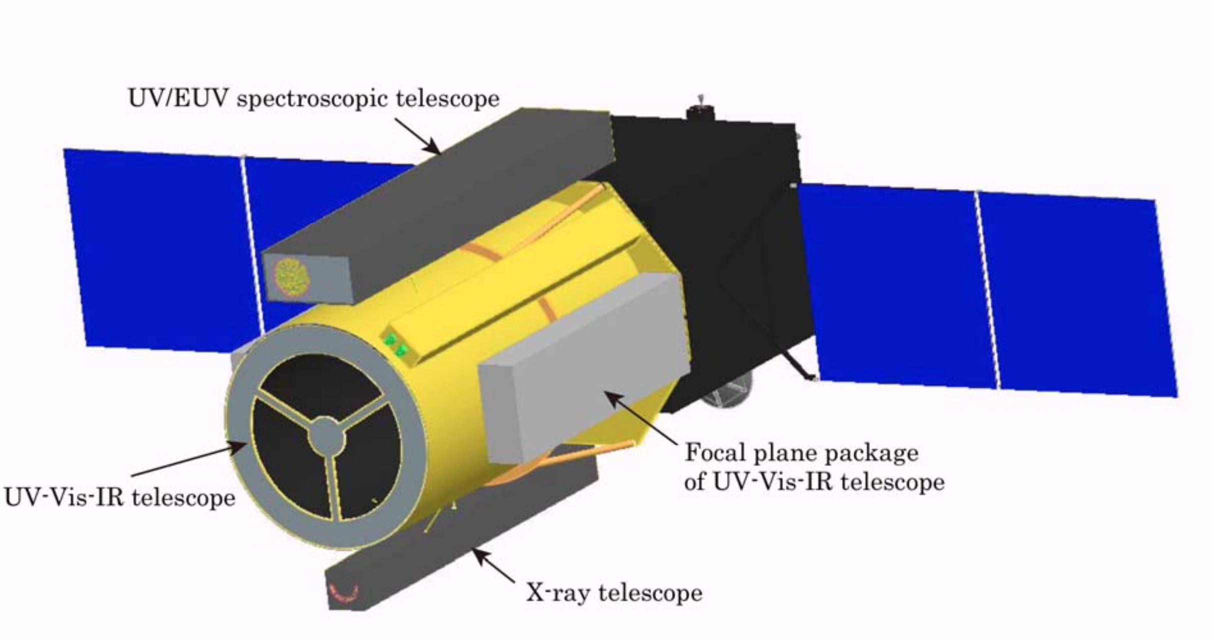
Interim Report:

SOLAR-C Plan-B

Toward understanding of the elementary structures & fundamental physical principles that govern manetized plasma



ISAS/JAXA SOLAR-C Working Group

Contents

Executive Summary

The Solar-C Plan B mission is proposed to study energy transport and dissipation of the magnetic energy governing the dynamic solar atmosphere through elementary magnetic structures. For this purpose, the plan B mission has three large state-of-art advanced telescopes that can perform for the first time high spatial resolution, high throughput, high cadence spectroscopic and polarimetric observations seamlessly covering the entire atmosphere from photosphere and chromosphere to transition region and corona.

Top-Level Science Goals

At the core of all the questions related to how the Sun floods the heliosphere with hot plasma, radiation, particles, and magnetic fields is the need **to understand the elementary structures and fundamental physical principles that govern a magnetized plasma**. Theory and laboratory experiments provide many useful insights, but the insights have been mostly triggered by new observations of the Sun's atmosphere, which is the only astrophysical plasma accessible with spatially resolving magnetic structures and dynamics.

By performing high spatial resolution imaging observations under extremely stable condition never realized so far, "Hinode" opened a new frontier in solar physics researches. For example, series of high resolution Ca II H images allow us for the first time to identify waves existing along magnetic fields, which can be considered as a key part in heating of the corona. Magnetic reconnection, which was firmly settled in solar physics with flare observations by "Yohkoh", is now used in explaining many aspects of dynamics observed in the solar atmosphere. However, details of fundamental physical processes governing the heating and dynamics in the solar atmosphere have not yet been described well with physical terms. This is because of the lack of spectroscopic measurements, which are most useful to diagnose plasma conditions. With Hinode observations, we also recognize that the chromosphere, which is the interface layer between the photosphere and corona, is the most key atmospheric layer in understanding the heating and dissipation in the magnetic atmosphere.

