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Design of all-reflective space-borne 1-m aperture solar optical telescope

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ABSTRACT

A 1-m aperture optical telescope is planned for a future Japanese solar mission. The telescope is designed to provide high spatial resolution data of solar lower atmosphere from the photosphere to the uppermost chromosphere with enhanced spectroscopic and spectro-polarimetric capabilities covering a wide wavelength region from UV to near IR where many useful spectral lines and continua exist for physical diagnosis of the solar magnetized atmosphere. We designed an all-reflective telescope to fulfill the scientific and engineering requirements. From a thermal view point, a Gregorian telescope is the most suitable. To avoid chromatic aberration, a tri-aspheric-mirror collimator coupling to the Gregorian was designed to give a diffraction-limited performance over the FOV by allowing a field curvature. The field curvature can be compensated by an off-axis Ritchey Chretien reimaging optics at an entrance of focal plane instrument, which has an opposite sign in the field curvature to the Gregorian. We also briefly studied structural design of all-reflective 1-m aperture solar optical telescope for the space solar mission.

Keywords: optical telescope, solar space telescope, structural design of telescope

1. INTRODUCTION

The Sun is a magnetically active star. Magnetism governs its extended atmosphere and is responsible for solar activity. However, how solar magnetism works is still poorly understood. The solar atmosphere, stretching from the Sun's surface (photosphere, 6000 K) to the outer corona, covers domains that differ widely in terms of physical nature and processes. The plasma structuring goes from optically thick to optically thin and from gas-dominated to magnetically dominated. The whole atmosphere is a uniquely coupled magnetic system. The chromosphere of temperature approximately 10^4 K is located only one photospheric convection-cell size (1000 km) above the photosphere and is extremely dynamic. Higher up one encounters the hot corona with temperatures that occasionally exceed 10^7 K during flares. Because the chromosphere is subject to efficient radiative cooling, the energy required to maintain the chromosphere is substantially larger than that for the hotter corona. Both, chromospheric heating and the more famous coronal heating problem are not yet resolved, although it is clear that magnetism is the key agent. Recent discoveries show yet more complexity than thought before. Much-improved insights that come from advances in theory and modelling highlight the need for new data to test and extend this understanding.

The chromosphere plays a special role for investigations of atmospheric activity, because the conditions change from plasma dominated to magnetically dominated. Here the interaction between magnetic field and plasma is particularly rich, including phenomena such as wave mode conversion, shock formation, ambipolar effects, or reconnection, all of which are essential to understand the energy deposition driving and heating the atmosphere. Because the magnetic and plasma effects are tightly interwoven, the diagnostics of the chromospheric magnetic field through spectro-polarimetric observations holds the key to our understanding of the processes in the chromosphere and to determining the transport of energy and mass to the higher layers of the atmosphere. Only a large telescope on a platform in space can provide the stability of the observational conditions required to reach the polarimetric accuracy at high spatial resolution necessary to investigate the small-scale and weak magnetic fields in the chromosphere. In addition, combining established diagnostics of chromospheric magnetic fields, e.g., in the He I lines at 1083 nm and the Ca II 854 nm line, with the option of unprecedented polarization measurements in Mg II lines near 280 nm provides new diagnostic capabilities through the Hanle and Zeeman effect not explored so far[1].

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Therefore, we are studying a large aperture solar optical telescope, which provides high spatial resolution data of solar lower atmosphere from the photosphere to the uppermost chromosphere with enhanced spectroscopic and spectro-polarimetric capabilities covering a wide wavelength region from UV to near IR where many useful spectral lines and continua exist for physical diagnosis of the solar magnetized atmosphere. We here present a progress in designing the optical telescope for the future space solar mission.

2. ALL-REFLECTIVE SOLAR TELESCOPE

Large-sized solar telescopes employ a Gregorian system because of the easiness of telescope thermal design which is crucially important for solar telescope: a field stop can be placed at a primary focus to reject unwanted out-of-field solar light to outside the telescope[2]. Taking this advantage, the baseline optical design of the telescope adopts the Gregorian system. In addition, the telescope is designed to fulfill the following scientific requirements: (1) To resolve at least 0.1 arcsec solar magnetic features over a field view of 300×300 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 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 unit for precise polarization measurements.

