2-2 L5 Mission and Observation of Interplanetary CME

AKIOKA Maki, OHTAKA Kazuhiro, NAGATSUMA Tsutomu, MARUHASHI Katsuhide, and MIYAKE Wataru

CME (Coronal Mass Ejection) is one of the most important drivers of space environment disturbances. The "L5 mission" is the first challenge to track propagating CME toward the earth by side-view observation from the 5th Lagrangian point of the sun and the earth system. On 2002, international corporation program for construction space weather observation network with space missions (International Living with a Star). Our L5 mission plan is expected as an important component of the program and CRL will promote the plan under collaboration with ISAS scientists and NASDA. Study and BBM development for wide field of view camera and high performance mission processor are already started in CRL. In this article, overview of the plan and the status of the development are briefly introduced.

Keywords
L5 mission, Space weather, Wide field camera, Data processor for space application

1 Introduction

The conditions of the space environment are closely linked to solar surface phenomena and levels of solar activity. In recent years, the conditions and changes in the space environment originating from solar activity, including variations in space radiation environments, have come to be known as "space weather." Research on space weather phenomena and space weather forecasting has rapidly gained significance with human expansion into space and with the rapid increase in the significance of space systems for social infrastructures, including developments in satellite communications and broadcasting.

The goal of the L5 mission is to deploy observation mission instruments at the L5 point, with observation ranges covering the Sun-Earth line in space; and to clarify the propagation and interactions of disturbances originating from the Sun. The ultimate goal of the mission is to enable the forecasting of space environment disturbances. Fig.1 shows the relationship between the different space environment disturbances with sources on the Sun. Kinetic energy of the solar surface plasma is stored as magnetic field's energy, to be released during events known as solar flares and coronal mass ejections (CMEs). Flares produce X-rays and solar cosmic rays and induce the Dellinger phenomenon, a temporary interruption of HF communications. Solar energetic particles (SEP) increase the dose of radiation to which spacecrafts and astronauts are exposed. CMEs accelerate SEP as they propagate and create geomagnetic

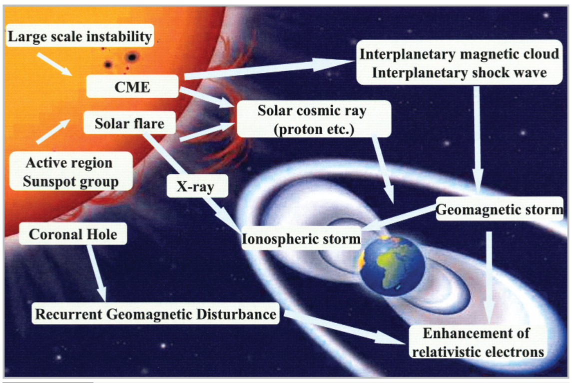

Fig.1 The Sun and various space environment disturbances

storms upon their arrival at Earth's radiation belt. High-speed solar winds ejected from coronal holes are also sources of geomagnetic disturbances. Space weather phenomena are dynamic and complex phenomena that involve the Sun, interplanetary space, and the Earth's magnetosphere, ionosphere, and thermosphere.

Understanding space weather phenomena and acquiring the capacity to forecast them requires observation, by various methods, of a wide expanse of space in which such phenomena occur. This in turn requires a wide-area observation network using various missions and observation instruments, including ground observation networks. To enable effective study and forecasting of space weather phenomena, this large-scale observation network must be built and operated through international and inter-agency collaboration. As one of world leaders in space development, Japan is obligated to help achieve this goal by promoting and implementing appropriate missions. The L5 mission will play an important role in the international initiative in space science research of the IACG. Expectations for the mission are high among foreign scientists, including IACG members.

The key to the success of the L5 mission will lie in partnerships and collaboration with other comprehensive observation networks within an international framework. The L5 mission is also expected to make significant international contributions to space studies by undertaking observations at a critical point in the observation network. One of the main goals of the L5 mission is to make side-view observations of plasma clouds propagating along the Sun-Earth line. These observations will enable remote sensing of plasma gas propagating in the Sun-Earth direction before it strikes the Earth's magnetosphere. Combining these remote-measurement data with in situ measurement data in interplanetary space and in the magnetosphere, we should be able to produce results whose significance far exceeds those of independent missions. Through joint observations with near-Earth satellite missions and ground observations, the L5 mission will also be able to make 3-D observations of the solar atmosphere above sunspots.

Since 1999, the CRL has proposed and promoted the research necessary for the L5 mission with the onboard instruments listed in Table 1. The L5 mission spacecraft will be deployed at the 5th Lagrangian point in the Sun-Earth system, as part of the study of the space environment observation mission for space weather forecasting. For this mission, prototype research and development were undertaken in advance with respect to subsystems incorporating new technologies. The following sections will provide an overview and discuss the purpose of the overall L5 mission (**2**), the wide-field coronal imager (WCI) (**3**), and the high-function onboard data processing (mission processor) (**4**). We will then briefly discuss our future plans including an in-orbit validation project using small satellites (**5**).

