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The Solar-C (EUVST) mission: the latest status

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ABSTRACT

Solar-C (EUVST) is the next Japanese solar physics mission to be developed with significant contributions from US and European countries. The mission carries an EUV imaging spectrometer with slit-jaw imaging system called EUVST (EUV High-Throughput Spectroscopic Telescope) as the mission payload, to take a fundamental step towards answering how the plasma universe is created and evolves and how the Sun influences the Earth and other planets in our solar system. In April 2020, ISAS (Institute of Space and Astronautical Science) of JAXA (Japan Aerospace Exploration Agency) has made the final down-selection for this mission as the 4th in the series of competitively chosen M-class mission to be launched with an Epsilon launch vehicle in mid 2020s. NASA (National Aeronautics and Space Administration) has selected this mission concept for Phase A concept study in September 2019 and is in the process leading to final selection. For European countries, the team has (or is in the process of confirming) confirmed endorsement for hardware contributions to the EUVST from the national agencies. A recent update to the mission instrumentation is to add a UV spectral irradiance monitor capability for EUVST calibration and scientific purpose. This presentation provides the latest status of the mission with an overall description of the mission concept emphasizing on key roles of the mission in heliophysics research from mid 2020s.

Keywords: Solar Physics, EUV, Spectroscopy, Heliophysics

1. THE MISSION: REQUIREMENTS

In the SPIE conference held in August 2019, Shimizu et al. presented the overall description of the Solar-C (EUVST) mission.[1] It should be noted that the Solar-C_EUVST mission has been renamed to Solar-C (EUVST) at the JAXA final down-selection for the 4th in the series of competitively chosen M-class mission. In the period after the 2019 SPIE conference, one of major efforts the mission proposing team has made is to polish up the mission requirement and system requirement for the mission. Here we provide a brief description of the requirements.

1.1 Mission Requirement

As a fundamental step towards answering how the plasma universe is created and evolves, and how the Sun influences the Earth and planets in the solar system, the Solar-C (EUVST) mission is designed to comprehensively understand how mass and energy are transferred throughout the solar atmosphere. For providing a conclusive answer to the most fundamental question in solar physics, i.e., how does the interplay of magnetic fields and plasma drive solar activity, we have defined two primary science objectives:

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.

For the primary objectives, 6 specific science objectives with 16 observing tasks in total are defined to clearly specify the scope and requirements of the mission, leading to 7 mission requirements and mission success criteria.

1.2 System Requirements

To achieve the science objectives, the mission takes the following unique approaches:

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

B. To resolve elemental structures of the solar atmosphere and track their changes with sufficient cadence, and,

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

Following these approaches, we have identified the most suitable wavelength bands to be in the vacuum ultraviolet (VUV), comprising the extreme ultraviolet (EUV - 10 to 120 nm) and in the Far Ultraviolet (120 to 200 nm). This concept provides a completely new set of spectroscopic tools to examine the solar atmosphere. Table 1 summarizes the mission's system requirements for science investigations and instrument design specifications. 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.[2] This interplay happens at spatial and temporal scales that have not been resolved over the full range of the temperature regime. The mission is required to cover the temperature range from 0.02 MK (the chromosphere) to 20 MK (flare plasma) to provide emission line spectroscopy without any substantial gaps. The spatial resolution is required to be 0.4" (or 300 km on the solar surface) or less within a field-of-view of 100×100 arcsec^2 and 0.8" or less over the whole field-of-view (larger than 280×280 arcsec^2). The temporal resolution can be high as 0.5 sec with spectroscopic capability to measure Doppler velocity with an accuracy of 2 km/s. The spatial and temporal resolution requirements define a sensitivity requirement for the planned observations. With these major requirements for the mission instrument, many other requirements have been defined not only for the mission instrumentation but also for the entire system including the spacecraft and ground facilities for mission operations and data flows.