2.1 Optical Design of Telescope to Re-imager at Focal Plane Instrument

To attain the requirements of high spatial resolution and the large number of photons collection capability, we study a 1-m aperture Gregorian, which can give a theoretical resolution of 0.1 arcsec at Fe I 630 nm ($1.22\lambda/D$ rad) where accurate polarization measurements can be performed. The distance between the primary and secondary mirror is to be 2 m, after preliminary opto-mechanical tradeoff studies within the allowable size of a launcher's nosecone. This short Gregorian configuration 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.

We adopt a collimation optical interface between the telescope assembly and accompanied focal plane instruments because of its clear definition of optical interface and also easiness of optical tests of the telescope assembly using a laser interferometer throughout an integration, opto-thermal and system level optical tests. We design a collimator unit to be placed behind the primary mirror and to reduce beam size, making an exit pupil of about 40 mm diameter (beam reduction factor of 1/25) to accommodate clear apertures of critical image stabilization (TTM) and polarization modulation unit (PMU), followed by focal plane instruments. A schematic optical configuration is given in Figure 1.

To fulfill the achromatism over the wavelength from 280nm to 1100nm, collimator unit was designed with all-reflective system. Among all-reflective collimator designs, we selected on-axis three mirror systems which can accommodate the requirements of wide field performance, compactness in size. A design was found all three mirrors are on-axis aspherical; the surface figure expressed with Zernike first eleven terms, and that is capable to give the diffraction-limited performance, allowing spherically curved focus (field curvature), when combined with the Gregorian within the field of 300 arcsec square. Nominal optical performance of the baseline optics can be designed to give the Strehl ratios in the FOV of 300x300 arcsec^2 at 632.8 nm greater than 0.999 when a field curvature is allowed (Figure 3). It should be noted that the conic constants of the Gregorian need to be modified and it has a slight aberration even at a field center. By configuring the TTM folding mirror to be an orthogonal reflection to the CMU (Figure 1), an instrumental polarization caused by the CMU can be much reduced.

The field curvature thus designed can be compensated by an off-axis Ritchey Chretien re-imaging optics which has an opposite sign in the field curvature to the Gregorian at an entrance of the focal plane instrument; off-axis design was adopted to avoid any ray vignetting (Figure 4). With this re-imager, an excellent optical performance can be realized in the wide wavelength region from 280 nm to 1100 nm over 180x180 arcsec^2 FOV (Figure 5). Optical parameters of telescope optics through the Ritchey Chretien re-imager are given in Table 1.

The Heat Dump Mirror (HDM) is located at the primary focus and is a 45deg. flat mirror with a central hole passing through 540 arcsec diameter. The HDM is designed to reflect more than 90 % of incident solar energy out to space through a heat dump window at the side of telescope envelope. 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 as 337×337 arcsec^2, which is slightly oversized the area of the detectors in focal plane instruments with a margin of 15 arcsec (Figure 2). The solar light outside this field is designed to be reflected back through the telescope entrance aperture (Figure 2).

