8. Threshold science mission (draft) [1-4-3]
最低限達成しなければならない科学 output のドラフト

The threshold science mission shall execute the observations necessary to: trace the mass and energy flows through the atmosphere from the chromosphere into the corona; study energy release in small-scale transients (e.g., explosive events, bright points); and determine the properties of waves throughout the atmosphere.

The threshold science mission will meet all of the Solar-C_EUVST requirements with the following exceptions:

- Spatial Resolution: An angular resolution better than 0.8”, which is two times worse than the target spatial resolution.
- Temperature Coverage: At least three wavelength bands to measure line intensities and derive electron densities and temperatures in the thermal coverage from the chromosphere to the flaring corona.
- Field of View: Obtain repeated raster scans of representative targets in the quiet Sun, active regions, and coronal holes on the solar disk over a limited field of view [100” (scan range) × 100” (along the slit)].
- Effective Area: Reduced throughput by factor 4 that still has more than twice larger effective area than past and current instruments
- Co-alignment: Shall obtain images by the slit jaw imaging camera in at least one wavelength for co-alignment.

The minimum spatial resolution is still better than that achieved so far with past and current on-going missions covering coronal temperatures; the spectroscopic data from Hinode/EIS has 2”-3”, and from SoHO/SUMER has 1.6”, and the coronal images from SDO/AIA has 1.6” (Table 6.4). Seamless temperature coverage is still maintained with three cameras, although some spectral lines would not be available. Velocity diagnostic performance, i.e., Doppler shifts and non-thermal broadening, is kept to trace mass and energy flows through the atmosphere. The target region could be restricted to inside the solar disk due to pointing limitations, but some of specific tasks relating to the solar wind in objective I-3 would be affected. The minimum field of view of a nominal raster scan allows us to perform many of the observing modes defined in Table 6.7. Small-scale transients, such as nanoflares, microflares, various types of jets, bright points, and explosive events, can be captured within the limited field of view. High temporal resolution is required to detect the Alfvenic signatures (1 sec exposure per 1” slit scan step to follow the Alfven speed at the corona, i.e., ~1,000 km/s). If the effective area is reduced by factor of 4, the signatures can be followed by slit scanning with exposure 1.6 sec and 1.6” step (equivalent to the spatial resolution of SUMER and AIA). Slit jaw imaging at one wavelength will allow for co-alignment with ground based observations.

9. Gross characterization of space environment [3-2-3]
ミッションを実施する宇宙環境

The proposed mission concept requires the achievement of sub-arcsec spatial resolution of spectroscopic observations for spatially resolving elemental magnetic structures in the upper solar atmosphere. It also requires continuous viewing of the Sun from the orbit for investigating the temporal evolution of solar phenomena on timescales longer than at least one hour. Experience from previous spectroscopic telescopes on SoHO and on Hinode has shown that a stable temperature environment is mandatory to reach optimum optical performance characteristics. There are three orbit candidates for a stable temperature environment with continuous viewing of the Sun: 1) L1 point, where SoHO is operated, 2) sun synchronous orbit (SSO), into which Hinode, TRACE and IRIS are installed, and 3) geosynchronous orbit (GSO), where SDO is currently operational. The Epsilon rocket vehicle is used for the orbit installation of the proposed mission, which can install a

590 kg spacecraft into SSO in 500-650 km, as described in section 4.2. It can bring a very small mass to GSO and L1. Thus, SSO is the only option for the proposed mission. In SSO, the adverse effects of Earthshine and Albedo on the instruments need to be minimized by optimal radiator placement and a specific orientation on the instrument. Moreover, compensation heaters will be needed to dampen short-term temperature excursions, as determined from the Hinode experience.

The following three environments will be considered when the orbit height of the SSO is determined in the design phase. 1) The proposed launch timing is at the solar maximum phase, in which the atmospheric density is increased in the orbit, giving larger atmospheric drag to the spacecraft. A sufficient height of at least 550 km is required for a longer duration mission. 2) Solar UV light is slightly absorbed by the Earth's atmosphere. It is better to reduce the period of the eclipse season in UV light. To achieve this, a height higher than 600 km is required (see Section 15.4.1). 3) Radiation effects (snow noise) appear in the images when the spacecraft travels through the South Atlantic Anomaly (SAA), and in high latitude Aurora zone during magnetic storms. Radiation effects are more significant at higher altitude.

9.1. Identification of planetary protection requirements [14-2-1]
Planetary protection の認識

Not applicable.

10. Draft requirements on spacecraft system [4-2-1]
宇宙機（衛星・探査機）システムへの設計パラメータ・性能要求のドラフト

Performance requirements to the spacecraft system with design parameters are described here.

(a) Structure design

- The proposed EUVST instrument shall be accommodated on the bus module, and the entire envelope of the spacecraft shall be fitted within the Epsilon fairing envelope.
- The mounting for the EUVST instrument will be designed so that the optical performance of the EUVST instrument should not be affected by the thermal deformation of the bus module.
- The ultra fine sun sensor (UFSS), for attitude control system, shall be mounted either on the EUVST instrument or the mission tower for mounting the EUVST instrument.
- The spacecraft design shall satisfy the requirements on the interface with the Epsilon rocket, including the mechanical interface at the rocket separation, payload environmental condition, static balance and 1st natural frequency, which are specified in Epsilon Rocket Users' Manual (NC, March 2016).

(b) Spacecraft orbit and propulsion

- The spacecraft orbit (and its parameters, such as altitude, inclination and local time at the descending node) during science operations shall be chosen to meet a) the requirement on the continuous viewing of the Sun (section 9), b) the requirement on the data transfer (section 6.4), and c) the requirement on stable temperature environment for achieving optimum optical performance characteristics of the mission instrument (section 9). In any low Earth orbit, such as sun synchronous orbit (SSO), the orbit parameters also need to be considered for the three environment conditions discussed in section 9.
- The propulsion system, i.e., RCS (reaction control system), shall be onboard to perform the orbit maintenance, if the total duration of non-eclipse season (continuous viewing of the Sun) is reduced to less than 8 months per year within three years after the launch. The accuracy of the initial orbit to the sun synchronous condition and the decrease of the altitude due to air

drag at the time of the solar maximum are considered. When the spacecraft is installed into SSO by Epsilon rocket with PBS (Post Boost Stage), the accuracy (3σ) in the altitude and inclination of the installed orbit is ±20 km and ±0.2 deg, respectively, according to Epsilon Rocket Users' Manual (NC, March 2016).

- The risks for producing debris shall be considered, including 25 years deorbit requirement.
- The eclipse season shall be taken into consideration for best coordinating with ground-based observatories. **Not** having the eclipse season during the winter in the northern hemisphere is the best option for coordinating with DKIST.

(c) Attitude determination and control

- The spacecraft attitude shall be controlled by commands to point to any direction in the inertial reference system. This mode is mainly used in the initial phase without sun sensors.
- During the observations, the spacecraft attitude shall be stabilized in three axes with its Z-axis pointed to the Sun.
- During the observations, the spacecraft Z-axis shall be directed to any position on the solar disk as well as in the off-limb region (less than 9 arcmin or 0.15 deg) above the limb. The positions are specified on a sun-oriented coordinate.
- The absolute accuracy of the pointing on the solar disk shall be defined as follows to easily capture the target of interest within the EUVST medium-sized field of view:

  θx, θy: 20 arcsec (0-p)
  (the angle around two axes (X and Y-axes) perpendicular to the Z-axis)
  θz: 100 arcsec (0-p)
  (the angle around the Z-axis).

  The scientific operation team will determine a more accurate relationship between the attitude command and the actual pointing of the EUVST instrument by analyzing the scientific data acquired with the EUVST on orbit.
- As a baseline, the spacecraft shall track a region on the solar surface by correcting for solar rotation during the observations. For each tracked target, the angular velocity around the rotation axis of the Sun can be specified; The parameters for specifying the angular velocity are prepared in the planning on the ground and uploaded to the spacecraft before the observations. The onboard attitude control computer calculates the tracking motion depending on the solar latitude and longitude and updates the spacecraft pointing in real time. The maximum duration of the continuous tracking is two weeks.
- The other tracking/observing mode is the spacecraft pointing to a fixed position on the solar disk and above the limb. The fixed pointing is particularly important when observing the region above the limb.
- As a baseline, the Y-axis, which is parallel to the slit of the EUVST, is directed toward the solar north. In addition to the baseline orientation, the spacecraft shall have a capability for roll control around the Z-axis, i.e., a capability to tilt the Y-axis from the solar north. The purpose of this capability is to increase the observing cadence of spectroscopic observations, by aligning the slit direction to a specific target, e.g., the coronal loop of an active region of interest. It is noted that a reduced performance on the mission data telemetry speed is acceptable in the roll orientation far from the baseline orientation.
- The attitude determination is made onboard for attitude control. It uses the attitude knowledge from attitude sensors, including Ultra Fine Sun Sensor (UFSS), Inertia Reference Unit (IRU), and Star Tracker.

- The calculation of the orbit phase, i.e., where the spacecraft flies, is needed onboard for the EUVST instrumentation (note in Table 10.1). It is also needed for scientific data analysis. Sufficient accuracy has been achieved according to Hinode experience.
- The pointing stability specified in Tables 10.1 and 10.2 and Figure 10.1 shall be achieved with a combination of the attitude control, the image motion compensation system in the EUVST instrument (Section 15.1.4), and the structure. In general, the attitude control takes care of jitter in the low frequency region, the structure avoids the jitter (micro-vibration) in the high frequency region, and the image motion compensation system compensates the jitter in between the low and high frequency regions.

Table 10.1: Pointing stability[1)]: θx, θy

Time	Requirements	Unit	Note
5 sec	0.2	arcsec (3σ)	Based on the budget allocation for the spatial resolution (see Table 15.4).
1 hr	2.0 [2)]	arcsec (0-p)	Drift smaller than the narrow FOV for the fast scan shown in Sections 5.1 and 6.4.1.

1) Only for out of the eclipse season.
2) Pointing may slowly drifts with the orbital phase due to the thermal deformation. Building on the IRIS's heritage on the correction by an orbital wobble table (De Pontieu et al. 2014), this orbital drift will be suppressed to the goal level depicted by the red dashed line in Figure 10.1 (0.4 arcsec [0-p]) by a look-up table for correcting the tilt of the primary mirror.

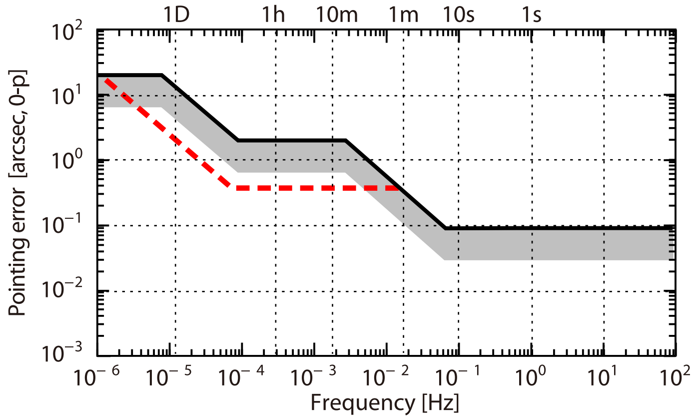


Figure 10.1: Pointing stability (θx, θy) requirements in the frequency domain. See note (2) in Table 10.1 for the red dashed line. Assuming sinusoidal oscillations, $\Delta\theta(0-p) = \sqrt{2}/3\,\Delta\theta(3\sigma)$ was used to convert $\Delta\theta(3\sigma)$ to $\Delta\theta(0-p)$.

Table 10.2: Pointing stability[1)]: θz

Time	Requirements	Unit	Note
1 hr	100	arcsec (0-p)	~ 1 pixel at the edge of FOV

1) Only for out of the eclipse season.

- When a pointing change is commanded, the pointing stability specified in the previous bullet shall be achieved in the timescale less than 5 minutes after the pointing change.
- In the contingency of the attitude control, the spacecraft attitude mode shall immediately be changed to safe-hold, in which the spacecraft attitude is kept in a safe orientation in respect to the solar direction. The safe orientation shall be defined in the design phase. In the safe orientation, the mirror in the EUVST instrument focuses the solar light into a robust area in the instrument, not giving any damage to the telescope structure.
- The spacecraft shall control its attitude properly to allow the EUVST instrument to perform the observations even during solar eclipses (the Moon passage between the Sun and Earth).

(d) Thermal design

- The thermal design shall guarantee the requirements on the temperature of onboard parts and components both in operational and survival (non-operational) modes.
- The external surface of the structures in the bus module and the EUVST instrument is covered by the MLI (multilayer insulation) to minimize the radiative coupling with the external environment.
- The exception is the radiators necessary for the dissipation of the heat from onboard optical and electrical components.
- In the SSO orbit, the thermal design shall carefully investigate how significantly the Earth's Albedo influences the thermal stability, especially the orbital variation in optical performance of the EUVST instrument.
- The eclipse season is the thermally unstable period in the SSO orbit. Especially in the night period and a certain time after the sunrise at each orbit, it is acceptable that the EUVST performance, such as the spatial resolution, would be partially degraded.

(e) Power

- The spacecraft will have solar array paddles (SAP). Choosing the SAP configuration shall be determined from the power budget from the mission payloads. The upper limit of the power supply capability during day periods is 1,000W for the entire spacecraft and payloads.
- The standard bus has a Li-ion battery (50Ah), which supplies the electric power to the spacecraft components in the period when the sufficient power is not generated by the solar array paddles.
- During the launch phase, the battery shall supply the power to the spacecraft system components until the sun acquisition is completed.
- During the observation phase, the eclipse season happens about four months every year. In the SSO orbit, the duration of the eclipse is 15-20 minutes in each orbit.
- During the observation phase, solar eclipses (the moon passage in front of the Sun) are observed a few times every year. The battery may be used when insufficient power is generated by the solar array paddle.
- The battery Depth of Discharge (DOD) shall not exceed 25% in solar pointing and safe-hold attitudes, and 80% in case of transient battery mode, such as during launch and solar eclipses.

(f) Command and data handling

- The science requirements on the mission data rate are specified in section 6.4.2.
- The spacecraft shall allow the EUVST instrumentation to perform continuous observations for 24 hours every day with the average telemetry rate of 0.72 Mbps.
- To download the science data acquired by EUVST, a high-speed data downlink system (X-band 8 Mbps as the baseline, or Ka-band) shall be onboard as a part of the mission payload. With 15 downlink passes (duration: 10 min each) per day, 72 Gbits can be downloaded to the ground in each day, making it possible to perform continuous observations with an average rate of 0.8 Mbps for 24 hours.
- The spacecraft shall have a data recorder (2 GBytes) for recording house-keeping data without losing the data. The house-keeping data will be downlinked via the standard S-band system (2Mbps maximum).
- In addition, a mass memory is required to store the science data from the EUVST instrument. The minimum data storage for the science data is 20 Gbits (section 6.4.2), but a larger volume is preferable for flexible observations. The proposed concept is that this memory is located in the EUVST instrument.

- The spacecraft shall handle the science data without losing the data, even when the data is rapidly generated with a burst rate (the highest rate) specified in section 6.4.2.
- The time information shall be attached to the science data from the EUVST instrument. The accuracy of the time information shall be better than 0.1 sec, after the ground post-processing.
- For downlinking the science data, the mission plans to use the ground stations not only in Japan but also those supported by other space agencies (similar to the case of Hinode). The compatibility shall be confirmed during the ground testing phase.

(g) Mission duration

- The science team requests two years as the normal operation phase after the launch, early operation and verification phase, and consumables to support an additional three years of extended operations.

(h) In-flight fault management

- The spacecraft shall have the failure detection and recovery (FDIR) logic onboard.
- When the FDIR detects anomalies specified in the design, the spacecraft shall issue onboard commands to turn off the components that are not needed to keep the spacecraft functional in minimum and save the power.
- When the spacecraft detects anomalies critical to maintain the spacecraft pointing, the spacecraft shall change the attitude mode automatically to a safe-hold mode.

10.1. Comparisons to similar spacecraft systems[4-2-2][4-3-1] 過去の類似なシステムとの比較

Previous similar spacecraft systems are compared with the proposed spacecraft system and the unique requirements of the proposed system are highlighted.

a) Hinode (Solar-B), launched on September 2006

If the system functions and performance achieved in the Hinode spacecraft are available, they meet most of the requirements in the proposed mission.

The satellite Hinode (Kosugi et al. 2007) was launched by the seventh M-V launch vehicle into an elliptical polar orbit (perigee 280 km, apogee 686 km). It boosted its perigee and controlled the plane of the orbit with its own thrusters to acquire a circular, sun-synchronous, polar orbit of about 680 km attitude, 98.1 deg inclination, and 98 min period. With this orbit, Hinode has been observing the Sun continuously for a duration of nine months every year. The height of the Hinode spacecraft is 4,000 mm and the weight about 900 kg, including 130 kg thruster gas, meaning that the proposed Solar-C_EUVST spacecraft is lighter than Hinode by a factor of 1.8. Three telescopes onboard Hinode are aligned in the Z-axis of the spacecraft and supported by an optical bench tube, which is mounted on the bus module. The spacecraft is stabilized in three axes with its Z-axis pointed to the Sun. The Y-axis is always directed toward the solar north, while a roll capability of the Y-axis is proposed in the Solar-C_EUVST spacecraft. As a baseline, the spacecraft tracks a region on the solar surface by correcting for solar rotation. The achieved stability of the Z-axis is 0.3 arcsec (3σ) in 10 s and 1 arcsec in 1 min, helping the telescopes to perform high spatial resolution and highly precise measurements of the solar atmosphere. One of the telescopes, the Solar Optical Telescope (Tsuneta et al. 2008), with 50 cm aperture, has an image stabilization system consisting of tip-tilt mirror mechanism and correlation tracker (Shimizu et al. 2008), achieving the extremely stable pointing of the telescope in order of 0.03 arcsec (3σ).

For data downloads, besides the S-band, Hinode has a X-band (4Mbps, QPSK) for mission data downlink, with an onboard data recorder (1GB). During the period when the X-band was fully functional, X-band downlinks were carried out at almost all the passes over the north pole (15 passes at Svalbard). In the proposed mission, more telemetry and data recorder capacity are requested to enhance the science output.

b) Hisaki (Sprint-A), launched on September 2013

The ISAS small bus module developed for Hisaki and subsequent Epsilon's M-class missions is planned to adapt to the spacecraft system of the proposed mission. Comparing to the Hisaki system, some new additions will be required to the small bus module system.

Hisaki has a single EUV spectroscopic telescope with a height of about 2,850 mm and is mounted on the top panel of the bus module. The overall layout of the proposed mission is quite similar to that of Hisaki. The weight of Hisaki is 350 kg, which is lighter by 150 kg than the mass budget of the proposed mission. A thruster engine is not included in the Hisaki system. The spacecraft is stabilized in three axes with its Z-axis pointed to planets. The pointing stability is requested to be 2.5 arcsec (0-p), when the pointing signal from the guide camera is utilized in the attitude control. Note that the ultra-fine sun sensor (UFSS) is used in the proposed mission. Hisaki has only S-band, which is used not only for housekeeping but also for science data downlinks. The data recorder is 2GB.

c) ASNARO-1, launched on November 2014

ASNARO-1 is an earth observing satellite developed by Japan Space Systems (JSS) and NEC, with a high-resolution optical imaging instrument that can deliver imagery at a ground resolution of under 0.5 m in the panchromatic band and under 2 m for multispectral images. ASNARO satellites use the same bus that Hisaki does. The total spacecraft mass is 495 kg with 250 kg allocated to the bus, 200 kg reserved for the payload, and a nominal propellant load of 45 kg.

The spacecraft bus is outfitted with a number of Attitude and Orbit Determination and Control Systems to ensure accurate navigation and precise pointing capability. The exact achievement of the pointing stability is not publicly available, but high resolution images available on internet as well as the initial study carried by NEC for this proposed mission indicates a good pointing stability.

The acquired images are recorded in a 120 GB Flush memory. The X-Band system achieves a data rate of 800 Mbps using a 16-QM modulation. The antenna pointing mechanism allows precise pointing of the X-Band antenna to track a ground station.

d) IRIS (NASA's SMEX), launched on June 2013

Interface Region Imaging Spectrograph (IRIS, De Pontieu et al. 2014) is a NASA solar observation satellite, funded through the Small Explorer program. The spacecraft consists of a satellite bus and a spectrometer built by Lockheed Martin. The mission has been operated in a sun-synchronous polar orbit with the perigee of 623 km, providing eclipse-free observations for up to eight months per year. The satellite's instrument is a 19-cm UV telescope that feeds a slit-based dual-bandpass imaging spectrograph. IRIS obtains spectra in 4 UV passbands in 130 – 280 nm. A spatial resolution of better than 0.5 arcsec is required and spectroscopic observations with 0.4 arcsec spatial resolution are realized.

The IRIS mass is 183 kg with 87 kg for the instrument and 96 kg for the spacecraft bus. The spacecraft bus, designed and delivered by Lockheed Martin Civil Space (formerly LM Sensing and Exploration Systems), is a rigid design whose frame is machined from a single piece of aluminum with honeycomb aluminum forward and aft decks. IRIS is three-axis stabilized. The attitude control system (ACS) is gyroless, using two star trackers, four reaction wheels, coarse and digital sun sensors, and a magnetometer. The instrument guide telescope provides a high-resolution pointing signal to the ACS during normal science operations. Magnetic-torque rods are used to manage the momentum of the reaction wheels, transferring energy to the Earth's magnetic field as needed. There is no propulsion system onboard. The ACS can point the IRIS telescope to any location on the solar disk or above the limb within 21 arcminutes from the disk center, and roll the spacecraft (and thus, the spectrograph slit) up to ±90 deg (at 0 deg the slit is oriented parallel to N–S on the Sun). IRIS is equipped with two omnidirectional S-band antennas for commands uplinking and downlinking of engineering data, and an X-band antenna for downloading of science data. The X-band provides downlink at 15 Mbps including the overhead of Low Density Parity Checking (LDPC) 7/8 encoding. The effective downlink rate is 13 Mbps (excluding overhead) during up to 15 passes per day at Svalbard, as well as some passes in Alaska and Wallops.

From a survey of the spacecraft discussed above, we have identified new requirements for the proposed missions concept. The requirements for the spacecraft system are based on the ISAS small satellite bus.

- High pointing stability: The stability is already achieved in the Hinode spacecraft, but it is necessary to achieve the equivalent stability on a small satellite bus. Similar to Hinode, the pointing signal from the ultra-fine sun sensor (UFSS) is used in the attitude control. The micro-vibration control, which is important in stability at the high frequency range, is required in the development, although the method has been developed during the Hinode development.
- High mission telemetry rate: The ISAS small satellite bus has 2Mbps S-band telemetry system only, which is insufficient for downloading the mission data. A higher telemetry system (X-band or Ka-band) with a large mass storage is needed as a part of the mission payload.

11. Mission operation profile [6-2-1][6-3-1]
ミッション運用方針案

11.1. Science operations plan

The EUVST instrument will be operated to maximize science output and achieve the mission's science objectives. As the guideline for daily operations, the following items are considered in order to prepare for a variety of programs (observing sequences) that optimize the science return:

- Tunable parameters available for the instrument, such as the selection of spectral lines to be recorded, exposure duration, spatial binning, scanning range and steps, and map cadence,
- The free space in the onboard data recorder available for recording and the downlink schedule of the recorded data,
- The solar conditions, such as the appearance of active regions and their activity level, coronal holes and prominences, and
- The coordination with ground-based and other space-based observations.

The system of daily operations follows the format of the Hinode operations that have been used and improved during its 11 years of operation. The mission is developed and operated under international collaboration, here we have the following essential conditions for designing the operation system (Table 11.1).

Figure 11.1 describes the baseline concept of nominal science planning, with the list of key elements in Table 11.2. This baseline concept is almost same as what has been done in Hinode operations. The only exception is that the daily meeting will not be necessary during normal operations -- the chief observer handles target selection and program selection and coordinates collaborations, similar to IRIS operations, because there is only one instrument onboard.

Table 11.1: Essential basis for designing science operations

1. Japanese leadership in satellite operations.	ISAS/JAXA takes responsibility for spacecraft operations.
	Daily commanding and housekeeping status checking will be conducted at SSOC in ISAS.
2. Balanced contributions to science operations from Japan, US and Europe.	To ensure that researchers and graduate students can spend sufficient time on data analysis to maximize science return through refereed publications and PhD and MSc theses.
	The team shall take care that too much burden is not placed on graduate students who work in daily operations.
3. Related researchers and graduate students are highly encouraged to participate in the science portion of daily operations.	They will be involved in the roster of chief observer, who makes daily plan and checks the quality of latest downlinked data.
	The science portion of daily operations is a good educational opportunity for graduate students to learn in depth spacecraft operations and onboard instruments, broadening their knowledge and enhancing their ability to communicate with scientific proposers from over the world. This is crucial to improve their employability.
4. Remote operations from home institutes (after stable daily operation is established)	The science portion of daily operations is conducted at ISAS at the early phase of science operation phase.
	A system will be considered to allow researchers to make planning remotely. Note that the remote planning has been used for Hinode operations since 2009.

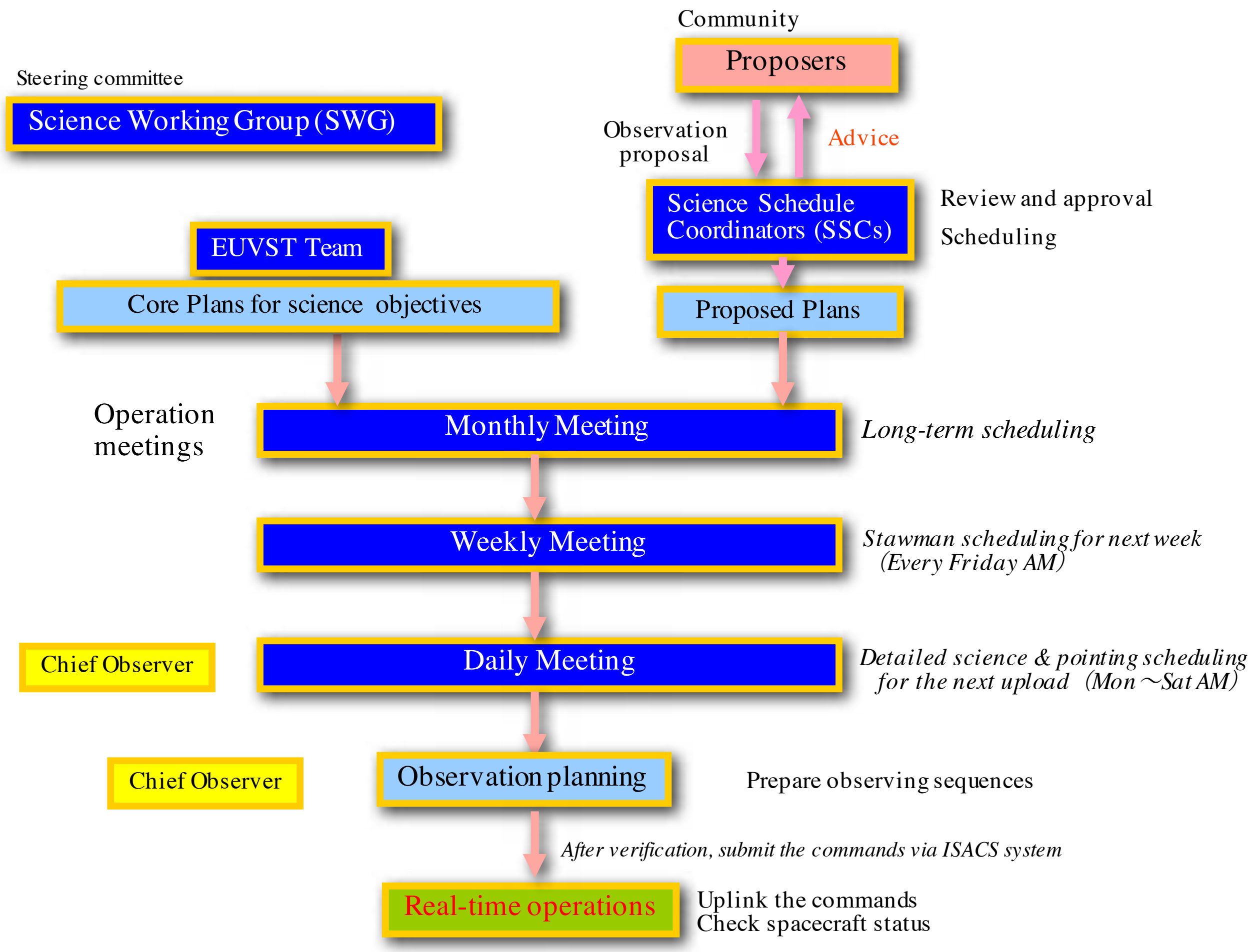


Figure 11.1: Basic concept of nominal science planning

Table 11.2: Key required elements in science planning

1. Strike a balance between core observations and proposed observations	The EUVST science team has core observations which will be prepared prior to launch to achieve the minimum science objectives.
	The team will also perform proposed observations, which are defined by receiving proposals from scientists in research communities over the world. This is useful for scientists to conduct the observations coordinated with ground-based and space-based facilities.
2. Regularly review operations and science activities	Science Working Group (SWG) reviews operations and science activities regularly and give guidelines and advice to the operations team.
3. Operate on-orbit solar observatory accessible from scientists over the world	Science Schedule Coordinators (SSCs) receives and reviews proposals for observations, and schedules the approved proposed observations.
4. Plan the optimum observing timeline for the changing solar conditions	The stream of monthly, weekly, and daily meetings provides opportunities to discuss observation plans in the operation team. Note that, similar to IRIS operations, a daily meeting will not be necessary during normal operations -- the chief observer handles the target and program selection and coordinates collaborations, with a guidance from weekly meeting.
	Considering variable solar condition, the frequency of timeline upload will be changed from every day in weekday period (at the early phase of the operations) to three-days interval (weekend, and at the late phase).
5. Quickly act for unpredicted flare possibilities.	The team will have the list of priority for science objectives. When a priority is given to flare observations, the team utilizes any information for "flare watch" and makes a decision on last minute changes in the observing region.
6. Verify the contents of the commands before uplinking to the spacecraft.	User-friendly chief-observers' tools (COT) will be developed to make the timeline and exposure setup. The tools (in COT and the ISACS_PLN system) have protective functions to prevent incorrect parameters from being sent to the spacecraft.

