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The Solar-C_EUVST mission

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ABSTRACT

Solar-C_EUVST (EUV High-Throughput Spectroscopic Telescope) is a solar physics mission concept that was selected as a candidate for JAXA competitive M-class missions in July 2018. The onboard science instrument, EUVST, is an EUV spectrometer with slit-jaw imaging system that will simultaneously observe the solar atmosphere from the photosphere/chromosphere up to the corona with seamless temperature coverage, high spatial resolution, and high throughput for the first time. The mission is designed to provide a conclusive answer to the most fundamental questions in solar physics: how fundamental processes lead to the formation of the solar atmosphere and the solar wind, and how the solar atmosphere becomes unstable, releasing the energy that drives solar flares and eruptions. The entire instrument structure and the primary mirror assembly with scanning and

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tip-tilt fine pointing capability for the EUVST are being developed in Japan, with spectrograph and slit-jaw imaging hardware and science contributions from US and European countries. The mission will be launched and installed in a sun-synchronous polar orbit by a JAXA Epsilon vehicle in 2025. ISAS/JAXA coordinates the conceptual study activities during the current mission definition phase in collaboration with NAOJ and other universities. The team is currently working towards the JAXA final down-selection expected at the end of 2019, with strong support from US and European colleagues. The paper provides an overall description of the mission concept, key technologies, and the latest status.

Keywords: Solar Physics, EUV, Spectroscopy, Instrumentations, Spacecraft

1. INTRODUCTION

The visible Universe is mostly made of plasma, including the Sun and stars, the interplanetary, interstellar and the intergalactic medium, all of which display a large variety of dynamical behavior. The dynamical solar atmosphere has a significant impact on the Earth and other planets in our solar system. As a fundamental step towards answering how the plasma universe is created and evolves, and how the Sun influences the Earth and planets, the Solar-C_EUVST (EUV High-Throughput Spectroscopic Telescope) mission has been proposed to JAXA (Japan Aerospace Exploration Agency) by the Japanese solar physics community in collaboration with scientists from the US and European countries. The proposed mission is designed to comprehensively understand how mass and energy are transferred throughout the solar atmosphere. Understanding the solar atmosphere, which connects to the heliosphere via radiation, the solar wind, coronal mass ejections and energetic particles, is pivotal for establishing the conditions for life and habitability in the solar system.

2. SCIENCE OBJECTIVES AND STRATEGY

The mission is designed to provide a conclusive answer to the most fundamental question in solar physics: how does the interplay of magnetic fields and plasma drive solar activity? The most significant examples of this interplay are atmospheric heating, such as coronal heating and solar wind, and explosive energy release, such as flares and coronal mass ejections (CMEs). Thus, the two primary science objectives for Solar-C_EUVST are defined to:

I. Understand how fundamental processes lead to the formation of the solar atmosphere and the solar wind.

II. Understand how the solar atmosphere becomes unstable, releasing the energy that drives solar flares and eruptions.

Recent missions such as Hinode and SDO have clearly demonstrated that different layers of the solar atmosphere are highly coupled with each other via magnetic fields.[1] This interplay happens at spatial and temporal scales that have not been resolved over the full range of temperature extremes 0.01 MK in the chromosphere to 1 MK in the corona to 10 MK in flares. To understand the physical interplay between the plasma and magnetic field, we must determine how mass and energy are transported, stored, and converted into other forms of energy over vastly different physical domains. Therefore, to achieve the science objectives defined above, the mission is designed to

A. Seamlessly observe all the temperature regimes of the solar atmosphere from the chromosphere to the corona at the same time,

B. Resolve elemental structures of the solar atmosphere with high spatial resolution and cadence to track their evolution, and,