Table 1. Key system requirements for science instrumentation and design parameters

Investigations' system requirements	Instrument design parameters	specifications
Temperature coverage: 0.02-20 MK without substantial gaps	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)
Spatial resolution: $\leq$0.4 arcsec (100×100 arcsec^2) $\leq$0.8 arcsec (280×280 arcsec^2)	Spatial resolution	 $\leq$0.4 arcsec (100×100 arcsec^2) $\leq$0.8 arcsec (280×280 arcsec^2)
Temporal resolution: 0.5 sec (shortest) with spectroscopic capability	Effective area Cadence of area coverage	Higher than 0.6-5.6 cm^2 0.5 sec (shortest)
Field of view: 280×280 arcsec^2	Field of view	280×280 arcsec^2
Velocity resolution: $V_d \sim 2$ km/s	Spectral resolution ($\lambda/\delta\lambda$)	SW: 5000, LW: 13500
Image observations: chromosphere/photosphere	Slit-jaw images (λ)	279.6, 283.3, and 285.2 nm include the corresponding ions Mg II, continuum, Mg I

2. THE EUVST INSTRUMENT

The EUVST instrument consists of the minimum number of optical components for a spectrograph, i.e., the primary mirror and grating with a slit and detectors. Figure 1 shows the overall layout of the EUVST instrument and its major components. The instrument will be developed under Japanese leadership with hardware contributions from the US and European countries, which are shown by national flags in the figure to indicate which portions will be contributed by these countries.

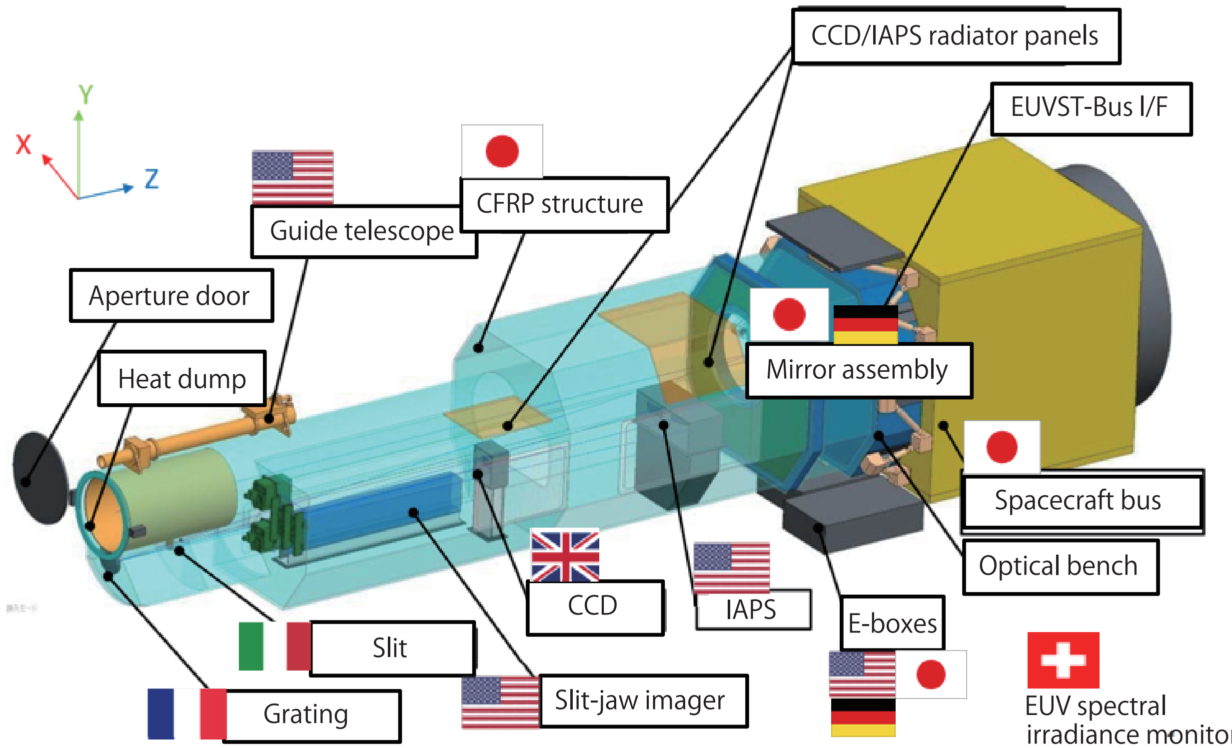

Figure 1. The EUVST instrument with international contributions.