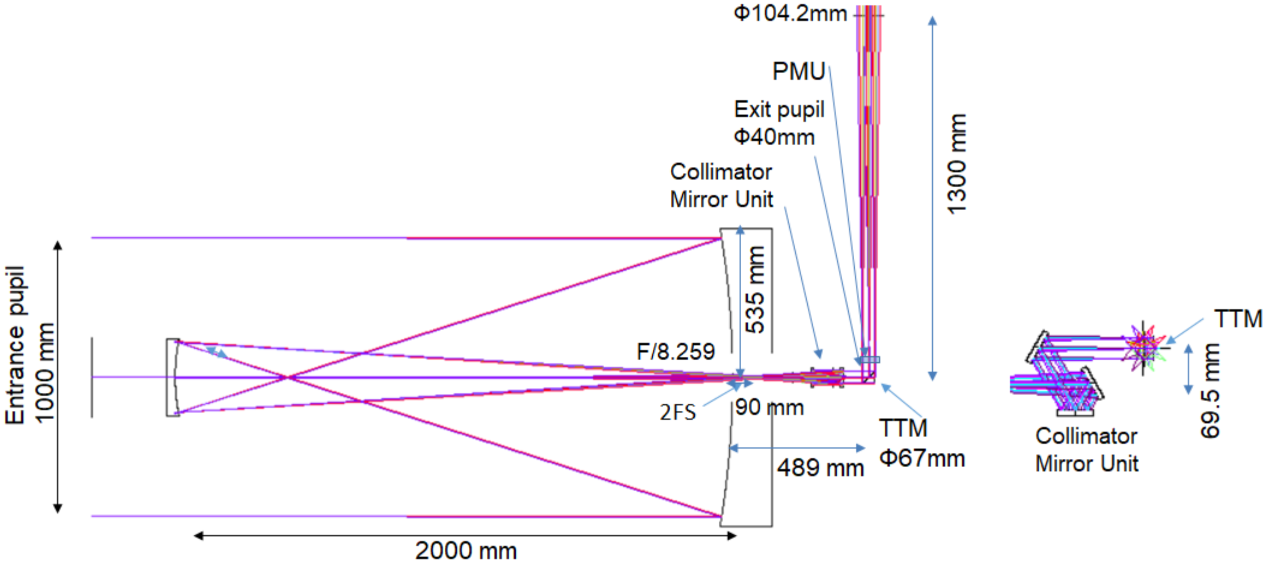

Figure 1. Optical configuration of 1-m aperture telescope. Units are in mm. The telescope consists of a Gregorian; the primary mirror (M1) and the secondary mirror (M2) of effective aperture of 1000 mm, a Collimator Mirror Unit (CMU) behind the primary mirror, followed by an image stabilization tip-tilt mirror (TTM) and a polarization mirror unit (PMU). In addition, it 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.

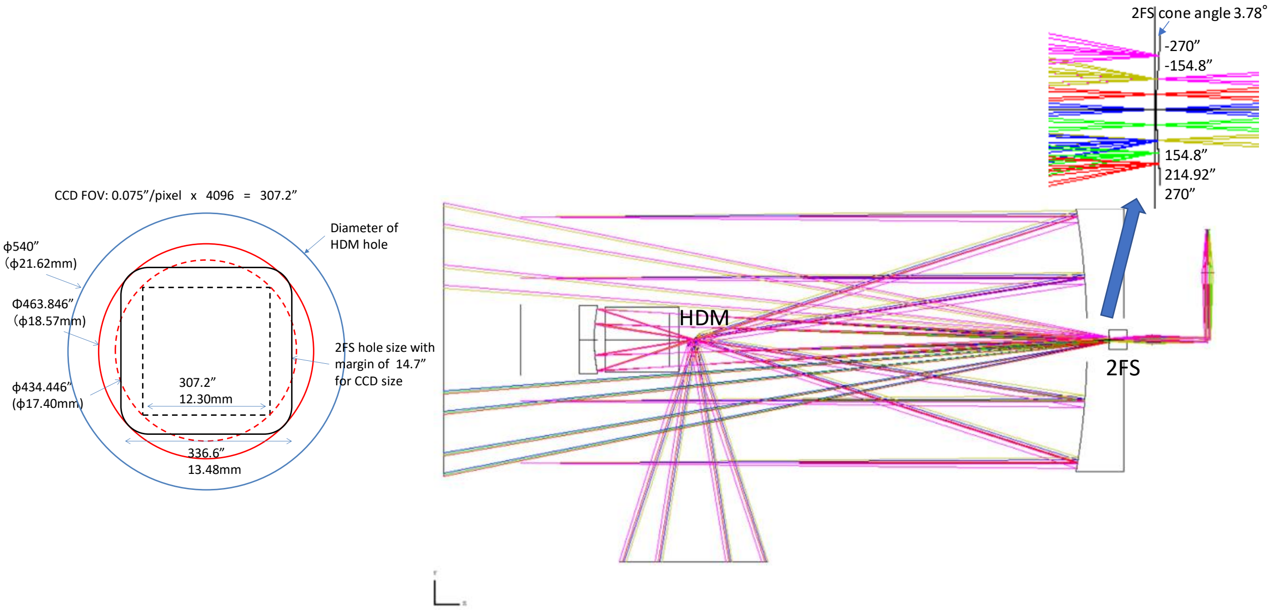

Figure 2. Design of secondary field stop (2FS) (left) and confirmation of off-field solar light rejection by HDM and 2FS (right).