C. Obtain spectroscopic information on the dynamics of elementary processes taking place in the solar atmosphere.

Table 1 summarizes driving requirements on investigations and instrument design requirements of the mission concept. This mission concept provides a completely new set of spectroscopic tools to examine the solar atmosphere. A unique approach of the mission is to perform photometric and Doppler observations without temperature gaps from the chromosphere to the corona. Hinode is blind to much of the transition region (TR) and has no diagnostic capability in the chromosphere. It has become clear from analyses of Hinode data that these observational gaps prevent complete understanding not only of these layers, but also part of the corona and heliosphere, since the solar atmosphere is a coupled system. Solar-C_EUVST will rectify this with an instrument that simultaneously observes emission from the chromosphere, transition region, and corona at similar high spatial resolution. This has been previously impossible and it is one of the most innovative and challenging properties of this instrument. But this will be possible due to technical challenges that have been solved in recent years and will be described in section 4.

The spatial resolution is defined to reach 0.4" (or 300 km on the solar surface), which is about 7 times higher (50 times in the area size) than Hinode EIS[2] that is currently observing at the coronal temperatures. This high spatial resolution will allow for very small scale structures to be observed over the full range of temperatures in the solar atmosphere. The spatial scale is based on recent observations of typical chromospheric spicules and coronal rain, estimates of the filling factor of EUV coronal loops, and EUV images of twisting magnetic field lines revealed with Hi-C sounding rocket experiment. This resolution will allow the plasma properties of these structures to be observed directly for the first time throughout the atmosphere. Such spectroscopic observations will provide diagnostics of Doppler shifts, non-thermal velocities, temperature, and density at a spatial resolution and cadence currently only achievable by imaging instruments. This ability to observe 2D plasma properties at high cadence for the complete atmosphere has the potential to be as transformational as the first high-resolution imagers of the corona.

Table 1. A summary of Solar-C_EUVST science and instrument design requirements

Investigations' driving requirements	Instrument design parameters	design requirements
Temperature coverage: 0.02-15 MK, seamless	Wavelength	17.0-21.5 nm (SW) 69.0-85.0 nm (LW1) 92.5-108.5 (46.3-54.2) nm (LW2) 111.5-127.5 (55.7-63.7) nm (LW3)
Target spatial scale: 0.4 arcsec	Spatial resolution	0.4 arcsec
Temporal resolution: 2 sec/0.4" 0.5 sec/0.8"	Effective area Cadence of area coverage	Higher than 0.6-5.6 cm^2 0.5 sec (shortest)
Target size (max): 280 arcsec × 280 arcsec	Field of view	280 arcsec × 280 arcsec
Velocity resolution: $V_d \sim 2$ km/s, $V_{nt} \sim 4$ km/s	Spectral resolution ($\lambda/\delta\lambda$)	SW: 5000, LW: 13500
Context images: chromosphere/photosphere	Slit-jaw images (λ)	279.6, 283.3, and 285.2 nm include the corresponding ions Mg II, continuum, Mg I

3. MISSION CONCEPT

3.1 Trade off studies

The baseline instrument in the proposed mission concept was defined through analysis of the following six trade-off studies: 1) Recognising the highest priority direction of future research in the solar physics domain, 2) Identifying the most appropriate instrument to achieve the science goals, 3) Choosing the best wavelengths to enable high

S/N spectroscopy across the entire atmosphere, 4) Designing the spacecraft necessary to accommodate a UV spectrograph, 5) Surveying the optical parameters (Kawate et al. in this proceedings), and 6) Performing an orbit and telemetry trade-off study. For 1) and 2), the Next Generation Solar Physics Mission's Science Objectives' Team (NGSPM-SOT) *, chartered by JAXA, NASA and ESA, identified key science objectives, based on extensive reviews of the broad interests of the community with a public call for white papers of science objectives, and gave priority to the exploration of physical mechanisms on elemental (small) scales as a near-term mission opportunity in 2020s. The NGSPM-SOT also recommended three types of instruments (0.3" coronal/TR spectrograph, 0.2"-0.6" coronal imager, and 0.1" chromospheric/photospheric magnetograph/spectrograph) as the highest priority instruments to be realized in mid 2020s for the study of fundamental physical processes occurring in the solar atmosphere. The baseline instrument in the proposed mission concept is similar to the recommended 0.3" coronal/TR spectrograph. For 3), UV spectroscopy was chosen for the mission concept by comparing with different spectroscopic methods in soft X-rays and in the visible light from the viewpoint of scientific performance. Studies 4), 5), and 6) were carried out to identify the optical configuration of the instrument, the instrument accommodation in the spacecraft system, and the orbit selection of the mission. Since the Solar-C_EUVST has been proposed to a call for proposal for JAXA's competitively chosen M-class missions to be launched by an Epsilon rocket, the Epsilon rocket performance constrains the mission design in the 4), 5), and 6) studies.