Table 1 *Candidates for onboard observation instruments for the L5 mission*

Wide field coronal imager	Tracking CME at the sun-earth space
High energy particle instrument	In situ measurement of high energy particles
Magnetometer	Interplanetary magnetic field measurement
High resolution Coronal Imager	High resolution imaging of CME near the sun
EUV Imager	EUV imaging of solar upper atmosphere
Solar full-disk imager	Visible observation of the full-disk sun
Solar wind plasma analyzer	In situ measurement of solar wind plasma
Plasma wave detector	Solar and interplanetary radio burst observation

2 Observations and Research Themes for the L5 Mission

2.1 Space Weather Forecasting Experiment in the L5 Mission

Most major geomagnetic storms and ionospheric storms are caused by collisions between magnetized plasma clouds released by flares and CME events at the solar surface, which are propagated at high speed through interplanetary space, and the Earth's magnetosphere. However, even for a major CME event, the effects upon the near-Earth space environment are negligible or nonexistent if the plasma is released in the direction away from the Earth. Positioned at the L1 point (at a point approximately 1 million km from the Earth along the Sun-Earth line), the ACE satellite now provides solar wind observation data, enabling predictions of the occurrence of geomagnetic storms. However, this system can predict storms only one hour before the collision of the high-speed plasma cloud with the Earth's magnetosphere. To forecast geomagnetic storms with more lead time, we must observe and track the CME directly as it propagates though space by remote observation of the Sun-Earth region.

CMEs are illuminated by sunlight scattered by electrons within CMEs, a phenomenon known as Thomson scattering. Due to the angle-dependency of Thomson scattering, CMEs should be observed from a direction perpendicular to the direct line from the light source to the scattering electrons; in other words, viewed from the side. Points for observing CMEs heading towards Earth must be positioned to give a side view of the Sun-Earth line. Following development of technology for making precise estimates of the velocity structure and density distribution of the solar wind in the inner heliosphere, a combination of data taken at the L5 point and in-situ data of space probes orbiting the inner heliosphere (for example, the Inner Heliosphere Sentinel being planned by NASA) (Fig.2) should enable predictions of the arrival time and scale of such disturbances.

The second purpose of the L5 mission is to make advance evaluations of the potential danger posed by active regions (sunspot groups) on the solar surface. If the probability of a solar proton event can be adequately predicted, it will be possible to reduce the operational risks of various space systems, including radiation exposure in manned space flights. However, solar physics has yet to determine the exact mechanism of solar flares and proton events, and it is quite difficult to make useful predictions of their occurrence based only on observations of the solar surface. Sunspot groups shift from east to west with the rotation of the Sun. But since solar protons propagate along the spiral interplanetary magnetic field (IMF) originating from the Sun, the effect is especially pronounced when the sunspot group is located within the western hemisphere. Thus, if the existence or absence of a proton event can be confirmed by direct observation when the sunspot group is

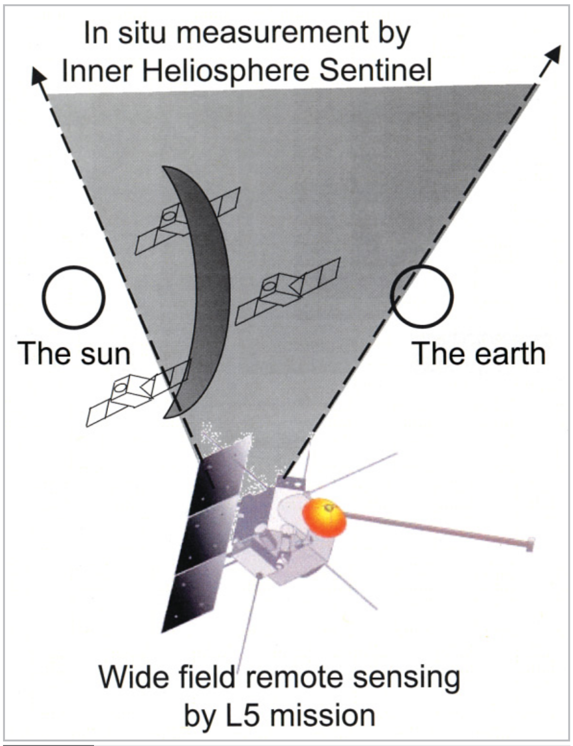

Fig.2 *Sun-Earth space mapping by combining remote and in-situ measurement data*

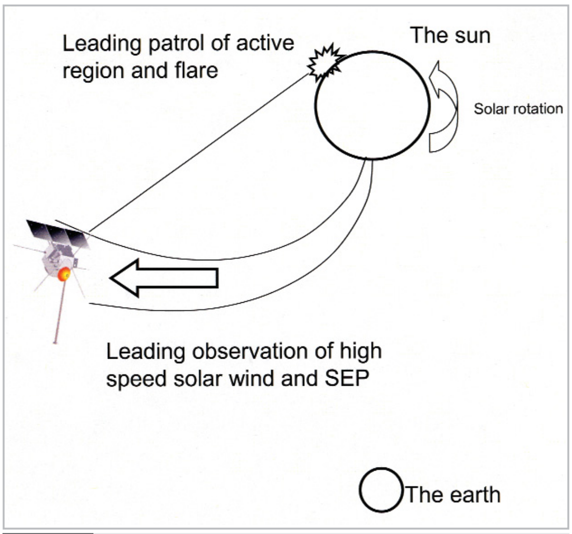

Fig.3 *Scheme of advance monitoring of space environment disturbances*

still within the eastern hemisphere or near disk-center, it should be possible to evaluate potential hazards three or four days before their effects spread to near-Earth regions. This would allow enough time to make appropriate changes to operating plans, including postponing or aborting extra-vehicular activities in manned space flights. Observations at the L5 point will also enable observations of sunspot groups when they are on the reverse side of the Sun, making it possible to "forecast" radio propagation anomalies caused by solar flares, based on data on sunspot activity (Fig.3).

