Instrument Design of the Large Aperture Solar UV Visible and IR Observing Telescope (SUVIT) for the SOLAR-C Mission

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Abstract. We present an instrumental design of one major solar observation payload planned for the SOLAR-C mission: the Solar Ultra-violet Visible and near IR observing Telescope (SUVIT). The SUVIT is designed to provide high-angular-resolution investigation of the lower solar atmosphere, from the photosphere to the uppermost chromosphere, with enhanced spectroscopic and spectro-polarimetric capability in wide wavelength regions from 280 nm (Mg II h&k lines) to 1100 nm (He I 1083 nm line) with 1.5 m class aperture and filtergraphic and spectrographic instruments.

1. Introduction

The next Japanese solar space mission, SOLAR-C, aims at studying small-scale plasma processes and structures in the solar atmosphere which attract researchers growing interest, followed by many Hinode discoveries (e.g. Suematsu 2010), for a fully understanding of the dynamics and magnetic nature of the atmosphere. With a large aperture optical telescope aboard SOLAR-C, a high resolution investigation of the entire solar atmosphere is planned with enhanced spectroscopic and spectro-polarimetric capability as compared with Hinode, together with enhanced sensitivity towards ultra-violet wavelengths. The SOLAR-C will be proposed for launch in late-2010s.

In this paper, we present the basic design of one major instrumental payload (Shimizu et al. 2011): the Solar Ultra-violet Visible and near IR observing Telescope (hereafter referred to as SUVIT). The basic concept when designing the SUVIT is to take advantage of the heritage from a successful space telescope; the Solar Optical Telescope (SOT) aboard Hinode (Suematsu et al. 2008; Tsuneta et al. 2008). Major differences between SUVIT and SOT are the about three times larger aperture (∼ 1.5 m), which enables to collect one order of magnitude more photons than SOT, a relatively shorter telescope length (2.8 m M1–M2 distance), and a much wider observing wavelength coverage from the UV (280 nm) through the near IR (up to 1100 nm). The large aperture is essentially important to attain the scientific goals of the SOLAR-C, especially for accurate diagnostics of the dynamic solar chromosphere as revealed by Hinode, although this makes it difficult to design the telescope because of the ten-times larger solar heat load introduced into the telescope.
2. Design of Telescope Assembly

Most designs of large-sized solar telescopes employ a Gregorian system. The advantage of the Gregorian configuration is that field stops can be placed at a primary and a secondary focus to reject unwanted out-of-field solar light to space. 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 $184 \times 184$ arcsec$^2$, with 4k×4k-pixel detectors 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 with accompanying focal plane instruments, and (3) to give negligible instrumental polarization before a polarization modulator or polarization calibration unit for precise polarization measurements.

The requirements derived from the high spatial resolution and the large number of photons collection capability lead to a 1.5-m class aperture, 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 the limited capacity of the launcher’s payloads (JAXA H-II rocket). The distance between the primary and the secondary mirror of the Gregorian is to be 2.8 m after preliminary opto-mechanical tradeoff studies within the
allowable size of the launcher’s nosecone. This short Gregorian configuration demands very small static mis-alignment tolerances for the primary and secondary mirrors; for instance, a short-term separation stability of the order of microns (< 3 µm) on-orbit during observations. To meet this tolerance, the framework is assumed to be made of a truss of ultra-low-expansion CFRP pipes, whose CTE was proven to be smaller than 0.1 ppm K⁻¹ (Suematsu et al. 2008).

To fulfill the achromatism over a wavelength range from 280 nm to 1100 nm, the collimator unit was designed with a fully-reflective system to be placed behind the primary mirror and with a reduced 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 an on-axis three-mirror system (Suematsu et al. 2011) which can accommodate the requirements of wide field performance, compactness in size and beam folding to the focal plane instruments attached at a side of the telescope assembly. A design was found in which two of the three mirrors are simple spherical and the third one is aspheric, with a surface figure expressed with the first nine Zernike terms, and that is capable to give the diffraction-limited performance when combined with the Gregorian system within the field of 200 arcsec diameter in wavelengths longer than 633 nm. A baseline optical layout is given in Figure 1.