3.2 Baseline architecture

The EUVST instrument consists of the minimum number of optical components for a spectrograph, as shown in Figure 1. The two-element design, pioneered by the Hinode EIS instrument, minimizes the number of reflections in the system, i.e., the primary mirror and grating, which is essential to achieve high throughput performance, i.e., improving temporal resolution in the required spatial resolution. Kawate et al. (2019, this proceedings) have found an optical configuration for achieving the required 0.4" spatial resolution.

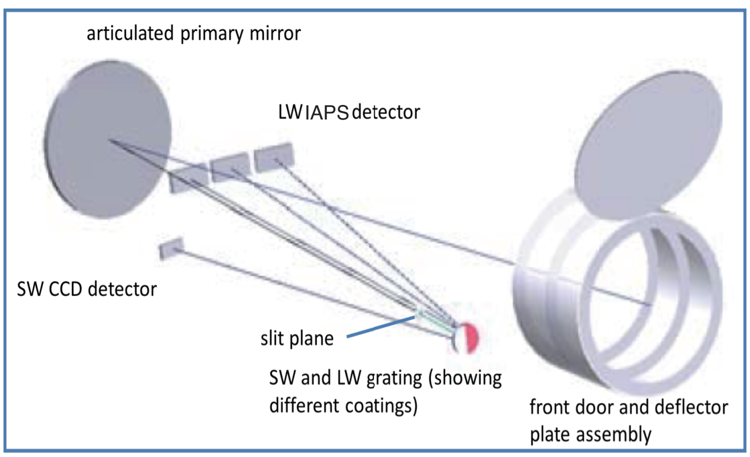

Figure 1. Schematic optical layout of the EUVST instrument. The path of EUV radiation through is shown.

Figure 2 is the physical block diagram and Figure 3 is the opto-mechanical layout of the EUVST instrument, showing major components in the instrument. The main structure of the instrument module is made of Carbon Fiber Reinforced Plastics (CFRP) and has support structures to mount components for the spectrograph. The entire structure is attached to the robust optical bench, which is jointed by bipods to a mechanical interface on the top panel of the bus module. This mounting interface needs to provide thermal independence from the Al honycomb top panel of the spacecraft bus.

The primary mirror assembly located almost at the bottom of the instrument receives the solar light from the entrance at the top, where an aperture door is attached for protecting the optics from contaminants during

*The report is available at https://hinode.nao.ac.jp/SOLAR-C/SOLAR-C/Documents/NGSPM_report_170731.pdf the launch and on the ground. The primary mirror assembly has a light-weight off-axis parabola (28 cm in diameter, focal length 280 cm), which makes a solar image on the slit located near the top of the instrument. The parabola is mounted on a two-axis tip-tilt mechanism with a focus mechanism. The tip-tilt mechanism stabilizes the solar image on the slit by compensating the spacecraft pointing jitter, which is measured by a guide telescope attached beside the telescope structure. In one direction, the tip-tilt mechanism provides the slit scanning capability, allowing to scan the field of view by moving step by step the position of the solar image on the slit. The focus mechanism is a linear translator that ensures the best focus image on the slit. The tip-tilt scanning mechanism and focus mechanism are controlled by the telescope electronics box.