The outer atmosphere of the Sun (or stars) is a complicated system consisting of the photosphere, chromosphere, and the corona. The energy is built up in the magnetic atmosphere. The energy is transported via various methods, especially waves along magnetic fields. The dissipation of the magnetic energy is the central engine for causing variability in the emissions from the Sun. The energy build up, transport, and dissipation are mixed and complicated in the magnetic atmosphere, thus making it difficult to understand the governing physical processes without spectroscopic and polarimetric measurements over the entire atmosphere. Thus, the Solar-C Plan B mission is designed to make spectroscopic and polarimetric measurements over the entire atmosphere with necessary spatial and temporal resolution.

Scientific objectives of the Solar-C Plan B mission are summarized in Table 1. **As a path to exploring the fundamental physical principles**, we seek to understand:

- How **elementary structures** of the magnetic atmosphere responsible for heating and dynamics **are created and evolve** over each temperature domain of the atmosphere;
- How the energy that sustains the atmospheric structure is **transported through small elementary structures** into large-scale corona and **energizes the solar wind**; and
- How **the magnetic energy is dissipated** in the astrophysical plasma.

The solar atmosphere consists of elementary structures, one of which is magnetic flux tubes. The elementary structures shall be understood with their relationship with the magnetic field at all relevant temperatures. It is essential to quantitatively trace how they are created and evolve in association with magnetic fields and plasma flows over wide temperature domain. Magnetic field strength and direction in the chromosphere and corona, which is far above the photosphere and where the plasma is in low plasma ($\beta<1$) condition, is the crucial information to identify the magnetic structures and their roles for causing heating and dynamical nature in the atmosphere. Coronal loops are well known magnetic structures in the corona, but EUV density diagnostics suggests that coronal loops contain elemental structures that are about 10% volume of the coronal loops. The unresolved elementary structures would reflect the source of energy inputs responsible for creating the hot temperature corona.

The energy for solar activity and heating is transported from the photosphere into the corona associated with magnetic fields. The origin of the energy is the kinetic energy of the gas convection in and below the photosphere. The magnetic fields rooted on the photosphere play key roles in transporting the energy upward the chrosmosphere and corona, but we have not identified the mechanisms because of the complexity of fine structures, although some candidates have been proposed, such as high-speed upward ejections of plasma, propagation of MHD waves, and winding and braiding of magnetic fields for forming field discontinuities in the corona. It is extremely important to quantitatively evaluate how much energy is carried by waves and how the magnetic energy is dissipated in the stratified atmosphere both for heating the chromosphere and the corona and for energizing the solar wind.

A complex system of magnetic fields in the solar atmosphere triggers various types of dynamics and heating at different timescales and at different temperatures. They require the conversion of magnetic energy to heat plasma, drive flows, and accelerate particle to high energies. This conversion mechanism is “magnetic reconnection,” which may be the central engine in many solar phenomena, including the explosion of solar flares, the heating of the solar corona, and the initiation of coronal mass ejections. The solar atmosphere has a wide variety of plasma conditions; the inner corona consists of fully ionized, collisionless plasma, whereas the chromosphere is in weakly ionized plasma condition. We seek to address three important questions about magnetic reconnection. Quantitatively evaluation of fast reconnection in the weakly ionized chromosphere would be helpful to understand what plasma condition controls the energy release rate. What controls the energy distribution among thermal, kinetic, and non-thermal energies in early stage of flares? This would help to understand a wide variety of solar flares. How can reconnections in small scale develop to a large-scale flare structure?