11.2. Telecommunications, Tracking, and Navigation

The standard S-band system in the ISAS small bus is used for telecommunication for commanding, housekeeping and ranging operations. USC34m, 20m, and KTU4 antennas as well as JAXA GN antennas will be used for this purpose.

The standard S-band 2Mbps system is insufficient for downloading the scientific data. Thus, a high-speed telemetry system is requested for downlinking the mission data. The X-band QPSK 8Mbps, which was used in Hitomi, could be the baseline, and Ka-band system with much higher rate might be considered if NASA support is available. The mission data will be received at USC34m, 20m, and KTU4 antennas in Japan as well as at additional oversea antennas supported by ESA and NASA.

There are no requirements for the spacecraft to know the precise location in orbit in real time for navigation. As for Hinode, the orbital information may be uploaded on a regular basis to the attitude control system to recognize orbital events, such as night and day. For science purposes, there are no requirements for the onboard instruments to know the location of the orbit, but scientists may want to know the location on orbit for calibrating the mission data.

11.3. Ground systems and facilities

Figure 11.2 shows the overall structure of ground systems and facilities, mainly focusing on the mission data flow. All the mission data, received at some ground stations, are delivered to the JAXA

Sagamihara campus via a dedicated line or the internet. The overseas station data server at Sagamihara retrieves the telemetry files from ESA and NASA stations with a time delay (typically less than a couple of hours), as performed for Hinode telemetry. In ISAS, the data distributor and storage servers are used for data distribution.

All the telemetry data is archived after time stamping on the SIRIUS database. For science purposes, the telemetry data is reformatted as FITS files; Quick Look files are automatically generated immediately after the telemetry delivery, whereas the final reformatted files are created after confirming all the telemetry data achieved in SIRIUS. The final reformatted files are open to the researchers via the DARTS system.

For the promotion of the Solar-C_EUVST science, a Japanese science center will be formed at ISEE, Nagoya University, where analysis tools, calibration, and the computer environment for data analysis are provided to researchers. The reformatted data are copied to science centers at US and Europe for the American and European communities.

The lower left portion in Figure 11.2 is the section for planning the observation timeline and commands, referring to the latest mission data available for science planning. We utilize the operation tools developed in ISAS, including GSTOS (Generic Spacecraft Test and Operations Software) for planning spacecraft commands and verifying the commands, SIB2 (Spacecraft Information Base version 2) for definition of the commands and telemetry, and ISACS-DOC for automatic monitoring of the telemetry status. SIB2 and GSTOS will be used for developing and testing of the spacecraft and instruments. For science planning, PI-prepared chief observer's tools (COT), evolved from Hinode's planning tools, will be used to schedule the timeline and commands for exposure sequence of the EUVST instrumentation. A pointing scheduling tool, based on Hinode's pointing tool, will be also required for safely preparing the sequence of attitude control commands for pointing changes.

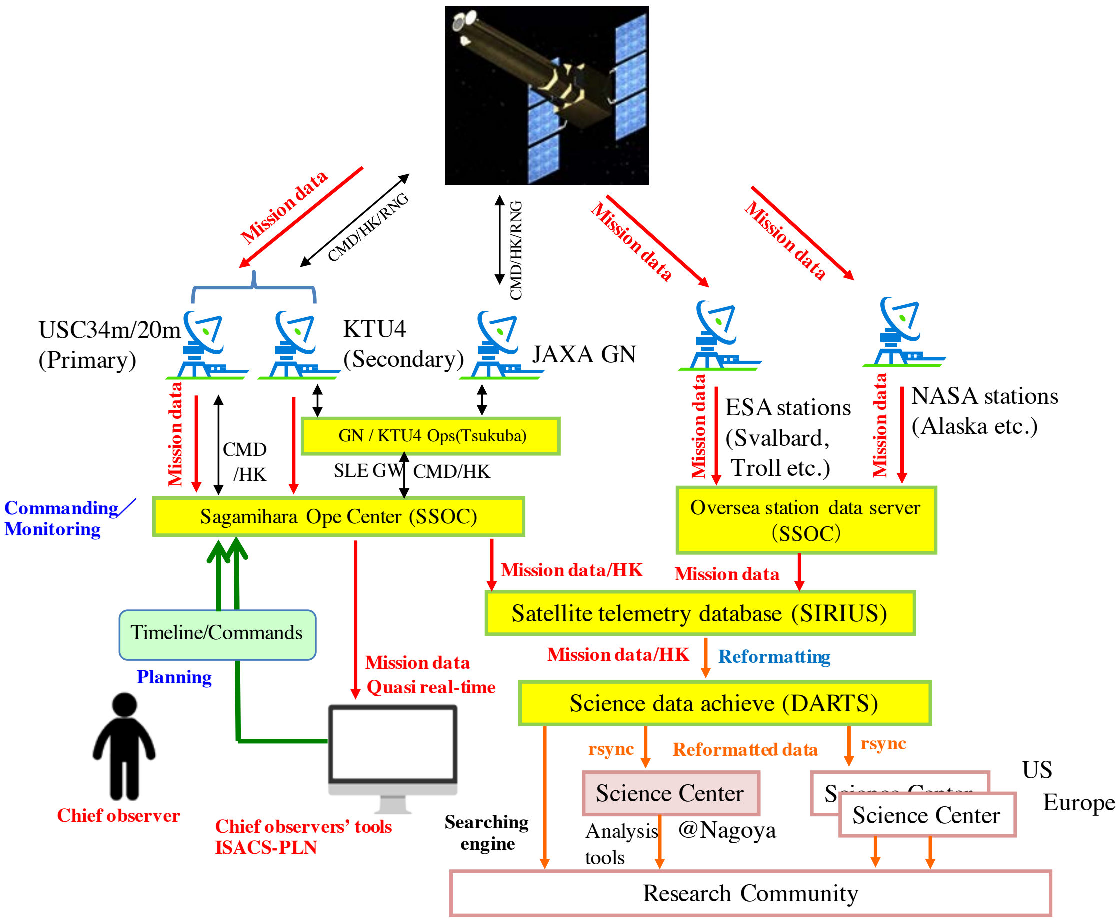


Figure 11.2: Ground systems and facilities.

11.4. Launch and early operations, contingency

At the launch, the sequence of operations, such as the deployment of solar array paddles and the acquisition of the Sun, is critical for the survival of the spacecraft. The selection of ground stations and their required functions (commanding, status monitoring, ranging and real-time connection from SSOC) shall be carefully considered when the launch sequence is designed.

Close approach of space debris can be considered as one of contingent events, something relatively frequent for the satellites in SSO. If the thruster system is on board, we are requested to avoid possible collisions, by following the JAXA guideline concerning space debris risks (QNX-160019).

12. Key technologies [8-2-1]
主要技術要素

Table 12.1 shows the list of key technologies for the proposed mission. The items which require new development are highlighted in beige, and are described in section 12.2.

Table 12.1: Key technologies and development items.

Category	Requirement	Technology	Heritage	Development item
Mission	Seamless temperature coverage	Multilayer coating ($Mo/Si+B_4C$)	Hinode/EIS SoHO/EIT, SO/EUI STEREO/EUVI Proba2/SWAP SPICE (for B_4C)	Combining Mo/Si coating and B_4C coating
		CCD E2V 42 (EUV)	SDO/AIA, Hinode/EIS STEREO/SECCHI	
		Intensified APS (UV)	WISPR/PSP SO/EUI, SO/SPICE	
	Spatial resolution	Wavefront error of the mirror	Hinode/OTA	Ensure small thermal deformation of the mirror
		Optical performance	Hinode/SOT, Hinode/EIS, SO/EUI	Ensure small optics misalignment and thermal deformation
		Heat dump	Hinode/OTA	Heat dump from the primary mirror
		Focus mechanism (1) Primary mirror	heritage from MELCO, Solar-C R&D	Application of flight heritage parts to the mechanism.
		Focus mechanism (2) Grating	Hinode/EIS, SoHO/SUMER	
		Image stabilization (1) Tip-Tilt mechanism for the primary mirror	Hinode/SOT, IRIS, Solar-C R&D	Application of SOT heritage and Solar-C R&D development to this mechanism.
		Image stabilization (2) Guide telescope	Duplicate of IRIS flight GT. Similar to SDO/AIA, GOES/SUVI, STEREO/SECCHI, TRACE	
		Grating (EUV)	Hinode/EIS, SO/SPICE	Tolerance/manufacturing accuracy of high-density grating
		Grating (UV)	Hinode/EIS, SO/SPICE, CLASP	Tolerance/manufacturing accuracy of grating
	Temporal resolution	Enlarged mirror diameter	Hinode/OTA	
		Multilayer coating ($Mo/Si+B_4C$)	SoHO/EIT, STEREO/EUVI	Ensure high reflectivity

			Proba2/SWAP SO/EUI SPICE (for B_4C)	
	Spectral resolution and coverage	Grating (EUV)	Hinode/EIS, SO/SPICE	Optimizing the grating parameters
		Grating (UV)	Hinode/EIS, SO/SPICE, CLASP	Optimizing the grating parameters
		Slit assembly (narrow slit on silicon wafer)	VERIS SoHO/SUMER Hinode/EIS	2.5 um slit
	Slit imaging for coalignment	APS imaging sensor	WISPR/PSP SO/EUI, SO/SPICE	
		filter wheel mechanism	Direct copies of flight mechanisms on IRIS, SDO/HMI, SDO/AIA, or Hinode/SOT	
		Band selection filters	Based on filters on SDO/AIA or IRIS	
Spacecraft	Pointing for observing targets	Solar rotation tracking	Hinode/AOCS	
		Absolute pointing accuracy	Hinode	Determine the relation of telescope pointing and UFSS pointing based on observations.
		FDIR and safe-hold attitude	Hinode/AOCS + OTA	Protect the telescope hardware damage from oblique incidence of the solar light.
		Roll maneuver around the Z-axis	IRIS	Design X-band configuration (location, number of antennas)
	Pointing stability	Pointing stability (low frequency)	Hinode/UFSS	Re-development of UFSS due to change in company developing UFSS
		Pointing stability (high frequency)	Hinode	Micro-vibration control
	Data rate	Large mass memory	(heritage from LM)	
		High speed downlink (X-band 8Mbps)	Hitomi	Use Hitomi X-band system
	Mission life	Contamination control in UV	SoHO, Hinode/SOT, EIS, STEREO, SDO, SO, Solar-C study etc	Implementation issue
Operation &ground-based	Data transfer	Data transfer from Svalbard/Troll to SSOC	Hinode	

12.1. Assessment of uncertainties in technologies [8-2-1]
技術的不確定性の大きな要素のリスト化

12.1.1. Active primary mirror

The primary mirror of the telescope contains key technologies for determining a large part of optical performance, such as the spatial resolution and throughput. 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 50 cm diffraction limited mirror system for Hinode/SOT 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℃). With such a high temperature, the mechanism for supporting the mirror may deform the surface figure, for example by a stress due to the difference of CTE 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℃), but the thermal deformation caused by a temperature change from ~23℃ to ~80℃ needs to be controlled below the required level. With the design of a kinematic mount with three pads bonded on the side of the mirror, a major aberration due the thermal deformation is a trefoil coma, which is controlled during the polishing of the mirror. The mirrors of Hinode/SOT were well designed to minimize the thermal deformation in their operational temperature up to 47℃ (Suematsu et al. 2008), which were verified with extensive thermal-optical tests. A micro-roughness of <5 Å rms in the spatial frequency range from 10^{-3} to $5\mathrm{x}10^{-2}$ nm^{-1} will be achieved based on the experience in fabricating the 20cm Zerodur mirrors for SDO/AIA (Lemen et al. 2012).

Another technology required for the mirror assembly is a focusing mechanism for obtaining sharp/on focus images and a tip-tilt mechanism for stabilizing the image during the slit scanning. A launch lock mechanism will be also required to hold the mirror during the launch. Each one of the mentioned mechanisms has been developed (section 16.2.1) and applied to various space missions. Our baseline is to utilize the heritage technologies, but whether or not these technologies are applicable without major design changes largely depends on the design of the assembly.

12.1.2. Multilayer coating

A robust Mo/Si multilayer coating with a B_4C capping layer is applied to the 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 reflections induced by a split-mirror telescope. Moreover, a uniform coating (uniform reflectivity and emissivity) minimizes thermal stresses throughout the mirror.

A design example of the mirror coating is shown in Figure 12.1, which has high normal-incidence reflectance in the EUV wavelength ranges 170 − 215 Å and above 460 Å. 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. Although the individual coatings have been qualified at temperatures up to 200°C, the temperature and EUV reflectivity characteristics of the coating selected for the telescope mirror will undergo extensive testing early in the design phase to verify its performance for flight.

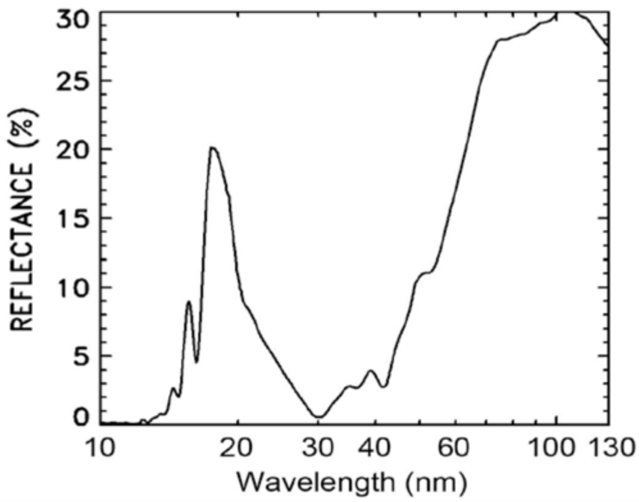


Figure 12.1: Performance of a broadband Mo/Si multilayer mirror coating (reflectance peak around 18.5nm) with 10nm B4C capping layer.

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 (Fludra et al. 2013).

We should also note that, as mentioned in section 16.2.3, the alternative coatings may be available, which would reduce the mirror temperature.

12.1.3. Gratings

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 and VERIS). However, instead of the traditional constant line spacing, EUVST uses rulings with variable line-spacing (VLS) of the form developed by Kita et al. (1983) and Harada et al. (1995) in order to minimize optical aberrations. Spectrographs using VLS ruling on spherical substrates have been flown on several astronomical satellite missions such as EUVE (Hettrick et al. 1985) and ORFEUS (Hurwitz & Bowyer 1991). A VLS grating was used in the Hubble Space Telescope, Cosmic Origins Spectrograph. The EUVST design combines these previous concepts by using a toroidal substrate with variable line-space grooves (TVLS grating). 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 (Fludra et al. 2013, Caldwell et al. 2017). TVLS gratings have been flown on the NASA SUMI (holographic, HJY, West et al. 2000) and RAISE (mechanically ruled, Bach, Laurent et al. 2016) sounding rockets. As shown in Table 15.1, the SW grating of EUVST has a relatively high groove density of 4200 lines/mm. The Hinode/EIS uses 4200 grooves/mm toroidal grating with constant line-spacing (TCLS) grating (fabricated by Zeiss). The FUSE experiment used a 5700 lines/mm TVLS grating (fabricated by HJY). There is no fundamental difference between a TCLS and a TVLS, the substrate figure having no influence on the holographic recording process. Nevertheless, we need to investigate achievable tolerance and manufacturing accuracy by optimizing the grating parameters with vendors.

12.2. Assessment of heritages [10-2-1]
既存技術の活用条件

12.2.1. Detectors

The detector systems for the EUVST have extensive heritage as described in Table 12.1.

CCD focal plane assembly – The EUV focal plane assembly will consist of two E2V 42-40 detectors. These detectors are butted together for minimal gap. The combined format is 2048x4096. 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 analog drive electronics will be nearly identical to the electronics used on previous missions and the expected readout rate of 2Mpixels/s is well within the device capability. The camera front end electronics development will incorporate an engineering model to reduce programmatic risk. 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°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.

IAPS focal plane assembly – 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 are 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. Residual devices from the SoloHI lot run will be used for the EUVST. Each focal plane assembly will incorporate two 1920x2048 detectors with 20 μm equivalent pixels (at the micro-channel plate surface). The APS detectors are radiation hard (>100krad) and have excellent photometric performance (high gain: 19,000 electrons full well with read noise of ~3 electrons; low gain: 87,000 electrons full well with a read noise of ~15 electrons). The APS front end drive electronics will be nearly identical to that built for SO/SoloHI. The APS detectors will be coupled to the back end of the microchannel plate (MCP) intensifier by a 2:1 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 intensifiers are robust and no difficulties with radiation are expected (O. Siegmund, private communication). The intensifiers have relatively large area (8cmx4cm) but are well within the previous experience. The MCP front faces will carry the selective photocathode coatings with CsI and/or KBr. The APS detectors will be cooled to <-45°C. This requirement will be revisited during the initial design phase. To protect the photocathode and MCP, each detector assembly is equipped with a vacuum door. The MCP and door assemblies have extensive flight heritage on a number of space missions. Prior to delivery, the MCPs are scrubbed to minimize gain changes with accumulated use. After scrubbing, the MCP housing is maintained at vacuum levels until launch using an ion pump. All three IAPS assemblies share the same vacuum pumping line. To develop these detectors, a full qualification model focal plane assembly and IAPS front end electronics will be incorporated into the EUVST development plan.

12.2.2. Mechanisms

Table 12.2 shows the list of mechanisms which will be fabricated based on the heritages for the spectrograph unit.

Table 12.2: Mechanisms in the spectrograph unit from heritage missions

Mechanism	Requirements and characteristics	Heritage
Slit selection	5 slits on a linear translation or rotating mechanism	VERIS, SoHO/SUMER SoHO/UVCS, Hinode/EIS
Grating focus	Linear grating translation for ~2 mm range with 10 μm accuracy/repeatability.	SoHO/SUMER, Hinode/EIS
CCD shutter	Direct driven shutter mechanism with optical encoding. > $4x10^7$ cycles.	Hinode/EIS Others
IAPS detector door and order sorting filter mechanism	Re-closable door. Motor mechanism to insert Al filter to observe Ne VII 46.5nm line in second order.	HST and other missions SO/SPICE
Filter wheel	Select a broadband filter in Slit-jaw imaging system.	TRACE, SDO/AIA

12.2.3. Guide Telescope

The Guide Telescope (GT) can be a near-identical duplicate of the IRIS GT that has worked flawlessly on-orbit for 4 years. Similar GT's have flown successfully on SDO/AIA, GOES/SUVI, STEREO/SECCHI and TRACE.

12.2.4. Pointing stability ~ UFSS

Ultra Fine Sun Sensor (UFSS) is a compact but high accuracy sensor for measuring the direction of the Sun with the accuracy of 0.3" (σ) for ±0.5 deg field of view. The component consists of two orthogonally oriented sensors, where each one uses an optical reticle and a 1-dimensional CCD. An onboard smart algorithm determines the solar direction with a high accuracy. The UFSS has been perfectly working on the Hinode satellite. However, since this UFSS manufacturer no longer manufactures the UFSS, ISAS is working with a new manufacturer to develop the second generation of UFSS based on the design and knowledge acquired during Hinode (Section 16.2.4) with support from the chief engineer who designed the original UFSS.

12.2.5. Pointing stability ~ micro-vibration

Since high spatial resolution is at the heart of the proposed mission, achievement of the required image stability given in Table 10.1 is of crucial importance. Although the attitude control system and the image stabilizing system of EUVST contribute respectively to the image stability at low (<0.1Hz) and middle (0.1–10Hz) frequency ranges, image jitter at high frequency range (>10Hz) is beyond their capabilities. Such high frequency image jitter is caused by the micro-vibration of optical components in the telescope and the spectrometer. Therefore, the suppression of their amplitudes below the allowable level is an issue. There are several factors that determine the amplitude of high frequency image motions; i.e., the level of disturbances of moving components in the spacecraft (disturbance sources), influence of the micro-vibration of optical components on the image motion (sensitivity) and transfer of mechanical disturbance from the disturbance sources to optical components (transfer function).

The potential risk on the micro-vibration issue is in the fact that the accurate prediction of the transfer function of the mechanical disturbance is difficult to determine during the design phase especially in high frequency range in f >100Hz. For this reason, the amplitude of the micro-vibration of optical components is highly sensitive to the resonance frequency and the amplification factor of the structure, and a slight difference between the mechanical model and the real hardware, results in a significant difference in the final amplitude of the micro-vibration of optical components between the prediction and the experiment. Therefore, in order to ensure the image stability to be satisfied in orbit, we need to combine the evaluation/control of disturbance with the Finite Element Method (FEM) analysis in design phase and experiments using the real hardware in development phase. A strategy plan for avoiding a significant amplification of micro-vibration is given in section 16.3.3.

The scheme and methodologies for controlling the micro-vibration were established in the development of Hinode, especially for the Solar Optical Telescope (SOT). After extensive works including the evaluation of disturbance sources, prediction of the mechanical transfer functions by FEM and their evaluation by measurements using MTM, and final end-to-end measurements, Hinode/SOT finally achieved a superior image stability of 0.03" (3σ) in orbit. We utilize this successful heritage of Hinode at most in the development of EUVST. The overall scheme developed in Hinode can directly be applied to EUVST. Note that the required level of the image stability in EUVST (0.2 arcsec (3σ), Table 10.1) is about twice less tight compared to that of the Hinode/SOT (0.09 arcsec (3σ)). However, there are some differences from the Hinode/SOT, i.e., the structure and the performance of ACS of the standard bus module for the small satellite is significantly different from those of Hinode, the image stabilizing system of EUVST will not be as fast as that of the Hinode/SOT because of the large mass of the active mirror, and EUVST does not have a fast imaging sensor in its focal plane that is available for the final end-to-end testing of the micro-vibration. These issues and revised methodologies, if necessary, will be investigated during the design phase.

12.2.6. Contamination control in UV

Contamination degrades the optical performance of the science payload by obscuration and scatter due to the presence of particulates on the optical surfaces and by absorption of incoming light due to materials deposited on optical surface originating from organic material outgassing from the payload structures. Regarding the particulate contamination, the surface cleanliness of Level 300, which is adopted in the Solar-B mission, is sufficient. The wavelength ranges that EUVST observes, the extreme-ultraviolet (EUV) and vacuum-ultraviolet (VUV) wavelength ranges, are the most contamination sensitive regions for the molecular contamination that degrades the key performance of the high instrument throughput.

The requirement of the limiting molecular contamination needs to be defined for the longest EUVST wavelengths near the hydrogen Lyman alpha line. The tolerable amount of the contaminants on the optical surface is 250 ng cm^{-2} (so-called A/4 level [TBD]) during any time of the whole mission life. The budget is more severe than that in the Solar-B (Hinode) mission by an order of magnitude. However, the EUVST international team members have experience in developing the science payloads on SoHO, IRIS, CLASP, and Solar Orbiter that work in the same wavelength range, and the same methodology that has so far been successful will be applied to the EUVST development program. The most critical issue in the EUVST is the molecular contamination on the primary mirror for the photochemical deposition process under the direct solar UV illumination. The contamination budget control, modelling, and verification activities that were employed in the Solar-B program will be applied to the EUVST program as the baseline, with the efficient bake-out methodology adopted for UV instrumentation in the SoHO and Solar Orbiter programs. A severe material selection and screening process will be employed that guarantees only materials with proven space heritage will be used and the bake-out will be applied to all hardware.

12.3. Technical risk identification [7-2-1] and major risks [7-2-2] 技術リスク分析と主要リスク要因

Based on our knowledge at the current phase, we listed the potential risks that may hamper the achievement of the science objectives, in particular, in the performances of investigations, in developments of the instruments and flight systems, and in the mission operation profile and the ground system (Table 12.3, in the next page). Risk assessment has been made based on the criteria defined in Table 12.4 – 12.6. Five major-risk (“high” risk) level items (highlighted in Table 12.3) have been identified at the current phase. They are related to the active primary mirror (2 items), grating (1 item), which are key components in EUVST, and micro-vibration control (2 items). For these items, risk level will be reduced to lower levels, by performing the feasibility studies in coming years, and micro-vibration evaluation at early phase of the development (Pre-Phase A to Phase A).

Table 12.4: Definition of risk “level”

	Possibility of occurrence [High]	Possibility of occurrence [Med]	Possibility of occurrence [Low]
Impact of occurrence [High]	High	High	Med
Impact of occurrence [Med]	High	Med	Low
Impact of occurrence [Low]	Med	Low	Low

Table 12.5: Definition of “Probability of occurrence” (%)

Level	Definition
Low	The possibility of the occurrence is low, and this risk will be typically avoided.
Med	The possibility is not low, the action to avoid/mitigate the occurrence is needed.
High	The possibility is high, and there may be no substitute for avoiding the occurrence.