The third purpose of the L5 mission is to make advance observations of high-speed solar winds. If the IMF and solar winds are assumed to be in a steady state, it should be possible to observe the IMF and solar wind conditions from the L5 point approximately four days before their arrival at Earth's magnetosphere. This lead time should make it possible to forecast geomagnetic storms and disturbances of radiation belt particles.

2.2 Observation of Space Weather Phenomena with the L5 Mission

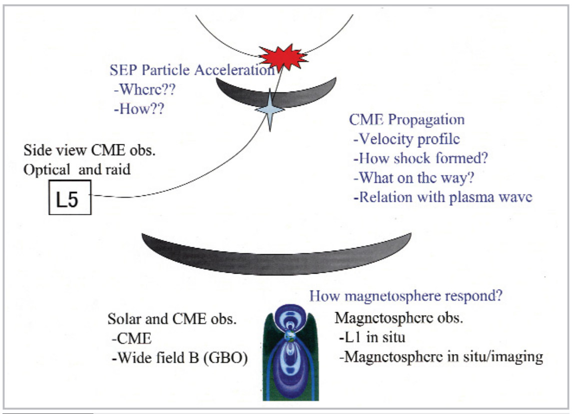

Fig.4 *Observation of space weather phenomena with the L5 mission*

The L5 mission is expected to revolutionize not just space weather forecasting, but solar-terrestrial physics, and our understanding of space weather phenomena and the inner heliosphere. The major themes of the research and observation (Fig.4) of the L5 mission are briefly summarized below.

<Mechanism of Flare and CME Generation (Accumulation and Release of Energy)>

Observation by the *Yohkoh* satellite provided much evidence on the generation of flares through magnetic reconnection. We can now say that a consensus has been achieved. The next step is to resolve the mechanism of the accumulation and release of energy by reconnection, and to determine why magnetic reconnection occurs. Also unresolved is the important problem of particle acceleration due to flares.

From the perspective of space weather, flares that accompany instabilities over a wide range (called dynamic flares or two-ribbon flares) are especially important. Major flares accompany rapid changes in the solar atmosphere over a wide area (magnetic loop). Therefore, it is necessary to resolve through observations changes to the large-scale 3-D structure of the coronal magnetic field and to determine the manner in which conditions leading to magnetic reconnection arise. Observations focusing on the 3-D structure of magnetic loops in the corona above active regions and changes to the loop structure should contribute to observations of the building-up process of flares and CME events. Wide-field coronal observations encompassing the entire active region and 3-D observations of the chromosphere are regarded as two key methods for making such observations.

<Energetic Particle Acceleration Process>

Broadly speaking, solar energetic particle (SEP) events can be classified into two types: impulsive and gradual events. This classification scheme is based on the theory that in an impulsive event, particles accelerated in the corona during solar flares propagate directly along magnetic field lines. In contrast, in a gradual event, coronal or interplanetary shock accompanying flares or CME events play the major role in particle acceleration. However, at this point, no proton event has been observed closely enough to verify such theories in terms of spatial distribution and source CME. The idea that the CME and not the flare itself drives the gradual SEP event over a long duration is relatively new, and direct observations of SEP events and observations of related flare and CME events are major themes for future research.

Observation of interplanetary shock and CME propagations and accompanying changes to the spatial structure will help clarify the relationship between interplanetary shock, flares, and particle acceleration. Reports based on observations indicate that when observations are made at a point where the source of flares or CME connects smoothly with magnetic field lines, the ratios of He and heavy ions are high, even extremely early in the phenomena[1]. Based on this finding, a model has been proposed in which particle acceleration occurs at an early stage within the solar corona (at the flare site) with high ratios of He and heavy ions, while the particles accelerated at the flare site are supplied along magnetic field lines to the interplanetary shock, where they experience further acceleration[2]. To understand the mechanism of particle supply into the acceleration region, we must observe the spatial structure and changes in the interplanetary shock and CME, seeking to clarify their relationship to the flare region.

One effective approach to resolving these problems involves tracking observations of the Sun-Earth line using wide-field cameras to follow the propagation of the CME gas ejected from the Sun to near-Earth, thereby clarifying the structure and development of the shock waves created by a CME. Visible-wavelength cameras for such observations must be sensitive enough to track CME gas to 1 AU, since the intensity of CME gas declines rapidly with distance from the Sun, making observations difficult. Other potentially useful approaches to gaining a better understanding of the detailed physical conditions inside the CME and near the shock include joint observations with radio sensors equipped with direction-finding functions, and observations from space probes orbiting the inner heliosphere, measuring in-situ plasma parameters.