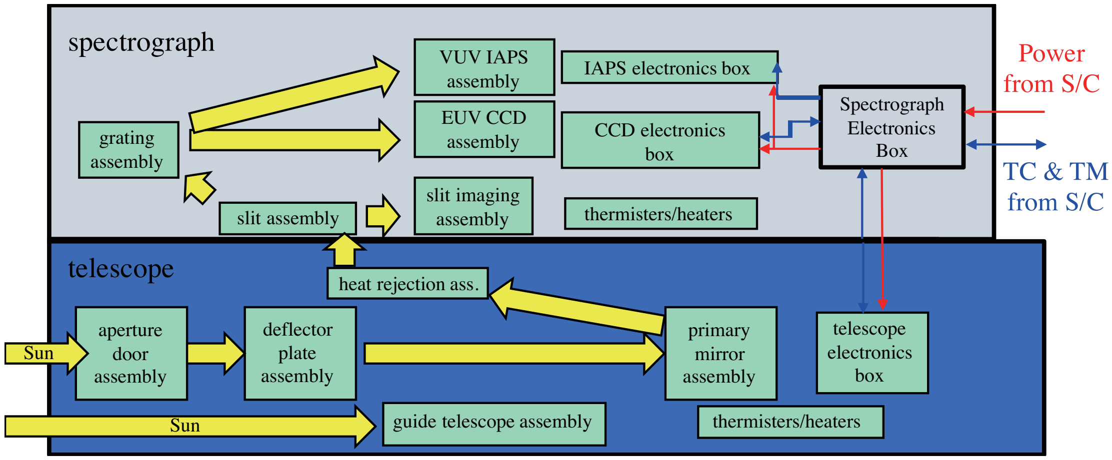

Figure 2. Physical block diagram of the EUVST instrument, showing major components in the instrument.

The slit selects a one-dimensional portion of the solar image and this radiation is incident onto a concave diffraction grating. The beam from the slit is incident on the SW and LW gratings. The SW grating is for a shorter channel covering 17.0 - 21.5 nm and the LW grating is for longer wavelengths in 46 - 127.5 nm. CCD and intensified APS (active pixel sensor) detectors are used for short and long bands, respectively.

The slit surface reflects UV light around 280 nm, which is fed to the slit jaw imager. The imager uses relay optics to form a narrow-band solar image including the entire slit and its surroundings on an image detector. This imager provides a series of complementary chromospheric and photospheric images, which are used not only for co-alignment purposes but also for investigating dynamics of the lower solar atmosphere.

3.3 Spacecraft

The EUVST instrument is mounted to the top panel of the bus module with the solar array paddles deployed from both sides (Figure 4). The latest conceptual study by spacecraft systems candidates shows that the current best estimated total mass of the mission is 520-550 kg, which is well within the capability of the launch vehicle, Epsilon rocket. The Epsilon with post boost stage (PBS) can install a 590 kg spacecraft into a sun-synchronous polar orbit at the height of 600-650 km and 560 kg for 700 km.

The spacecraft attitude is stabilized in three axes with the EUVST aperture pointed to the Sun. In a similar way to the Hinode attitude system, the spacecraft tracks a region on the solar surface by correcting for solar rotation in many observation cases, in addition to the spacecraft pointing to a fixed position on the solar disk and above the limb. The attitude control takes care of jitter in the low to medium frequency region (lower than about 1 Hz) through the combined use of attitude information from the Ultra Fine Sun Sensor (UFSS) mounted to the EUVST, high resolution gyroscope, and star tracker. Note that the tip-tilt mechanism in the EUVST instrument and the structure of the spacecraft and instrument take care of jitters in the medium frequency (about 1-10 Hz) and in the high frequency region (higher than 10 Hz), respectively. High pointing stability is achieved with a combination of the attitude control, the tip-tilt mechanism and the structure.