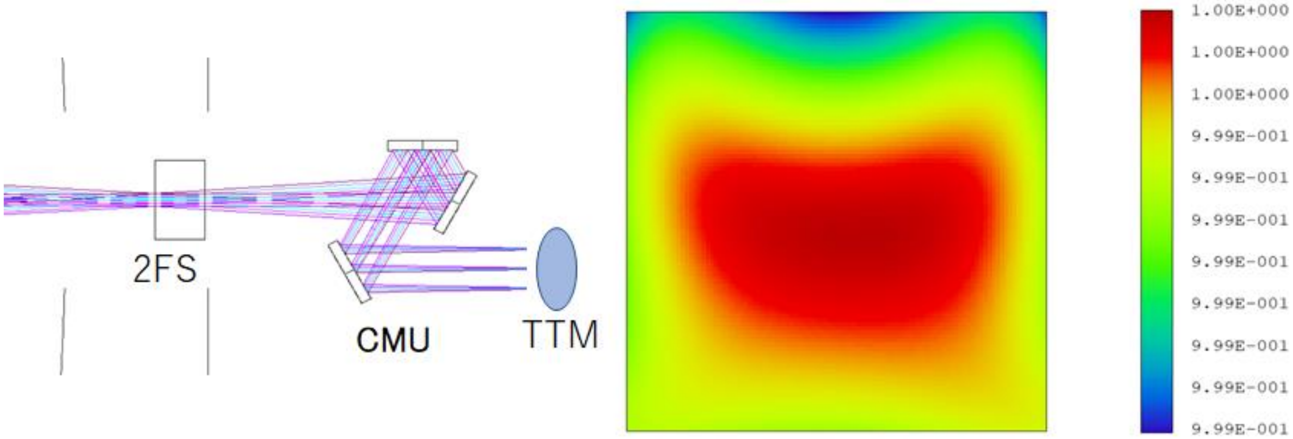

Figure 3. Optical layout of tri-mirror collimator unit (CMU, left) and Strehl ratio map of optics combined the Gregorian with the CMU over 300x300 arcsec^2 FOV (right). Note that a field curvature is compensated in the map.

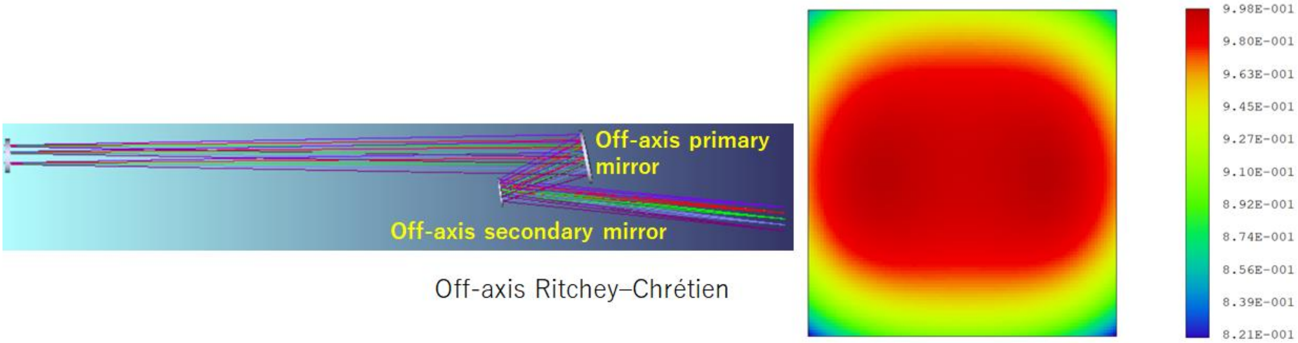

Figure 4. Optical layout of Ritchy-Chrétien re-imager (left) and Strehl ratio map of whole optics from the Gregorian through the re-imager over 300x300 arcsec^2 FOV (right).