<Multiple-Point Observation of Solar Wind Plasma>

Confining the Earth's magnetic field and forming the magnetosphere, solar wind plasma is also the energy source that dominates magnetosphere activity. Solar wind disturbances induced by phenomena such as CMEs and high-speed solar winds streaming out from the coronal holes result in disturbances in the Earth's magnetosphere, such as geomagnetic storms. Observation of the solar wind plasma is essential in identifying the causal factors of these magnetospheric disturbances.

The solar wind plasma also acts as the background medium of shock and corotating interaction regions (CIRs) within solar winds that generate geomagnetic storms. The shocks and solar wind disturbances that accompany CMEs interact with the preceding solar wind and arrive at the Earth orbit[3]. This interaction is known to decelerate the shock during its propagation from the Sun to the Earth. An understanding of the background solar wind structure is crucial for modeling and predicting the propagation of such disturbances.

To obtain the overall structure of solar wind through solar wind plasma measurements, we must perform simultaneous in-situ measurements at multiple points. This would be next to impossible in a single mission, but should be possible through partnerships within an international framework with missions by foreign countries. Plans call for the L5 mission to make joint observations with foreign space probes orbiting near-Earth and in the inner heliosphere, such as the one planned by the U.S. By deploying an observation mission at the highly significant L5 point, the L5 mission will contribute to the observation and understanding of the solar wind structure.

3 Wide-Field Coronal Imager

3.1 WCI Requirements

The wide-field coronal imaging (WCI) instrument observes how CMEs ejected from the Sun propagate through the inner heliosphere to near-Earth regions. The details of CME propagation through space, particle acceleration, and shock formation remain unclear at present, due to the lack of an effective method for observing CME structures and their changes and the manner of their propagation. To observe CMEs during propagation, a wide-field observation must cover the Sun-Earth line. It is inadvisable to cover the whole region between the Sun and Earth with a single sensor, since the intensity of the background zodiacal light is an order of a magnitude greater near the Sun than near the Earth. We plan to use two cameras to cover the Sun-Earth line.

The luminous intensity of the CMEs ejected into interplanetary space rapidly falls off as the CME draws away from the Sun. At 1 AU, the plasma's intensity is fainter by 10E15 than that of the Sun. The WCI will also make measurements with zodiacal light in the background. This will require a wide dynamic range. For WCI, the dynamic range will be determined by the SNR (signal-to-noise ratio), including the lowering of contrast due to stray light. Near 1 AU, background light (including zodiacal light and starlight) are stronger by a factor of 100 compared to CME gas intensity, the actual object of observation (Fig.5). The sensor S/N ratio required to detect a 10% fluctuation in CME gas intensity is 2,100. Detecting a 3 % fluctuation would require a S/N ratio of 7,000. Since the object of observation is extremely faint and buried within the background zodiacal light, the key factor for successful observations is a detector with SNR sufficient to extract the signal and to suppress stray light from the camera itself caused by the Sun and bright stars.

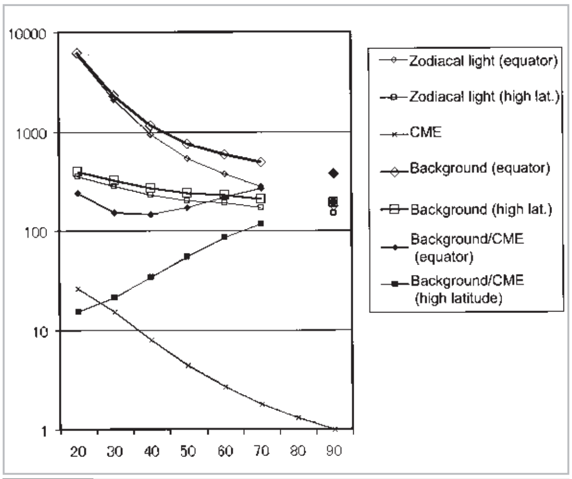

Fig.5 The dependency of background light and CME intensity on elongation from the Sun

3.2 The WCI Camera

The intensity of the background light (mainly zodiacal light) component rapidly falls off with increasing elongation from the Sun. The decline of zodiacal light near the equator and ecliptic are especially dramatic, falling off by a factor of nearly 3,000 between elongations of 2˚ to 60˚. It is thus inadvisable to attempt to encompass the required field-of-view with a single camera. In our plans, the required field will be covered by two similar camera systems (sunward: WCI-N; Earthward: WCI-W). The optimization of the field allocations to the two cameras is a theme for future study. At present, the WCI-N and WCI-W are tentatively allocated fields of 30˚ and 60˚, respectively. At these settings, the brightness of the background light (zodiacal light + starlight) at the sunward edge of field (elongation of 30˚) and near-Earth (elongation of 60˚) differs by a mere factor of 4, a realistic value for a proposed system.

In addition to the zodiacal light, starlight is another component of background light that must be taken into account. Since stars are observed as bright spots, a sufficiently bright star can be distinguished from CME gas, which appears as a wide, diffuse region. However, dark stars and densely concentrated regions such as the galactic plane cannot be identified individually in the same way. A method must be established to evaluate background starlight. To do so, the camera must have sufficient imaging resolution, matching that of the pixel size of the detector. However, the number of image planes in the camera (or, the number of lenses) must be minimized to reduce backlight such as scattered light produced at the surfaces of the camera, and to ensure that sufficient dynamic range is retained. In general, increasing the number of lens elements improves the imaging capabilities of wide-field cameras; this constraint and the high resolution requirement are thus in conflict. One solution to this problem is to adopt a camera with aspherical lenses. We are currently evaluating the feasibility of such a camera, including the construction of an experimental prototype.