Table 12.6: Definition of “Impact” by the occurrence
(Technology, Schedule, Cost are judged with their “or” relation)

Level	Technology	Schedule	Cost
Low	Minor or no influence	Major milestone is delayed in less than 1 month, or no impact to major milestone.	Cost increase less than 10M yen or no increase.
Med	Possible to accept or next best available	Major milestone is delayed 1 month – 3 months.	Cost increase between 10M and 200M yen.
High	Impossible to accept	Major milestone is delayed longer than 3 months	Cost increase larger than 200M yen

Table 12.3: Risk evaluations

No.	Risk			Risk evaluation			After phase A		
	Category	Risk and impact	Risk origin	Impact	%	Level	Impact	%	Level
001	Performance	The grating performance cannot be achieved, resulting in degradation of spatial or wavelength resolution.	The tolerance in some grating parameters is too tight and exceeds the manufacturer's capability of delivering according to schedule.	High	Med	High	High	Low	Med
002	Performance	Wavefront performance of the primary mirror after mounting does not meet the requirements in the allowable budget table.	A thermal deformation is induced to the mirror surface when the temperature is changed from the room temperature to operational temperature.	High	Med	High	High	Low	Med
			The reflectivity and IR emissivity of multilayer coating surface deviates from the design parameters.	High	Med	High	High	Low	Med
003	Performance	Mis-alignment between the primary mirro and spectrograph unit becomes large, resulting in degradation in spatial resolution and shift in observable wavelength bands.	The mis-alignment is caused by the launch environmen	High	Low	Med	High	Low	Med
			The thermal deformation is induced by the temperatur change on orbit.	Med	Med	Med	Med	Low	Low
004	Performance, system development	Microvibration from MW degrades the EUVST spatial resolution performance.	The magnitude of microvibration caused by some MWs purchased exceeds the specification.	High	Low	Med	Med	Low	Low
			Transfer function from the MWs to the optics in the EUVST is larger than the assumption.	High	Med	High	High	Low	Med
005	Performance, instrument development	The image stabilization system does not work properly, resulting in degradation of spatial resolution.	A tilt angle sensor of the active primary mirror shows malfunction.	High	Low	Med	Med	Low	Low
			An actuator of the active primary mirror does not work	High	Low	Med	Med	Low	Low
			Guide telescope does not measure the solar direction correctly (due to brighter sunlight, stray light etc).	High	Low	Med	High	Low	Med
006	Performance, Operation	A focus mechanism does not work, resulting in degradation of spatial resolution.	The focus mechanism of the active primary mirror doe not work.	High	Low	Med	High	Low	Med
			The focus mechanism of the grating does not work.	High	Low	Med	High	Low	Med
007	Performance, Operation	Slit cannot be changed.	The mechanism for changing slit does not work properly	High	Low	Med	Med	Low	Low
008	Performance	CCD/ICCD performance is degraded.	The molecular contaminants are condensed on the cooled CCD surface, reducing the throughput performance.	Med	Med	Med	Med	Low	Low
			The CCD cannot be cooled down to required temperature.	Med	Low	Low	Med	Low	Low
			The radiation damage increases the number of hot pixels, giving noise in spectral profiles.	Med	Med	Med	Med	Low	Low
009	Performance, Operation	ICCD cannot make observations.	The door mechanism in the ICCD housing does not open.	High	Low	Med	High	Low	Low
010	Instrument & system development	The throughput of the entire EUVST is degraded, resulting in increased exposure duration and slower cadence.	The optical surfaces are contaminated by molecular materials.	Med	Low	Med	Med	Low	Low
			The reflectivity of multilayer coating surface is decreased.	Med	Low	Low	Low	Low	Low
011	Performance, Operation	No throughput, leading to the mission failure.	The telescope door does not open.	High	Low	Med	High	Low	Low
012	Instrument development	The stiffness of the EUVST system including the Bus I/F point is too low.	If the damper is needed at the Bus I/F point for reducir the transfer function, the 1st eigenmode may be significantly decreased.	High	Med	High	Med	Low	Low
013	System development	The total mass exceeds the rocket launch capability.	The mass of EUVST is much larger than the allocation.	Med	Low	Low	Low	Low	Low
014	System development	UFSS does not meet the random/bias noise requirements	The light level is largely deviated from the setpoint due to improper calibration.	Med	Low	Low	Med	Low	Low
015	Operation	Numer of ground station passes insufficier for science	Due to lack of international supports and budget limitation.	Med	Low	Low	Med	Low	Low
016	Operation	A limited part of telemetry is occassionally missed at ground stations.	Due to last-minutes cancellation by station's reason, an due to low level of signal received at stations at low elevations.	Low	Med	Low	Low	Med	Low

12.4. Margins in major-risk items [8-2-2][8-3-1] 主要リスク要因に対するマージン

In Table 12.3, five items have been identified as “high” (major) risk items at the current phase. The numbers below are identical to those used in Table 12.3. For these risk items, there are uncertainties that will be addressed through extensive technical studies. By discussing the origins of each risk, the approach for reducing risk levels and setting reasonable margins is achieved.

- No. 001: *The grating performance cannot be achieved, resulting in degradation of spatial or wavelength resolution*. The aim of the flight gratings is to achieve the requirements for the spatial and spectral resolutions. The spot diagrams to be shown in Section 15.1.2 for the baseline design are derived by ray tracing analysis with the grating parameters, and readily meet EUVST imaging requirements. The imaging error budget (Table 15.4) includes an experience based fabrication tolerance and generous margins. To reduce risk, the EUVST team will procure and test prototype gratings prior to finalizing the flight grating procurement as described in Section 16.3.

- No. 002: *Wavefront performance of the primary mirror after mounting does not meet the requirements in the allowable budget table for achieving the required spatial resolution*. Two factors will be considered. The first is minimizing the thermal deformation at a high operational temperature (+80°C). We designed Hinode's 50 cm mirror assembly with thermal deformation of 15nm rms (~1/42λ) at temperatures up to +47°C. A first thermal-mechanical analysis for the assembly will be carried in pre-phase A in order to know the magnitude of the deformation and set a large margin for the deformation. The second factor is the uncertainty in reflectivity of the mirror coating in visible and IR. Small changes in the reflectivity cause changes in mirror temperature, producing thermal deformation. This will be considered in the thermal analysis. Additionally, we will study alternative mirror coating with higher reflectivity in the visible. The thermal properties will be characterized with coating samples during phase A.

- No. 004: *Micro-vibration from momentum wheels degrades the EUVST spatial resolution performance*. As described in section 16.2, a first micro-vibration analysis with the ISAS small bus indicated that the momentum wheels have potential to give vibration to the EUVST at an unacceptable level. In this analysis, a model fidelity is not high because of many assumptions, such as the structural model of the instrument and a large Quality factor as an uncertainty in the structural properties. Efforts are required to reduce uncertainties in the evaluation.

- No. 012: *The stiffness of the EUVST structure including the Bus interface point becomes low, if a damper is needed at the Bus I/F point to isolate the mission payload from momentum wheels' micro-vibration*. The experimental study mentioned in No. 004 will determine the necessity of the damper. Depending on the mechanical design, the 1st eigenmode may be significantly decreased to below the eigenmode frequency required by the rocket. A sufficient margin for the eigenmode frequency should be checked in phase A study.

13. Cost assessments from similar missions [21-2-1]
類似ミッションからコストの規模推定

The proposed Solar-C_EUVST mission consists of an UV spectroscopic telescope with the ISAS small standard bus. Hisaki (SPRINT-A, see section 10.2), launched as the first satellite for series of Epsilon rockets, has the similar configuration and thus the cost used for Hisaki can be used as the basis for the proposed mission. The EUVST telescope is bigger than the telescope EXCEED on Hisaki (28cm vs. 20cm diameter of the primary mirror) and requires higher spatial resolution, hence increased cost.

Because of the cost cap, Japan will take responsible for a limited portion of the EUVST, with substantial contributions from US and European countries. As described in section 15.10, the main part of the Japanese contribution is the telescope. Thus, as an initial guess for the telescope, we can refer to the cost in the development of the Hinode Solar Optical Telescope (SOT; 50cm in diameter, 0.2 arcsec spatial resolution). It spent 4,000M yen in development of the entire optical telescope (so-called OTA), including the precise combination of 50cm primary mirror and secondary mirror, collimator lens unit, and tip-tilt mirror mechanism and its control system (so-called CTM). The

EUVST has the primary mirror only and its diameter is about half of the OTA primary mirror, whereas the primary mirror becomes more complicated by including the focusing and tip-tilt functions. Considering the differences, the initial target for the development of the EUVST telescope would be around 3,000M yen.

The estimated total cost for the Hinode/EIS instrument was $30-40M and was dominated by the cost of the spectrograph. The projected cost for the EUVST spectrograph is approximately $60M. The additional cost is driven by the increased complexity of the electronics, the additional cameras and grating for the long wavelength channel, and the slit-jaw imaging system.

14. Trade studies among mission concepts
異なるミッションコンセプトとの trade off

14.1. Trade space [12-2-1]
Trade-off study 対象

The instrument in the proposed mission concept is compared with other possibilities of mission concept in this section. The following six steps have been taken to compare it with various investigations and instrumentations, finally drawing the baseline concept.

(1) Direction of future research in the solar physics domain

There are many science objectives in the solar physics area which should be tackled in 2020s. It is beneficial to compare the different investigations. This review has been carried out by the NGSPM-SOT team.

(2) Comparisons with various types of instruments

The previous trade study will conclude one direction of investigations (observations of elemental-scale processes). As briefly described in section 14.2, the Next Generation Solar Physics Mission's Science Objectives Team (NGSPM-SOT) report (a supplement to the proposal; Supplement A) recommends the following instruments as the high priority instruments to be realized in mid 2020s to the study of fundamental physical processes occurring in the solar atmosphere.

1. 0.3" coronal/TR spectrograph (T-09) (= EUVST)
2. 0.2"-0.6" coronal imager (T-07)
3. 0.1" chromospheric/photospheric magnetograph/spectrograph (T-01/04/05).

In addition, a photospheric/chromospheric magnetograph with a reduced size of telescope is also considered for the trade-off study.

4. 0.2"-0.5" photospheric/chromospheric magnetograph (T-02)

Of these instruments, T-09 and T-01/04/05 are basically the same as the instruments that have been considered in the Solar-C for JAXA's strategic large mission opportunity. The EUVST in the proposed mission concept is quite similar to T-09. These instruments are also compared with the Solar-C for JAXA's strategic large mission.

(3) Instruments for spectroscopy

In section 6.2, UV spectroscopy (selected for the proposed mission concept) was compared with three different spectroscopic methods (in soft X-rays and in visible light) from the viewpoint of scientific performance. They are compared with each other as a trade-off study from programmatic aspects, in addition to scientific trade-off.

(4) Spacecraft and fairing accommodations for UV spectroscopy

The EUVST instrument was originally studied as a European instrument called LEMUR, which was proposed to ESA as a Mission of Opportunity during the ESA 2010 call for an M-size mission (Teriaca et al. 2012). This proposal submission was evolved to the EUVST instrument in the Solar-C proposal for JAXA's strategic large mission in 2015. The length of this EUVST instrument was very long (4.3 m) to achieve a high spatial resolution. Thus, instrument designs of various lengths are considered in the spacecraft layout to accommodate each of these designs in the given Epsilon nose fairing volume. This trade off study determines the maximum length of the instrument.

(5) Survey of optical parameters

In order to define the baseline architecture of the EUVST instrument, we have made a parameter survey in optical parameters, i.e., a trade study in optical parameters under the requirements from the science (section 5 and 6).

(6) Orbit and telemetry trade study

As described in section 9, three orbit candidates (Sun synchronous orbit, Geosynchronous orbit, and L1 point) exist for achieving sub-arcsec spatial resolution with continuous viewing of the Sun. The high telemetry requirement, given in section 6.4, should be also considered in the trade-off study.

14.2. Trade studies [12-3-1, 5-3-2, and other various points]
トレードオフスタディ

(1) Direction of future research in the solar physics domain

As briefly described in section 3.1, the NGSPM-SOT team has identified key scientific objectives in all the research areas related to solar physics, based on extensive reviews of the broad interests of the community with a public call for white papers of science objectives. The list is categorized as 3 scientific objectives, consisting of 17 science sub-objectives with 56 tasks (Table 3-1 in NGSPM's SOT report attached as Supplement A). Based on eight criteria (1. Relevance to NASA/JAXA/ESA objectives, 2. Scientific impact on solar physics, 3. Scientific impact on other disciplines and research fields, 4. Inability of current/planned missions and ground-based facilities to accomplish the objective, 5. Need for space observations, 6. Maturity of technology -- measurements can actually be made, 7. Maturity of methodology -- data can be inverted to get findings, 8. Widespread interest within the solar physics community), the team made evaluations and determined priorities of objectives and tasks for next generation solar physics missions to be realized in mid 2020s.

Although the full range of science objectives are compelling, supported by the community, and technically feasible within the next decade, no single mission could achieve all the identified objectives. Thus, the team considered conceptual groupings of the objectives to clarify how the most science could be achieved within expected constraints and resources. They are two avenues: *physical mechanisms on elemental (small) scales*, versus *global processes affecting/involving large fractions of the solar interior and/or atmosphere and propagating into the solar wind*. This division is imperfect and subjective, as the processes are certainly not decoupled. However, for the purposes of planning a mission to carry a suite of instruments, it is necessary to consider the physical scales of the observables, and this 'bimodal' division is useful. It is the sense of the team that the better near-term opportunity for breakthrough discoveries by the NGSPM will be achieved through the former avenue, probing beyond the state of our present spatial and temporal resolution. Global, multi-vantage observations are scientifically compelling, but also more technically challenging.

Global, multi-vantage observations

For understanding global processes affecting/involving large fractions of the solar interior and/or atmosphere and propagating into the solar wind, the team has identified the large benefit of vantage points away from the Earth-Sun line, including both in or near-ecliptic stereo views or out-of-the-ecliptic high-latitude views. The science motivating these observations is compelling. Two major gaps exist in our current observational capabilities that could be addressed by such observations. First, although the STEREO and Ulysses missions moved away from Earth-Sun line, neither observed the solar magnetic fields and flows needed for progress on several key science topics enabled by these vantages. Solar Orbiter will, for the first time, obtain remote sensing observations out of the ecliptic. However, like STEREO, Ulysses, and the Parker Solar Probe, it will not maintain a sustained vantage point -- a second requirement on several science goals. Sustained polar/high-latitude views (which, depending on the science goal, may range from multiple months to the solar cycle) can be achieved by a constellation of spacecraft or by a single spacecraft on a carefully selected orbit. Transformative progress would certainly be made possible by sustained, multi-vantage views. However, such an implementation concept exceeds the capability (cost cap, weight of the mission) of this Epsilon opportunity. Thus, this concept is out of our scope.

Observations of elemental-scale processes

Solar activity on the smallest length and time scales illuminates fundamental physical processes, often with less complex interactions and configurations than larger-scale analogues. Game-changing discoveries may be found on these elemental scales, such as the nature of magnetic stresses resulting from braiding of magnetic field lines; the magnetic topology at the footpoints of spicules, jets, and prominences; the transport of energy via Alfvén waves in flares; and the development and effects of turbulence in all levels of the solar atmosphere. Most of the tasks for these science topics make use of wavelengths that are not accessible from the ground or require long-duration observations in a stable, seeing-free environment, necessitating observations from a space platform. There is every reason to believe that a higher-resolution focus for NGSPM will be rich scientifically. Given constraints on the capability (cost cap, weight of the mission), continuing to increase resolution is both feasible and well-suited to this Epsilon opportunity.

(2) Comparisons with various types of instruments

Each of the tasks for investigating elemental-scale processes (Table 3-1 in NGSPM's SOT report) implies certain requirements for instrumental capabilities, such as spatial resolution, wavelength range, temperature sensitivity, etc. The team identified notional 'strawman' instruments to execute each observation. As a result, it becomes clear how many instruments are required for each sub-objective. Table 3-1 in the NGSPM's SOT report provides the list of key observations and notional instruments (T-##). In consideration of a minimum set of instruments with which NGSPM can address the greatest number of high-priority Tasks, we find that a majority of the key required measurements can be met with a suite of instruments including:

1. 0.3" coronal/TR spectrograph (T-09)
2. 0.2"- 0.6" coronal imager (T-07)
3. 0.1"- 0.3" chromospheric imager and magnetograph (T-04)
4. 0.1" photospheric magnetograph (T-01)
5. 0.1" chromospheric spectrograph (T-05)

While other combinations of candidate instruments would likely also produce significant results, the list above represents the smallest set of instruments addressing as many as 32 of the 56 listed Tasks; it is the list of instruments that the team feels should receive the highest priority for selection. Of these 5 instruments, T-04, T-01, and T-05 can potentially be merged into a single telescope with focal plane instruments, when suitable wavelengths in near IR, visible and near UV are chosen in the design. Therefore, in the subsequent sections, the team considered some mission concepts for accommodating the following three instruments.

1. 0.3” coronal/TR spectrograph (T-09)
2. 0.2”-0.6” coronal imager (T-07)
3. 0.1” chromospheric/photospheric magnetograph/spectrograph (T-01/04/05)

The team recommended that NGSPM aims should be realized with a single-platform, as a JAXA Strategic Large mission with contributions from NASA, ESA, and ESA member states. If the single-platform approach is not possible or available, a combination of two or three spacecraft can achieve many of the NGSPM objectives, with some loss of capability and at increased risk. Table 14.1 summarizes the results of the trade-off study among the nominated 3 + 1 instruments and Solar-C for JAXA’s strategic large mission with some additional aspects for trade-off, i.e., cost, size/weight, capabilities of domestic and international communities and data volume. As the result, we reached the conclusion that the 0.3” coronal/TR spectrograph (T-09), i.e., EUVST is the most promising choice.

Table 14.1: Results of a trade study for selection of instruments

	0.3” coronal/TR spectrograph (T-09 ~ EUVST)	0.2”-0.6” coronal imager (T-07)	0.1” chrom./photo. magnetograph/spectrograph (T-01/04/05).	0.2”-0.5” photo./chrom. magnetograph (T-02)	Solar-C large mission (T-09+ T-01/04/05+ T-07)
Science return, achievement level of scientific objectives	*A*	*B*	*A*	*B*	*A+*
Uniqueness / synergy with other telescopes	*A* Significant advantages from others	*B*	*B* some overlaps w/ 4m ground telescope	*C* moderate jump from Hinode/SOT	*A+* Coordinated observations
Cost (fit to epsilon)	*A*	*A*	*F* high	*B* high	*F* Very high
Size/weight (fit to epsilon)	*A*	*A*	*F* Too large/heavy	*A*	*F* Too large/heavy
Technical and programatic risks	*A* No serious risks	*A* No serious risks	*B* Large and high precision optics	*A* No serious risks	*B* Large and high precision optics
capabilities of domestic and international communities	*A* World-wide support	*B* Limited interests in Japan	*B* Require large resources	*A*	*B* Require large resources
data volume, data rate, and size of post analysis	*A* High but treatable	*A* High but treatable	*A* High but treatable	*A* High but treatable	*A* High but treatable
Evaluation summary	*7A*	*4A, 3B*	*2A, 3B, 2F*	*4A, 2B, 1C*	*2A+, 1A, 2B, 2F*

The meaning of ranks: *A* – Excellent, *B* – Good, *C* – Fair, *F* – Fail

(3) Instruments for spectroscopy

UV spectroscopy, which the 0.3” coronal/TR spectrograph (T-09) uses, was compared with soft X-ray and visible-light spectroscopies scientifically discussed in section 6.1. This trade study was made from various points of view, such as cost and risks, and summarized in Table 14.2. The study shows that the UV spectroscopy is the most feasible method for performing the coronal spectroscopic observations.

Table 14.2: Results of a trade study for spectroscopic methods

	UV spectroscopy (=EUVST)	Soft X-ray spectroscopy (high dispersion)	Soft X-ray spectroscopy (low dispersion)	Visible light spectroscopy
Science return: Achievement level of scientific objectives	*A*: High	*B*: Low (temperature coverage)	*B:* Low (temperature coverage, velocity measurement)	*B*: Low (off-limb observations, temperature coverage)
NGSPM-SOT report	*A*: Identified as key instrument	*B*: Not identified as key instrument	*B*: Not identified as key instrument	*B*: Not identified as key instrument
Cost (fit to epsilon)	*A*: Treatable	*B*: High	*A*: Treatable	*A*: Treatable
Size/weight (fit to epsilon)	*A*	*F* Too large/heavy	*A*	*C* Large
Technical and programatic risks	*A*: No serious risks	*B*: Big cooling system, long optics	*A*: No serious risks	*B*: Large & high precision optics
Capabilities of domestic and international communities	*A* World-wide support	*B* Limited interests in Japan	*A* Interests in Japan (PhoNEiX)	*B* Limited interests in Japan
Feasibility of key Technologies	*A* See Section 12 TVLS grating	*B* Grazing incidence Segmented mirrors Microcalorimeter	*B* Grazing incidence Segmented mirrors	*B* Mirror coronagraph
Availability of heritages	*A*: SoHO/SUMER SoHO/CDS Hinode/EIS	*C*: none	*C*: None (Hinode/XRT)	*B*: SoHO/LASCO
data volume, data rate, and size of post analysis	*A* High but treatable	*A* High	*A* High	*A* High
Evaluation summary	*9A*	*1A, 6B, 1C, 1F*	*5A, 3B, 1C*	*2A, 6B, 1C*

The meaning of ranks: *A* – Excellent, *B* – Good, *C* – Fair, *F* – Fail

(4) Spacecraft and fairing accommodations for UV spectroscopy

Instrument designs of various lengths were considered. We investigated the spacecraft layout to accommodate each of these designs in the Epsilon rocket nose fairing volume. This trade off study determines the maximum length of the instrument. Three spacecraft configurations (Figure 14.1) were compared with each other:

Case (1) The instrument is mounted on the +Z surface of the ISAS small standard bus.
Case (2) The instrument is obliquely mounted at one side (one surface from ±X and ±Y surfaces) of the ISAS small standard bus.
Case (3) The instrument is located at the center, the lower portion of which is surrounded by the hollow-like bus.

The results from this trade-off study are summarized in Table 12.3, giving a conclusion that the layout of Case (1) is more suitable, when the length of the telescope is about 3 m or shorter.

Case (1) is the layout in which the instrument is mounted on the +Z surface of the ISAS small standard bus. This layout is fully based on the design standard of the ISAS small standard bus, in which mission payloads are basically mounted via interface fasters on the +Z surface of the bus. The instrument is vertically oriented, and thus the maximum allowable length for the instrument is limited to about 3-3.5 m, depending on the interference with the taper shaper of the nose fairing. The most important advantage of this layout is that the bus design is already verified, resulting in the cheapest and less risk option for the spacecraft bus.

Case (2) is the layout in which the instrument is obliquely mounted at one side (one surface from ±X and ±Y surfaces) of the ISAS small standard bus. Originally, case (2) was considered as one layout option, in which the instrument is mounted at one side (one surface from ±X and ±Y surfaces) of the ISAS small standard bus. This may be similar to the mount configuration of EIS and XRT on the Hinode spacecraft. However, the length of the instrument is limited due to the taper shape of the fairing and the center of gravity has a fairly large offset from the axis of the rocket. It is difficult to find merits in this layout. Thus, as a modified version, the instrument is obliquely mounted at one side (one surface from ±X and ±Y surfaces) of the ISAS small standard bus. The optical axis of the instrument is 10 degrees tilted from the rocket axis. This layout can reduce the offset in the center of gravity. Moreover, it allows us to have the instrument with a length longer than 4 m. The instrument is mounted at three points to the bus structure. The bus structure is modified from the original small standard bus, giving additional cost and development risks.

Case (3) is defined by considering a layout similar to Suzaku and Hitomi. The bus structure is octagonal prismatic and hollow shaped. The lower portion of a long-length instrument is surrounded by the octagonal prismatic bus structure. The heritage of the structural design from Suzaku and Hitomi can be utilized, but this design increases the cost and development risks. Since the lower portion of the instrument is fully surrounded by the bus, the heat dump at the radiators located at the lower portion, needs to be newly designed. For this purpose, heat pipes may be required from the heat source in the instrument to a radiator on the bus panel.

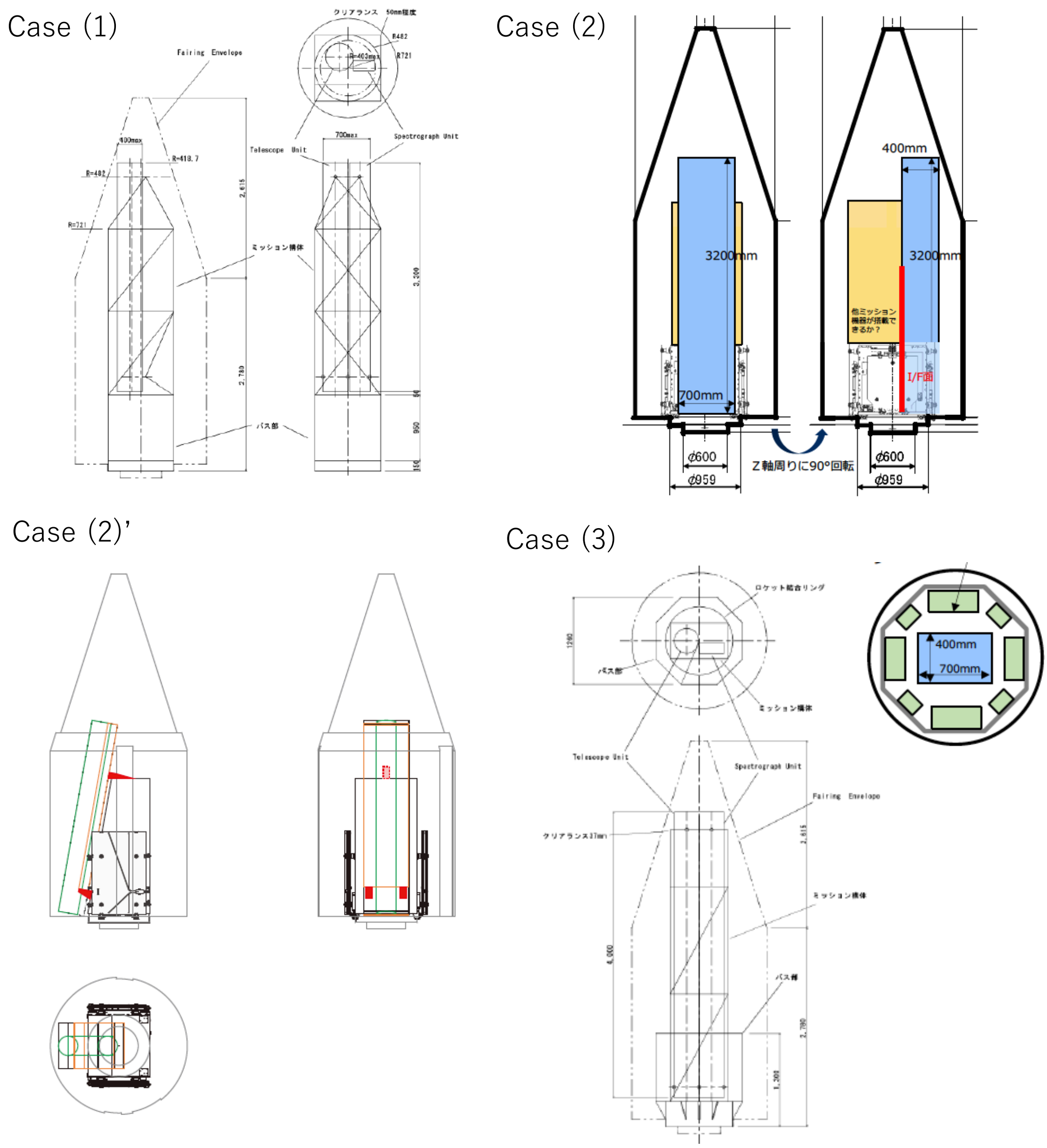


Figure 14.1: Accommodation of a 3.2m length telescope (40cm x 70cm x 320cm) to spacecraft

Table 14.3: A trade-off study on the accommodation of a long telescope

	Case (1): +Z mount	Case (2): oblique side mount	Case (3): hollow mount
Past heritage	*A*: Hisaki, Arase	*A*: Hisaki, Arase, (Hinode)	*A*: Hitomi, Suzaku
Mass merit	*B*: Heavier because the standard bus is used as is.	*A*: Can be optimized by reallocating components on the mount side.	*A*: Can be optimized with a hollow-type bus newly developed.
Mass properties	*B*: The center of gravity is located at higher position. Lower rigidity.	*A*: The center of gravity is located at the position slightly lower than case 1. Higher rigidity.	
Layout design	*A*: The ISAS small standard bus layout can be applied.	*B*: A large offset in center of gravity from the rocket axis.	*B*: A new design based on Hitomi bus.
Telescope length	*B*: The telescope length is limited at 3-3.5m.	*A*: 4m or longer telescope can be accommodated.	
Location of radiators	*A*: More flexible location for radiators in the instrument.		*B*: The lower portion is fully surrounded by the bus. Need heat pipes.
Alignment design	*A*: The telescope axis can be aligned to the rocket axis.	*B*: The telescope axis is tilted from the rocket axis, may give demerit.	*A*: The telescope axis can be aligned to the rocket axis.
Development	*A*: The bus is already verified.	*B*: New verification of the bus is required.	
Cost	*A*: Cheapest because the small standard bus is used as it.	*B*: Additional cost to modify a part of the bus.	*B*: Additional cost for the new design.
Development Risk	*A*: Less risks for the bus because the small standard bus is used as it.	*B*: No significant risks for the bus, but requires MTM/TTM.	
Evaluation summary	*7A, 3B*	*5A, 5B*	*5A, 5B*

The meaning of ranks: *A* – Excellent, *B* – Good, *C* – Fair, *F* – Fail

(5) Survey of optical parameters

A survey of optical parameters was performed to determine the strawman design under following constraints:

- Minimizing the number of optical elements in the optical configuration should be taken to achieve high temporal resolution, i.e., high throughput performance. That is the optical configuration consisting of the primary mirror, slit, grating, and detectors.
- Spatial sampling should be less than 0.3” per pixel at the CCD/IAPS to achieve a high spatial resolution.
- In order to fit the instrument into the payload fairing of the Epsilon rocket, distances between the primary mirror and the grating, and between the grating and CCD/IAPS, should be equal to or less than 3100 mm.
- In order to relax the curvature of the grating, the grating-CCD/IAPS length should be as long as possible, while the magnification of the grating should be as small as possible, which makes the development of the TVLS grating more feasible.
- F/# (focal ratio) should be as large as possible to achieve high resolution in a wider field of view.
- The diameter of the primary mirror should be as large as possible to provide a large effective area.

