light, and ensuring thermal control of the entire OTA. The TA is estimated to be 450 kg weigh in total and its rigidity (first eigen mode) is as high as 70 Hz.

C. Thermal Model of Telescope Assembly

About 2 kW of solar light is impinged onto the primary mirror at the bottom of the TA during solar observations from its 1.5-meter diameter entrance aperture. To realize a high-performance solar telescope, a thermal design is critically important to dump unnecessary heat input to space and maintain critical optical and structural components to within allowable temperature ranges with small temperature fluctuation. In this sense, Coating of optical components is critical, which should limit solar light absorption to a minimum, giving high throughput in the observation wavelengths. A silver-based reflective coating is desirable because of low solar light absorption (α~6.5%) although it has a problem of very poor reflectivity in the wavelengths below 350 nm [4]. Therefore, we adopted Al+MgF_2 coating (α~12%), which is the most probable for the UV observations down to 280 nm, for telescope mirrors except for field stop mirrors to study the thermal design (Table 1).

Table 1. Input and resulted absorbed energy by telescope optical components in the case of begin of life (BOL) and end of life (EOL). In EOL, solar light absorption by mirrors increases to 17 % and 11.5 % for Al+MgF_2 and Ag coating, respectively.

	BOL		EOL	
Component (coating)	Input (W)	Absorption (W)	Input (W)	Absorption (W)
M1 (Al+MgF_2)	2073.2	244.6	2073.2	348.3
M2(Al+MgF_2)	56.6	6.7	53.4	8.97
HDM (Ag)	1772.0	88.6	1671.5	167.2
2FS (Ag)	25.5	1.3	22.7	2.3
CMU (Al+MgF_2)	24.4	7.7	21.7	9.2

Based on the predicted orbit of SOLAR-C, extreme cases were defined and studied for thermal design; 'hot case' and solar light absorption by mirrors is given by EOL condition in Table 1. The basic concept of the TA thermal design follows Hinode SOT-OTA passive control design [4] 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.

(2) A sunshade and upper half of the telescope upper 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 upper tube, not covered by multi-layer insulation (MLI), is covered with a silverized teflon sheet.

(3) Solar heat absorbed by the M1 is radiatively transmitted to a telescope lower tube from its side and from a bottom cooling plate just beneath the M1 which radiatively absorbs the heat of the mirror from its back face.

(4) Solar heat absorbed by the M2 is radiatively transmitted to the radiators from its back side.

(5) Heat absorbed by the 2FS, CMU is conductively transferred to the 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.

(7) The heat of the lower tube and the upper 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 tube.

(8) The TA is thermally insulated from the spacecraft; The TA is physically connected to the optical bench unit (OBU) only by mounting legs and is radiatively de-coupled from the OBU by MLI covering the lower tube and a bottom cover.

The nominal thermal model is simply a scaled-up model of Hinode SOT telescope assembly and we found it gives unacceptably high temperatures both for the primary mirror and HDM, especially in the case of polar orbit compared with the case of geosynchronous orbit [5]. Therefore, drastic modifications of the model are inevitable to lower temperatures of those components, in which additional radiator or heat dump system efficiently transfer heat from the primary is accommodated. Some case study indicates that about 100 to 200 W of heat from the primary should be dumped to lower the temperature to 40 ℃ in geosynchronous orbit and EOL condition.

III. DESIGN OF FOCAL PLANE INSTRUMENTS

The collimated beam from the telescope exit pupil of 60 mm diameter is fed into focal plane instruments. Conceptual designs of filtergraph and spectro-polarimeter in the focal plane are given in the following, which are capable of providing data of high spatial and temporal resolution in interesting photospheric and chromospheric lines.

A. Filtergraph Design

Two types of filtergraph are considered; one is a broad-band filtergraph (BF) focused on high spatial and temporal resolutions and the other is a narrow-band filtergraphs (NF) for imaging spectroscopic observations [6].