Exploring energy transfer and dissipation governing the solar phenomena is directly linked to the space weather researches. Better understanding and predicting the space weather events are the basis on human related activities in the space. One of the important goals of solar physics research is to improve ability to predict geo-effective solar phenomena. High spatial

Table 1. Solar-C scientific objectives and required instruments

Scientific Objectives	***Specific questions to be answered***	***Section***	***Required Instruments***			
			SUVIT	*EUVS*	*XIT*	
					PC	*NI*
A. Elementary structures of the magnetic atmosphere responsible for heating and dynamics	**1. What generates dynamical chromosphere, such as jets?**	1.1.3	◎	○		
	2. What are the tunnel structures for energy transport from chromosphere to corona?	1.1.1 1.1.2 1.2.1	◎	◎		◎
	3. How are waves excited inside magnetic flux tubes?	1.1.4	◎	○		
B. Energy transport and dissipation through small-scale magnetic structures	**1. How do the observed waves behave in stratified atmosphere and contribute to the chromospheric heating?**	1.2.2	◎	◎		
	2. How much energy is carried by the waves that penetrate to the corona?	1.2.2	◎	◎		
	3. What are signatures of energy dissipation in coronal loops?	1.2.3		◎	◎	○
C. Magnetic energy dissipation: Unveil the mask of reconnection region	**1. What determines energy distribution in the energy conversion by reconnection?**	1.3.4 1.3.5		◎	◎	
	2. How can reconnections in small scale develop to a large-scale flare structure?	1.3.6	○	◎	○	
	3. Does fast reconnection really occur in the chromosphere?	1.3.3 1.3.4	◎	○		
D. Small-scale physical processes initiating large-scale phenomena regulating space weather	**1. What are the magnetic field structures during filament eruptions?**	1.4.1	◎	○	○	○
	2. How do magnetic flux and mass energy transport through the atmosphere and initiate flares and CMEs?	1.4.1	◎	◎	○	○
	3. What types of magnetic structures at the low atmosphere are origins of solar winds?	1.4.2 1.1.4 1.2.2	○	◎		

Note: [Origin] [Transport] [Dissipation]: Color indicates main physical process involved in each specific question.

Note: SUVIT = Solar UV-Visible-IR Telescope (Section 2)
EUVS = EUV/FUV high-throughput spectrometer (Section 3)
XIT = X-ray Imaging Telescope, PC= Photon counting, NI= Normal incident

and temporal resolution spectroscopic observations will much improve our knowledge about the initiation of space weather phenomena. Small-scale physical processes in the emergence of magnetic flux may play key roles in initiating the phenomena. Also, direct measurement of magnetic fields in the prominence or filaments tells how the magnetic field structures of prominences are evolved and developed to eruptions. Thus, as a goal toward the space weather researches, we seek to understand:

- How **small-scale physical processes initiate** large-scale dynamic phenomena regulating space weather.

The four science goals defined above are discussed in more details in section 1.

Scientific Measurement Requirements and Proposed Model Payloads

The following scientific measurements is required for the set of mission instruments. All of them have not yet realized in any currently operating and planned missions, and they are unique.

- **Precise polarimetric (S/N~10^{-4}) and spectroscopic measurements** for probing nature of magnetic fields both in the chromosphere and photosphere.
- **High throughput spectroscopic measurements** for probing nature of dynamics with high time resolution (0.5-1sec).
- **Seamless and simultaneous coverage of spectroscopic measurements over each temperature domain of the solar atmosphere** from chromosphere to the corona and flares for understanding the entire picture of energy transport and dissipation.
- **High spatial resolution measurements** for resolving elementary structures.

These measurement requirements are realized by the set of the following three science instruments:

1) Solar UV-Visible-IR telescope (SUVIT)

2) EUV/FUV high throughput spectroscopic telescope (EUVS)

3) X-ray imaging (spectroscopic) telescope (XIT).

EUVS will provide the crucial link between the photospheric and chromospheric magnetic field and plasma characteristics obtained by the SUVIT and the high temporal and spatial resolution diagnostics of the corona provided by the XIT. Two possibilities are considered for XIT: photon counting imaging spectroscopy telescope and ultra-high spatial resolution telescope.