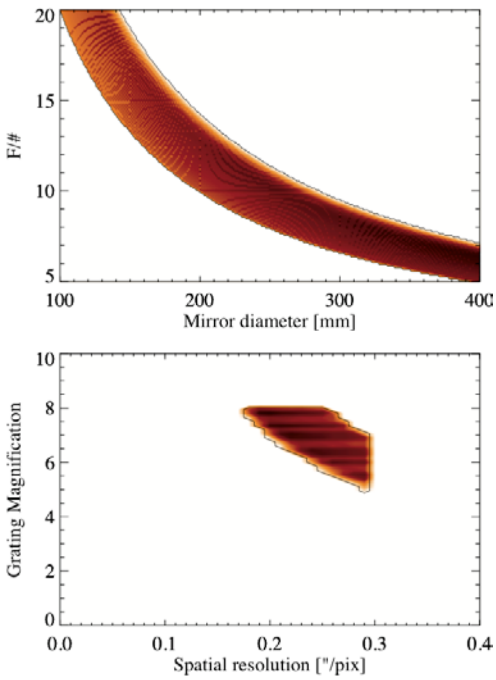


Figure 14.2: Examples of the parameter space that satisfy the conditions. Darker-colored regions show the larger number of solutions.

- The optical parameters of LW bands have longer distance between the grating and IAPS, and have more tight constraints than those of SW bands. We first determine the parameters of LW, and determine such parameters of SW that all bands have the same pixel size.

With the optical configuration, optical parameters are related as the following relations:

- [F/# ( )] = [focal length (mm)]/[mirror diameter (mm)]
- [mirror-grating distance (mm)] = [mirror focal length (mm)] + [slit-grating distance (mm)]
- [spatial resolution at CCD/IAPS (”/pix)] = [pixel size at CCD/IAPS (µm/pix)]/([plate scale at slit(µm/”)]<x[grating magnification ( )])
- [slit-grating distance (mm)] = [grating-CCD/IASP distance (mm)]/[grating magnification ( )]
- [plate scale at the slit (µm/”)] = [mirror focal length (mm)] x tan(1”) x 1000
- [pixel size of IAPS in LW channel] = 20 µm (equivalent pixel size at the intensifiers’ surfaces)
- [pixel size of CCD in SW channel] = 13.5 µm

To find preferable parameters, we set the following inequalities:

- [mirror-grating distance] ≤ 3100 mm
- [grating-CCD/IAPS distance] < 3100 mm
- [spatial sampling at CCD/IAPS] < 0.3”/pixel
- [Grating magnification] < 8

The parameter spaces satisfying the inequalities are shown in Figure 14.2. Among the parameter spaces, one of the solutions was chosen to gain the “largest mirror diameter”, “largest grating-CCD/IAPS distance”, and “largest F-number”. The optical parameters are listed in Table 14.4 and used as the baseline in section 15.

Table 14.4: optical parameters for the strawman design

Spatial sampling at CCD	0.184 ”/pix		Focal length of the primary mirror	2800 mm
Plate scale at slit	13.57 µm/”		Slit-grating distance	300 mm
Mirror diameter	280 mm		Mirror-grating distance	3100 mm
F/#	10		Grating-SW CCD distance	1650 mm
Grating magnification	5.5 (SW), 8 (LW)		Grating-LW IAPS distance	2400 mm

(6) Orbit and telemetry trade-off study

Trade-off studies on the orbit were performed for several orbit candidates to identify concerns that need to be dealt with. As a result of those trade-off studies (Table 14.5), the baseline orbit was identified: a sun-synchronous polar orbit (SSO), similar to the Hinode orbit. This orbit was compared with low earth orbit (LEO) with an inclination (31 deg), geo-synchronous orbit (GSO) with an inclination (28.5 deg) and a Halo orbit at the Lagrangian point L1. The LEO was not an option because of the difficulty of the thermal design and the continuity of observations. The GSO and L1 orbit were not an option from the point of view of the difficulty of carrying a 400-500 kg class spacecraft by an Epsilon vehicle.

The following required items were primarily studied for each orbit candidate:

a. High-rate science telemetry downlink
   The orbit will allow downlink of the mission data continuously produced with the average rate of data output specified in section 6.4.
b. High pointing stability
   Stable thermal environment with less orbital variation.
c. Thermal design
   The orbit shall ensure that the thermal design of the EUVST instrument is technically feasible.
d. Continuity of observation
   Shorter eclipse seasons, shorter duration of each eclipse and minimal orbit maintenance is preferable.

e. Real-time science operations
   Real-time operations are carried out to upload the science plans to the spacecraft. Some science data downlinked are used to make fine pointing adjustment.
f. Feasibility of the launch by Epsilon rocket.

Table 14.5: Result from orbit and telemetry trade-off study

	Low earth orbit (LEO)	Sun-synchronous polar orbit (SSO)	Inclined geosynchronous orbit (GSO) 1)	Halo orbit at the Lagrangian point L1
Altitude	500-700 km	500-700 km	36,000 km	L1 point
Inclination	31 deg	97-98 deg	28.5 deg	
Period	98 min	98 min	1 day	
Heritage (solar obs.)	Hinotori, Yohkoh, RHESSI	Hinode, TRACE, IRIS	SDO	SoHO
High-rate science telemetry downlink	*B*: X-band (8Mbps) is recommended and requires >15 passes (10min each) per day. Supports by ESA and NASA stations are essential to increase the telemetry.		*A*: X-band is recommended and required ~3hrs contact with USC 34m or Katsuura.	*B*: X-band (8Mbps) is possible with 30W transmitter. Needs ~3 hr occupation of the 64m Usuda antenna.
High pointing stability	*A*: No antenna pointing mechanism is needed, giving no micro-vibration.		*B*: The motion speed of the antenna is slow (~30 deg/hr), but need to evaluate the micro-vibration level.	*B*: The motion speed of the antenna is slow (~15 deg/month), but need to evaluate the micro-vibration level.
Thermal design	*F*: day/night transition every orbit causes large thermal deformation, giving difficulty in high resolution.	*B*: The orbital variation by the periodic infrared radiation is a concern for high resolution performance. Earth albedo & IR radiation increases the size of the radiators required.	*A*: The orbital variation is very small, providing a stable thermal environ- ment. Earth albedo and infrared radiation is very small, making the thermal design easier.	
Continuity of observation	*F*: The longest duration is 60 minutes. A night (~30 minutes) every orbit.	*A*: The longest duration is 8 months. An eclipse season (for 4 months) with about 20 minutes (at maximum).	*A*: Eclipse seasons with 70 minutes (at max) per day, each continues 20 days, twice every year. Related potential demerit is to need a large capacity of the battery. Orbit mainten-ance maneuvers (twice a year) are needed.	*A*: No eclipse season. Orbit maintenance maneuvers (several times a year) are needed every year.
Real-time science operation	*A*: Real-time access is possible but it is restricted to 10 minutes each at 5 USC passes.	*A*: Real-time access is possible but it is restricted to 10 minutes every 98 minutes for a polar ground station.	*A*: Real-time access can be arranged in the duration of pass (8 hr maximum).	
Feasibility of the launch by Epsilon rocket	*A*: No critical issue		*F*: The vehicle cannot carry 500kg class mass to this orbit	
Evaluation summary	3A, 1B, 2F	4A, 2B	4A, 1B, 1F	3A, 2B, 1F

The meaning of ranks: *A* – Excellent, *B* – Good, *C* – Fair, *F* – Fail
Note 1) GEO (Geo-stationary earth orbit, inclination 0 deg) is almost equivalent to GSO except for the orbit inclination, and brings few benefits compared with GSO. Rather, it requires more ~200 kg propellant to install the spacecraft to the GEO, compared with inclined GSO.

15. Baseline architecture (draft)

ベースラインアーキテクチャ（ドラフト）

15.1. Subsystems and their dependencies [12-3-2]

サブシステムとその間の要求の依存関係

15.1.1. EUVST Instrument Module Design

The EUVST instrument consists of two portions, i.e., a Telescope Unit and a Spectrograph Unit (Figure 15.1). The entire package will be mounted to a mechanical interface at the top panel of the bus module. This configuration needs to provide thermal independence from the spacecraft. The Telescope Unit structure is the main support structure of the instrument module and has provisions to mount the Spectrograph Unit structure. The opto-mechanical layout of the system is shown in Figure 15.2. The Telescope Unit will consist of a front door assembly, the single-mirror telescope assembly (an off-axis parabola with pointing capabilities), the guide telescope, the telescope electronics, the heat rejection assembly and the deflector plate assembly. It provides a solar image in the focal plane, the entrance to the Spectrograph Unit, and provides image stabilization and slit scanning capabilities. The Spectrograph Unit houses the slit assembly, the slit imaging assembly, the grating assembly, the focal plane assemblies, CCD electronics box, the intensified APS (IAPS) electronics box and the detector radiator assembly. It accepts the light from the telescope passing through the entrance slit towards the grating and the detector assemblies.

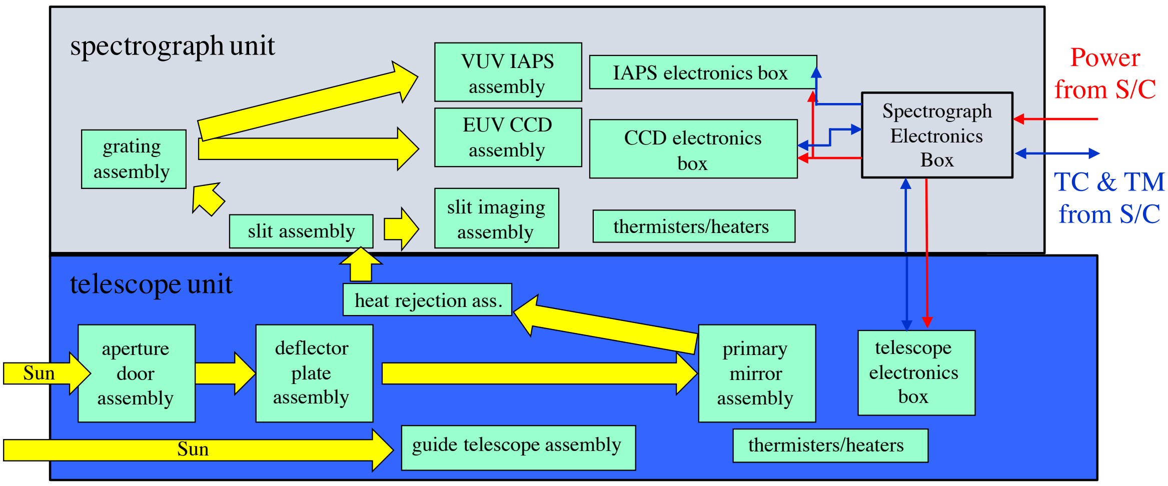


Figure 15.1: Physical block diagram of the instrument, showing major components in the instrument and digital communication links.

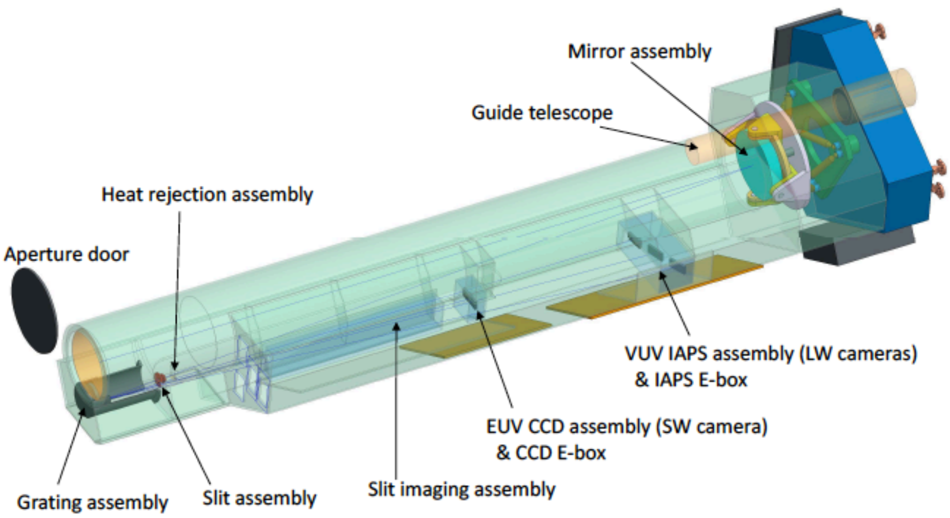


Figure 15.2: The instrument opto-mechanical layout

15.1.2. EUVST Optical Configuration and Assembly Dependencies

The optical configuration follows the two-element design pioneered by the Hinode/EIS instrument. This two-element design minimizes the number of reflections in the system – an essential feature in VUV instrumentation. Minimizing the number of reflections in the system is essential to meet the scientific requirement for high throughput. A schematic view showing the layout of the optical elements is given in Figure 15.3. Characteristics of the telescope are given in Table 14.4.

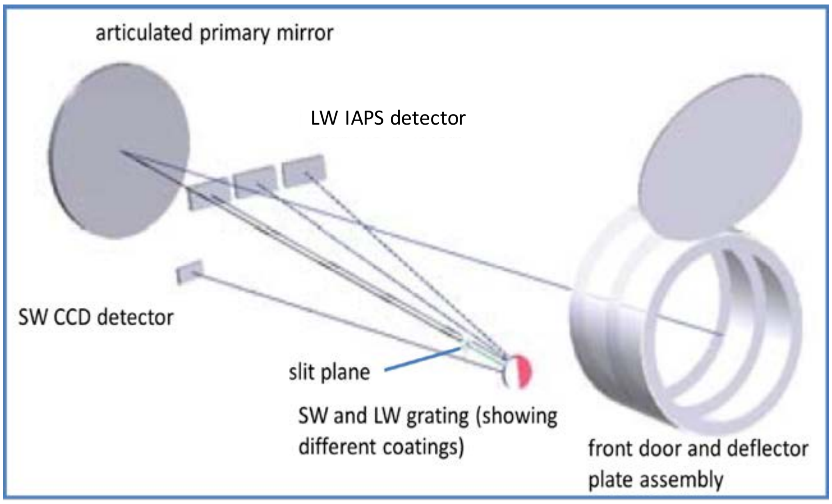


Figure 15.3: EUVST optical schematic. The figure shows the nominal geometry of the EUVST design. The path of EUV radiation through the instrument is shown.

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. These two grating halves are mounted in close proximity. The gratings are figured and coated to optimize the image quality and efficiency of each pass-band. The highly corrected off-axis toroidal gratings with variable line spacing provides excellent image quality at the focal plane across all wavelength ranges. Table 15.1 describes the grating geometry and the spectrograph characteristics. The imaging performance of the combined telescope and SW/LW spectrograph at the central wavelength of each CCD/IAPS plane at the slit center, ±50, and ±150 arcsec from the slit center is shown in Figure 15.4. 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.

Table 15.1: Spectrograph design characteristics

	SW waveband	LW wavebands
Spectral ranges	170-215 Å	1st order: 690-850 Å, 925-1085 Å, 1115-1275 Å 2nd order: 463-542 Å, 557-637 Å
Detectors	4096 × 2048 CCD, 13.5 μm pixels	Intensified APS, two 1920 × 2048 devices for a total of 3840 × 2048[1)], 20 μm pixels
Geometry and dispersion	4200 grooves/mm 165 cm grating to detector 20 mÅ/pixel	2000 grooves/mm 240 cm grating to detector 37 mÅ/pixel
Plate scale	0.184”/13.5 μm pixel	0.184”/20 μm pixel
Slit length	368” (2000 pixels)	368” (2000 pixels)
Magnification	5.5	8.0

1) The 2048 will run along the spatial direction and 3840 along the spectral domain.

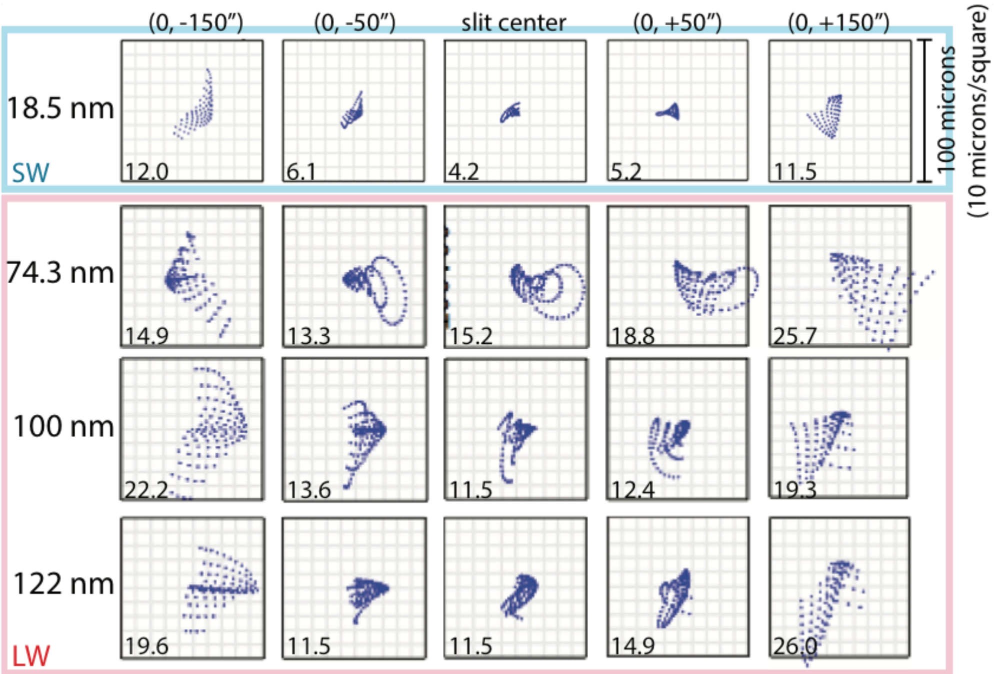


Figure 15.4: Imaging performance of the combined telescope and SW/LW spectrograph at 18.5, 74.3, 100, and 122 nm. Spots shown are for slit center, ±50, and ±150 arcsec from the slit center. FWHM of the spot size in μm is shown in the left bottom of each panel.

15.1.3. Slit Imaging Assembly

The Slit Jaw Imaging system uses relay optics to form a solar image including the entire slit and its surroundings on an APS sensor, through relatively narrow bandpass spectral filters to isolate specific wavelength ranges. The concept design demands a FOV of a few hundred arcseconds, with spatial resolution of ~0.5 arcsec and pixels of ~0.16 arcsec; the final design requires a more detailed definition of the slit jaw itself and the envelope and structure available for mounting components. The camera will be a simple framing camera with flight heritage; there are no challenging requirements for speed, read noise or operating modes. A rolling curtain shutter is used to vary exposure time, from tens of milliseconds to seconds as needed, with optional automatic exposure control to avoid saturation during flares. Structural/thermal/optical analysis of the flight structure will determine whether a focus mechanism is needed; IRIS did not have independent focus for its slit jaw system. The baseline slit jaw imaging system is a 1600 Å broadband system, similar to that on SDO/AIA (Lemen et al, 2012). This would use one or more interference filters on MgF2 substrates to reject the visible light and isolate a band that includes strong lines of He I, Fe II and C IV. The 1600 Å region generally shows the upper photosphere but includes the transition region emission during flares. A filter wheel could be used to provide additional channels such as the 1700 Å and white light channels of SDO/AIA.

A more interesting possibility would be to follow the scheme used by the IRIS slit jaw system, that provide narrowband images of the chromospheric Mg II k line emission and nearby bands of continuum and photospheric lines. The Mg II images show chromospheric structures totally absent from the 1600 or 1700 Å images, which have scientific interest themselves and would provide a more accurate co-alignment with DKIST chromospheric images or MUSE transition region images. The key component of this system is a Solc birefringent filter with a FWHM of 3.6 Å and free spectral range of 33 Å (Berger et al., 2012). This filter contains no moving parts or oil; the optical elements are mated with high-viscosity optical grease, as the Lyot filters flying on SoHO/MDI and SDO/HMI, and are hermetically sealed in an enclosure. A filter wheel with blocking filters of ~15 Å bandwidth centered on 2796 and 2832 Å provides the Mg II k images and far wing images, which shows photospheric granulation and bright points. A four-position filter wheel could have an additional clear filter for ground testing and another UV blocking filter, perhaps on the strong Fe II lines at 2630 Å for upper photospheric images.

15.1.4. Image motion compensation and raster system (IMC)

To obtain the required observations, the telescope line of sight must be precisely pointed to the Sun. During a single exposure (typical 1 s), the line-of-sight must be maintained with an error of < 0.2"(3σ) to obtain an overall resolution of <0.4" (Table 15.4). Moreover, the solar image focused on the slit must be moved to make mapping in a field of view. An image motion compensation and raster system takes care of these functions. As shown in Figure 15.5, the combined capability of the tip-tilt mirror and the guide telescope will allow image motion stabilization and raster scanning. An externally mounted guide telescope provides the necessary aspect information by measuring the position of the solar limb with four redundant photodiodes. Intensity differences between opposite diodes are used to derive a displacement error signal. A fast steering mirror provides the mirror tip/tilt articulation. Similar to IRIS, raster steps are implemented as offsets within the main control loop. The system will operate at >10Hz frequency and will provide the required 0.2"(3σ) stabilization. Line of sight jitter with frequencies above the effective bandwidth will be addressed by the control of micro-vibrations (Section 12.2.5). This is an open-loop control system in the sense that the error signal is derived from the GT rather than from motions of the image in the telescope focal plane. Therefore, careful calibration is needed to match the voltage scale of the tip/tilt actuators with that of the GT error signals, and this is routinely achieved to accuracy on IRIS of < 2%. A pair of independently rotatable optical wedges (Risley prisms) are mounted between the entrance filter and the objective lens so that the GT can be oriented off the optical axis of the primary mirror by up to 21 arcmin. When the ACS repoints to a target away from disk center using the UFSS, the wedges are rotated so the image will be approximately centered on the GT sensor, within its linear range. Table 15.2 details the expected performance of the mirror assembly, the guide telescope and the servo-control loop.

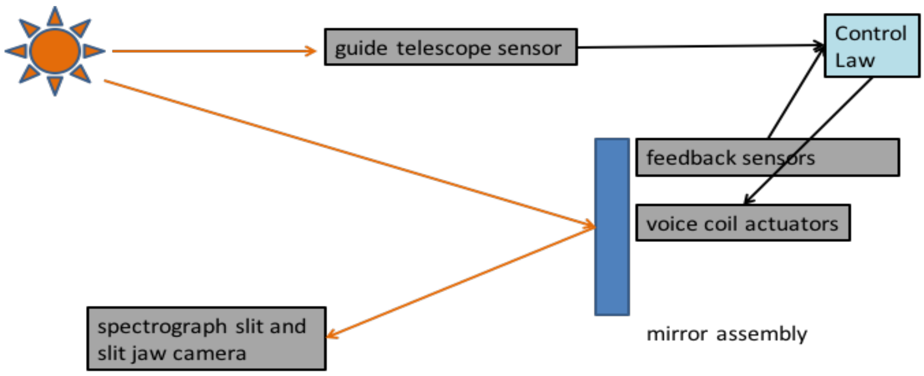


Figure 15.5: Image motion compensation and raster system functional block diagram.

Table 15.2: Guide telescope and tip-tilt characteristics

Guide Telescope: Characteristics and Performance based on IRIS		**Tip-tilt Mirror: Servo Control Loop Operating Characteristics**	
Wavelength	$\lambda0 = 570$nm, $\delta\lambda = 50$nm	Overall operation frequency	> 50Hz nominal
Focal length	1.88 m		
Acquisition range[1)]	> ± 21 arcmin	Sensor sampling frequency	250 Hz
Linear range	> ± 80 arcsec		
Noise equivalent angle	0.02 arcsec rms	Expected bandwidth cutoff	>10Hz

Note 1) The line of sight can be adjusted with wedges.

15.1.5. Thermal design and interface requirements

The instrument shall be designed as a passive, cold biased thermal system, optimized for insusceptibility to external heat sources. It draws strong heritage from the spectrometers on SoHO and on Hinode, where experience has shown that an ultra-stable temperature equilibrium of the optical bench is required to reach high optical performance characteristics. Long-term variations (seasonal, aging effects) are less critical. These requirements put severe constraints on the thermo-mechanical S/C interface, and call for an isostatic mount of the instrument to prevent thermo-elastic cross-effects and to minimize radiative and conductive coupling to the S/C. The sun synchronous orbit (SSO) provides a relatively stable thermal environment. The varying effects of Earthshine and Albedo on the instrument are minimized by optimal radiator placement and orientation. In SSO, an eclipse of up to 20 min will occur every orbit for 3-4 months in a year. Compensation heaters will minimize the post-eclipse recovery time.

An analysis based on a simplified 16-node thermal math model has shown that the thermal concept as shown in Figure 15.6 can be separated into three basically independent blocks.

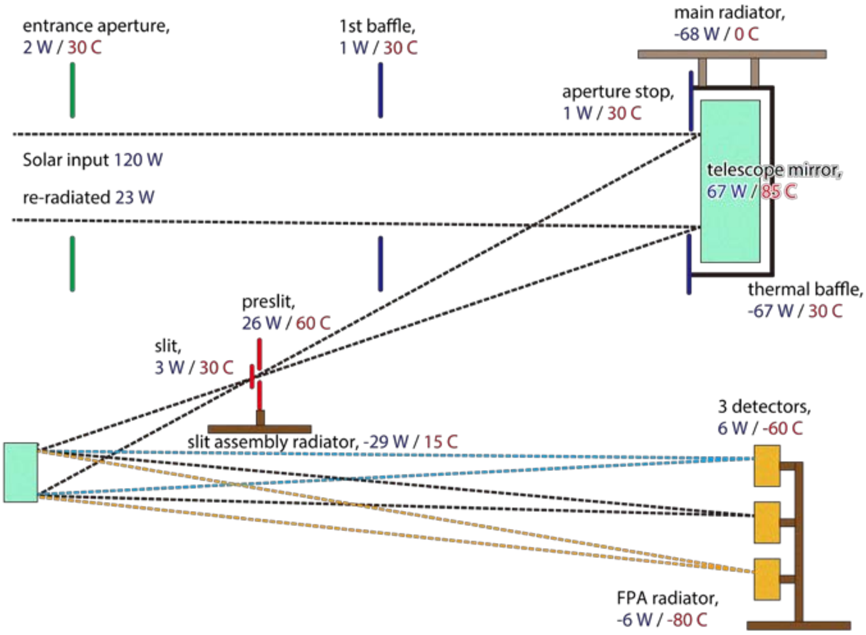


Figure 15.6: Schematic drawing of the thermal design and results obtained from a 16-node thermal model to verify the conceptual design.

1) Telescope mirror and open-aperture section: With an absorption coefficient of 0.7 for its surface, the mirror will absorb most of the solar input. An alternative coating with reduced alpha will be studied during Phase A as described in section 16.3. The mirror will be cooled passively with an external radiator as shown in Figure 15.6. Optical performance requirements do not allow conductive cooling. The mirror and mount will be designed to operate at elevated temperatures while maintaining the optical figure. The mount design will follow the successful example of Hinode/SOT which was designed for temperatures up to 47°C. A very similar design was used for SUMER (Wilhelm et al., 1995) and is currently implemented for the mirror of the SPICE spectrometer of Solar Orbiter (Schühle et al., 2007).

2) Pre-slit heat rejector: The pre-slit, which collects most of the light reflected from the telescope mirror, will protect the slit from excessive heat load by coupling to a second radiator in the telescope. The section behind the spectrometer slit is regarded as free from solar heat input.

3) Focal Plane Assemblies: The CCDs and APSs require mechanical stability, thermo-elastic insusceptibility, cooling (<-60°C for the CCDs and <-45°C for the APS) and optimized accommodation of the proximity electronics. These requirements will be achieved by an advanced design that is based on Hinode/EIS experience. The SW CCDs will be thermally isolated from the structure and cooled using a flexible strap to an external radiator. Depending on the results of the

Phase A modelling, the EUVST team will incorporate an active thermoelectric cooler if required. The LW IAPS will be cooled using an additional external radiator.