Fig.6 shows an example of an optical design with aspherical surface currently being examined. In this design, the combination of 5 lenses (10 surfaces) achieves fairly good imaging capability, with spot diameter of 13.5 microns (= I CCD pixel) or less over 84˚ of the angular field of view. However, it must be noted that in order to reduce chromatic aberration and while obtaining the optimum design, observed wavelength range should be limited to 100 nm width. To minimize dispersion, the design wavelength was set near 800 nm, at which the resulting chromatic aberration is expected to be small.

Furthermore, to minimize damage to the lens materials by space radiation, the foremost lens element, which will be directly exposed to the space environment, will be made of silica. The design adopts a triple aspherical lens to achieve the required imaging capability. Future system development will examine the feasibility of manufacturing aspherical lenses with the requisite properties—in particular, to what extent surface microroughness can be reduced to minimize light scattering.

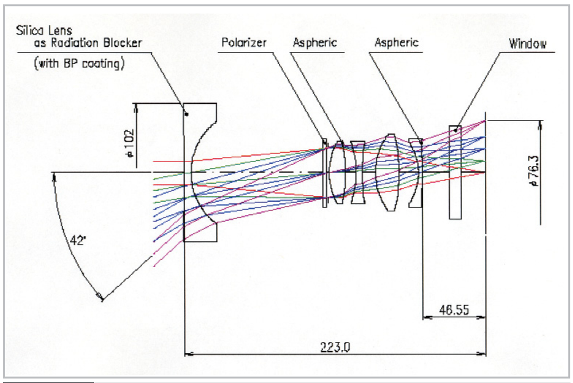

Fig.6 *Schematic of the WCI camera*

3.3 The WCI Detector

The primary observational requirement of the WCI detector is to measure the intensity of the main body of the CME to a precision of several percent. However, since the CME gas must be observed against a bright background of zodiacal light and starlight, the detector must have considerable dynamic range. The SNR required for imaging observations under conditions of strong backlighting is given by the following relationship[4]:

SNR = (signal from object of observation)$^{1/2}$ × (luminous intensity of object/background intensity)$^{1/2}$.

Since the proposed detector element is a CCD, signals from the observational target in the above are photoelectrons produced by photons incident upon the CCD, the number of which is counted. Assuming that the intensity ratio (object/background intensity) has the value 1/300 of our worst-case scenario, and by assuming an SNR of 100, we find that the count for signals from the observed objects (photoelectrons) must exceed 1E6. A full well for 1 pixel of CCD (the maximum number of accumulated electrons) is approximately 2E5, but most electrons impinging upon the sensor will originate from backlight sources, such as zodiacal light. If we assume that the ratio of the brightness of the CME to background light is 1/300, the number of electrons in a full well of CCD produced by signals of CME light sources is only 6.7E2. Thus, to collect 1E6 electrons from CME light sources, we must integrate the signals over approximately 1,500 pixels. This requires a high-precision, low-noise detector using CCDs of sufficiently large format (pixel count), since noise is statistically reduced when integrated over a large number of pixels. A method frequently used in astronomy to improve SNR is to take the same object several times and superimpose the images (frame integration). However, this method cannot be applied to CME, since CMEs move rapidly compared to required integration time (exposure time).

Table 2 shows the main specifications of the CCD currently being considered. The CCD chips are back-illuminated CCD (44-82) chips made by Marconi Applied Technologies. Two chips are aligned to create a mosaic CCD with 1.6 megapixels (4 K × 4 K pixel format). Prospects are good for building a clock pattern generation circuit for the CCD by radiation hard FPGA with 20,000 gates. The readout will be converted using a 16-bit AD converter (ADC). The readout will be performed at 100 kHz to satisfy noise and temporal resolution requirements.

Table 2 *Main specifications of detector*

Fullwell	2E5 e/pix
QE at 500nm	90%@500nm 75%@700nm
Pixel format	4096×4096
Pixel size	15 micron
Imaging area	61.7×61.7mm
Dark current (153K)	0.01 e/pix/hr
Read out	Double integration
ADC	16 bit
CCD temperature	Lower than −193K
Readout speed	100KHz

From experimental data tested by the Jet Propulsion Laboratory (JPL), we know that it is possible to obtain 16-bit ADCs with total dose resistance sufficient for the L5 mission. However, plans call for total dose resistant experiments to be conducted independently at the CRL to acquire data on the detailed characteristics of performance changes accompanying deterioration due to exposure. Cases have been reported in which ADCs subjected to irradiation have exhibited single event upset (SEU) in the register. Thus, proton and heavy ion irradiation tests are also being considered. While the performance and reliability of ADCs have a directly bearing on measurement precision, few high-precision 16-bit ADCs have been verified by actual deployment in space. The ADC unit for our mission will be selected carefully, based on independent testing.