Solar UV-Visible-IR Telescope

The primary purpose of the UV-Visible-IR telescope (SUVIT hereafter, Table 2) is to physically capture nature of gas dynamics and magnetic fields in the lower atmosphere, i.e., from the photosphere through the upper chromosphere, and to understand dynamical evolution of elementary structures of magnetized atmosphere. The telescope is a diffraction-limited telescope with a **1.5 m aperture in diameter** (the size may be optimized in the future). It has potential to **resolve structures with 0.1 arcsec or better for the first time** from the space observations (Figure 1), which can reveal dynamical behaviors of the low atmosphere through elementary magnetic structures and key physics responsible for energy transfer and dissipation in the photosphere and the chromosphere.

Table 2. Key characteristics of UV-Visible-IR telescope

Item	Description
Telescope	Aplanatic Gregorian telescope equipped with an image stabilization system
Aperture diameter	φ1.5 m
Focal plane instruments	Specto-polarimeter (SP) Broadband filtergraph (BF) Narrowband filtergraph (NF)
Wavelength coverage	280 nm to 1.1 μm
Spectral lines (spectroscopic observations)	(polarimetry in the chromosphere) He I 1083 nm, Ca II 854 nm (polarimetry in the photosphere) Si I 1082.7 nm, Fe I 853.8 nm (dynamics in the chromosphere) Mg II h/k 280 nm
Spectral lines (imaging observations)	(chromosphere) Mg II h/k 280 nm, Ca II 854 nm, H I α 656 nm, Na I D 589 nm, He I D 587 nm (photosphere) Fe I TBD nm
Spatial resolution	<0.1” at UV and visible <0.2” at near-IR
Exposure time	(intensity observations) 0.1 - 1 sec (polarimetric observations) 1 – 20 sec
Spectral resolution	~120,000 with the spectro-polarimeter ~50,000 with the narrowband filtergraph
Field-of-view	180” x 180”

SUVIT will take **the first attempt to measure magnetic fields in the chromosphere from the space**. The Hinode Solar Optical Telescope measures magnetic field vectors at the thin photospheric layer with spectro-polarimetric capability with polarimetric sensitivity of ~10^{-3}, and scientists have recognized that measuring magnetic fields in the chromosphere, 1,000-2,000 km above the photosphere, is essentially important to explore the stratified magnetic atmosphere. SUVIT can diagnose magnetic fields both at the chromosphere and photosphere (Figure 1).

Polarimetric sensitivity of ~10^{-4} is needed for diagnosing the chromospheric magnetic fields with combination of the Zeeman effect and the Hanle (scattering polarization) effect. Comparing with the Hinode Solar Optical Telescope (50cm in diameter), SUVIT can accumulate **roughly one order of magnitude larger number of photons** in the same spatial sampling and in the same exposure duration. **The polarimetric sensitivity of 10^{-4} is achieved with 20 s exposure times for 0.2” pixels.**

SUVIT covers a wide wavelength region from UV (~2800 Å) to near infrared (1.1 μm), in which there are **several spectral lines best suitable for diagnosing dynamics and magnetic fields in the chromosphere as well as the photosphere.** He I 10830 Å and Ca II 8542 Å spectral lines are identified as best lines for diagnosing magnetic fields and Mg II h/k lines at 2800 Å are for diagnosing dynamics in the chromosphere.

As the focal plane instruments, two instrument capabilities are equipped to the SUVIT: **Precise spectroscopic and polarimetric measurements** allow us to determine physical parameters such as temperatures, velocities, and magnetic fields. **Imaging of intensities and magnetic fields with high temporal cadence** is another capability to capture dynamical behaviors of magnetic fields within an observing field of view. Narrow-band imager is used for polarimetric and Doppler measurements at limited number of positions in spectral lines. Broad-band imager is for best possible high spatial monochromatic images of the chromosphere and photosphere.