15.1.6. Electrical System and Interfaces

The electronics block diagram is given in Figure 15.7. The power and digital interface with the spacecraft is through the spectrograph electronics box. As shown in Fig. 15.7, the spectrograph electronics box (SEB) receives uplinked commands from the spacecraft and communicates directly with the transponder. The SEB power converter provides conditioned power to the SEB box. The SEB relay card provides switched power to the various detector electronics boxes and the telescope electronics box. Communication within the SEB is with a high speed backplane. A spacewire interface card services the various EUVST spacewire links. The SEB incorporates a mass memory storage card with 39Gb. This provides a buffer equivalent to roughly 12 hours of downlinked telemetry. A mechanism driver card services the slit exchange mechanism, the grating focus mechanism, the shutter mechanism for the EUV CCD, the filter wheels for the slit jaw imaging system and the order sorting filter, three reclosable detector doors and the guide telescope. Thermister, heater and thermoelectric coolers are controlled with a separate card. A microprocessor card provides ample capability to control and sequence spectrograph operation. During phase A, additional possibilities will be evaluated. The SEB box architecture is similar to the Secchi electronics box provided by NRL to the STEREO spacecraft.

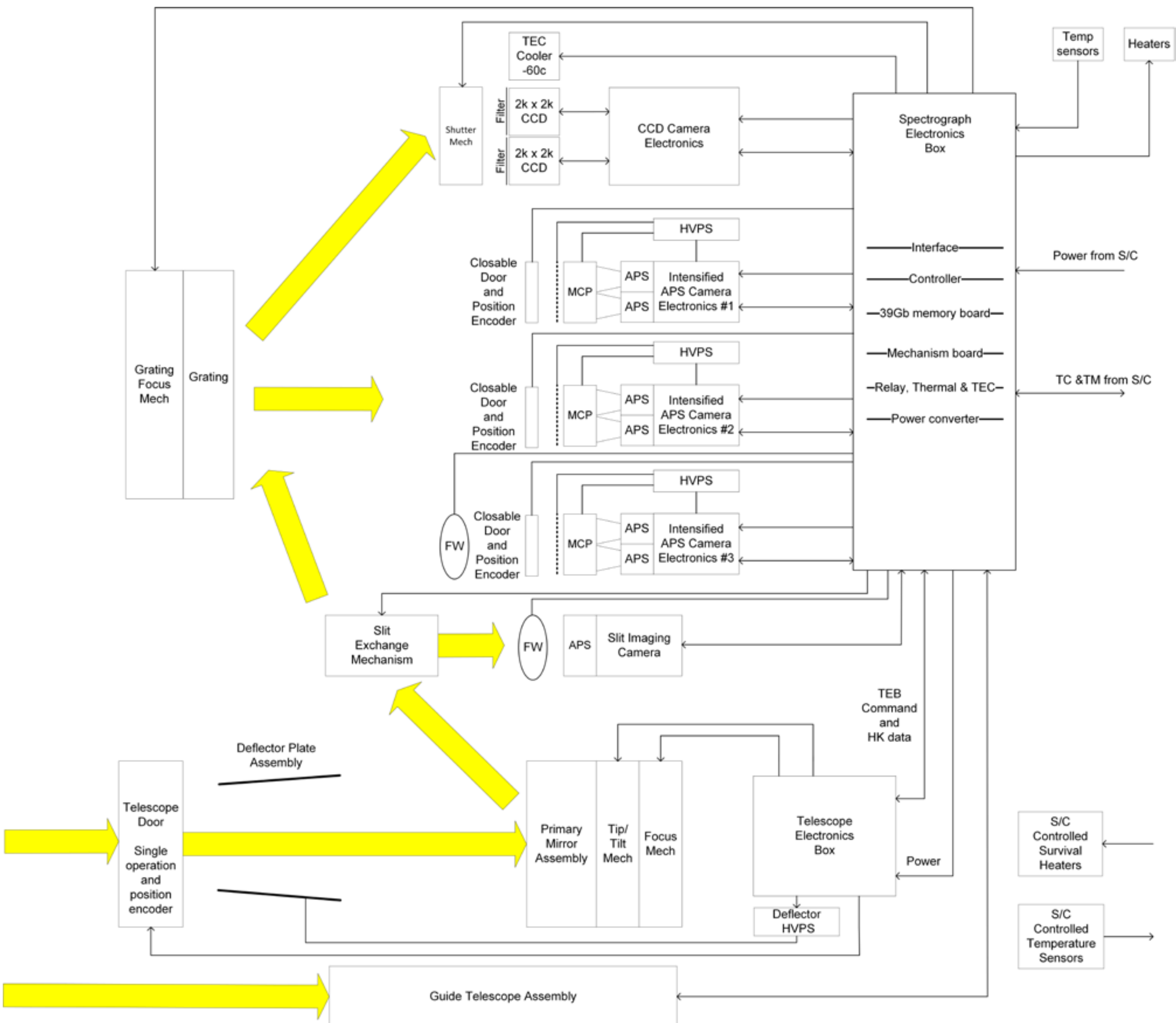


Figure 15.7: Block diagram of Electronics in EUVST

Separate electronics boxes are envisioned for control of the CCD and IAPS detectors as shown in Figure 15.7. The detector electronics will also provide compression of the spectra and formatting of the data into CCSDS packets. Compression will be implemented with a CCSDS 122.0 compatible compression chip (for example, CWICOM). The spectra will be compressed using both lossy (JPEG2000, wavelet compression and H-compress) as well as lossless (for example, RICE and DPCM) compression. The JPEG compression is currently being used on EIS and has a compression factor of 4-5. The software will also have the capability to bin pixels as well as provide overall image statistics. An analysis shows that the CWICOM chip has sufficient capacity (60Mpixels/second) to process the output of two ADCs (4Mpixels/second total) in each camera head. Sustained operations of observing modes with a telemetry rate of >0.8Mbps would require lossy compression (~8) to fit into the available downlink. The front end electronics of the detector electronics boxes will be nearly identical to electronics provided for SO/Metis, SO/SoloHI, SO/EUI, STEREO/Secchi and Hinode/EIS. The high voltage power supplies are expected to be identical to supplies provided by MPS for SO/Metis and SO/EUI. The APS slit jaw camera electronics will be a reduced functionality version of the IAPS camera.

The telescope electronics box will provide control of the tip/tilt mechanism, the focus mechanism, the door and deflector plate voltage. Mirror voice coil actuators will be operated using customized analog/digital drivers; direct feedback of the position will be available from the capacitance micrometers. Operations of the telescope electronics box will be controlled by an embedded microcontroller.

15.1.7. Spacecraft system

The system block diagram is shown in Figure 15.8. Our proposed baseline for the spacecraft system is to utilize the bus system defined in the ISAS small standard bus, as also shown in Table 15.3. However, as discussed in section 10.2, a few modifications are needed to meet the high pointing stability and high mission telemetry.

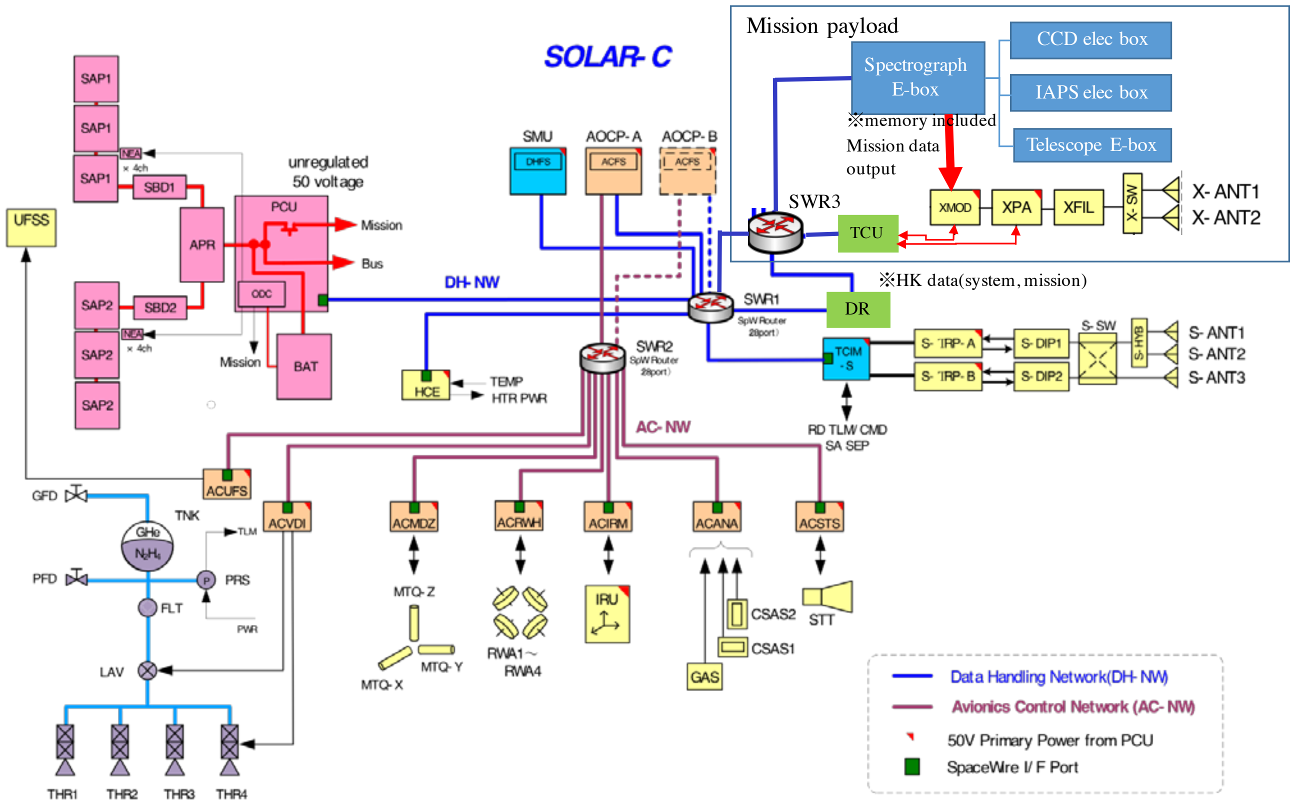


Figure 15.8: System block diagram.

Table 15.3: List of components in the proposed baseline. Highlighted items are not available on the standard bus.

Component	Code	#	Used in proposed baseline	Ref: Default standard bus
Mission				
Mission payload				
EUVST	EUVST	1	√	
X-band telemetry system	XMOD, XPA, XFIL X-SW, XANT	1 set	√	
Telemetry & command unit	TCU	1	√	
Bus system				
Management (SMS)				
Satellite management unit	SMU	1	√	√
Data recorder	DR	1	√	√
Telemetry/command IF module	TCIM	1	√	√
Spacewire router	SWR	2	√	√
Radio Communication (RF)				
S-band antenna	SANT	3	√	√
S-band diplexa	SDIP	2	√	√
S-band switch	SSW	1	√	√
S-band hybrid	SHYB	1	√	√
S-band transponder	STRP	2	√	√
Power Supply (EPS)				
Solar array paddle	SAP	2	√	√
Paddle drive motor	SADM	0		
Power control unit	PCU	1	√	√
Array power regulator	APR	1	√	√
SAP blocking diode	SBD	2	√	√
Battery (50Ah)	BAT	1	√	√
Attitude and orbit control system (AOCS)				
Attitude orbit control computer	AOCP	2	√	√
Reaction wheel assembly	RWA	4	√	√
Magnetic torquer	MTQ	3	√	√
Star tracker	STT	1	√	√
Inertia reference unit	IRU	1	√ (upgrade)	√
Coarse sun sensor	CSAS	2	√	√
Sun presence sensor	SPSH	0		√
Ultra fine sun sensor	UFSS	1	√	
Geo-magnetic sensor	GAS	1	√	√
AOCS interface module	AC***	6~7	√	√
Thruster system (RCS)	RCS	1 set	√	√
Thermal control (TCS)				
Heater control electronics	HCE	1	√	√

For the high pointing stability, Ultra Fine Sun Sensor (UFSS, sections 12.2.3, 16.2, and 16.3) will be used instead of sun presence sensor as a sensor for measuring the accurate direction of the Sun in real time and delivering the measured angles to the attitude control computer for controlling the attitude. Gyroscope (Inertia Reference Unit; IRU) will be upgraded from the standard one to higher resolution IRU (for example, pulse wait 0.05” to 0.005”). Higher resolution IRU means a narrower range of measurements (for example, 4 deg/sec to 0.4 deg/sec). Additional studies associated with this modification will be needed during the design phase, such as the acquisition of the Sun after the launch and contingency cases with the given battery capacity. A thruster system is assumed according to an initial study in section 15.4.2.

High telemetry mission data line is required in the mission. An X-band telemetry system with a large mass data recorder will be accommodated for this requirement. Since no space is available in the ISAS small standard bus, a small electrical panel structure for accommodating the electrical components consisting of the X-band telemetry system and data recorder will be added and mounted on the +Z surface of the bus.

15.2. Risk mitigation [7-3-2]
リスクの mitigation

The major risks of the proposed mission concept were listed and briefly discussed in section 12.4. Four major risks have been identified and all of them are related to the requirement for spatial resolution. For the requirement for spatial resolution, we define a strawman budget table as shown in section 15.3, in which the target value is given to each of error sources. The design and evaluation studies will be carried out to confirm whether each target value is achievable. Depending on results from the studies, the budget table will be updated. Tests for verification of the flight model will be carried out to confirm that each term in the budget table is achieved and finally that the flight model has the required performance. The major risks listed in section 12.4 are a part of the terms in the budget table. Here we explain how to proceed for the major risks and discuss alternative considerations for mitigating the major risks.

- No. 001: The grating performance: The grating parameters have been determined for the baseline design. For confirming the manufacturing feasibility, it is important to study the tolerance in the parameters and its manufacturing feasibility with grating providers. We have initial contacts with a few grating providers (Horiba JY and Zeiss). These contacts have shown that the grating specifications are achievable. Further iteration on the grating design and its tolerance analysis with the grating providers is planned during phase A. Prototype gratings will be procured and tested during Phase A as described in Section 16.3.4. We will also have plans for backup solutions (spherical VLS grating, reduced groove density).
- No. 002: Wavefront performance of the primary mirror: The primary mitigation will be to complete the thermal-structure design and analysis for the baseline early in Phase A. The analysis will provide the mirror deformation as a function of temperature and mechanical mounting arrangement. Temperatures up to +80°C will be considered. The EUVST team will also finalize the primary mirror coating during Phase A and measure the coating reflectivity in the visible and UV. To avoid contamination of the primary mirror, the operating temperature of the mirror will be >50°C.
- No. 004: Micro-vibration from momentum wheels: A first micro-vibration analysis with the ISAS small bus model carried out in summer 2017 (section 12.4 and 16.2.5) indicated that the micro-vibration from momentum wheels have potential to exceed the 0.1 arcsec (3σ) level, giving blurring to the spatial resolution at unacceptable level. It is important to define more clearly the direction of design before going to phase A study. A large uncertainty exists in the first micro-vibration analysis, efforts for mitigate it focus on reducing the magnitude of the uncertainty, by 1) carrying out an experimental measurement of the transfer function with the ISAS small bus as well as 2) by starting to discuss the amount of micro-vibration with wheel vendors during pre-Phase A study. These two efforts will improve our model fidelity and the second micro-vibration analysis with the updated model would provide more accurate prediction on the micro-vibration level. If the results from the improved micro-vibration analysis still show that the vibration level exceeds the allocated value, we will take the following actions: 1) the trade-off studies of the isolation damper (with the major risk numbered No. 012), and 2) the revision of the budget table. If those actions do not allow to meet the spatial resolution requirement, we shall consider a slight relaxation of the requirement.

15.3. Worst case analysis [8-3-2]
最悪ケース解析

High spatial resolution is one of the key challenges of the EUVST. The EUVST team has assessed the image quality of the baseline design and created an imaging error budget. The imaging error budget contains the major error components as well as significant margin. The results are summarized in Table 15.4.

Table 15.4: Initial budget allocation for achieving the FWHM spatial resolution requirement.

Term	FWHM[1]		Remarks
Optical design	0.11”	0.19”	SW Avg Spot size: 6μm in FOV ±50” LW Avg Spot size: 15μm in FOV ±50”
Spectrograph fabrication and assembly	0.09”		Based on Hinode/EIS grating experience
Telescope diffraction-limited Performance at 182nm[2]	0.16”		13nm rms wavefront error is assumed; Scaled performance of SOT primary mirror
Total optical resolution	0.22”	0.27”	
Pointing jitter	0.16”		Table 10.1: <0.2” (3σ)
Total EUVST Resolution	0.27”	0.31”	
Margin vs 0.4” [3]	50%	29%	Table 5.1: Science requirement

1) FWHM: SW (left) and LW (right)
2) If the telescope has a 26nm rms wavefront error, the total EUVST resolution is 0.4” for the SW case.
3) EUVST spatial resolution performance has significant margin which accommodates a reasonable range of worst case scenarios. The threshold requirement of 0.8” FWHM is not expected to be reached during the mission development.

The term “optical design” is the optical performance of the entire instrument that has been confirmed with ray tracing, as shown in Figure 15.4. Thus, this is the worst case for the optical design and we will continue to optimize the optical design for more better spatial resolution. 13nm rms wavefront error which is diffraction-limited wavefront error for 182 nm is allocated to the telescope as the initial budget. The active mirror assembly and the telescope structure for maintaining the positional relations among optical elements will be developed to achieve this allocated value. This allocated wavefront error is about a half of the wavefront error achieved in the primary-secondary mirror configuration of Hinode/SOT. The allocated error is roughly scaled from Hinode/SOT, by considering the difference in mirror diameter (SOT 50cm vs. EUVST 28cm). Even when the telescope has a 26nm rms wavefront error, the total EUVST resolution is 0.4” for the SW channel. The SOT’s achieved wavefront error was designed in the temperature up to 47°C. Since the EUVST mirror is operated at a high temperature (currently 80°C), thermal deformation may be caused in the temperature change from 47°C to 80°C and this is currently unknown quantitatively. The mirror assembly design will be carried out to minimize this thermal deformation in pre-Phase A and Phase A study. On the other hand, as described in section 16.2.3, the team is studying a coating with enhanced reflectivity and significantly lower solar absorption and this effort will be helpful to reduce the mirror temperature significantly.

Assessment of Pointing Stability

With the pointing signals from UFSS, the pointing stability of ISAS standard bus was evaluated by the bus company, based on knowledge from Hisaki and ASNARO-1. Table 15.5 shows that it would be possible for the spacecraft systems to achieve the science requirements given in Table 10.1, although further studies are needed in the co-alignment between UFSS and payload instrument, UFSS internal variation, and micro-vibration from reaction wheels. Note that the IRU is upgraded to a higher accuracy component.

Table 15.5: Summary result from an initial analysis of the spacecraft pointing stability

		θx [arcsec] (3σ)	θy [arcsec] (3σ)	θz [arcsec] (3σ)
Short (<10 [sec])	Requirement	0.2	0.2	7.00
	Evaluation result	0.12	0.12	0.57
Medium (1 [hour])	Requirement	4.2	4.2	212.0
	Evaluation result	1.89	1.89	14.53
Mission life (absolute pointing)	Requirement	42.0	42.0	212.0
	Evaluation result	3.89	3.89	117.52

The magnitude of spacecraft jitter in the short timescale (corresponding to individual exposures) may exceed the budget in Table 15.4 and, thus, EUVST is required to have an image motion compensation system in the instrument (section 15.1.4). Additional sources of error such as drift between the UFSS and the telescope optical axis were not considered in the analysis. The noise equivalent angle from the guide telescope is 0.02 arcsec rms (Table 15.2), which will be sufficient to achieve 0.2 arcsec (3σ). On IRIS, the use of the GT error signals with the tip/tilt secondary mirror keeps the solar image stably positioned on the slit with a precision of <0.05 arcsec. A similar performance would meet the EUVST requirement jitter requirement in Table 15.4.

Optics Alignment Tolerance

The error budget for the entire telescope and spectrograph will be divided into terms, such as the design, fabrication errors of the optics, errors from mechanical and thermal deformation, and focus positional error. We will update the budget table in the development efforts (section 16.3). We should note that the wave front error of 13nm rms (equivalent to 0.16") was allocated to achieve the diffraction limited performance. The Hinode/SOT experience indicates that 13nm rms is achievable. The study of the mirror figure deformation is one of the key areas because of the high operational temperature.

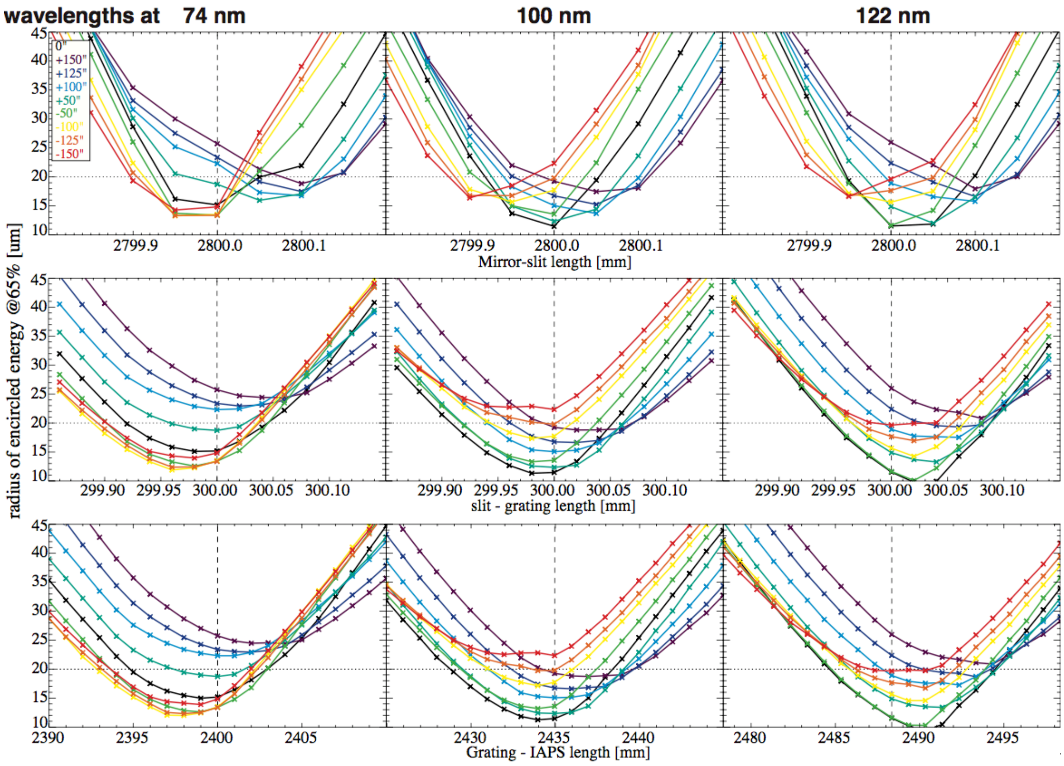


Figure 15.9: Instrument alignment sensitivity. FWHM of the spot diagrams at the LW detectors as a function of the distance between the mirror and the slit, the slit and the grating, and the grating and the detectors. Each column shows the different wavelength. Colors display different incident angle along the slit direction described in the left-top figure. The plate scale of the detectors is 20 μm per pixel.

The optical performance computed by changing the distances between optical elements are shown in Figure 15.9. This figure shows that the adjustment of ±50 μm is needed for the distances between the primary mirror and the slit, and between the slit and the grating to fulfill the spatial resolution of 0.4" FWHM in the field of view of ±50". The distance between the grating and the CCDs are, on the other hand, adjusted within 5 mm. Assuming that the accuracy of the alignment during the integration of the optical elements is about 100 μm, focus adjustment mechanisms are considered in the primary mirror and the grating as the baseline concept. Tolerances of the decenters of the primary mirror, slit, grating, and CCDs are 500, 500, 1000, and 200 μm, respectively. This means that optical elements have no need of positional adjustment in non-focus directions.

15.4. Space environment [3-3-2] 宇宙環境

15.4.1. Lower limit in the altitude of sun synchronous orbit

A sun synchronous orbit is selected for the proposed mission to satisfy the requirement of the seamless observation for 24 hours per day for nearly nine months of the year. However, the line-of-sight atmospheric length of the Earth becomes longer in the SSO orbit than that in the small-inclination low-earth orbit (LEOs), which leads to a low atmospheric transmission in EUV and UV wavelengths by absorption processes. The absorption is reduced when the orbital altitude is higher. The lower limit of the altitude in the requirement is determined by the atmospheric absorption, and the upper limit is given from the radiation environment to be allowed.

The absorbers are mainly molecular nitrogen, molecular oxygen, and atomic oxygen in the thermosphere, and the density of the absorbers varies according to the solar activity. The absorption cross sections are large for wavelengths of 40-80 nm and largely fluctuate between 80 and 100 nm depending on wavelength. The deep absorption occurs when the axis of the Earth is tilted to the direction of the Sun. The nominal orbit altitude of 630 km in the Solar-B mission was determined from the EUV observations at the longest wavelength of 29 nm by considering the atmospheric absorption at the solar maximum in 1991.

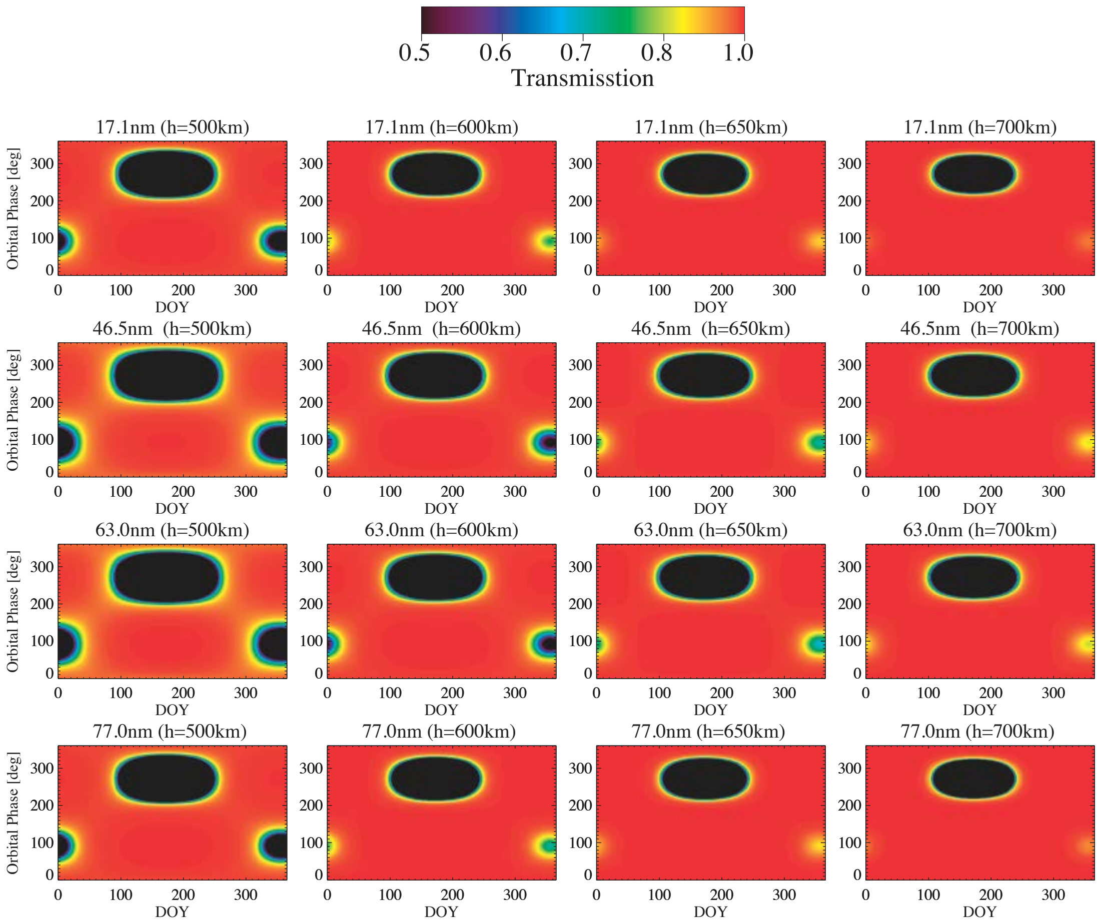


Figure 15.10: Atmospheric transmission of the Earth to several wavelengths to be observed with EUVST for the spacecraft altitude of 500, 600, 650, and 700 km. Day of the year (DOY) is in the horizontal coordinate, and the vertical coordinate is the phase angle of the spacecraft orbit around the Earth.