The main structure of the instrument module is made of Carbon Fiber Reinforced Plastics (CFRP) and it is about 3.5 meters in length. It has support structures to mount components for the spectrograph. The entire structure is attached to a 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. It is noted that major revisions for this mounting interface concept will be expected to reduce the total weight while keeping high rigidity according to the technical feasibility study on-going in 2020.

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 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 the position of the solar image on the slit step by step. 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.

The slit selects a one-dimensional portion of the solar image and this radiation is incident onto a concave diffraction grating. Several types of slit are available for observations and calibrations. The beam from the slit is incident on the SW and LW gratings. The SW grating is for the Short Wavelength channel covering 17.0 - 21.5 nm and the LW grating is for the Long Wavelength channel covering 46 - 127.5 nm. CCD and intensified APS (active pixel sensor) detectors are used for short and long bands, respectively to record spectrally dispersed light from the gratings.

In addition, 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 a detector.

This imager provides a series of complementary chromospheric and photospheric images, which are used not only for co-alignment purposes with other observing facilities on the ground and in space but also for investigating the dynamics of the lower solar atmosphere.

Besides the EUVST instrument briefly described above, a spectral irradiance monitor for two EUV and VUV channels will be intalled to the upper portion of the EUVST instrument structure. The wavelength ranges that EUVST observes are the most sensitive to the molecular contamination that degrades the key performance of the high instrument throughput. The irradiance monitor, by providing how the solar UV irradiance is variable during the mission, is highly valuable for the purpose of intensity cross-calibration of the EUVST spectral data. Scientific gains are also to be expected to open the mission to different science fields, such as space weather and climate research.

3. MISSION STATUS

After pre-down-selection review in January-March 2020, ISAS/JAXA has selected the mission in April 2020 as the 4th in the series of competitively chosen M-class focused missions, which will be launched with an Epsilon launch vehicle in mid 2020s (the latest target is December 2026). Immediately after the down-selection, Solar-C (EUVST) is listed as the 4th M-class mission in the timeline at the revision of the Japanese government's basic plan on space policy in June 2020. In the JAXA phase-up process, the team is currently in Pre-Phase A2 (Mission definition phase) as of November 2020. Along with polishing up requirements documents that will be authorized as the baseline requirements at Mission Definition Review, this phase has been used to carry out front-load feasibility studies to access technical feasibility with conceptual design efforts by contractor candidates in Japan and to reduce development risks. Although the technical readiness of the key technologies to be used in the Japanese EUVST telescope are mature, these feasibility studies in FY 2019 have provided our identification of some areas that require more detailed design efforts, such as optical layout optimization,[3] thermal deformation of the primary mirror,[4] weight reduction in the tip-tilt mechanism and launch lock for the tip-tilt mirror. More detailed design efforts are on-going in 2020, and from the efforts, some reports will be expected in future SPIE conferences. To achieve high spatial resolution performance required for the EUVST instrument, a high precision but compact sun sensor (Ultra Fine Sun Sensor, UFSS[5]) is one of the key components for the spacecraft system. A breadboard model for the UFSS sensor and cross-correlation circuit has been developed, giving fairly good performance while identifying areas for further improvements.

The 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 (Figure 1). NASA has selected our Partner Mission of Opportunity proposal for the NASA contributions to the EUVST development as one of Phase A concept studies of missions in September 2019. The US team performed a concept study for US components during the October 2019 - August 2020 timeframe, and the concept study report has been delivered to NASA. NASA is now performing final reviews, with a final selection expected by March 2021. Each European representative in Germany, UK, France, Italy, and Switzerland has coordinated with each national space agency to define the European contributions to the EUVST development. All of these national agencies have sent endorsement letter to ISAS/JAXA in response to invitation letter from ISAS/JAXA director general and have been working for funding. With some initial funds, European institutes are in Phase-A studies. JAXA is interested in the involvement of ESA (European Space Agency) for downlink ground supports, similar to the Hinode mission, and potential hardware contributions to the spacecraft. Agency-level communications are under way for the coordination.