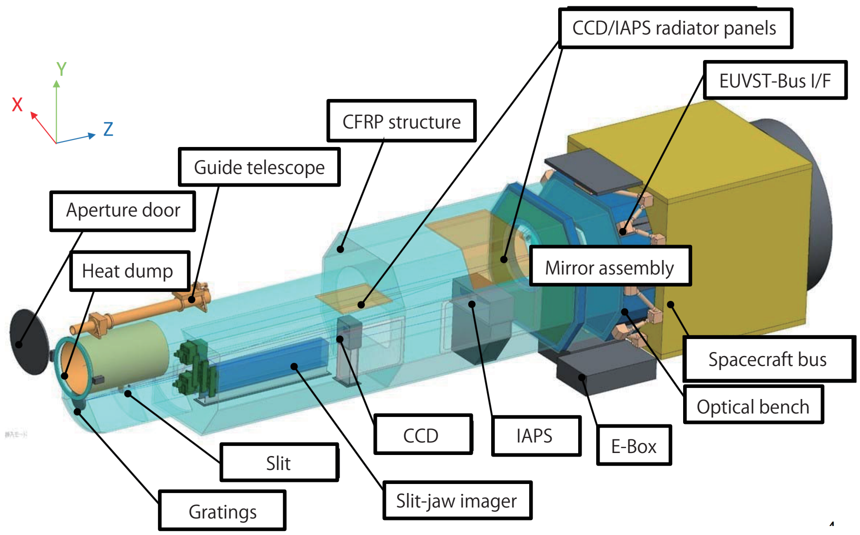

Figure 3. The opto-mechanical layout of the EUVST instrument.

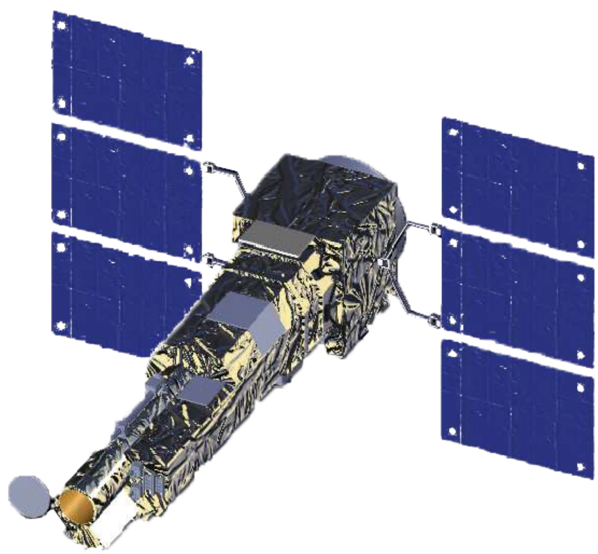

Figure 4. The artist impression of the Solar-C_EUVST mission.

4. KEY TECHNOLOGIES

Although the combination of the components briefly described in section 3 will achieve the performance required for the EUVST mission, some components contain key technologies that drive the optical performance. In this section, we briefly discuss the following key technologies: 1) active primary mirror assembly for high spatial resolution, 2) multilayer coating for high throughput and broad temperature (wavelength) coverage, 3) grating for high spatial and dispersion performance, and 4) detectors covering broad wavelength range.

4.1 Active Primary Mirror Assembly

The mirror is made of an ultra-low expansion glass material, such as Zerodur or ULE, which has advantages to ensure very low thermal deformation and realize very low surface micro-roughness for suppressing unwanted scattered light. The heritage from our development on the 50 cm diffraction limited mirror system for Hinode/SOT[3] can be extensively utilized, but the control of thermal deformation on the mirror surface figure will be one of the new key technologies because the mirror will be operated at a relatively high temperature (80 deg C). With such a high temperature, the mechanism for supporting the mirror may deform the surface figure, for example through stress due to the difference of CTE (Coefficient of Thermal Expansion) between the mirror and mounting metal pads bonded on the mirror. The high-quality mirror surface figure will be achieved by polishing and verified at the room temperature (23 deg C), but the thermal deformation caused by a temperature change from 23 deg C to 80 deg C needs to be controlled below the required level. Utilizing the basic design developed for the secondary mirror of SOT,[4] the mirror assembly design was carried out to minimize this thermal deformation, enabling us to achieve a wavefront error caused by the thermal deformation that is negligibly small - at most 1 nm rms - over the temperature change (Suematsu et al. 2019 in this proceedings).