The BF (Fig. 5) is to provide monochromatic images of the solar photosphere and chromosphere using interference filters at the best possible spatial and temporal resolution. Observations at UV wavelengths shorter than 400 nm are emphasized in observations with BF owing to higher diffraction-limited resolution. The diffraction-limit resolution of 0.05 arcsec can be achieved in the Mg II h&k 280nm lines with the 1.5 m aperture, which is factor of 4 better than Hinode SOT. In order to make the best use of the high spatial resolution, the pixel sampling as high as 0.015 arcsec is used in BF. The high pixel sampling is also useful to recover image quality by post-fact deconvolution using an estimated point-spread function on-orbit.

The high pixel sampling leads to narrow field-of-view (FOV) because of the limitation of the detector size. In the 4k×4k pixels detector, the FOV of 61×61 $arcsec^2$ is covered, which is one third of the possible maximum FOV (184×184 arcsec2). For observations requiring a larger FOV, another observation mode is also considered with pixel sampling of 0.045 arcsec. Candidates of the observing wavelength bands are Mg II h&k line pair, CN band 380 nm, Ca II K 393 nm, etc., and a few continua of wavelength shorter than 500 nm.

The BF has sub optical channels between the relay lens and the detector to realize the high resolution mode and the wide FOV mode. The one of two modes are selected by opening and closing the shutters located at each channel.

The NF (see Fig. 5) is important to perform imaging-spectroscopy at chromospheric and photospheric lines to provide 2D images of Doppler velocities and vector magnetic fields with relatively wide FOV. A tunable filter (TF) is a key component. There are two possible types of TF for SUVIT; Lyot- type filter or Fabry-Perot filter. Our current baseline is a Lyot filter because relatively smaller aperture size (hence light-weight) works to get wider FOV with the focal ratio of F/40 telecentric beam, tuned with either rotating wave plates or liquid crystal variable retarders.

The FOV of about 100 arcsec wide is expected with 40 mm clear aperture calcite with F/40 telecentric focal length. A blocking filter whose bandwidth is smaller than the free spectral range is located in front of TF, and is used to select the passbands. Candidate spectral lines for TF are Mg I 517 nm, Fe I 525 nm, H I 656 nm (Hα), Ca II 854 nm line, etc.

B. Spectro-Polarimeter Design

The spectro-polarimeter (SP, see Fig. 6) is an instrument for obtaining full Stokes profiles of magnetic sensitive spectral lines, and provides precise polarimetric measurements of the chromospheric and photospheric lines to diagnose magnetic fields on the solar surface. The spectrograph employs a Littrow-type configuration similar with the spectro-polarimeter of Hinode SOT7. It consists of an Echelle grating and an off-axis aspheric mirror for collimating and reimaging the beam before and after the grating [6].

We choose parameters of the grating to observe the three spectral bands containing the important chromospheric lines of He I 1083 nm, Ca II 854 nm, and Mg II h&k 280 nm at close diffraction angles of different orders. The wavelengths are selected by switching corresponding blocking filters located in front of the slit. The observing bands include not only the chromospheric lines but also a few photospheric lines to allow simultaneous observations for both the photosphere and the chromosphere. Scanning over the FOV across the slit is done with a scan mirror located in front of the slit.