4. A STEP TOWARD NGSPM SCIENCE

The Next Generation Solar Physics Mission Science Objectives Team (NGSPM-SOT) report in 2017 * has recommended a minimum set of instruments with which NGSPM can address the greatest number of major objectives in solar related research field and maximize the science return of the mission. The team consisted of 14 scientists from US, Europe and Japan and was chartered by NASA, ESA, and JAXA to develop and

*https://hinode.nao.ac.jp/SOLAR-C/SOLAR-C/Documents/NGSPM_report_170731.pdf document scientific objectives that should be addressed in 2020s and to make priority of notional instruments for an NGSPM within the resources and framework specified by the agencies. The report recommends a suite of instruments that can meet a majority of the key required measurements for the scientific objectives. The EUVST instrument has been planned to realize the highest priority instrument T-09, i.e., 0.3 arcsec coronal/transition region spectrograph, in the suite of instruments.

The Solar-C (EUVST) mission will also be important for physically connecting the Sun to the inner heliosphere. 2020s will be a golden age for high resolution observations of the Sun. New ground-based solar telescopes, such as Daniel K. Inouye Solar Telescope (DKIST), will start to operate from early 2020s. New explorers, such as Parker Solar Probe,[6] Solar Orbiter,[7] and BepiColombo,[8] will carry out in-situ measurements in the inner heliosphere in this decade. NASA's small explorer PUNCH will investigate the outer corona from 5 solar radii outward. EUVST would have great synergy with the proposed MUSE (MUlti-slit Solar Explorer) mission, currently in a phase A study for a NASA MIDEX. EUVST and MUSE together would address the two highest priority instruments in the NGSPM report, T-09 and T-07 (a high-resolution coronal imager). EUVST observations will provide spectroscopic measurements in the atmosphere from the chromosphere through the lower corona, which are unique observations to physically link the solar atmosphere to the inner heliosphere. In-situ measurements at vantage points by Parker Solar Probe, Solar Orbiter, and BepiColombo will be available, and the coordinated observations with EUVST will provide unique opportunities for connecting the Sun to the inner heliosphere. In addition, the close coordinated observations with Solar Orbiter will provide us fruitful and unique opportunities in EUV spectroscopy to diagnose dynamics and heating in the solar plasma by making stereoscopic measurements with SPICE[9] on Solar Orbiter.

5. MISSION OUTCOMES

Finally, we summarize a few expected outcomes from the Solar-C (EUVST) mission. First, towards answering how the plasma universe is created and evolves, new knowledge of the solar atmosphere based on the Solar-C (EUVST) observations can be applied to improvements in the understanding of other stellar atmospheres. The value of the Solar-C (EUVST) observations will be much enhanced in combination with ground-based observations, MHD numerical simulations, and other theoretical studies. Second, towards answering how and when the Sun influences the Earth and other planets in the solar system, our improved understanding of the solar atmosphere based on the Solar-C (EUVST) observations can be used to develop new algorithms for flare predictions and to estimate the impacts on the terrestrial environment by cooperating with other observations and theoretical studies. Third, Solar-C (EUVST) observations will be used to look into fundamental physical processes, such as magnetic reconnection, nonlinear damping of waves, shock heating, turbulence, radiative transfer, and plasma non-equilibrium. These processes are discussed not only in the context of solar physics but also in a broader perspective of astrophysics. Thus, the mission will enhance our knowledge on plasma physics, atomic physics, and magnetohydrodynamics. Finally, new knowledge on the fundamental physical processes working in the solar plasma will help us to infer long-time history of the solar terrestrial environment that is formed with the solar wind, solar irradiance, energetic particles, flares, and CMEs. We might be able to address the faint young-Sun paradox by inferring the solar terrestrial environment 3.5 billion years ago when earliest forms of life appeared on the Earth.

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