The tilt stage underneath the mirror consists of a two-axis gimbal mechanism for the tip-tilt image stabilization and the slit scan observations. The tilt stage is driven with four voice-coil actuators mounted on the mirror cell. The team has a rich history developing tip-tilt mechanisms, including the tip-tilt secondary mirror mechanism for the X-ray Doppler Telescope successfully launched by an S-520-22 sounding rocket in 1998[5] and the high precision tip-tilt mirror mechanism with piezo actuators for Hinode/SOT.[6] The SOT's image stabilization system with this tip-tilt mechanism achieved 0.03 arcsec (3σ) on orbit,[6] greatly contributing to diffraction-limited imaging observations for more than 12 years. For the Solar-C application, the team performed a conceptual study on the tip-tilt mechanism for both the tip-tilt image stabilization and slit scan functions, and identified the following three technologies that should be studied and evaluated first: 1) sensors to measure the tilt angle with sub arcsec accuracy, 2) low noise driver for actuators, and 3) launch lock mechanism. In 2015, the team developed a bread-board tip-tilt mirror mechanism (8 cm diameter) with built-in sensors for measuring the tilt angle and its servo controller and confirmed tilting and scanning control with accuracy of 0.3 arcsec (3σ). This stability performance would correspond to better than 0.05 arcsec (3σ) if the same built-in sensors are used in 28 cm diameter mechanism. The same type of tip-tilt and scan mechanism will be used as the scan mechanism for the Sunrise Chromospheric Infrared spectroPolarimeter (SCIP) instrument[7] onboard the international Sunrise balloon-borne telescope which will have its third flight in 2021.

The mirror cell is supported by a translational actuator like a ball-screw which is used for re-focusing. In the case of the ball-screw drive, the mirror cell needs to be additionally supported by leaf springs or guide rails. In 2011-2014, a focus mechanism assembly (FMA) was developed and qualified for usage in the space environment for EUVST. This mechanism uses a ball screw to translate the motor motion to the linear motion. This bread-board model was designed to have a step resolution of 100 μm in the range of 60 mm.[8] For adapting it to EUVST, higher step resolution will be required for a shorter range. As one of the important verification items, this bread-board model was successfully operated in high vacuum environment to verify over 1×10^5 cycles of the back-and-forth motions.[9]

4.2 Multilayer coating

A robust Mo/Si multilayer coating with a B_4C capping layer is applied to the primary mirror surface. This coating uses well-known and characterized materials and provides excellent performance over a broad wavelength range in the EUV-UV. The selection of a single mirror coating rather than two separate tailored coatings minimizes the risk of wavefront deflections induced by a split-mirror telescope. Moreover, a uniform coating (uniform reflectivity and emissivity) minimizes thermal stresses throughout the mirror. In addition, it maximizes the throughput performance.

A design example of the mirror coating has high normal-incidence reflectance in the EUV wavelength ranges 17.0 - 21.5 nm and above 46.0 nm.[10] The coating consists of a graded Mo/Si multilayer capped with a 10 nm thick B_4C layer. The B_4C capping layer on the telescope mirror provides a reflectance above 30% in the wavelength range of the LW channel. The individual coatings have been qualified at temperatures up to 200 deg C. Tests of the B_4C capping layer conducted for SPICE on Solar Orbiter showed that the coating must be protected from incoming solar wind protons. The EUVST primary mirror will be protected by a proton deflector, consisting of two parallel plates providing an electrical field strong enough to deflect incoming protons from their path towards the primary mirror. Such a design was successfully used in the SUMER spectrograph on SoHO and the SPICE spectrograph on Solar Orbiter.[11]

4.3 Grating

The gratings (both LW and SW) are ruled onto a toroidal surface like that used in many prior solar EUV spectrographs such as SoHO/CDS or Hinode/EIS, as well as several NASA sounding rocket payloads (EUNIS, VERIS and RAISE). However, instead of the traditional constant line spacing, EUVST uses rulings with variable line-spacing (VLS) in order to minimize optical aberrations.[12]