In order to minimize scanning duration, a multi-slit

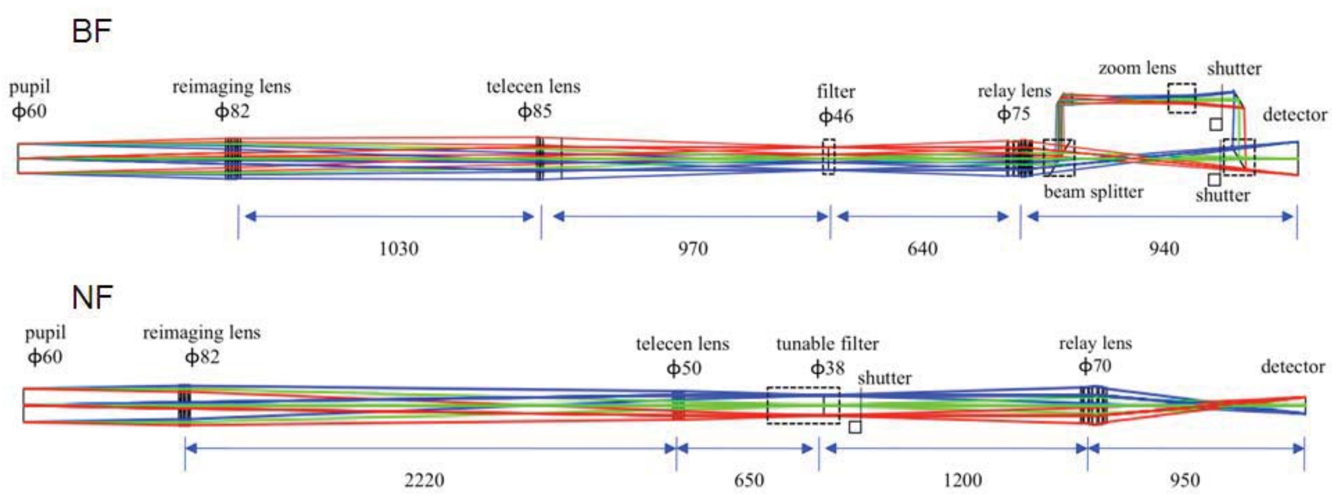


Figure 5. Optical layouts of the narrowband filtergraph (NF, bottom) and the broadband filtergraph (BF, top) with the high resolution sub-channel.