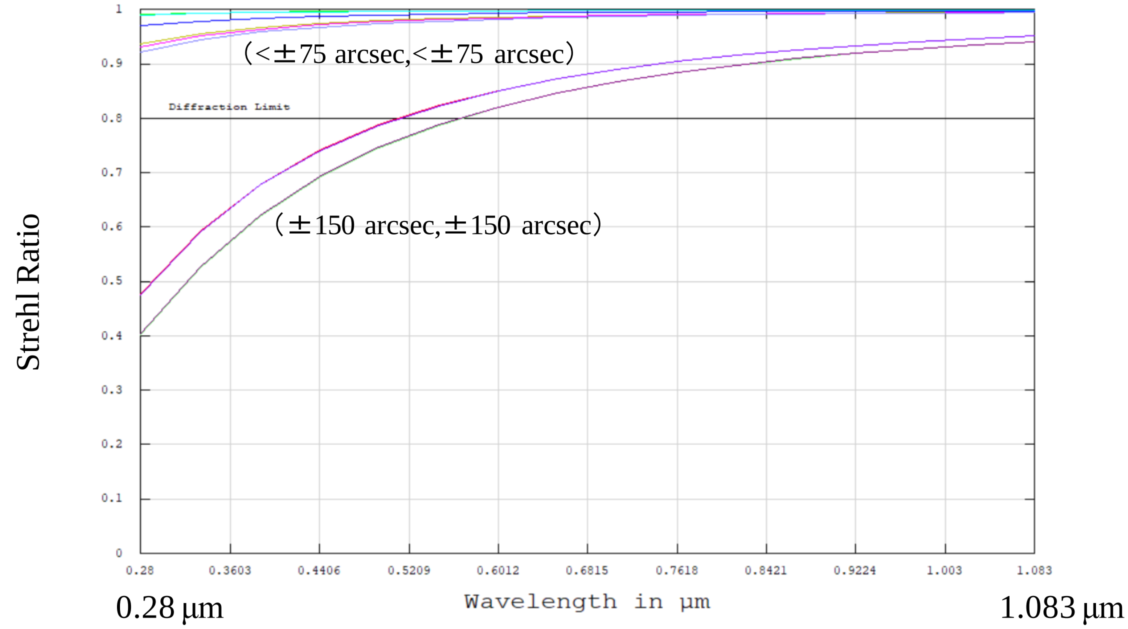

Figure 5. Strehl ratio vs. wavelength of whole optics from the Gregorian through the re-imager over 300x300 arcsec^2 FOV (right).

Table 1. Optical parameters of components for SUVIT telescope assembly

Component	Mirror	Clear aperture (mm)	Radius of curvature (mm)	Conic const.	Off-axis distance (mm)
Gregory	M1	1004.6	-3192.242	-1.003465	0
	M2	254.8	-676.9383	-0.447949	0
CMU	M3	61.85	-1649.919	Zernike 4-11	0
	M4	63.49	-1956.907	Zernike 4-11	0
	M5	60.17	-436.1516	Zernike 4-11	0
TTM	M6	66.81	infinity	0	0
PMU	--	45.2	--	--	--
Ritchey-Chretien Re-imager	M7	96	-637.7692	-1.088166	129.7
	M8	54	+365.8725	-3.142539	57.5

2.2 Structural Design of Telescope Assembly

The framework structure of the telescope assembly 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 frequent drives of dedicated alignment mechanisms. The Gregorian optics requires 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/SOT[2].

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: For this Gregorian, aluminum co-cured CFRP pipes and plates will be used to much decrease the dimensional change. 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 Figure 3. The center panel ring provides the mechanical interface to the spacecraft; The telescope assembly is supposed to be mounted on the CFRP-made cylindrical optical bench unit (OBU), which also works as a lower tube of the telescope, to the spacecraft with three quasi-kinematic mounting legs with stress-relief spring structures.