The instrument performance improvements are the result of a remarkable breakthrough in spectrograph design which incorporates a Toroidal Variable Line Space (TVLS) grating to perform the necessary measurements on the critical spatial and temporal scales. The highly magnifying mount allows an instrument of reduced size compared to that of a conventional spectrometer with similar spatial resolution. This design provides high-quality performance and unprecedented plate scale for the EUVST. A holographic, 2400 groves/mm TVLS grating has been fabricated by Horiba/Jobin Yvon (HJY) for the Solar Orbiter/SPICE spectrograph.[11] The SW grating of EUVST has a relatively high groove density of 4200 lines/mm. Note that the Hinode/EIS uses 4200 grooves/mm toroidal grating with constant line-spacing (TCLS) grating (fabricated by Zeiss). The FUSE experiment used holographically ruled, spherical gratings with 5767 lines/mm and 5400 lines/mm (fabricated by HJY).[13]

4.4 Detectors

The EUV focal plane assembly for the SW band consists of two E2V 42-40 detectors. These detectors are butted together for minimal gap. The combined format is 2048×4096. Back-thinning and coating of the CCD will achieve optimal EUV quantum efficiency and stability. These detectors have been used extensively in the past. Current solar missions with E2V CCDs include: Hinode/EIS, Hinode/XRT, Hinode/SOT, STEREO/SECCHI and SDO. The focal plane incorporates a 1000 Å thick aluminum foil filter to reject the visible radiation. The camera assembly is equipped with a focal plane shutter. The CCDs will be thermally isolated and strapped to an external radiator to be cooled to below -40 deg C. Previous work for the Hinode/EIS instrument has shown that this temperature will be sufficient to suppress dark current and warm pixels for the expected on-orbit dose.

The LW detectors consist of three independently operated intensified active pixel sensor (APS) detectors. The focal plane assembly is similar to previous intensified focal plane assemblies flown on SoHO/CDS, SO/SPICE, SO/Metis and SO/EUI. APS detectors have been developed and utilized extensively on the Solar Orbiter mission in the remote sensing instrumentation. The APS detector for EUVST is identical to the devices utilized on the SO/SoloHI. Each focal plane assembly will incorporate two 1920×2048 detectors with 20 μm equivalent pixels (at the micro-channel plate surface). The APS detectors will be coupled to the back end of the microchannel plate (MCP) intensifier by a 2:1 fiber optic taper. The MCP intensifier provides high efficiency and blindness to solar visible radiation such that no focal plane filters are needed. A filter wheel with an Al thin film, order sorting filter will be used to observe the Ne VII 46.5nm emission line. The MCP front faces will carry the selective photocathode coatings with CsI and/or KBr. The APS detectors will be cooled to below 45 deg C. To protect the photocathode and MCP, each detector assembly is equipped with a vacuum-tight or sealed door.

5. PERFORMANCE

The expected performance of the baseline architecture is briefly discussed based on our concept study in this section. Of the instrument design requirements in Table 1, we focus on the spatial resolution and effective area.

The image quality of the baseline design is evaluated as our current best estimate by creating an imaging error budget table. The latest evaluation shows that the total EUVST resolution is $0.27 - 0.31$ arcsec, which is $54 - 39$ % margin to the required 0.4 arcsec. The budget table contains the image quality achieved by the optical design, the wavefront error expected in fabrication and assembly based on Hinode experience, the wavefront error caused by the thermal deformation of the primary mirror surface, and the blur due to the pointing jitter.