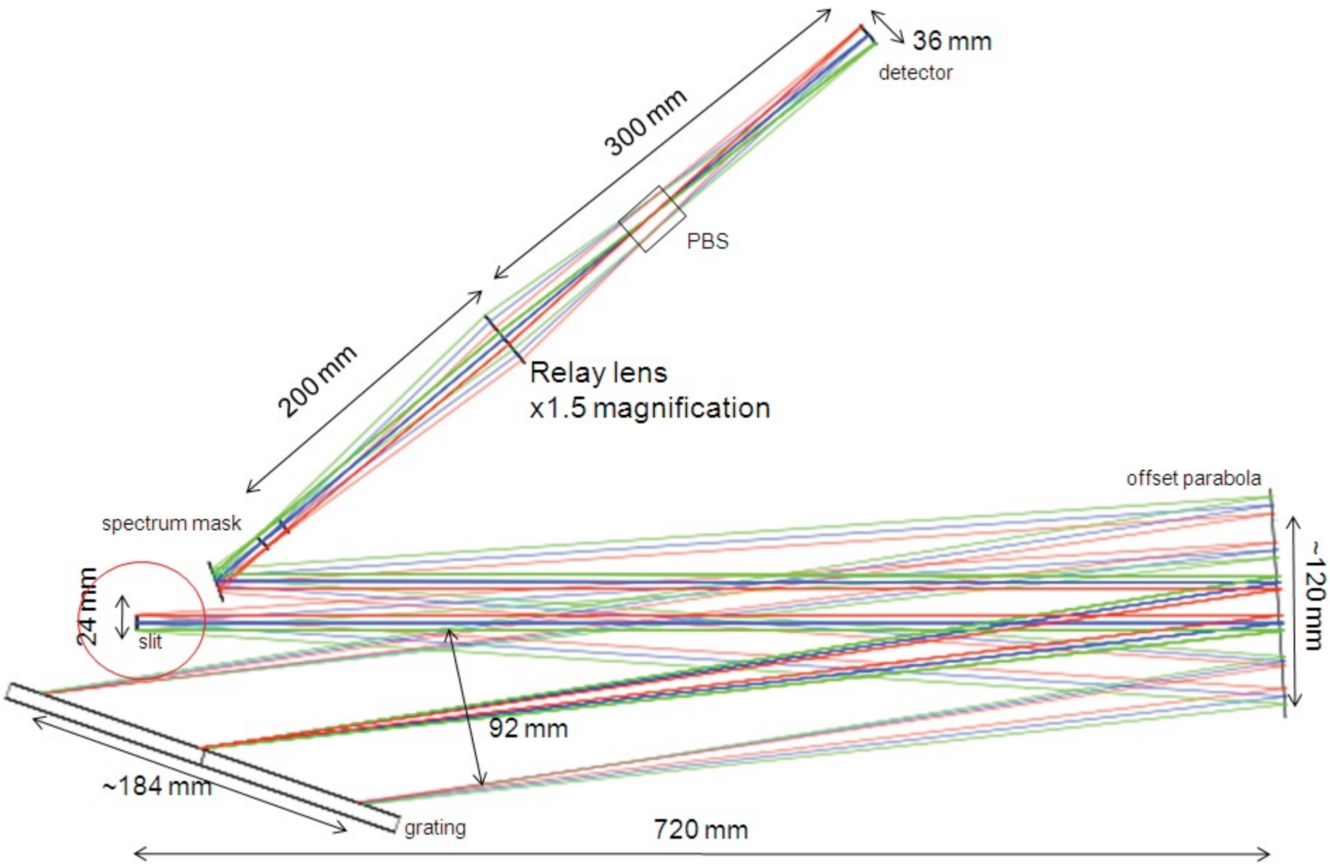


Figure 6. Optical layout of the spectro-polarimeter. The slit unit is considered to be switchable to an integral filed unit (IFU) like a fiber bundle image slicer.

configuration and an integral field unit like a fiber bundle image slicer [8] switchable to the slit unit is also considered, in which three slits are located with 60 arcsec separation to get spectra at multiple locations simultaneously. A Savar plate is placed in front of the detector to measure the orthogonal polarization states simultaneously with the single detector. This is essential to reduce polarization cross-talk generated by residual spacecraft pointing jitters that cannot be removed with the tip-tilt mirror.

In order to observe the He I line at 1083 nm with high sensitivity, it is required to use an infrared sensitive detector with very fast read-out to accumulate many numbers of photons within short duration. On the other hand, infrared detectors generally require low working temperatures to suppress noises and dark currents. We are now investigating a usage of an HgCdTe detector with a 1.7 μm cut-off which can be operated with relatively higher temperatures [9].

The temperature requirement for the detector is as low as 200 K to make dark currents negligible, which can be marginally achieved with radiation cooling without using any cryocooler. The HgCdTe detector is also sensitive to 854 nm with high efficiency. Precise polarimetric measurements for diagnostics of chromospheric fields require 10 to 20 sec integration at each slit positions to achieve the 10-4, polarimetric sensitivity. In addition to the deep polarimetric observation, the instrument is to be designed to support rapid scanning to make spectroscopic and spectro-polarimetric observations for study of chromospheric dynamics and photospheric magnetic fields over the FOV with integration shorter than 1 sec at each slit positions.

IV. SUMMARY

The optical, structural and thermal design for large aperture (1.5-m aperture class) Gregorian telescope for the SOLAR-C mission was described. The telescope consists of aplantic Gregorian, two field stops and the three-mirror collimator unit, to accommodate science requirements such as wide observing wavelength coverage from UV (280 nm) through near IR (1100 nm) and diffraction limited resolution in the wavelength longer than 633 nm in the field of 200 arcsec diameter. The accompanying focal plane instruments were also described with emphasis on observing He I 1083 nm line, Ca II 854 nm and Mg II h&k lines (280 nm). Those conceptual designs are in progress; the wide band filtergraph for shorter wavelength bands between 280 to 500 nm, the narrow band filtergraph tunable between 510 nm and 860 nm, and the Littrow-type spectrograph for high-precision spectro-polarimetry in the photospheric and chromospheric lines.

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