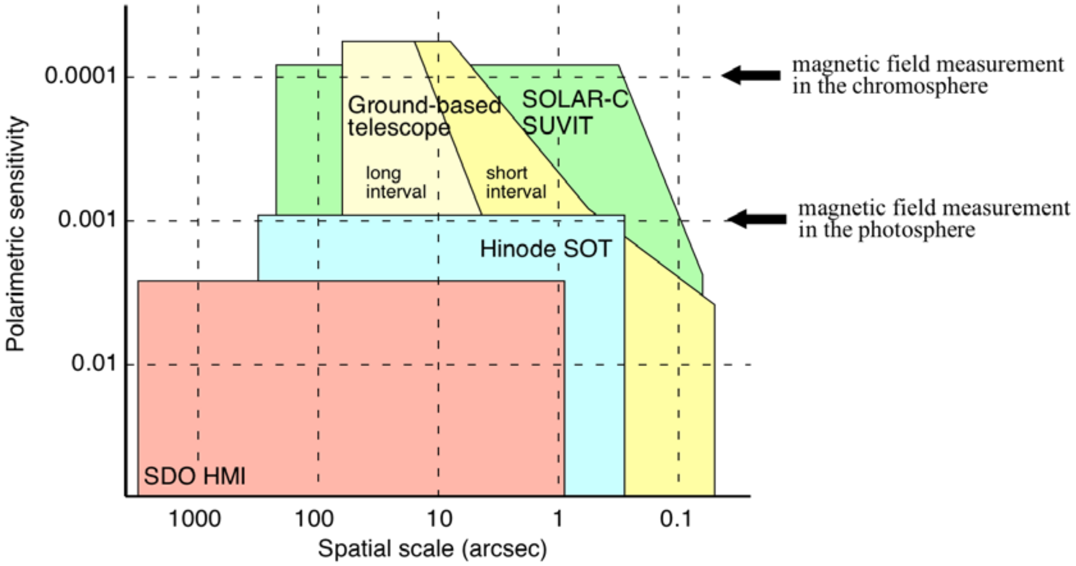


Figure 1. Spatial resolution and polarimetric sensitivity achieved with Solar-C UV-Visible-IR telescope, compared to other space-borne and ground-based large telescope.

EUV/FUV High-Throughput Spectroscopic Telescope (EUVS)

The EUV/FUV high throughput spectrometer (EUVS) is a telescope for imaging spectroscopy in the FUV-EUV region with a resolution and effective area an order of magnitude higher than currently available instruments for solar studies (Table 3, Figure 2). The spatial resolution of EUVS is **~0.3 arcsec (plate scale: 0.16 arcsec/pixel)**, which is much higher than currently operating SUMER and EIS (2-3 arcsec, 1 arcsec/pixel). This higher spatial resolution is required to spatially resolve elementary structures responsible for energy transport in the solar magnetic atmosphere. The volumetric filling factor of coronal loops derived from density sensitive line analysis suggests the existence of fine magnetic structures in order of 0.3 arcsec or ~200km. Magnetic structures in the chromosphere are also of this size, as seen as spicules. Thus, this performance allows us for the first time to trace flows of the energy from its origin (the photosphere) through the chromosphere and transition region and into the corona. Since the structures are small and dynamic, a high time cadence is necessary and consequently a high-throughput instrument is required. EUVS will have **1-5 sec** exposure for intense lines with 0.3 arcsec spatial sampling, and **0.5-1 sec or shorter exposure** for 1 arcsec sampling.

Simultaneous spectroscopic measurements sampling all temperature ranges of the solar atmosphere are essential to achieving the science goals of the Solar-C mission. EUVS is designed to seamlessly acquire spectral lines emerging from **a wide temperature in 10^4-10^7 K**. Since lower temperature lines are mostly observed in the FUV region and higher temperature lines are in the EUV region, EUVS is designed to cover a wide wavelength range in FUV-EUV and it is something like the instrument combining EIS and SUMER.

The strawman spectrometer consists of an off-axis primary mirror and grating mirror. This optical layout minimizes the number of optical elements, resulting in high throughput performance. The spectrometer measures emission lines and continua in some numbers of wavelength windows between ~100 Å and ~1200Å. **Low-scattering optics** should be used in the spectrometer to allow us to diagnose low emission measure pixels. Many important science discoveries may be hidden in low emission measure regions, such as, reconnection outflow regions that are much fainter than flare loops, and coronal holes where solar wind acceleration and shock formation may be observed in the high corona.