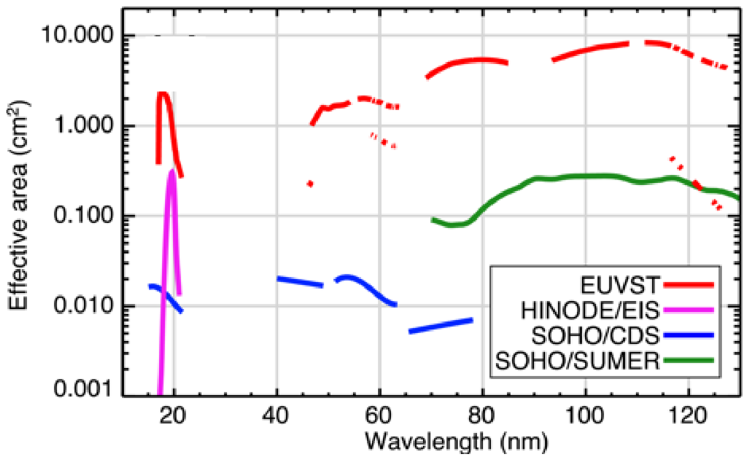

Figure 5. Effective area based on the baseline architecture. The effective areas of Hinode/EIS, SoHO/SUMER, and SoHO/CDS are also shown for comparison.

Figure 5 is the expected effective area based on the baseline architecture, which was estimated by a product of mirror reflectivity, grating efficiency, detector efficiency, telescope area and transmission of filters in the optical path. The calculation shows that the effective area will meet the design requirements. The peak efficiencies give a factor of 10 improvement with respect to Hinode/EIS in the EUV (SW) and an improvement of a factor of 40 over SoHO/SUMER in the FUV (LW).

6. MISSION STATUS

The Solar-C_EUVST mission was proposed to ISAS/JAXA in January 2018, in reply to the 2017 Announcement of Opportunity for competitive M-class missions to be launched by the JAXA Epsilon vehicle in the mid-2020s. The Advisory Committee for Space Science and Engineering evaluated all the submitted mission concept proposals including the Solar-C_EUVST mission concept and recommended two mission concepts including Solar-C_EUVST to ISAS to proceed to the next study phase Pre-Phase A1b (Idea implementation process in Mission exploration phase) for further studies in July 2018. As a part of the process to proceed to the next Pre-Phase A2 (Mission definition phase), ISAS held an international science review in December 2018 and the pre-project candidate selection review in March 2019 to organize the pre-project candidate team in ISAS. The committee for the international science review consisted of 6 world leading scientists appointed from Europe, US and Japan with the director of the solar system sciences department in ISAS as the moderator. The committee reviewed the documents and presentations on the science objectives, technical feasibility and international task shares of EUVST prepared by the EUVST team and confirmed that the science goals are justified and compelling and that the conceptual design is feasible and appropriate to meet the science goals, concluding that Solar-C_EUVST will make essential contributions to advance our understanding of the solar atmosphere, the heliosphere, solar-terrestrial relationships, and fundamental astrophysical plasma processes during the next decade. The Solar-C_EUVST is currently in the mission definition phase and ISAS has scheduled the final down-selection in December 2019 for competitively chosen M-class mission #4, whose launch is expected around 2025.

The proposed Solar-C_EUVST mission is a Japan-led mission with substantial participations from US and European countries. The EUVST instrument will be developed by a JAXA-led international hardware development consortium, and the development responsibilities reflect the expertise and strengths of each partner. JAXA will be responsible for managing the whole instrument development. Moreover, JAXA will build the spacecraft system and the EUVST telescope unit, including the active mirror assembly, and its accompanying spectrograph structure, and contribute to the design of the EUVST spectrograph. The overseas part of the consortium will be responsible for managing the overall development of the spectrograph and its hardware components. The US team submitted a Partner Mission of Opportunity proposal to NASA about the NASA contributions to the EUVST development, which is currently being reviewed for selection. Each European representative in Germany, UK, France, Italy, Belgium, and Switzerland has been coordinating with each national space agency to define the European contributions to the EUVST development. The involvement of ESA (European Space Agency) is desirable for securing involvement from the European national agencies as well as for downlink of large amount of mission data, similar to the Hinode post-launch operations. In order to realize these international collaborations JAXA has been coordinating with NASA and ESA.

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