We have calculated the atmospheric absorption as a function of zenith angle of the Sun from the spacecraft view, solar and geomagnetic activity represented by the F10.7 radio flux and Ap-index with the help of Hedin's thermospheric model. The zenith angle of the Sun seen from the LEO spacecraft changes within a short-duration spacecraft orbit around the Earth and in the orbital motion of the Earth around the Sun. Figure 15.10 displays the atmospheric transmission at the relatively high solar activity (F10.7=150 and Ap-index = 25) as a function of the orbital phase of the Earth in DOY (day of the year) and the spacecraft orbital phase in the horizontal and vertical axes, respectively. The zero degree in the vertical axis is the ascending node of the spacecraft to the Earth's equator, and 90 degree is the north pole in the case that the launch date is near the autumn equinox point like Solar-B. The eclipse of the Sun by the Earth occurs in the May-to-Sep season for the LEO spacecraft in SSO. The period of non-eclipse and non-absorption conditions for all EUVST observing wavelengths is not long for the altitude of 500 km. The lower-limit altitude of 600-700 km will be the solution and is achievable with the Epsilon.

15.4.2. Necessity of propulsion system

The stability of a sun synchronous orbit was studied to know the necessity of propulsion system onboard. The requirement from the science is that the total duration of the non-eclipse season is >8 months per year within two years after the launch (section 10.1.2). Two uncertainties were considered: 1) The injection accuracy of Epsilon rockets (Table 4.1), and 2) the height reduction due to air drag at 2024-2026. For 1), the total duration of the non-eclipse season is reduced to less than 5 months in the 2nd year if the installed orbit is 20 km lower than the target height and +0.2 deg larger than the target inclination. For 2), we obtained that the height reduction is 60 km/year (170 m/day), 18 km/year (50 m/day), 6 km/year (17 m/day) for the orbit height of 550 km (air density: 8.5×10^{-13} kg/m^3), 650 km (2.5×10^{-13} kg/m^3) and 750 km (8.4×10^{-14} kg/m^3), respectively. The height change caused by air drag will further increase the deviation from the sun synchronous condition. This initial study showed that the propulsion system should be included onboard the spacecraft as part of the baseline architecture.

15.4.3. Spacecraft environment

The EUVST has assessed the radiation, thermal and orbital environment as part of the proposal effort. The expected orbit is nearly identical to Hinode/SOT and is relatively benign.

15.5. Planetary protection [14-3-1]
惑星検疫

Not applicable.

15.6. New ground system [6-3-5]
新規地上系

Additional ground system software for converting the observations envisioned by scientists into data will be written. This software will be based on the heritage of Hinode/EIS, but will also include new ideas from more recent missions, such as IRIS. The first element of the ground system will be the software for generating and validating user-defined observing programs and storing them in a database. The next element will be a planning tool that allows the scientists to schedule these user-defined observing programs to be run at a specified time and pointed at a specified target on the sun. The output of the planning tool will be instructions that can be transmitted to the instrument via the already existing operation tools and facilities at ISAS/JAXA (section 11.3) and executed on board.

After the observing program is run and the data is downloaded to the ground (section 11.3), additional software routines will assemble the telemetry packets into data files that can be read using widely available computer languages. Software for "prepping" the raw data files to remove known instrumental effects, apply the calibration, and create a higher-level data product will also be written. Finally, basic analysis software for displaying the data and performing simple data analysis, e.g. Gaussian fits to the line profiles, will also be written and distributed to the user community.

15.7. Launch Vehicle [13-3-1]
打ち上げ機

The EUVST instrument is mounted on the standard bus. Three different spacecraft layouts were

Table 15.6: Mass budget table of the entire mission

Component	Code	#	Mass (kg)	Subtotal
Mission section				
Mission payload				156.8
EUVST	EUVST	1	156.8	
X-band telemetry system				10.5
	XMOD	1	2.4	
	XPA	1	2.5	
	XFIL	1	5.2	
	XSW	1	0.1	
	XANT	2	0.3	
X-COM panel			3.0	3.0
Telemetry & command unit	TCU	1	3.5	3.5
Bus section				
Management (SMS)				11.3
Satellite management unit	SMU	1	2.0	
Data recorder	DR	1	1.9	
Telemetry/command IF module	TCIM	1	2.1	
Spacewire router	SWR	2	3.4	
Mission control unit	MCU	1	1.9	
Radio Communication (RF)				8.2
S-band antenna	SANT	3	0.5	
S-band diplexa	SDIP	2	0.8	
S-band switch	SSW	1	0.1	
S-band hybrid	SHYB	1	0.1	
S-band transponder	STRP	2	6.7	
Solar Array Paddle (SAP)		2	32.4	32.4

Component	Code	#	Mass (kg)	Subtotal
Power Supply (EPS)				36.0
Power control unit	PCU	1	5.5	
Array power regulator	APR	1	4.0	
SAP blocking diode	SBD	2	0.8	
Battery (50Ah)	BAT	1	25.7	
Attitude and orbit control system (AOCS)				64.6
Attitude orbit control computer	AOCP	2	4.0	
Reaction wheel assembly	RWA	4	34.4	
Magnetic torquer	MTQ	3	2.1	
Star tracker	STT	1	3.3	
Inertia reference unit	IRU	1	9.3	
Coarse sun sensor	CSAS	2	0.01	
Ultra fine sun sensor	UFSS	1	3.1	
Geo-magnetic sensor	GAS	1		
AOCS interface module	AC***	6~7	8.4	
Thruster system (RCS)	RCS	1 set	15.4	15.4
Thermal control (TCS)				10.1
Heater control electronics	HCE	1	5.6	
Thermal control materials		---	4.5	
Structure				50.1
Instrumentation				33.1
EINT			22.0	
MINT			11.1	
Thruster fuel				29.5
BUS dry [kg]				**261.2**
MISSON [kg]				**173.8**
Wet [kg]				**29.5**
TOTAL [kg]				**464.5**

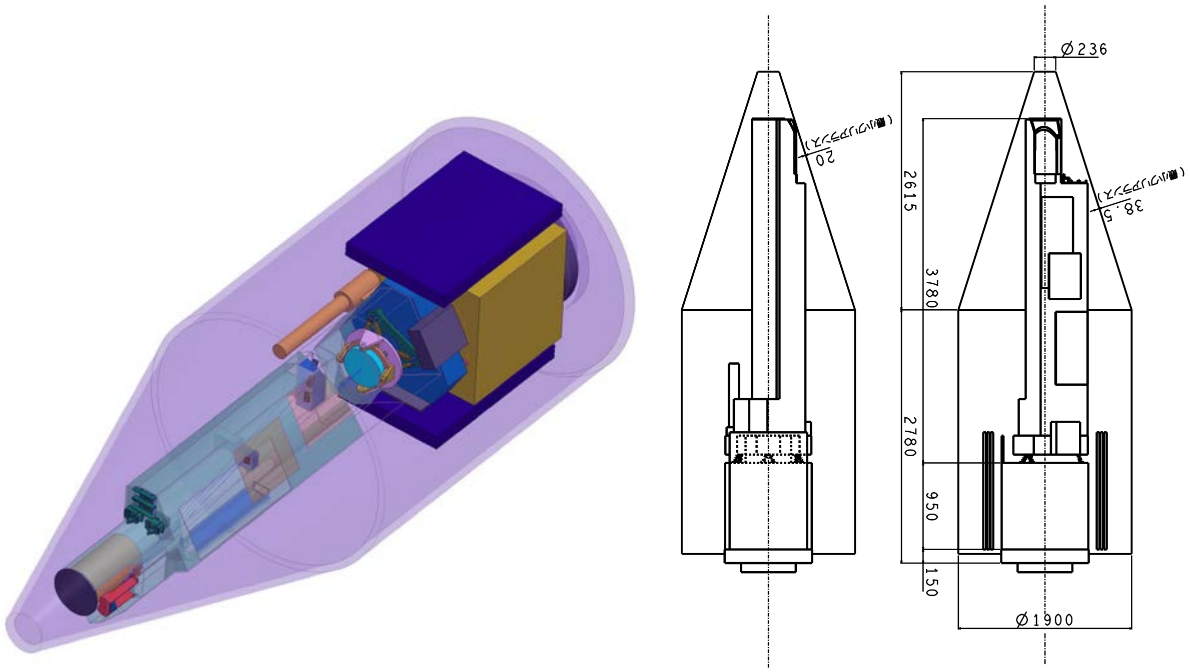


Figure 15.11: Spacecraft layout in the Epsilon rocket fairing

investigated with trade-off studies by a spacecraft system company as described in section 14.2(4). Figure 15.11 shows the spacecraft layout requiring minimal modification to the bus module. The EUVST instrument is mounted to the top panel of the bus module. The Ultra Fine Sun Sensor (UFSS) is mounted to the EUVST. The X-band module, an addition to the standard bus, is attached to a small electric panel on the top panel of the bus module. Figure 15.11 shows the fairing envelope, which has sufficient (20mm) clearance at the top edge of the EUVST instrument.

Table 15.6 is the mass budget table of the entire proposed mission. The mass of EUVST comes from section 15.8. The best estimated total mass of the mission (464.5 kg) is well within the Epsilon capability (590kg) given in section 4 and has ample margin (24%).

Table 15.7: Instrument module design characteristics and mass breakdown estimates.

<table>
<tr><th>Unit/Assembly</th><th colspan="2">Description/baseline value</th><th>Mass (kg)</th></tr>
<tr><td colspan="3">Telescope unit</td><td>87.1</td></tr>
<tr><td>Structure</td><td colspan="2">Precision manufactured CFRP structure, high stiffness tube type</td><td>43.4</td></tr>
<tr><td>Front door</td><td colspan="2">Single open door to protect the telescope for contamination control</td><td>3.0</td></tr>
<tr><td>Deflector plate</td><td colspan="2">A plate arrangement providing an electric field to protect the mirror from ambient charged particles. A static voltage is applied across the plates such that solar wind particles will be deflected from their path towards the mirror.</td><td>1.0</td></tr>
<tr><td rowspan="3">Primary mirror assembly</td><td>Mirror</td><td>off-axis paraboloid, 28 cm diameter, 280 cm focal length, overall < λ/60 rms figure, < 5 Å rms micro-roughness, broadband VUV coating, low-expansion substrate (Zerodur)</td><td rowspan="3">22.0</td></tr>
<tr><td>Pointing & scan</td><td>Fast raster/fine pointing mechanism: range 400”, image motion in pitch and yaw, <0.09” (3σ), >10 Hz response</td></tr>
<tr><td>Focus</td><td>Focus adjustment along telescope chief ray to make best solar image on the slit.</td></tr>
<tr><td>Guide telescope</td><td colspan="2">Section 12.2.2, 0.02” (rms) accuracy at 10 Hz, range >2000”</td><td>3.5</td></tr>
<tr><td>Heat rejection assembly</td><td colspan="2">Absorb solar heat outside FOV in front of slit. The absorber is linked to the radiator where the heat is dumped toward the space.</td><td>1.0</td></tr>
<tr><td>Telescope E-box</td><td colspan="2">Control of the mechanisms in the mirror assembly and telescope heaters.</td><td>3.2</td></tr>
<tr><td>Cable, thermal H/W, misc.</td><td colspan="2"></td><td>10.0</td></tr>
<tr><td colspan="3">Spectrograph unit --- magnified Rowland circle design</td><td>69.7</td></tr>
<tr><td>Structure</td><td colspan="2">Combined to the telescope structure which works as the optical bench for components. Covered by CFRP honeycomb panel structure.</td><td>31.2</td></tr>
<tr><td>Slit assembly</td><td colspan="2">5 slits on a slit plate, 0.184”, 0.368”, 0.74”, 1.47”, 2.94”, selected by linear translation or rotating mechanism.
Slit jaws reflective to feed the light to the slit imaging assembly</td><td>1.5</td></tr>
<tr><td>Grating assembly</td><td colspan="2">Houses the SW and LW gratings, both of which are Toroidal Variable Line Space (TVLS) gratings. Focus adjustment along telescope chief ray to make the best focused spectra on the detectors’ surface.</td><td>1.0</td></tr>
<tr><td>VUV IAPS assembly</td><td colspan="2">Three 3840 $\times$ 2048, 20 μm pixel LW intensified APS detectors
bare and CsI or KBr coated MCP</td><td>7.5</td></tr>
<tr><td>IAPS electronics box</td><td colspan="2">Controls and reads the IAPS detectors, provides MCP HV</td><td>4.5</td></tr>
<tr><td>EUV CCD assembly</td><td colspan="2">SW CCD with radiative cooling, 2 butted 2048 $\times$ 2048,
13.5 μm pixel with shutter mechanism, thin metal foil filter</td><td>1.5</td></tr>
<tr><td>CCD electronics box</td><td colspan="2">Controls and reads the CCD detectors</td><td>2.0</td></tr>
<tr><td>Slit imaging assembly</td><td colspan="2">Relay optics with >200” $\times$ 300” FOV, ~0.16”/pixel, CCD or APS detector, with shutter and filter wheel</td><td>4.0</td></tr>
<tr><td>Cable, thermal H/W, misc.</td><td colspan="2"></td><td>8.0</td></tr>
<tr><td>Spectrograph E-box</td><td colspan="2">Telemetry and command handling, data processing, camera operations
Digital and power interfaces to the S/C</td><td>8.5</td></tr>
<tr><td colspan="3" align="right">Total mass (including 15% reserves)</td><td>156.8</td></tr>
</table>

15.8. Mission instrument architecture [11-3-1]
ミッションアーキテクチャ

Table 15.7 is the list of unit and assembly for the EUVST instrument and their key characteristics. A preliminary mass breakdown (15% margin included) is also provided in Table 15.16.

An estimate of the average dissipated power for EUVST is 161 W (including 36 W for operational heaters), which includes a contingency of 20%. In the power budget for the entire mission (623 W in total), this value is still acceptable from viewpoint of battery balance of charge and discharge and the upper limit capacity of the power distribution by Power Control Unit (PCU).

15.9. Ground and flight verifications [15-3-1]
地上・軌道上検証活動

Figure 15.12 shows a draft chart describing the overall flows of the flight model development. The verification of performance, with respect to performance requirements, and the calibration of the EUVST instrument divide into three phases.

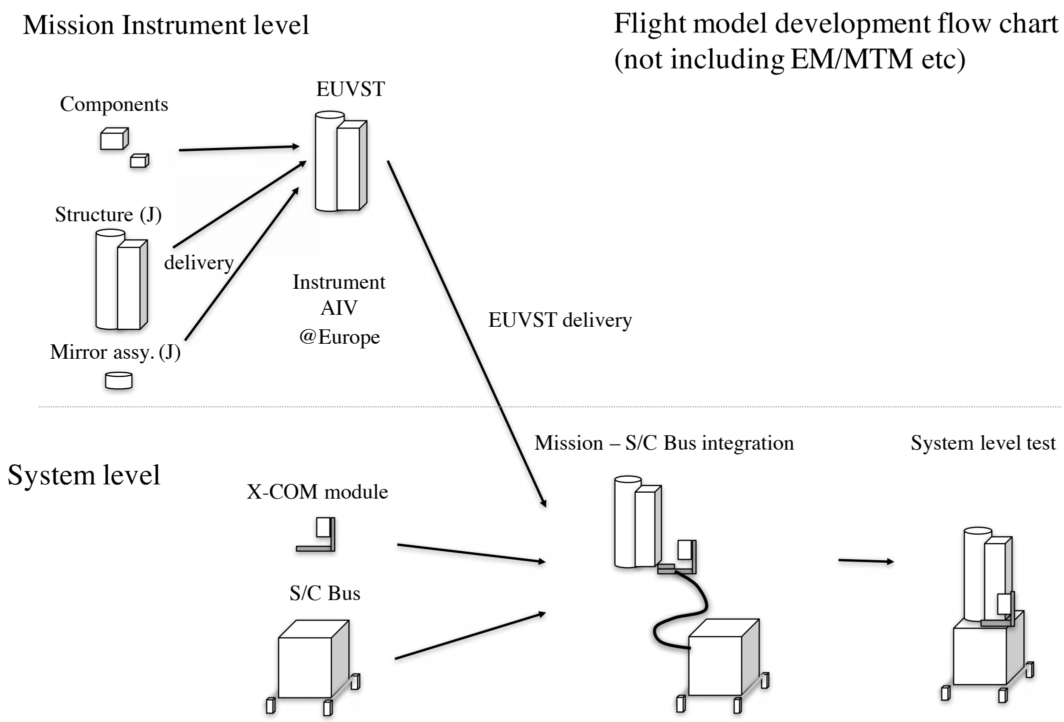


Figure 15.12 The development flow chart

15.9.1. EUVST subassembly

Prior to the instrument level AIT (assembly, integration and test), all the components will be verified by the responsible supplier. Especially, the key elements of the instrument will be characterized at subsystem level. The key subsystems that undergo characterization are:

- Mirror: optical performance and efficiency,
- Gratings: the diffraction efficiency and performance at all wavelengths,
- Detectors: the detection efficiencies of the cameras.
- Image motion compensation and raster system: servo control loop performance with guide telescope

The performance of the active primary mirror assembly will be characterized at a visible wavelength, e.g., 633 nm, using an interferometer. The resulting data will be used to verify and track the expected instrument scientific performance using a model of the end-to-end performance of the instrument. Each subsystem will be characterized by the responsible supplier.

15.9.2. EUVST assembly, integration and verifications

The EUVST instrument AIT flow is given in Figure 15.13. After subassembly verification is complete, the EUVST will be built up into a single structure. The first portion of the testing will be conducted with a primary mirror simulator. The mirror simulator will allow full test of the slit jaw imaging assembly and characterization of the spectrograph performance including cameras and electronics. For vacuum focus and alignment, the instrument aperture will be fully illuminated using an EUV collimator similar to Hinode/EIS. The light source is a commercially available hollow cathode lamp. Various gas and cathode/anode combinations will generate a variety of emission lines for image quality and throughput testing of the EUVST instrument. After the vacuum focus/alignment of the spectrograph and slit jaw camera are complete, the primary mirror simulator will be replaced with the primary mirror assembly. The telescope electronics box, door, guide telescope, deflector plates and heat rejection system will be installed to complete the EUVST instrument. The EUVST instrument performance will be verified end to end in both air and vacuum using techniques developed for IRIS, Hinode/EIS and SO/SPICE. As shown below, the EUVST will undergo a full suite of environmental testing at the instrument level prior to installation onto the spacecraft.

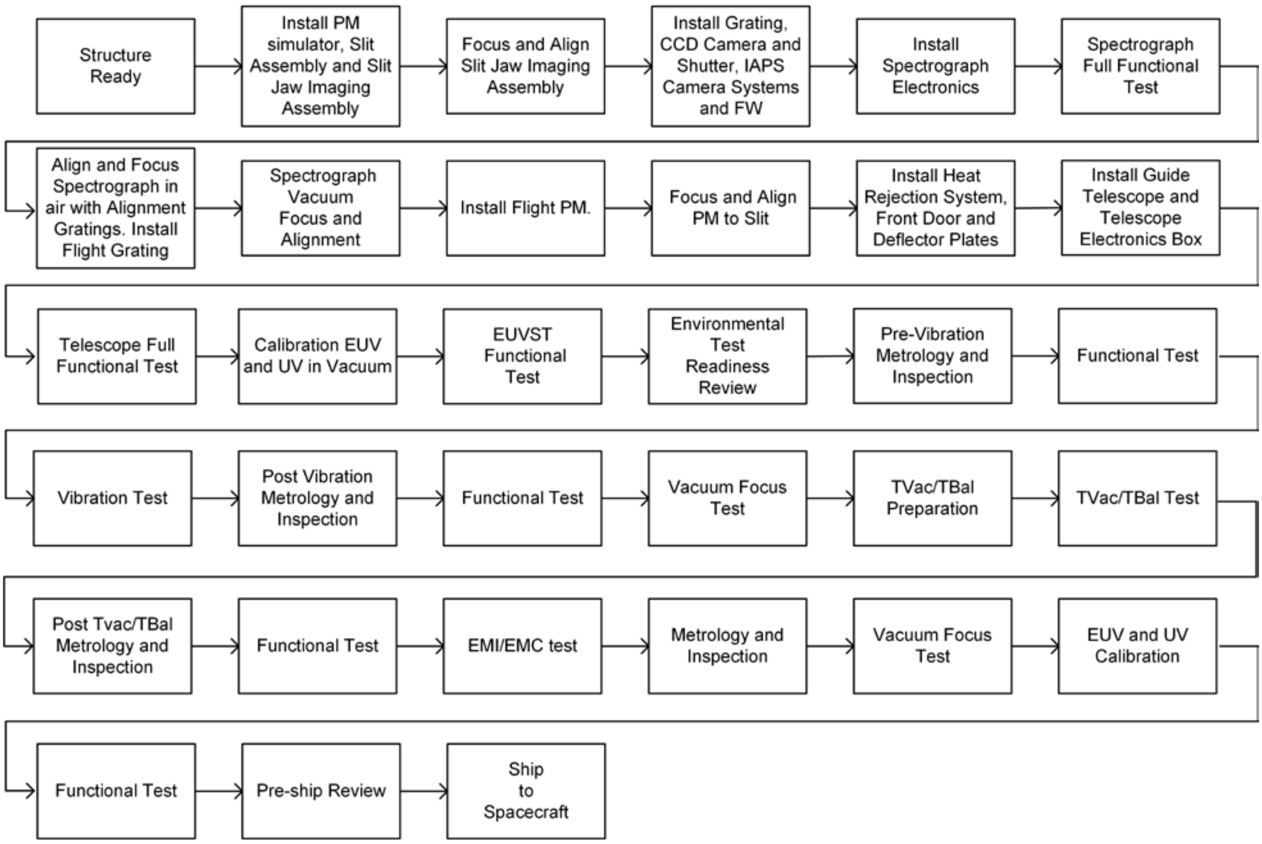


Figure 15.13: EUVST Assembly, Integration and Test flow. EUVST will be comprehensively tested prior to integration onto the spacecraft. PM= Primary mirror

15.9.3. System Level Verification

After integrating and verifying the mission module, which includes EUVST on a support structure and X-band system on the X-COM module, the mission module is integrated with the spacecraft bus (Figure 15.13). The system level test consists of standard tests, such as electrical and functional, vibration, thermal vacuum, and alignment. Moreover, as a special verification, micro-vibration test will be carried out during the system level test for verifying that the micro-vibration level is acceptable to EUVST.

15.10. Acquisition surveillance: make or buy [16-3-2]
調達

JAXA is responsible for procuring the spacecraft bus and rocket vehicle and for managing the overall development program. The EUVST instrument will be developed as an international collaboration among Japan, US, and Europe. The telescope unit and related hardware will be developed in Japan, whereas components installed in the spectrograph unit will be provided by an international consortium with institutional responsibilities given in Table 15.8. The consortium will oversee systems engineering, AIT and calibration for the spectrograph and EUVST complete instrument level testing. The project will utilize ground support equipment for commanding and telemetry handling at ISAS.

Table 15.8 Institute candidates of EUVST hardware contributions

	Item	Lead provider	Alternate
1	Telescope unit		
	Overall management	JAXA	
	Unit structure, thermal	JAXA	
	Aperture door assembly	JAXA	
	Deflector	RAL	
	Primary mirror assembly	JAXA	
	Mirror coating	MPS	NRL
	Heat rejection assembly	JAXA	
	Telescope electronics box	JAXA	
	Guide telescope assembly	LMSAL	
	Telescope unit AIT	JAXA	
2	Spectrograph unit		
	Overall management	NRL	
	Unit structure	JAXA (integrated with telescope unit)	
	Unit thermal	NRL	RAL, MPS, CSL
	Slit assembly	INAF	MPS
	Grating assembly	IAS	MPS (for focus mechanisms)
	VUV IAPS assembly	NRL	MSSL
	HVUs	MPS	
	IAPS electronics box	NRL	MSSL
	EUV CCD assembly	MSSL	RAL, NRL, CSL
	CCD electronics box	MSSL	RAL, NRL, CSL
	Spectrograph electronics box	LMSAL/NRL	MSSL
	Slit imaging assembly	LMSAL/NRL	
	Spectrograph unit AIT	NRL	
3	Assembled instrument		
	Final instrument AIT and calibration	NRL, MPS, CSL, JAXA for integration (may divide AIV/Calibration tasks)	
	Operations and analysis software	EUVST consortium	
4	High speed mission data downlink		
	Large mass memory (data recorder)	Merged to Spectrograph electronics box	ESA
	X-band telemetry sub-system	ESA	JAXA
5	UFSS	JAXA	

15.11. WBS [19-3-1]
WBS

Work breakdown structure (WBS) is given in Table 15.9.