Mounting of the primary mirror (M1) is one of the most critical parts of the telescope. The primary mirror, made of light-weighted (about 90% removed) ultra-low CTE glass material, 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 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. 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 found to be about 20 nm rms. 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 laser interferometer.

The secondary mirror (M2) is also made of ultra-low CTE material and light-weighted (about 60 % removed). The secondary mirror unit is mounted on the central disk of a ring plate which is tangentially supported with three spiders from an outer ring. 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 tangentially mounting spiders like M2 unit. The mounting points at the ring plate have a 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 initial optical alignment of the secondary mirror, de-center, de-space (focus), and tilt adjustment with respect to the primary mirror can be performed.

Mirrors of CMU are made of ultra-low CTE material and tangentially supported with leaf springs and configured in triangular structure as shown in Figure 6.

The frame structure is covered by a shield tube for the upper half and the OBU 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 telescope assembly. The telescope is estimated to be about 500 kg weigh without the OBU.

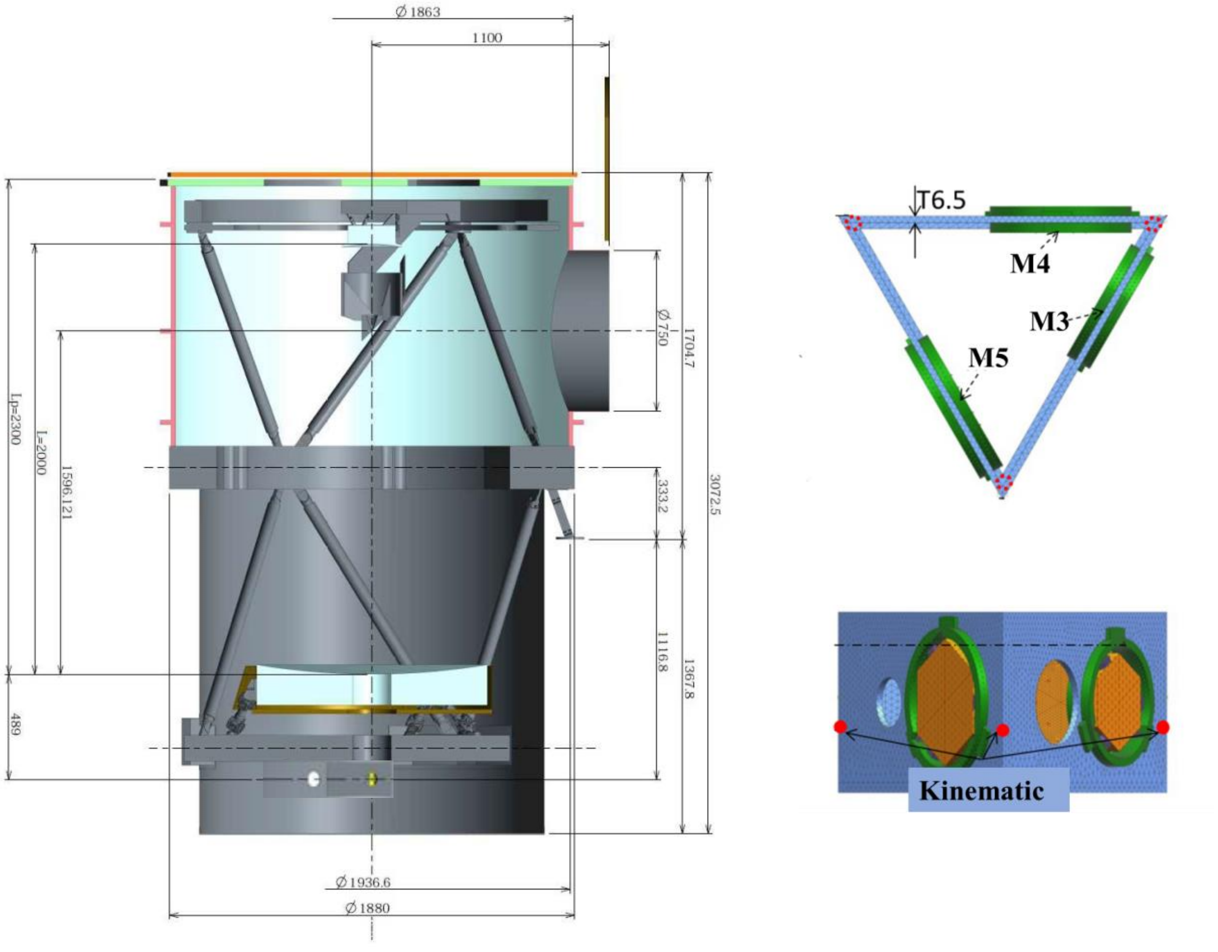

Figure 6. Structure design of telescope assembly (left) and collimator mirror unit (CMU, right).

2.3 Thermal Design of Telescope Assembly

About 1 kW of solar light is impinged onto the primary mirror at the bottom of the TA during solar observations from its 1-meter diameter entrance aperture. To realize a high-performance solar telescope, a thermal design is critically important which dumps unnecessary heat input to space and maintains 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 (<6.5%) although it has a problem of very poor reflectivity in the wavelengths below 350 nm[2]. To overcome this drawback, highly enhanced silver coating is under study in which the high reflectivity can extend down to 280 nm (REOSC). In thermal study, we used parameters conventional silver coatings. Provided field stops designed in Figure 2, heat loads into the optical components in the case of BOL and EOL are calculated (Table 2) to design a thermal model of the telescope.

Table 2. Solar light 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 are assumed to be incremented by 5% for each coating.

	BOL		EOL	
Component (coating)	Input (W)	Absorption (W)	Input (W)	Absorption (W)
M1 (protected Ag)	948.668	64.5	948.668	111.943
M2(protected Ag)	67.456	4.59	63.84	7.53
HDM (enhanced Ag)	816.7	40.84	772.89	77.29
2FS (enhanced Ag)	31.82	1.59	28.5	2.85
CMU (enhanced Ag)	31.05	4.42	27.81	7.54
TTM (enhanced Ag)	31.05	1.55	27.78	2.78
PMU (alpha=0.0075)	29.5	0.22	25	0.18
Re-imager	29.3	1.46	24.8	2.53