A BBM unit was developed using products available commercially to examine the feasibility of a low-noise readout circuit and to acquire characteristics data for the CCD element (Fig.7). Equipped with a cooler unit and a vacuum chamber, this BBM unit has a cooling capacity of -100˚C. Experiments performed to examine the temperature characteristics of the CCD showed that the dark current consisted of two components. One has a random, noise-like characteristic, while the other has moderate spatial distribution. We confirmed that the random noise component occurs randomly and decreases with temperature, as expected. The component of the dark current with moderate spatial distribution was also confirmed to decrease with temperature. Tests using the BBM unit showed that the dark current decreases rapidly at -80˚C, disappearing entirely at -100˚C (Fig.8). While the

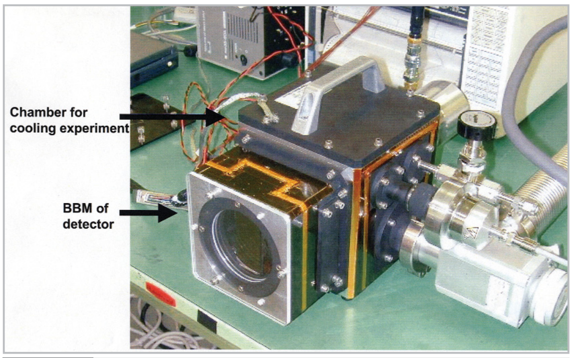

Fig.7 *WCI/BBM unit and the cooling chamber for the experiment*

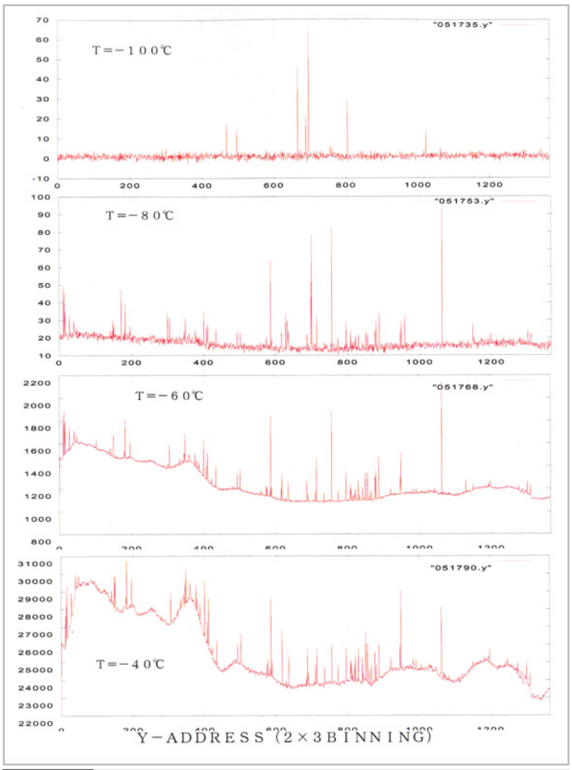

Fig.8 *Temperature dependency of the dark current of CCD (44-82) chip*

underlying reasons for this behavior are not yet fully understood, it is assumed to be attributable to the non-uniformity of the element material. The CCD chips proposed for onboard installation will be cooled and tested at approximately -100˚C. Thermal design and analysis are currently underway.

4 Mission Processor

4.1 Need for High-Performance MP

Plans for the L5 mission requires the installation of a sophisticated onboard high-performance mission data processor (MP) superior to existing onboard processors to perform onboard analysis of large-volume image data. However, it is not feasible to allocate onboard data analysis functions that require high processing power to processors aboard spacecraft, as this runs the risk of complete mission loss in the event of an error or problem. Processing information related to overall system controls (such as attitude controls) and command telemetry will be allocated to a spacecraft system processor whose reliability has been verified in past space operations. Alongside this processor, a high-performance, multi-purpose mission data processor will be placed onboard for dedicated processing of mission data. At this point, plans call for the mission processor to handle onboard mission data analysis for the mission system and to control observation and experimental sequences for mission instruments. The CRL currently assigns the highest priority in L5 mission research to evaluation and concept studies for the MP. Related research is already underway.

The need for a high-performance MP for the L5 mission can be summarized as follows:

- Reduction of data transmission volume by high-performance telemetry

Despite the lack of telemetry resources resulting from extreme communication distances, the data volumes produced by continuous observations by imaging sensors will be massive. From the perspective of space weather forecasting and observations of space environment disturbances, not all of this data needs to be transferred immediately to ground stations for detailed analysis. Instead, we can assign higher priority to data associated with major events, selectively transmitting important data to ground stations and scheduling data transmission accordingly. This would enable optimal mission results from limited communication resources. Such a system would require a high-performance data processor for onboard processing and analysis of large volumes of CCD data.

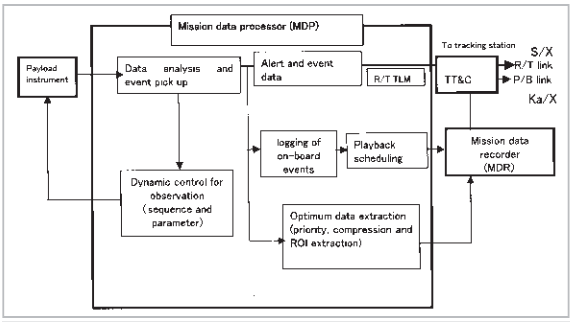

Fig.9 *Concept of High-Performance Telemetry*

- Real-time Data Transmission

The main purpose of the L5 mission is to conduct various experiments on the effects of space environment disturbances to enable real-time transmission of data and information, and to establish a monitoring, forecasting, and alert system for space environment disturbances. In addition to the normal mission link, the L5 mission is equipped with a real-time link that will continuously transmit relatively small-volume data.