Table 15.9: Work Breakdown structure

SOLAR-C Work Breakdown Structure (WBS)

Last update: 28 Dec, 2017
Prepared by SOLAR-C WG
Note: Composed at proposal submission

1000 Project management

- 1100 Scope management
- 1200 Schedule management
- 1300 Funding management
- 1400 Personnel management
- 1500 Risk management
- 1600 Reliability & quality management
- 1700 Configuration
- 1800 Communication management
  - 1810 Level organization
  - 1820 Project team
  - 1830 JAXA relevant departments
  - 1840 Science commnunities
  - 1850 Vendors
  - 1860 Overseas Cooperation Organizations
- 1900 Correnpondence to phase-shift/ engineering examinations
- 1A00 Document management
- 1B00 Contract & procurement management
- 1C00 Asset & financial management
- 1D00 Public relations
- 1E00 Correspondence to legal procedures & provisions
  - 1E10 Radio frequency adjustment
  - 1E20 Import & export procedures
  - 1E30 Other legal procedures & internal provisions
- 1F00 Activity records

MMOD= micro-meteoroid and orbital deb

2000 System design analysis

- 2100 Requirement analysi
- 2200 Interface design requirement
  - 2210 Rocket I/F
  - 2220 Tracking control I/F
  - 2230 Operation & data usdI/F
  - 2240 Bus system/subsystem I/F
  - 2240 Mission/System I/F
- 2300 System analysis
  - 2310 Mission analysis
  - 2320 Structure analysis
  - 2330 Thermal analysis
  - 2340 Mass property analysis
  - 2350 FOV & plume analysis
  - 2360 Attitude/Orbit control analysis
  - 2370 Pointing error (disturbance) analysis
  - 2380 Communication line analysis
  - 2390 Electric power analysis
  - 23A0 Reliability analysis
  - 23B0 Electromagnetic compatibility analysis
  - 23C0 Environmental condition analysis
    - 23C1 Ventilation analysis
    - 23C2 Radiation analysis
    - 23C3 Electrostatic charge analysis
    - 23C4 MMOD protectioin analysis
    - 23C5 Contamination analysis
  - 23D0 Operation analysis
  - 23E0 Orbit analysis
  - 23F0 Propellant analysis
- 2400 System design
  - 2410 Configuration design
  - 2420 Integration design
  - 2430 System Distribution management
    - 2431 Mass distribution management
    - 2432 Electric power distribution management
    - 2433 Command & telemetry distribution
    - 2434 Contamination management
    - 2435 Alignment management
    - 2436 Disturbance managemer
  - 2440 Safety design
  - 2450 Testing & ground test equipment & jigs

3000 Bus system development

- 3100 Bus development management
- 3200 TT & C management
- 3300 Data processing system
- 3400 Electric power system
- 3500 Solar battery paddle system
- 3600 Attitude/Orbit control systen
  - 3610 Attitude control system component procurement
  - 3620 UFSS development
  - 3620 AOCS onboard S/W development
- 3700 Propulsion system
- 3800 Structure system
- 3900 Heat control system
- 3A00 Harness system
- 3B00 Mission module system
  - 3B10 X-band communication system (TBD)
  - 3B20 X-COM module development

4000 Mission system development

- 4100 Mission system development management
- 4200 EUVST
  - 4210 EUVST development management
  - 4220 EUVST system
    - 4221 Interface design
    - 4222 System design/analysis
    - 4223 Development verification plan
  - 4230 EUVST telescope
    - 4231 Telescope structure/ Optical system
    - 4232 telescope heat control system
    - 4233 Function control system
    - 4234 Image stabilization control system
    - 4235 Deflector [E] I/F
  - 4240 Spectrograph [E/US]
    - 4241 Interface design
    - 4242 Component design
- 4300 Large volume DR
- 4400 X-band communication system

5000 Bus part AIT

- 5300 Bus part development test
  - 5310 I/F confirmation test
    - 5311 UFSS/AOCS EM fit check
    - 5311 X-band/System EM fit check
- 5200 Bus part FM test
  - 5210 Bus part subsystem FM test
  - 5220 I/F confirmation test
    - 5221 X-band/system PFM fit check
  - 5230 Attitude/Orbit control system performance test
  - 5230 Ground station compatibility test [E/J]
- 5300 Mission module system FM test
- 5400 Bus part baking

6000 Mission part AIT

- 6100 EUVST development test
  - 6110 EUVST Telescope Development Test
    - 6111 Optical design confirmation test
    - 6112 Thermal optical test
    - 6113 MTM mechanical environment test
    - 6114 TTM thermal equilibrium test
    - 6115 Primary mirror mechanism - control system EM combination
  - 6120 Image stabilization control system EM combination test
  - 6130 Spectrograph development test [E/US]
- 6200 EUVST FM test
  - 6210 EUVST telescope PFM test
    - 6211 Optical performance confirmation test
    - 6212 Thermal optical test
    - 6213 Mechanical environment test
    - 6214 Electric performance test
  - 6220 Integration
  - 6230 EUVST system integration test
    - 6231 Image stabilization control system PFM combination test
    - 6232 Electric performance test [E/US] (incl. large volume DR & X-band)
    - 6233 Optical performancef test [E/US]
    - 6234 Door opening test
    - 6235 Mechanical environment test [E/US]
    - 6236 Scientific calibration [E/US]

7000 System AIT

- 7100 System development test
  - 7110 MTM/TTM tests
    - 7111 Disturbance tranmission characteristics test
- 7200 System FM test
  - 7210 Integration
  - 7220 System integration test
    - 7221 Circuit check
    - 7222 Mission system function test
    - 7223 System integration test I
    - 7224 Disturbance response test
    - 7225 Alignment measurement
    - 7226 Sinosoidal vibration test
    - 7227 Acoustic test
    - 7228 Thermal vacuum test
    - 7229 System integration test II
    - 722A SAP extension test
    - 722B PAF fit/separation check
    - 722C EMC/System integration test III
    - 722D Propulsion system leak test
    - 722E Operation rehearsal test
    - 722F Synthetic alignment confirmatioin (final)
    - 722G Mass characteristics measurement
- 7300 Launch site work
  - 7310 Shipment
  - 7320 Final Integration
  - 7330 Electric test on launch site
  - 7340 Propellant filling
  - 7350 Rocket attachment
  - 7360 Y-0 rehearsal

8000 Ground facilities

- 8100 Tracking station facilities
  - 8110 Domestic station
  - 8120 ESA stations (Mission data download) [E]
  - 8130 NASA stations (Mission data download) [US]
- 8200 Test/Operation system(C-SODA)
- 8300 EUVSToperation system
- 8400 Operation room

9000 Operation

- 9100 Critical phase
- 9200 Initial operation
- 9300 Normal observation operatio
- 9400 Post observation operation
- 9500 Deorbit operation

A000 Science center

- A100 EUVST analysis tool
- A200 EUVST data open access

15.12. Cost evaluation [21-3-2]

コスト見積もり

Table 15.10 shows a cost evaluation on the Japanese portion of the baseline mission and flight-system architectures. US and European cost [redacted]tems will be proposed to eac[redacted]cy. The US portion (NASA) of the estimated c[redacted]; the European portion is [redacted] from the National agencies. ESA support of [redacted] requested. These amounts a[redacted]istent with the expected scope of both US and Eu[redacted]n missions of opportunity.

Table 15.10: Cost details

	Japan (10^8 JPY)	US/Europe (M$)	Justification	Uncertainty	Remarks
Program Management	[redacted]		A	M	
Comprehensive System Design	[redacted]		A	M	
Bus System Development	[redacted]				
S/C Management	[redacted]		A	L	
Communication (S-band system: Low speed link, Omni antenna)	[redacted]		A	L	
Solar Battery Paddle	[redacted]		A	L	
Electric Power System	[redacted]		A	L	
Attitude Orbit Control	[redacted]		A	M	incl. System Integration Test + UFSS 1-unit
Propelling System	[redacted]		A	L	
Thermal Control	[redacted]		A	L	incl. Thermal Harness
Mechanical Structure, Electronic Harness	[redacted]		A	L	
Mission System Development	[redacted]				
EUVST	[redacted]				
EUVST-TA (Telescope Unit)	[redacted]				
Project Management	[redacted]		B	M	
Telescope Structure Optical system	[redacted]		B	M	Telescope Tube: MTM assumed to be refirbished to PFM
Electronics & Drive Control	[redacted]		B	M	Systems for image stabilization control and telescope operation management
Integration, Adjustment, and Testing	[redacted]		B	M	
Procurement of Primary Mirror	[redacted]		C	M	30cm Mirror (FM + Backup)
Test Equipment and Facility (NAOJ)	[redacted]		C	M	NAOJ Test Facility (Extension flange for optical and thermal vacuum chamber)
Test Implement Cost	[redacted]		C	M	incl. oversea shipping costy
EUVST-SP (Spectrograph Unit)	0.00	[redacted]	D	H	US ($39.05M) and European ($20.6, ESA $5.64) Cost Sharing
Project Management		[redacted]	C, D	L	Based on past experience
Systems engineering		[redacted]	C, D	L	Based on past experience
Product assurance		[redacted]	C, D	L	Based on past experience
Slit imaging assembly		[redacted]	D	L	Similar to IRIS, provider is the same.
Slit assembly		[redacted]	D	L	Similar to Hinode/EIS mechanism
Grating assembly		[redacted]	C	M	Similar to Hinode/EIS mechanism
CCD and camera assembly		[redacted]	D	M	Similar to cameras fabricated for EIS, SECCHI and SDO.
SP mechanisms (shutter, Filter wheel x 2)		[redacted]	D	L	Similar to mechanisms bult for SECCHI
IAPS detector head		[redacted]	A, D	M	Similar to previous detectors for METIS/SO and Herschel SR
IAPS camera electronics		[redacted]	D	L	HVPS identical to METIS, APS electronics similar to WISPR
Spectrograph electronics		[redacted]	D	M	Similar to SECCHI/STEREO electronics box
Software		[redacted]	D	M	Similar to SECCHI and IRIS software, some revuse envisioned.
Guide telescope		[redacted]	D	M	Based on past experience
Thermal for SP portion		[redacted]	D	L	Based on past experience
Integration and Test for SP portion		[redacted]	C,D	M	Based on past experience
Large Capacity Recorder	0.00	--	—	—	US cost sharing: included in EUVST-SP unit
Communication System (X-band)	[redacted]	[redacted]	E	M	Appropriate sum of system I/F equipments X-band system: European cost sharing (ESA)
X-COM Structure Panel	[redacted]		E	M	Attaching panel for X-band communication system
System Test and Flight Operation	[redacted]				
Measurement of Disturbance Transmission Characteristics (pre-Phase A)	[redacted]		A	M	Measurement with existing bus structures
EM Disturbance Test	[redacted]		A	M	Measurement with MTM structure + EUVST (EM)
Integration Test (incl. FM Disturbance Test)	[redacted]		A	M	
Facility Operation for System Test,	[redacted]		D	L	Consumables for Test facilities, Liquid N2, etc. + Shipping
RF Compliance Test	[redacted]		D	L	2 stations (USC, Katsuura) X-band RF test with ESA stations (European cost sharing)
Launch Site Operation	[redacted]		A	L	ERG-like level of Operation Rehearsal/Training, Site Operation, Shipment for Launch Site (container reused)
Other Items	[redacted]				
Maintenance of Ground Facilities	[redacted]		D	M	Attitude control, system initial operation, ground-based computers, and data transfer system
Frequency Adjustment	[redacted]		C	M	Support by consultants
Travel, Labor, Public Outreach etc.	[redacted]		D	L	0.2×10^8 (JPY/year) x 5 (years)
Operatic	[redacted]				
Work Consignment (System Construction & Preparation of Operation) to Technical Dept. of Space Tracking & Communication Center (JAXA)	[redacted]		E	M	
Initial Operation	[redacted]		A	L	Preparation of Operation (SOOH, Operation Manuals) Initial Operation (20 days)
Tracking Control Operation (2-year Stationary Scientific Observation)	[redacted]		C	L	Tracking Control (commander), Data Archive
Scientific Operation (2 year)	[redacted]		C	L	Stationary Sceitific Observation (2-Year)
Tracking at Overseas Stations (Svalbard, Troll)	0.00	[redacted]	C	L	assuming (Hinode-case) International Collaboration with ESA
Data Center (Nagoya Univ.)	[redacted]		E	M	
Reservec	[redacted]		D	L	15% for EUVST-TA, 5% for system and operations
Rocket Procurement	[redacted]		D	M	assuming cost of 2nd Epsilon booster, incl. JAXA-safety
Project Cost (excl. Rocket, Reserved)	[redacted]				
Project Cost (excl. Rocket)	[redacted]				
Project Cost (Total)	[redacted]	[redacted]			

※A: Vender's estimate, B: Based on vender's estimate, C: Hinode experience, D: Based on other mission's estimate, E: Rough estimate (no reference)

15.13. Project Organization [17-4-1]

体制

The proposed mission is a Japan-led mission with substantial participations from US and European countries to the spectrograph unit of the EUVST. Figure 15.14 shows a preliminarily conception of the project organization in Japan, including ISAS/JAXA, NAOJ, Nagoya U. and Kyoto U. as the main body. The EUVST instrument will be provided to JAXA by a JAXA-led international hardware development consortium (Table 15.11, Refer to supplement letters of support), 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 candidates of hardware contributions from participating institutes are listed in Table 15.8.

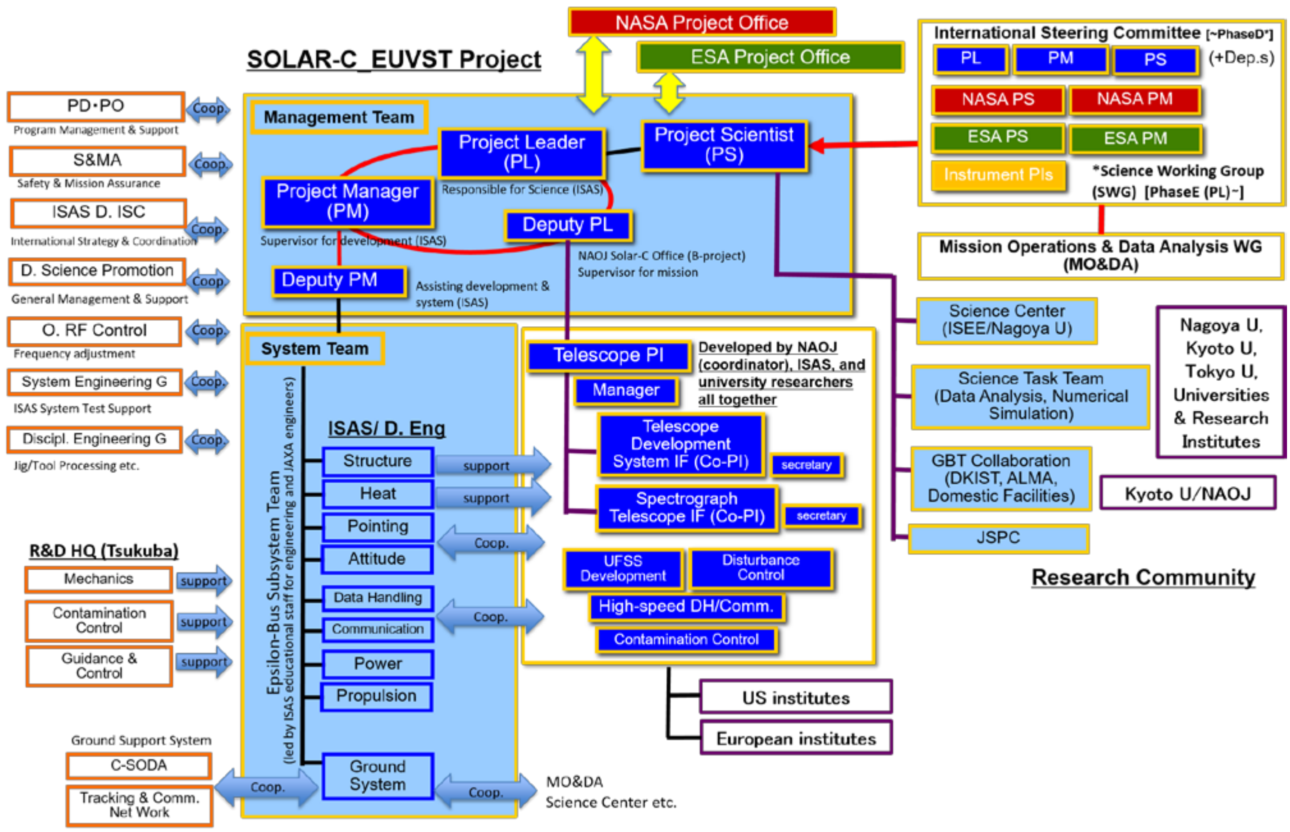


Figure 15.14: Project organization

Table 15.11: International EUVST hardware development consortium

	Organization		Country	Representative	Support letter
1	Naval Research Laboratory	NRL	USA	Dr. Clarence Korendyke	NASA
2	Lockheed Martin Solar and Astrophysics Laboratory	LMSAL	USA	Dr. Ted Tarbell	NRL LMSAL
3	Max-Planck Institut für Sonnensystemforschung	MPS	Germany	Prof. Sami K. Solanki	DLR
4	Mullard Space Science Laboratory, UCL	MSSL	UK	Prof. Louise K. Harra	UKSA
5	Rutherford Appleton Laboratory	RAL	UK	Dr. Andrzej Fludra	
6	Institut d'Astrophysique Spatiale	IAS	France	Dr. Frédéric Auchère	CNES
7	Instituto Nazionale di Astrofisica	INAF	Italy	Dr. Vincenzo Andretta	ASI
8	Università Degli Studi Di Padova	UNIPD	Italy	Dr. Giampiero Naletto	
9	Centre Spatial de Liège, University of Liège	CSL	Belgium	Dr. Serge Habraken	BELSPO
10	Royal Observatory of Belgium	ROB	Belgium	Dr. Andrei Zhukov	

16. Technical heritages, technology development status and plan
技術ヘリテージと技術開発状況と開発計画

16.1. Rationale for TRL [9-4-1]
TRL 根拠

The combined EUVST technical team has decades of experience developing and operating solar spectroscopic instrumentation. EUVST engineers and scientists have participated in the development of spectrographic solar space instrumentation since the 1970s. Technically, the instrument represents the logical next generation instrument for spectroscopic observation of the corona. The optical designs, mechanisms, guide telescope, slit jaw imaging system, electronics, software and detectors have extensive heritage on previous missions. EUVST will utilize a series of bread-board, engineering models and qualification models to demonstrate critical areas of instrument performance. The demonstrated performance of these models is sufficient to mature the overall instrument TRL (Technology Readiness Levels). The design and test of the mirror support

Table 16.1: TRL of key technologies and model development philosophy.

Yellow hatched : developed by international partners

Name		Component Name		Domestic or International cooperation	Flight helitage		TRL		Development models	Notes
					Design	Fabrication (material・production process etc)	Current	at SDR		
EUVST										
	Telescope Unit	Mirror ASY	Mirror	Import	New	Achieved	6(*)	6(*)	MTM/TTM (also FS)→PFM	*Heritage from SAGEM/REOSC, Need a study for light weight and thermal deformation.
			Mirror coating	Int. Coop.	New	New	4	5	BBM(*)→PM→FM/FS	*Evaluate coating samples
			Mirror supports	Domestic	New	New	2(*)	4(*)	BBM→MTM/TTM→PFM	*Based on heritage from Hinode/OTA (TRL>6 for key technologies), Need a study for thermal deformation and mechanical environment. Require front-roading study.
			Tip-tilt & scan mechanism	Domestic	New	Achieved	3(*)	4(*)	BBM→MTM/TTM→PFM	*Based on flight heritage (TRL>4 for key technologies) Tip-tilt & scan mechanisms have been developed under SOLAR-C R&D (2015) and flight component for Sunrise-3/SCIP. Need launch-lock study.
			Focus mechanism	Domestic	New	Achieved	2(*)	4(*)	BBM→MTM/TTM→PFM	* Heritage on hexapod or focus mechanism based on SOLAR-C R&D (2013-2015) (TRL>4 for key technologies)
			Thermal control structure	Domestic	New	Achieved	4(*)	4(*)	MTM/TTM→PFM	*Heritage from Hinode OTA
		Unit Structure		Domestic	New	Achieved	4	4	MTM/TTM→PFM(*)	*CFRP based, Refurbish MTM
		Aperture Door ASSY		Domestic	New	Achieved	4(*)	4(*)	MTM/TTM→PFM	*Based on flight heritage from Hinode OTA side door
		Heat Rejection ASSY		Domestic	New	Achieved	4(*)	4(*)	MTM/TTM→PFM	*No need to BBM (heritage from Hinode OTA/HDM)
		Optical Bench ASSY		Domestic	New	Achieved	4(*)	4(*)	MTM/TTM→PFM	*Based on heritage from Hinode OTA
		Telescope Electronics Box		Domestic	New	Achieved	5(*)	5(*)	EM→PFM	*Based on Hinode CTM-E
		Guide Telescope ASSY		Int. Coop.	Achieved	Achieved	9	9	PM(*)→FM	*Build a clone of the IRIS GT
	Spectrograph Unit	Unit Structure		Domestic	New	Achieved	4	4	MTM/TTM→PFM(*)	*CFRP based, Refurbish MTM
		Slit ASSY		Int. Coop.	New	Achieved	5	6	(BBM+)EM→PM(*)→FM/FS	*Based on heritage from SOHO/UVCS.
		Grating ASSY		Int. Coop.	New	Achieved	5	6	EM(*)→PFM	*EM used to demonstrate efficiency and imaging of the spectrograph split grating design. EM used to verify environmental performance.
		VUV IAPS ASSY		Int. Coop.	New	Achieved	6	8	PM(*)→FM	*Mechanical design of large format design to be qualified.
		IAPS Electronics Box		Int. Coop.	New	Achieved	6	6	BBM(*)→EM(*)→PFM	*Modify existing WISPR/SPP design to include compression chip. Repackage for EUVST mechanical constraints.
		IAPS HVPS		Int. Coop.	Achieved	Achieved	9	9	BBM(*)→PM(**)→FM/FS	*If need needed at earlier phases of camera development *Identical to SO/METIS HVPS.
		EUV CCD ASSY		Int. Coop.	Achieved	Achieved	9	9	EM→PM(*)→FM	*Die and package previously qualified for a number of programs.
		CCD Electronics Box		Int. Coop.	New	Achieved	6	6	EM→PM(*)→FM	*Need to modify design to accommodate compression chip and accelerated readout.
		Spectrograph Electronics Box		Int. Coop.	New	Achieved	6	6	PM(*)→FM	*Repackage existing design, add mass memory and unique software to schedule multiple spectrograph cameras
		Slit Imaging ASSY		Int. Coop.	New	Achieved	6	6	PM(*)→FM	*Repackage existing design from IRIS.
Large mass DR				Int. Coop.	New	Achieved	6	6	PM(*)→FM	*Expand previous MCM designs to 39Gbits.
X-band telemetry sub-system				ESA or Dom.	Achieved	Achieved	9	9	FM	*Existing design from various satellites
UFSS				Domestic	New	Achieved	4	4	BBM(*)→EM→PFM	*Front-roading development (BBM) is on-going with the manufacturer differerent from Hinode UFSS.

Yellow patched: components developed by international partners.

Reference: JAXA TRL guideline (BDB-06005 Rev.A) for details of the model and TRL definition.

Bread-Board Model (BBM) – A simple model (using commercial parts and materials) for studying key elements, such as structures and electronic circuits, and their functions at the early phase of the design.

Engineering Model (EM) – A model for evaluating the mass, dimension, electric power and so on, in addition to the results of functions by BBM, in order to determine the electrical and structural design.

Prototype Model (PM) – This model is subjected to qualification tests for confirming the design.

Flight Model (FM) – This model actually flies. Tested to acceptance-level testing.

Proto-Flight Model (PFM) – Two cases 1) Originally specified as prototype model and used in qualification tests. After that, this is refurbished and evaluated as flight model, specified as the flight model, 2) Specified in advance as both prototype model and flight model. This model is subjected to a proto-flight test (PFT) that serves both as a qualification test and as an acceptance test.

structure and selection of actuators for the mirror focus mechanism will be completed early in the development plan to reduce any residual risk. The development of the mirror assembly is described in Section 16.3.1. The EUVST team has conducted significant design studies of the mirror assembly as described in Section 16.2.1. Table 16.1 summarizes the instrument/subassembly heritage and EUVST model development philosophy.

16.2. Technology heritage, development history and status 技術ヘリテージと技術開発履歴と状況

16.2.1. Telescope and active tip-tilt mirror

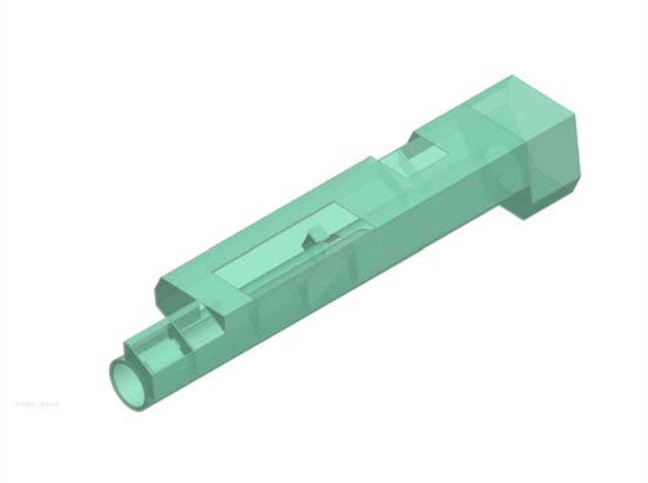


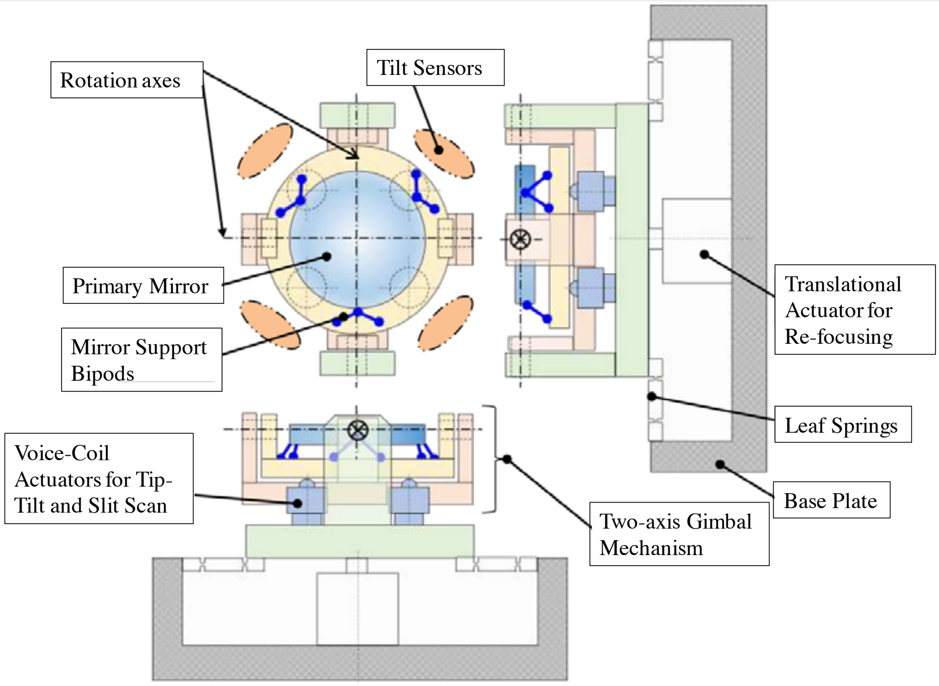
Figure 16.1: Integrated concept of the EUVST structure.

The proposed team (NAOJ and ISAS/JAXA) has successfully developed the 50cm aperture visible-light space telescope for Hinode/SOT. The telescope has a diffraction limited performance in space (Suematsu et al. 2008), providing 0.2-0.3 arcsec spatial resolution images and spectro-polarimetric data of the solar surface. This development was carried out with engineers of Mitsubishi Electric. Since then, for the original large-strategic Solar-C mission proposed in 2015, the proposed team with Mitsubishi Electric engineers carried out the series of technical feasibility studies in the development of a 1m class solar telescope which covers near infrared, visible and UV range widely and reached a conclusion that the technologies for the 1m class telescope are feasible to have diffraction limited optical performance, although it is challenging. In 2017, the team, with engineers of Mitsubishi Electric, has performed an initial conceptual study of EUVST, mainly from structural and thermal point of views, to define Japanese contributions in the baseline architecture and to identify any technical difficulty. Two structural designs were considered. The first used separate telescope and spectrograph structures to facilitate the integration and assembly procedure. The second incorporated a single CFRP structure integrating the telescope with the spectrograph portion (Figure 16.1). Our trade-off study found that the integrated concept better accommodated the optical layout. Sections 12–16 of the proposal are based on the results from this study.

Technologically, one of the key areas in the EUVST concept is the primary mirror assembly, which has a primary mirror (28 cm diameter) mounted on a tip-tilt and scanning mechanism and focusing mechanism. A schematic design of the primary mirror assembly is shown in Figure 16.2. The mounting of the primary mirror is one of the most critical parts in the primary mirror assembly. The primary mirror, made of light-weighted (70% removed and thus less than 3 kg) ultra-low CTE glass material, is supported by three stress-free mounting mechanisms (bipods) rooted on a tilt stage of rotational mechanism, interfaced with three pads bonded on the side of the mirror. The pad interface of the mounting mechanism provides a kinematic mount for the primary mirror and avoids stresses to the mirror resulting from dimensional errors in machining or temperature changes. Our heritage is the mounting mechanisms for the 50cm primary mirror used in Hinode/SOT (Figure 16.3), which would be the start point for designing the EUVST primary mirror.

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 proposed team has a rich history developing tip-tilt mechanisms. The team developed the tip-tilt secondary mirror mechanism for the X-ray Doppler Telescope successfully launched by an S-520-22 sounding rocket in 1998 (Kodeki et al. 1998) and the high precision tip-tilt mirror mechanism with piezo actuators for Hinode/SOT. The image stabilization system with this tip-tilt mechanism and servo controller achieved 0.03 arcsec (3σ) on orbit (Shimizu et al. 2008), greatly contributing to diffraction-limited imaging observations for more than 11 years. For the Solar-C application, the team studied 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) (Kodeki and Shimizu 2016, and Figure 16.4 of this proposal). 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. Currently, the same type of tip-tilt and scan mechanism will be used as the scan mechanism for the SCIP instrument onboard the international Sunrise balloon-borne telescope (Solanki et al. 2010) which will have its third flight in 2021.

Figure 16.2: Schematic design of focus, tip-tilt and image scanning mechanisms for the primary mirror assembly.



The mirror cell is supported by a translational actuator like a ball-screw or a hexapod drive 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, Figure 16.4) 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 (Shimizu et al. 2014). For adapting it to EUVST, higher step resolution will be required for a shorter range. As one of 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 (Oba et al. 2015).

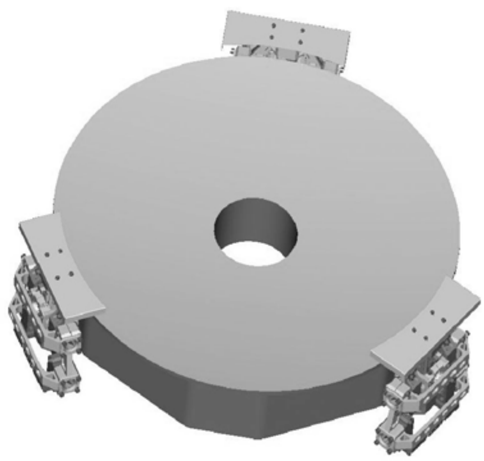


Figure 16.3: Primary mirror with mounting mechanisms for SOT.