3. Design of Focal Plane Instruments

The most important requirement in designing the instruments is to attain a polarimetric sensitivity high enough to measure polarized spectral lines emanating from the chromosphere. We identified that the He i spectral line at 1083 nm and the Ca ii line at 854 nm provide the best magnetic field diagnostic through the joint action of the Hanle and Zeeman effects. Simultaneous polarimetric measurements of the photosphere are also possible using the nearby photospheric spectral lines. The polarimetric sensitivity in Hinode SOT and existing ground-based telescopes 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 a 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.

Other important spectral lines are Mg ii h&k at around 280 nm to capture temperatures and velocities of fibril structures in the upper chromosphere because of the higher opacity at the lines. 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 aperture space telescope, the line can be a powerful tool for the diagnostics of the dynamics in the high chromosphere.

Both filtergraph and spectrograph are designed to provide capability of observing with those important chromospheric lines.

3.1. Filtergraph

Two types of filtergraphs are considered; one is a broad-band filtergraph focused on high spatial and temporal resolutions and the other is a narrow-band filtergraphs for 2D spectroscopic observations.

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

The small pixel sampling leads to a narrow field-of-view (FOV) because of the limitation of the detector size. With a 4k×4k-pixel detector, a FOV of 61 × 61 arcsec² 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 a pixel sampling of 0.045 arcsec. Candidates of observing wavelength bands are Mg II h&k line pair, CN band 380 nm, Ca II K band 393 nm, etc., and a few continua of wavelength shorter than 500 nm. An optical design is given in Figure 2, in which an interference filter is located at a telecentric focus. There are two optical channels between the relay lens and the detector to realize the high resolution mode and the wide FOV mode. One of the two modes is selected by opening and closing the shutters located at each channel.

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

A FOV close to 100 arcsec is expected to be achieved with 40 mm diameter calcite with F/40 telecentric focus. A blocking filter with a bandwidth smaller than the free spectral range of TF is located in front of it, 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. An optical design of the NF is shown in Figure 2.

### 3.2. Spectro-Polarimeter

The spectro-polarimeter (SP) is an instrument to obtain full Stokes profiles of magnetic sensitive spectral lines, and to provide precise polarimetric measurements of the chromospheric and photospheric lines to diagnose magnetic fields on the solar surface. The optical configuration of the spectro-polarimeter is given in Figure 2. The spectrograph employs a Littrow-type configuration similar to the spectro-polarimeter of Hinode SOT (Lites et al. 2001). It consists of an Echelle grating and an off-axis aspheric mirror for collimating and reimaging the beam before and after the grating. We chose the 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 i 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 the scanning duration, a multi-slit configuration is also considered, in which three slits are located with 60 arcsec separation to get spectra at multiple locations simultaneously. A Savart 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 Mg ii h&k lines at 280 nm in SP together with He i 1083 nm and Ca ii 854 nm, having co-focus at the slit plane among the three spectral bands is one of the challenging issues with refractive optics because of the chromatic aberration of the reimaging lens and limitation of lens materials transmitting in the UV light.

We investigated lens designs and found that we are able to have good co-focus in the three wavelengths when we use Lithium-fluoride (LiF) in addition to Silica and Calcium-fluoride (CaF2). The fabrication of LiF lens is not easy because of its high solubility. An alternative solution without LiF lens is possible with which a focus position correcting glass plate is added on the blocking filter for the 280 nm band.

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 a large number of photons within a short duration. On the other hand, infrared detectors generally require low working temperatures to suppress noise and dark current. We are now investigating the usage of a HgCdTe detector with a 1.7 μm cut-off which can be operated with relatively higher temperatures (Beletic et al. 2008).

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 10-20 sec integration at each slit positions to achieve the $10^{-4}$ polarimetric sensitivity. In addition to the deep polarimetric observation, the instrument is designed to support rapid scanning to make spectroscopic and spectro-polarimetric observations for the study of chromospheric dynamics and photospheric magnetic fields over the FOV with integrations shorter than 1 sec at each slit position.

4. Summary

The short telescope design with a 1.5-m class aperture Gregorian configuration was described with a compact design of an on-axis three-mirror collimator unit to accommodate the launcher nosecone size, wide observing wavelength coverage from UV (280 nm) through near IR (1100 nm), and diffraction limited resolution in wavelengths longer than 633 nm in a field of 200 arcsec in diameter. The 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), that is 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.

References

Suematsu, Y. 2010, Astron. Nachr., 331, 605