The data transmitted by the real-time link will include key parameter data after averaging, information on the occurrence of phenomena obtained through data analysis, and the parameters characterizing such phenomena. This real-time data will be used for space weather forecasting experiments, as well as for communications and broadcasting systems that require space environment information to provide their services. The data will also be distributed to and used by organizations involved in space studies. The system will make it possible to select observation plans for the solar surface according to the changes observed, and to transmit data via the real-time link, thereby maximizing the usefulness of mission results.

- Autonomous Execution of the Observation Mission

Real-time command operations of the L5 mission will face certain limitations due to the distances over which communications will take place. For this reason, startup and shutdown of observation instruments and emergency recovery procedures must be pre-registered in the MP. A high-level autonomous control function must also be installed to permit GO/STOP decisions to be made onboard for each step.

- Autonomous Alert Experiment

One important objective of the L5 mission involves an in-orbit experiment on autonomous alert by onboard data processing. Experiments are currently being planned to investigate and develop a function of the autonomous space weather module that would permit switchover to a mode with greater resistance to SEU when a space environment disturbance above an certain magnitude is likely to occur. Such in-orbit experiments will require powerful data processing capabilities, as well as an operational environment that permits the execution of various experimental functions, such as in-orbit software updating and installations.

4.2 Hardware

The MP for the L5 mission will perform onboard data analysis such as CME image analysis and solar phenomena detection and control observations via the mission instruments. The MP must provide both high computing power and durability. However, the devices and components currently available for space use were originally designed specifically for that purpose. They have been verified for space use through slow and prudent testing processes. Since spacecraft components often cannot be repaired or upgraded after launch, the design and selection of components have been based on past records of use. Naturally, decisions in this area tend to be conservative. After a survey of CPUs and OBCs (onboard computers) currently available for space use, we found that conventional OBCs are incapable of performing onboard 2-D image data processing for high volume (1.6 megapixel) data. A survey of CPUs and peripheral devices available indicates that the requirements for a sophisticated, high-performance MP in the L5 mission plan can be met using the combination of the Japanese SH-4 for the CPU and the Compact PCI bus, which has recently begun to see wide industrial application, as the internal bus.

When used in space, electronic components (CPUs and semi-conductors such as memory) must be carefully tested for tolerance to radiation, thermal vacuum, vibration, and shock and durability, all before the system is designed. Radiation hard characteristics in particular differ significantly from device to device and must be thoroughly tested in ground tests. Total dose tests by Cobalt-60 irradiation and SEU tests by heavy-ion irradiation undertaken to assess the radiation tolerance of devices are beginning to indicate that they indeed have radiation tolerance/hardness adequate to operate in the in-orbit environments of the L5 mission and to carry out the advance in-orbit validation experiments to be conducted in low-earth orbit (Fig.10)[5]. Plans are currently being drawn up for irradiation tests using relatively low-energy protons to validate the adaptability of the devices under the more severe radiation environments of the GTO orbit.

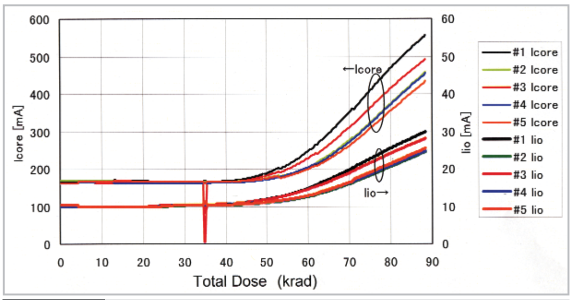

Fig.10 *Results of total dose tests on SH-4*

Resembling the PCI bus used for personal computer, the Compact PCI proposed for the internal bus is currently replacing the older VME as the data bus used in industrial applications. There is no record at this time of use of the Compact PCI in space flights. However, we believe that the PCI bus controller can be designed using an FPGA with approximately 20,000 gates, with performance verified in previous space flights. Various structural interfaces are also being examined to determine which can withstand the anticipated levels of shock and vibration. An example is a vibration test with Ariane-QT level performed on commercially available Compact CPI units, performed as part of the present study. This test confirmed that the Compact CPI functioned normally in the launch condition. The result suggests that the design standards of the Compact CPI back planes and sockets for normal commercial use are likely to satisfy the standards for vibration and shock resistance on board a spacecraft.

4.3 Operating System and Software

We have plans to use real-time OS (RTOS) widely used for embedded system applications. Between multi-tasking and multi-process operating systems, a multi-process OS is believed to be the safer choice. With multi-process OSs, when application software hangs up due to an error, only the process for the application experiencing the problem is terminated. Other processes, particularly the kernels, are generally not affected. Furthermore, given the desirability of permitting the researcher himself to develop analytical software for onboard data analysis and forecasting experiments, among other considerations, detailed studies are being made of the feasibility of installing QNX as the MP and its functionality both in space and in ground facilities. QNX is gaining popularity in fields related to space weather for use as a processor for controlling ground observation instruments, and represents an attractive option as the processor for the L5 mission, in which researchers on the science team must help develop the experimental application software.