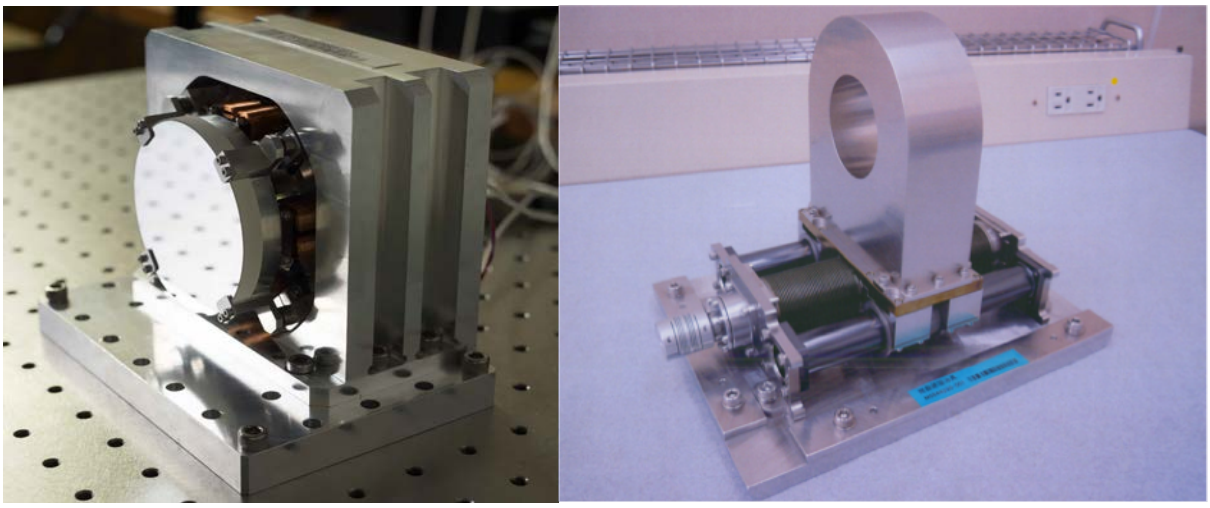


Figure 16.4: Left panel shows the bread-board tip-tilt mirror mechanism while right figure displays the translational actuator

16.2.2. Gratings

As described in section 12.1.3, EUVST gratings are based on the development history applied to various space instruments. Since challenging requirements will be face during the development of EUVST gratings, the team has contacted some vendors to investigate the technical feasibility. Table 16.2 is the initial optical prescription of the LW and SW gratings. Similar to SoHO/CDS, these two grating halves are mounted in close proximity. The gratings are figured and coated to optimize the image quality and efficiency of each passband. The highly corrected toroidal gratings with variable line spacing give excellent image quality at the focal plane across a large wavelength range. The grating efficiency performance has been modeled and is presented in Figure 16.5.

Table 16.2: Grating Optical Characteristics

Grating Characteristic	Short Wavelength TVLS	Long Wavelength TVLS
First Order Wavelength Coverage	17 nm – 21.5 nm	69-128nm
Grating Size (illuminated area)	Half of 50mm diameter with 2 mm edge margin	Half of 50mm diameter with 2mm edge margin
RMS figure error	$< \lambda/64$	$< \lambda/64$
RMS surface roughness	<0.5nm	<0.5nm
Material	Fused Silica	Fused Silica
Aspect ratio (full diameter to thickness)	5:1	5:1
Groove Efficiency	>40% average	>40% average
Blaze	Laminar	Triangular blaze
Coatings	Graded Mo/Si multilayer	Tb-W-Si multilayer with B_4C capping layer
Surface geometory: radii of curvature R1: dispersion direction	R1= 587.8836 mm R2= 545.74 mm	R1= 475.8877 mm R2= 503.13 mm
Nominal Angle of Incidence (degrees)	-3.5	-2.1
Central Ruling Density	4200 lines/mm	2000 lines/mm
Order of Diffraction	First	first and second

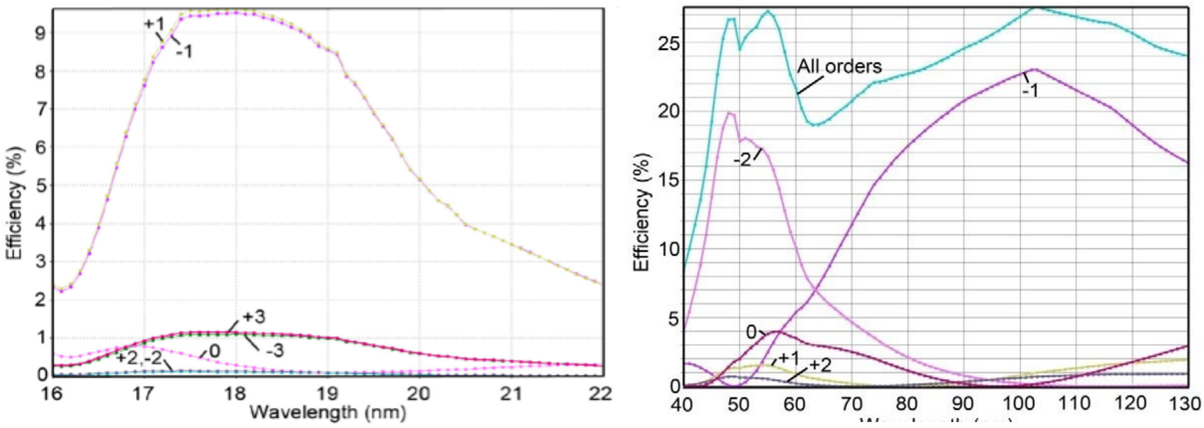


Figure 16.5: Left panel shows the modeled multi-order performance of the SW grating (including the laminar groove efficiency and the SW coating) while right panel displays the LW grating (including the triangular blaze and the multilayer coating). An opaque layer of B_4C was also modeled for the LW grating.

16.2.3. Coating

Coatings for the EUV and FUV spectral ranges have highly mature designs and extensive flight heritage. EUV multilayer coatings have been developed, implemented, qualified and flown for instruments such as SoHO/EIT, TRACE, SDO/AIA, STEREO/SECCHI, Hinode/EIS, the EUNIS and Hi-C rocket flights. Recently, the qualification phase has been successfully completed for SO/EUI and SO/SPICE (B_4C thin layer on quartz substrate). The coatings needed by EUVST (see Table 16.3) are based on what was already qualified and flown. The coating design will be modified to incorporate the broad bandpass required for the EUV and the B_4C thin cap layer for enhanced performance for the main mirror coating.

Table 16.3: The coatings for EUVST

Optical component	Required coating	Heritage	Development status
Main Mirror	Broad-band multilayer to cover the 17 to 21.5 nm range with B_4C thin cap layer to provide reflectivity in the 46 to 127 nm range.	SoHO/EIT TRACE STEREO/SECCHI Hinode/EIS SDO/AIA EUNIS	Feasibility study with sample production and reflectivity measurements for the baseline Mo/Si multilayer with thin B_4C cap layer carried out by consortium members.
SW Grating	Broad-band multilayer to cover the 17 to 21.5 nm range.		Feasibility study with sample production and reflectivity measurements for the baseline Mo/Si multilayer carried out by consortium members.
LW Grating	B_4C thin cap layer to provide reflectivity in the 46 to 127 nm range.	SO/SPICE	Mature design.

A feasibility study of a suitable multilayer coating (Mo/Si with B_4C barrier layers) with and without B_4C thin cap layer (for the main mirror and for the SW grating, respectively) was successfully completed and showed:

1) the coating shall be resistant to temperatures up 120°C, ideally up to 200°C.
2) micro-roughness of the surface should not be worsened more than 0.2 nm rms by the coating,

The study included coating different samples with various thickness of B_4C cap layer (7, 11 and 15nm), thermal cycling up to 100 h up to 200 °C, atomic force microscopy measurements of micro-roughness and VUV reflectivity measurements. The EUVST team is also studying an Al/Mo/SiC coating with enhanced reflectivity (25%) at shorter wavelengths and a significantly lower solar absorption (Figure 16.6). Similar coatings were used on EUI on Solar Orbiter. This coating will increase reflectivity ~25% over the entire wavelength range.

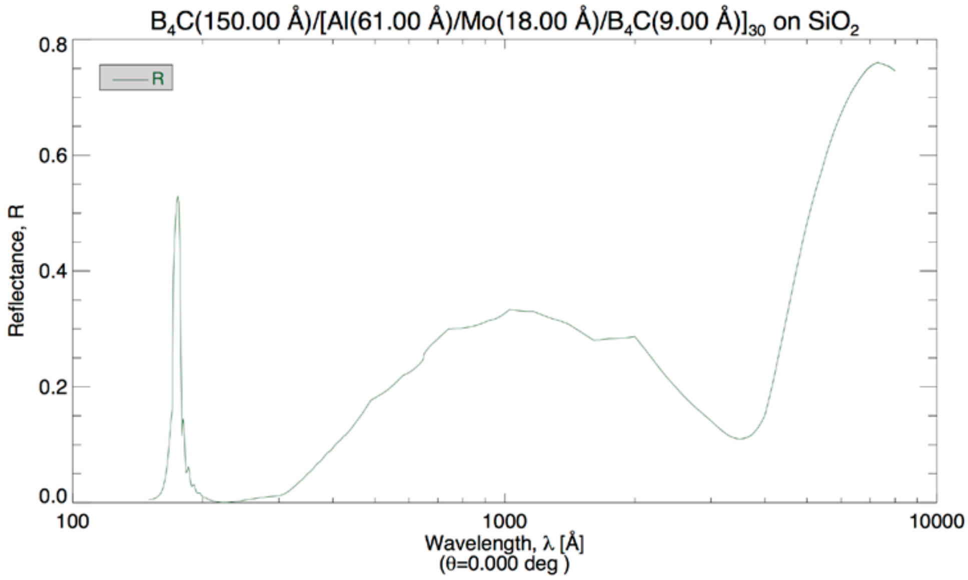
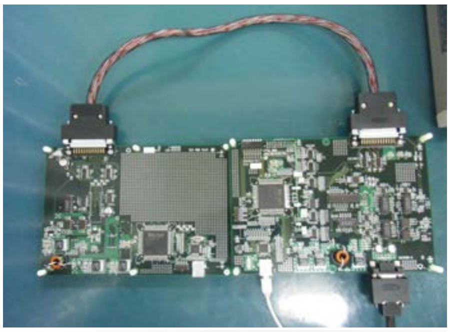


Figure 16.6: The reflectivity in UV and visible spectrum of an Al/Mo/SiC coating recently designed.

16.2.4. Ultra Fine Sun Sensor

The Ultra Fine Sun Sensor (UFSS) has been working with high precision on the Hinode satellite for over 11 years on orbit. The sensing accuracy was vastly improved over similar sensors on Yohkoh and Akari. However, the manufacturer no longer provides the UFSS. In 2013, we identified an alternate manufacturer and started to develop a second generation of UFSS with the participation of the chief engineer (Dr. Tsuno, currently at RIKEN) responsible for the original UFSS. The new development basically follows the design of the first generation UFSS but a couple of upgrades have been made. Specifically, the analog circuit designs were changed to digital. In 2014-2017, we carried out various development tasks, including the following: the performance of chosen 1-dimensional CCD sensors with radiation exposure were tested; each term in the error budget for achieving accuracy was evaluated; a bread-board model circuit was designed and evaluated with a bread-board model (Figure 16.7 top); the reticle glass (Figure 16.7 bottom) was evaluated; and the structural design and thermal deformation analysis was completed. The TRL has almost reached 4 in 2017. Currently, a structure is under fabrication for experimentally validating the expected thermal deformation. This structure will be also used to evaluate sensing performance by integrating the bread-board electronics model to reticle-CCD in a flight like structure.



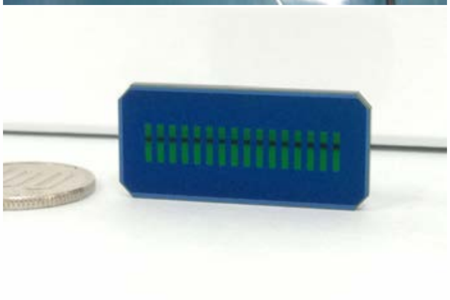


Figure 16.7: (top) Electrical circuit and (bottom) reticle developed for UFSS performance evaluation.

16.2.5. Micro-vibration evaluation

Using the heritage accumulated in the development of the Hinode/SOT, we developed a successful strategy for controlling the micro-vibration for EUVST. The following approach will be adopted in each development phase:

1) <u>Design phase</u>
   Identify the sources of the mechanical disturbance and evaluate the level of disturbance that they produce using the data of identical devices in hand. Identify the optical components that are

critical for the image stability and evaluate their sensitivity to the image shift. Calculate the transfer function of mechanical disturbance using the preliminary structural models of the bus module and EUVST, and predict the image motions on the image plane to identify the critical areas. Study the methods to mitigate the unacceptable vibration of optical components if it is observed in the measurements in later phase.

2) Component fabrication and procurement phase
   Control the disturbance levels of individual disturbance sources during their fabrication with vendors of each component.
3) Development and testing phase
   Using the MTM (or dummy structures) of the bus module and EUVST, measure the transfer function of mechanical disturbance from the disturbance sources to the optical components. In the measurement, a shaker that produces translational and torque forces is attached at the location of the disturbance sources and accelerometers are attached on the critical optical components to simulate the disturbance sources and to evaluate the image motion, respectively. Using the obtained data, improve the structural model to better predict the image jitter, and, if unacceptable level of image jitter is anticipated, the method for mitigating it will be applied.
4) Flight model phase
   Measure the end-to-end performance of image stability using the integrated flight model.

So far, we have identified the primary sources of mechanical disturbance as the 4 reaction wheels (RW) and one IRU unit containing 3 gyros, and the critical optical components for the image stability as the primary mirror, grating and slit of EUVST. Transfer functions from the 5 disturbance sources to the 3 optical components were evaluated using the preliminary structural model and the disturbance data of Honeywell's RWs and Type-II IRU of Mitsubishi Precession Corporation. In each combination of the disturbance source and the optical component, the transfer function was calculated for plausible injected disturbances of translational forces in x, y, and z and of torque force in θx, θy, and θz, and for the resultant motions of the optical component in lateral displacement in x, y, and z and rotations in θx, θy, and θz. Thus, 6 x 6 x 4 x 3 = 432 transfer functions were calculated in total in the frequency domain of 1-300Hz. Our preliminary study infers that the disturbance produced by the IRU unit is about one order of magnitude smaller than the requirement, but the RWs could produce unacceptable level of image jitter in the frequency range of 50-110Hz. Note that a conservative magnification factor of Q=400 is assumed in this study for the safety, while, even though the disturbance level of the IRU is small, the IRU unit may produce a significant image jitter once a resonance in the real hardware occurs at 155Hz. The accuracy of the prediction needs to be improved using the data obtained from the measurements with the dummy structures and MTM.

As for the methods for mitigating the potential risk on micro-vibration, we will use the following approach if unacceptable disturbances are observed during development phase.

1) Insert a vibration isolation damper in the path between the disturbance sources and EUVST.
   The dumper will be designed to reduce the transfer function by a factor 10 ~ 100 at the frequency range of f >50Hz. A possible location of the dumper will be the mechanical interface between the bus module and the EUVST telescope. Note that isolating the 4 RWs in the bus module is not easy because it requires a significant modification to the design of the standard bus module.
2) Reduce the disturbance level of RWs and IRU
   This needs to be worked out with the vendors of both components. In addition to the specification control by documents, accurate measurement of the disturbance levels of the real hardware, fine tuning of the mass balance of the wheels and screening of the devices will be required.
3) Limit the operational range of the spin rate of RWs

Since the amplitude of the dominant disturbance of RWs increases as the square of the spin rate, limiting the spin rate in the low rotational range (e.g. < 3000rpm) will contribute to reduce the micro-vibration. Resonance frequencies of optical components obtained from the measurement will be avoided. Possible drifts of the spin rate of RWs in orbit need to be studied.

4) Revisit the requirement of the image stability and/or the allocation of allowable disturbance to each component.

16.2.6. Contamination control in UV

A systems engineering approach on the contamination control was performed in the Hinode (Solar-B) development program. It contains the material selections, the sample outgassing measurements with the Thermoelectric Quartz Crystal Microbalance (TQCM), the contamination mathematical modeling activity, personnel training, parts cleaning, the bake-out for reducing outgas, outgassing measurements of the flight models with TQCM, contamination monitoring of flight models with witness plates in the subsystem and system integration and test activity. The throughput degradation of the optical telescope on Hinode has happened with a slightly higher rate than the predicted, especially at the short wavelength range of ~400 nm due to the molecular contamination. A further careful control needs to be applied in the EUVST program that requires a higher-level control than that in Hinode. More difficult contamination control has been applied to the SUMER instrument on SoHO and EUI, SPICE, and Metis on Solar Orbiter (SO), those of which function in the UV wavelength range that EUVST shares. While the metal structure was used in SUMER for an easier treating of the molecular contamination control, the structures of the SO science instruments are built with CFRP materials for light-weight payload requirement, as EUVST does. The heritage of the SO contamination control is to be fully used. The primary difference from the Hinode's treatment is the high-temperature bake-out of the payload parts under a low vacuum condition of a few Torr during a low-rate GN2 purging in an oven for effective cleaning before a high vacuum bake-out in 10^{-6} Torr.

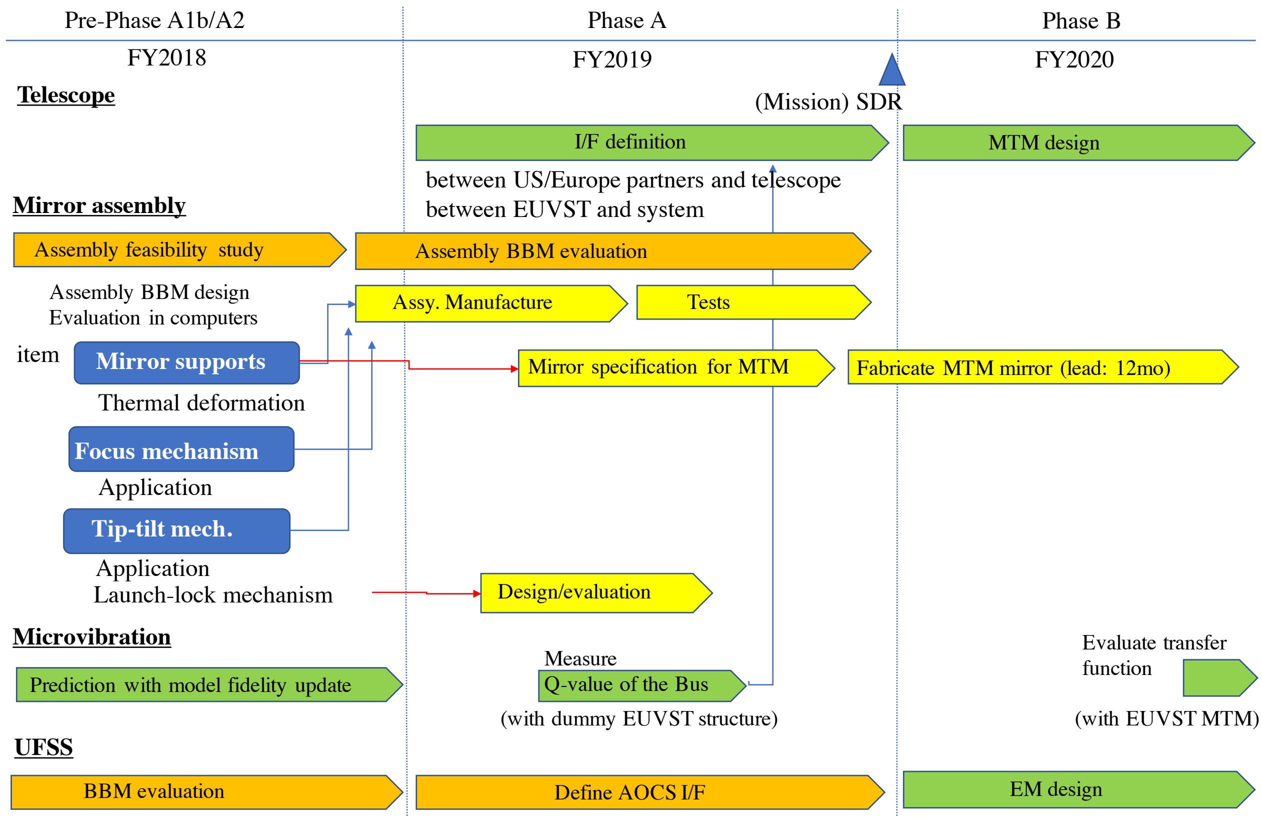


Figure 16.8: Technology development schedule

16.3. Technology development plans
技術開発計画

Table 16.1 shows a draft of the model development strategy for assemblies and units in the mission payloads. Figure 16.8 describes the overall development for Japanese portions of the technology, i.e., telescope unit and its mirror assembly, micro-vibration control, and UFSS. Details of each development plan is explained in the subsequent subsections. In Phase A, we will take efforts for defining the interfaces. These efforts include the studies and negotiations to define the interface between the telescope and US/European partners as well as between the EUVST instrument and the spacecraft system. For some critical technologies in Figure 16.7, we will make R&D efforts in Pre-phase A1b/A2 phase.

16.3.1. Strategy for developing the mirror assembly

The primary mirror assembly will be developed as a single assembly based on three key technologies, i.e., mirror supports developed for Hinode, tip-tilt mirror mechanism and focus mechanism which have been studied for a Solar-C telescope.

Pre-phase A1b/A2 is the time to take an assembly design for bread-board model to evaluate the thermal deformation performance and its feasibility evaluation based on model calculations. The thermal deformation of the mirror surface is required to be minimized at the mirror temperature as high as +80°C. The baseline design of the mirror supports and mirror pad that holds the glass mirror were developed for the 50cm primary mirror of Hinode/SOT. The mirror supports use bearings to release the moment properly and give less deformation to the surface figure when the mirror is mounted on the assembly as well as when the temperature is changed significantly. The mirror supports must survive the launch environment and be light weighted to minimize the weight of the steering portion. The mirror pad uses an Epoxy adhesive to contact the mirror, but the outgas properties are one of key portions in design. In case that the adhesive does not meet the outgas requirement, we will consider a backup non-adhesive support method, which has been used as the mirror supports for the Hinode/SOT tip-tilt mirror mechanism. The multilayer coating may also have internal stress and deform the surface figure. The measurement of the coating stress will be used to evaluate the deformation caused by the coating. After evaluating the thermal deformation of the mirror supports with computer software, we will manufacture a bread-board model in the later period of pre-phase A2 and phase A, and experimentally verify the results from the model calculations. The bread-board model consists of three mirror supports with a dummy mirror, which has sensors for measuring the stress. The important milestone in the development of the mirror assembly is the start of the MTM mirror fabrication by the mirror company. The lead time of a mirror is long (between 12-18 months, depending on the specification). By the beginning of FY 2020, the specification of the mirror should be defined and agreed to keep the schedule proposed in section 4.

The structural design concept for the tip-tilt and scan mechanism as well as the focus mechanism in the mirror assembly will be studied in pre-phase A1b/A2. The study includes a couple of technical trade studies to choose the best solution from the existing technologies, such as pivot and flexure for steering. A trade-off study for actuators and sensors was carried out in 2015 R&D development for the Solar-C 1m telescope, but this study should be revisited for the EUVST to define the baseline design parameters. The focus mechanism to be designed for the mirror assembly uses results from R&D in 2011-2014 as the baseline, but it is important to confirm whether the developed ball-screw mechanism is applicable to the mirror assembly in pre-phase A1b/A2. These desk studies will give inputs to the structural design included in a bread-board model of the mirror assembly in phase A. A launch lock mechanism will be needed to hold the steering portion during the launch. The lock mechanism will be investigated in pre-phase A1b/A2 with help of spacecraft systems and JAXA mechanical experts. Our plan is to adapt a non-shock type actuator recently developed to the launch lock in the mirror assembly.

16.3.2. Strategy for developing the UFSS

The R&D efforts with bread-board model have been in progress as described in section 16.2.4. The remaining major items to be evaluated are: 1) experimental evaluation of the thermal deformation by using the structure fabricated in FY2017, and 2) experimental evaluation of the performance (random noise and bias noise) by combining the bread-board electronics with the reticle-CCD built in the structure. These works will be carried out in Pre-phase A1b/A2. The interface with the attitude control system will be discussed in Phase A before going to the EM design.

16.3.3. Strategy for performing the micro-vibration evaluation

Micro-vibration evaluation will be carried out in the following steps:

1) Pre-phase A1b/A2

Our preliminary study summarized in section 16.3.2 was carried out by NEC engineers, assuming the EUVST structure which is in form of separated telescope unit and spectrograph unit. As shown in Figure 16.1, an EUVST study has suggested that the integrated structure is preferable. According to further updates on optical and mechanical designs in Pre-phase A1b/A2, the mechanical model of the EUVST will be updated to improve the model fidelity and thus the prediction of the micro-vibration. For mitigating risks of the micro-vibration and of the procedure of the micro-vibration testing, it is important to define details of verification plans in this phase.

2) Phase A

Using the existing structure of the ISAS small bus module with a dummy EUVST structure, we plan to perform an evaluation test. This test will measure Q-values of the transfer functions from the locations of RWs and IRU to the location of optical components in EUVST. Especially, this will be the first opportunity to know transfer functions inside the bus module. A small shaker is used as a disturbance source and the level of micro-vibration will be measured with accelerometers attached to the EUVST dummy structure. The results from the measurements are incorporated in the mathematical model to improve the prediction. The supporting structures of EUVST will be designed, including the necessity of a vibration isolation damper, based on this prediction.

3) Phase B

Using the existing structure (or MTM if needed) of the ISAS small bus module with a MTM model of the EUVST, we will measure transfer functions of the mechanical disturbance from the locations of RWs and IRU to the optical components in EUVST. A shaker is used as a disturbance source, with accelerometers attached on the critical optical components. The results from this test are incorporated in the mathematical model and we will identify whether any modification is needed for the final design of the EUVST supporting structures to avoid any type of resonance between the disturbance sources and the optical components.

4) Phase D

In the final spacecraft test, we plan an end-to-end testing of micro-vibration using the integrated flight model of the spacecraft and confirm the amplitude of the image jitter to be within the required level. Test procedures to measure the amplitude of the image jitter will be studied in Pre-phase A1b/A2. Based on the results from this final test, we will finalize the operational range the spin rate of RWs.

16.3.4. International contribution items

1) Gratings

Two vendors (Horiba JY and Zeiss) have indicated that they can provide holographic TVLS gratings for EUVST. We plan to order prototypes during the formulation phase of the mission in order to validate the detailed grating specifications (groove profile, depth, density, etc.). The gratings will be thoroughly tested in the EUV prior to the start of Phase C to verify groove efficiency and imaging performance. As a backup, the EUVST team has considered the procurement of a spherical VLS grating and a mechanically ruled VLS grating from Bach Associates. Both backup options are viable and would satisfy the science threshold requirements. The backup designs will accommodate the existing mechanical interfaces. The backup options will only be exercised if the prototype gratings prove to have unacceptable performance.

The grating coatings multilayer technology has flown on numerous imagers (SoHO/EIT, STEREO/EUVI, TRACE, SDO/AIA, etc.) and spectrometers (SERTS, SoHO/CDS, Hinode/EIS, VERIS). The baseline design of the SW coating is a very robust Mo/Si multilayer design. Alternate, more efficient designs based on other combinations of materials will be studied during phase A. Structures giving more than 50% reflectivity around 19 nm include Al/Mo/B_4C and Al/Mo/SiC, as used on Solar Orbiter/EUI (Delmotte et al. 2013).

2) Coating for the primary mirror

The feasibility study summarized in section 16.2.3 shows the readiness and adherence to requirements of the baseline Mo/Si multilayer based the design. On the other hand, simulations run at the Institute of Optics (based on the coatings developed for Solar Orbiter/EUI) show beneficial effects from the addition of aluminum layers to the multilayer formula in terms of increased reflectivity at visible and IR wavelengths (Auchere, private communication) that translates in a lower equilibrium temperature of the main mirror. During phase A, further studies will be conducted in order to fine-tune the multilayer response in terms of reflectivity in the selected science band-passes as well as at visible and IR wavelengths to minimize the heating of the mirror. The optimization will include sample production and reflectivity and emissivity measurements. The realization of the flight coating will follow a BB (samples), PM and FM/FS approach on samples and optics provided by the mirror assembly responsible.