The significant surface error of the M1 mirror is caused by the difference of CTE between the pads and the mirror substrate; preliminary study of M1 thermal deformation by pads gives sensitive wavefront error (trefoil coma). M1 thermal deformation is very sensitive and its temperature need to be controlled close to a room temperature. Therefore, the thermal design was studied so that M1 temperature is controlled with a cold plate beneath it which has a heater and heat pipes efficiently transferring heats to a radiator placed near the top of telescope. In addition, the temperature of entire telescope structure is maintained close to the room temperature with heater control system. A design was found that the temperature of M1 and entire structure can be maintained close to the room temperature with reasonable radiator area and heater powers.

3. SUMMARY

We have presented an optical and structural design of all-reflective 1-m aperture solar optical telescope for space solar mission. The telescope was designed to provide high spatial resolution data of solar lower atmosphere from the photosphere to the uppermost chromosphere with enhanced spectroscopic and spectro-polarimetric capabilities covering a wide wavelength region from UV to near IR where many useful spectral lines and continua exist for physical diagnosis of the solar magnetized atmosphere. We designed an all-reflective telescope to fulfill the scientific and engineering requirements: (1) to resolve 0.1 arcsec solar features over a field-of-view of 300x300 arcsec^2, (2) to realize chromatic aberration free optics for observing wavelength range from UV to near IR, (3) to give a collimated optical interface with a following focal plane instrument, placing moving optical component like a rotating polarization modulator and a tip-tilt image stabilization folding mirror around an exit pupil of diameter about 40 mm, (4) to give negligible instrumental polarization before a polarization modulator for precise polarization measurements, and (5) to accommodate thermal design to reject unwanted solar light from the telescope components as early as possible. From the thermal design, A Gregorian telescope is the most suitable, because heat dump mirrors can be placed at both a primary and secondary focal plane. On the other hand, the Gregorian optics need to be designed so that the heat dump mirror units do not vignette the solar light from the observing FOV. To observe in the wide wavelength from UV to near IR, a tri-aspheric-mirror collimator coupling to the Gregorian was designed to give a diffraction-limited performance over the FOV by allowing a field curvature which mostly comes from the Gregorian optics. The field curvature can be compensated by an off-axis Ritchey Chretien reimaging optics which has an opposite sign in the field curvature to the Gregorian at an entrance of the focal plane instrument. With heritages from the previous space solar optical telescope onboard Hinode mission, we designed the structure of telescope assembly for the future space solar mission.