Table 3. EUVS scientific characteristic

Item	Description
Instrument design	- Φ 30-40 cm, off-axis paraboloid mirror - Single grating spectrograph - Two detectors, one for EUV band and the other for long wavelength bands - Image stabilization, slit-jaw camera
Plate scale	~0.16"/pixel
Simultaneous field of view	Slit: 0.16", 0.32", 0.96"; Slot: 10", 40", 200" Slit/slot length: 200" nominal, >300" extended
Maximum raster width	+/- 75" nominal, +/- 200" extended
Wavelength bands	Four channels (Å):130-250; 510-630; 690-810; 940-1060
Exposure times	1-5 s with 0.33" spatial sampling 0.5-1 s in active regions with 1.0" spatial sampling
Velocity resolution	Doppler (centroid) shift measurement accuracy <3km/s Turbulent velocity (width) <10km/s
Temperature coverage	10^4 – 10^7 in active regions with Δ(logT) <0.3

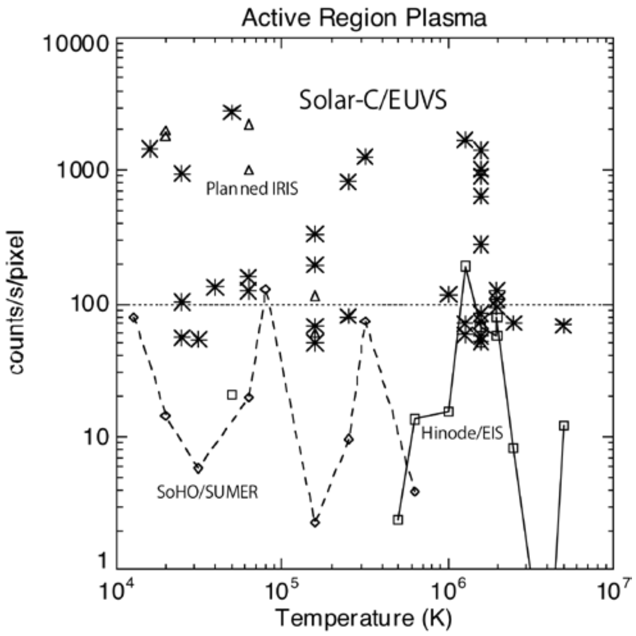


Figure 2. EUVS count rates for active region plasma, compared with currently operating telescopes (SUMER and EIS) and planned IRIS. At least 100-1200 counts are needed for spectral analysis.

X-ray Imaging (Spectroscopic) Telescope

The X-ray imaging telescope images, with spectroscopic information, the uppermost layer of the Sun, the corona, in soft X-rays or EUV to achieve comprehensive understanding on magneto-hydrodynamic processes across the entire layers of the solar atmosphere jointly with SUVIT and EUVS. The telescope should aim to (a) understand forms and mechanisms of storage and dissipation of energy transferred upwards through the photosphere and the chromosphere, (b) quantitatively understand physics of magnetic reconnection with its possible role for particle acceleration, and possibly, (c) perform diagnostics on wave phenomena in the corona. In order to pursue such scientific objectives, the telescope is required to have 1) wide coverage on coronal temperatures to observe the entire portion of single coronal loops, particularly, for the core portion of active regions, 2) high spatial resolution consistent with that for EUVS, and 3) advanced spectral diagnostic capability for quantitatively investigating physical processes in the corona.

Table 4. Outline of the photon-counting X-ray telescope

Item	Description	Remarks
Overall description	Perform imaging investigation of the X-ray corona with the following two modes. Two modes selectable (not simultaneously). (1) Photon-counting mode: Imaging spectroscopy for a limited region of interest. (2) Photon-integration mode: Imagery with the entire, or part of, the imaging array. Walter Type I (-like) grazing-incidence telescope with a segment mirror. A CMOS-APS detector to be used as the focal-plane imaging array.	
Envelope dimensions of the telescope	~40cm × 40cm × 4.5m (TBD)	Telescope plus the focal-plane camera. Includes housings.
Mirror focal length	4 m	
Angular resolution & Temporal resolution for photon counting	For photon-integration mode: ~1" (~0.5"/pixel) For photon-counting mode: For active regions and flares, generate an X-ray spectrum for spatial area whose size* ~< 2"×2" (goal) / ~4"×4" (min.) within every < 10 s (goal) / 30 s (min.)	* Spatial area size in which a spectrum with good counting statistics can be synthesized with reasonable integration time.
Field of view	For photon-integration mode*: ~13'×13' For photon-counting mode**: >~3'×3' (goal) ~80"×80" (nom.)	* Off-axis image blur not taken into account. ** Area with which photon-counting analysis can be performed.
Energy range	~0.5-5 keV* (baseline) ~0.5-~10 keV* (under study)	* Energy range above 2 keV available during flares, with photon-counting mode.
Data rate	max. 110 Mbps for 512×512 photon-counting area max. 6.9 Mbps for 128×128 photon-counting area	

A photon-counting imaging spectroscopy X-ray telescope (Table 4) is proposed, with a ultra-high spatial resolution normal incidence EUV telescope (Table 5) as another option. The photon-counting X-ray telescope will provide first-ever opportunity to perform imaging-spectroscopic investigation of the corona in soft X-ray wavelength range, by measuring energy and location of each incident X-ray photon onto the detector. In addition to the photon-counting capability, the telescope is designed to have photon-integration capability for imaging observations (just like past solar soft X-ray telescopes) with one of the two modes to be selected for a certain period of observation. The main observational targets for the photon-counting X-ray telescope is to 1) investigate quantitatively, with spectroscopic information, structure and dynamics of magnetized plasmas around the site of magnetic reconnection, and 2) investigate temperature structure of active region corona, in particular that for high temperatures (above ~5MK). It should be noted that the photon-counting X-ray telescope provides a unique chance of investigating electron temperatures of thermal plasmas and even detecting non-thermal emission in soft X-ray wavelengths, which is mostly not visible with emission lines but should manifest itself as continuum component(s) in X-ray spectra.

The other option, ultra-high spatial resolution normal incidence EUV telescope, will focus on understanding connection between the transition region and the lower corona in collaboration with EUVS. The normal incidence telescope serves as delivering complementary observables with EUVS, providing context imagery information for EUVS with higher spatial resolution (0.2"-0.3") and wider field-of-view, and with overlapping temperature coverage. Thus, the main target of this telescope is to resolve fine, hopefully elemental, structures in the corona, study energy flows and magneto-acoustic waves as well as small-scale heatings in coronal temperature range.

Table 5. Outline of the ultra-high resolution EUV telescope (Preliminary)

Item	Description	Remarks
Overall description	Consists of two telescopes each with Cassegrain optics. Each telescope equipped with 3-sector mirrors for different wavelengths. Image stabilization system necessary.	
Optical properties	32 cm aperture diameter. TBD focal length.	
Angular resolution	0.2"-0.3" with 0.1"/pixel	
Field of view	~400" × 400"	
Wavelength Bands	171 Å, 195 Å, 211 Å, 335 Å, 94 Å and broad-UV band	TBD
Exposure time	1 s for an active region, 0.1 s for a flare	
Cadence	< 10 s	
Data rate	TBD	

Spacecraft and Mission Design

The spacecraft designed to meet required scientific performance is summarized in Table 6, and the conceptual layout is shown in Figure 3. The spacecraft is designed mainly with considering the following items.

■ High pointing stability is required to realize the high spatial resolution and precise polarimetric performance. The spatial resolution of the telescopes is twice to five times higher than that of telescopes onboard Hinode. For the telescopes with angular resolution better than about 0.4 arcsec, tip-tilt mirror system is equipped inside the telescopes to stabilize solar images on their focal plane detectors.

- High rate science telemetry is required to acquire spectroscopic and polarimetric data with high cadence and spatial resolution. The minimum requirement is that the three telescopes can acquire the data continuously with the post-compression data rate of about 8 Mbps in total. We will use an X-band telemetry system (16-QAM, 16Mbps) with 12-hour or longer duration of contacts at ground stations or a Ka-bad telemetry system (QPSK, ~80Mbps) with shorter duration of contacts at a ground station.