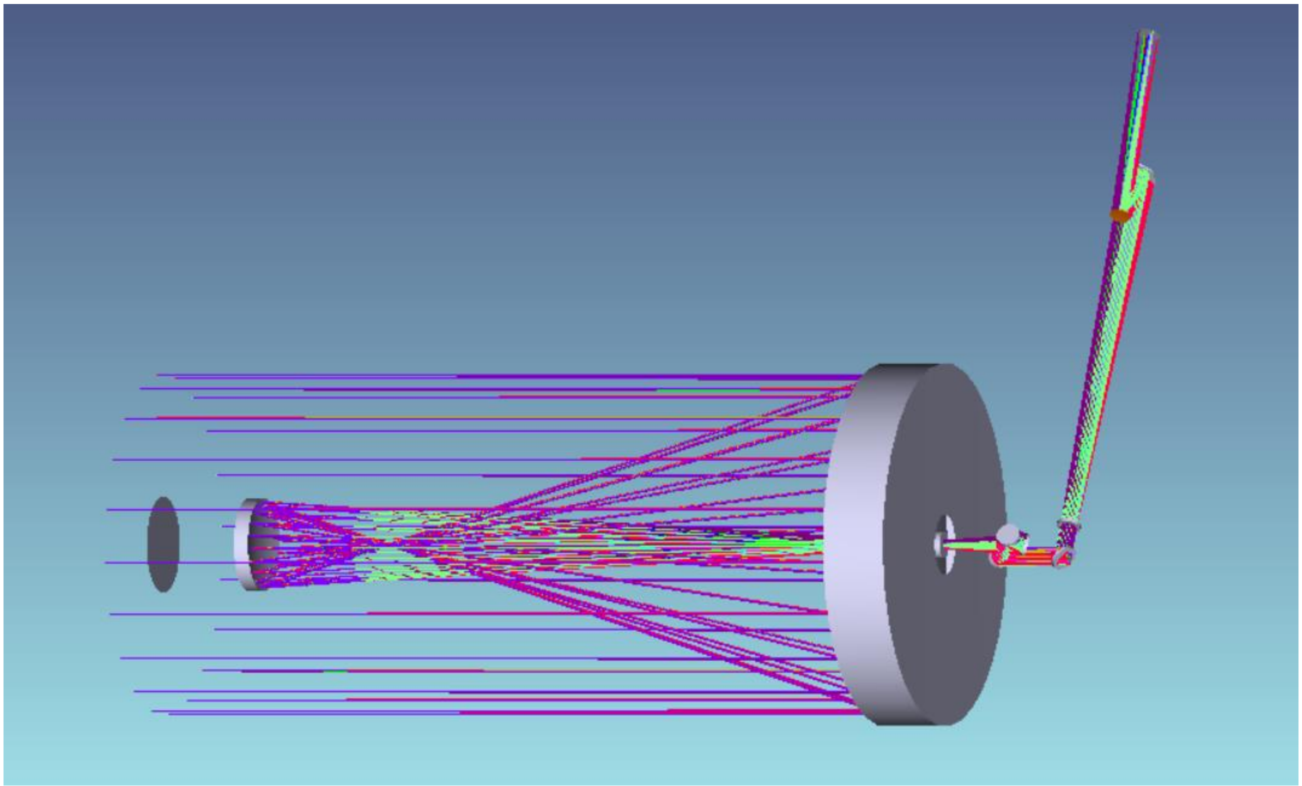

Figure 7. Overall optical layout from the telescope assembly (TA) to the re-imager at the entrance of focal plane instrument.

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