Table 6. Solar-C plan B mission overall characteristics

Spacecraft layout	Telescopes mounted on the optical bench, which is on the Bus module. See Figure 1.x
Weight	4930 kg (at liftoff), 2330 kg (dry weight)
Size	3.2 m x 3.2 m x 7.4 m, excluding solar array paddles
Launch vehicle	JAXA H-IIA (type 202)
Orbit	An inclined geo-synchronous orbit (Baseline) A sun-synchronous polar orbit (optional)
Power	~3,500 W (maximum)
Command & Telemetry	Uplink and housekeeping downlink: S-band Downlink: X-band 16-QAM (16Mbps) Ka-band QPSK (80Mbps, optional)
Attitude control	3-axis body pointing with high accuracy Image stabilization system in some telescopes A function to change the pointing around Z-axis for matching spectrograph slit direction to the observing target.
Science operations	Hinode operation scheme, with a final target selection around 10 to 15 minutes before the uplink in cases where this is essential for the science.

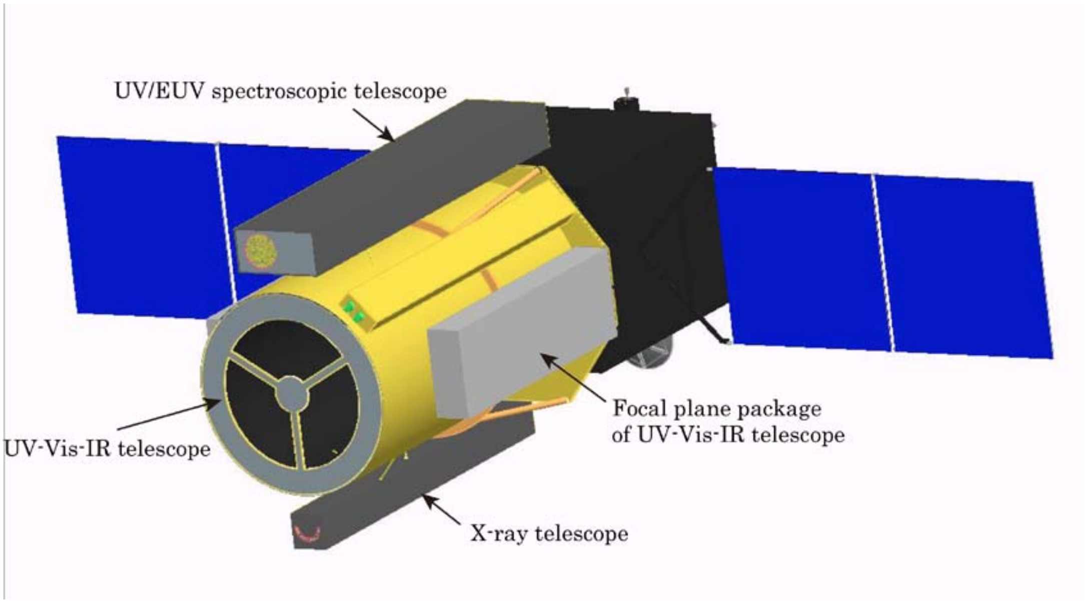


Figure 3. Solar-C plan B mission conceptual layout

- An inclined geo-synchronous orbit (GSO, altitude 36,000km, inclination < 30 deg, period 1 day) is considered as the baseline, with a sun-synchronous polar orbit as the backup. The GSO orbit provides almost uninterrupted observations of the Sun and much stable thermal environment, compared with Hinode, for minimizing the thermal deformation of the structure. It also provides long duration viewing from a ground station, allowing us to use X-band for high data rate, although the spacecraft weight and size become bigger.

- Another advantage of having a long-period downlink is that we can respond to dynamical changes on the Sun much faster, by monitoring solar images in real time. The optical and EUV spectrometers have relatively small fields of view and it is important to be able to choose the observing region as close to real-time as possible.
- The spacecraft design should utilize technical heritage from Hinode, especially the structural design and pointing related technologies for the high pointing stability and telescope alignment.