However, this will be the first occasion in Japan on which a commercial RTOS will be used in space. A thorough preliminary survey and validation test of the reliability of the RTOS using BBM-level hardware and mission software prototypes must be performed before the final selection and development of the L5 mission satellite. These validations will be carefully designed and conducted END-to-END using BBM units and simulators for single or multiple mission instruments.

The development of the observation instruments, data recording instruments, and mission software for communication with the command telemetry system on the S/C side, basic data acquisition, and execution of basic mission functions will follow standard procedures for spacecraft software development and validation, shown to be reliable by past experience, with the objective of producing highly-reliable system and software. On the other hand, software for advanced data processing and in-orbit data processing experiments will be regarded as application software, and must offer greater flexibility compared to mission software. Our plans are to ensure a certain minimum level of mission success, even in the event of problems with the application software.

5 Implement the L5 mission

5.1 The Spacecraft Bus and Launch

The CRL has collaborated with NASDA in studying the L5 mission profile, spacecraft system, and launch method. The general sequence for deployment at the L5 point will be as follows: The spacecraft will be launched to the parking orbit by the appropriate vehicle. It will then be accelerated by approximately 3.4 km/s until attaining escape velocity and inserted to L5 transfer orbit. slightly outside Earth's orbit, and the spacecraft will gradually lag behind the Earth. Approximately 1.2 years later, the spacecraft will arrive at the L5 point. Decelerating by approximately 1.7 km/s at the L5 point will allow the spacecraft to enter a stationary orbit at the L5 point[6] (Fig.11).

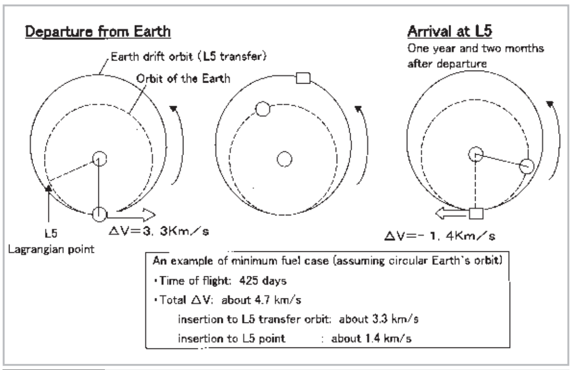

Fig.11 Schemeatic of orbit for deployment at the L5 point

We found that a relatively small spacecraft bus of approximately 450 kg will be sufficient to complete the mission (Fig.12). Given the amount of propellant estimated to be necessary for accelerating the spacecraft from Earth orbit into transfer orbit to the L5 point, and for deceleration upon arrival at the L5 point, the required launch capability to the Earth-parking orbit (Earth orbit at an altitude of approximately 200 km) is calculated to be approximately 4 tons. This is about half the launch capacity of a large Japanese rocket, and can be realized with even a dual launch by H-2A rockets or by a single medium rocket. This mission can be realized at half the scale of other large engineering test satellites.

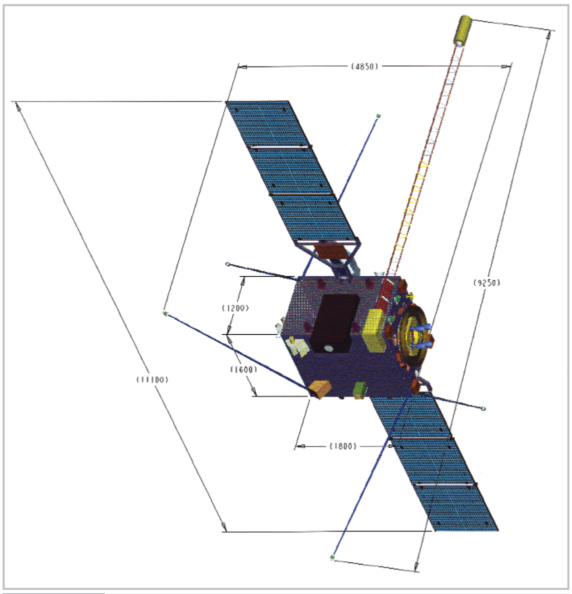

Fig.12 Spacecraft configuration

5.2 In-orbit Validation Experiments by Small Satellites

The sensor and spacecraft technologies aboard the L5 mission will consist of subsystems that have never been validated, such as the WCI and MP. In-orbit validation experiments on these subsystems will be required before the mission. The Solar and Solar Wind Group at CRL is collaborating with the Smart Satellite Technology Group of the Wireless Communications Division to acquire a window of opportunity to perform required experiments and validations of the new space and sensor technologies, through space missions using small satellites. This research project will be a collaborative effort with related research institutions and space agencies, as well as with manufacturers interested in the development of small satellites. The research and development will be undertaken in an open and flexible manner.

Under the current plans, as the first step in the experiment, two small satellites will be deployed into orbit to perform experiments for a period of about one-half to one year. The satellites will carry instruments for a space weather observation experiment, in-orbit service experiment, and inter-satellite communication experiment, including advance validation studies for the L5 mission. Their launch schedule has not been set, as they may be launched together with other large or medium-scale missions. Our system concept of small satellites is applicable to either a stationary transitional orbit or low Earth orbit.

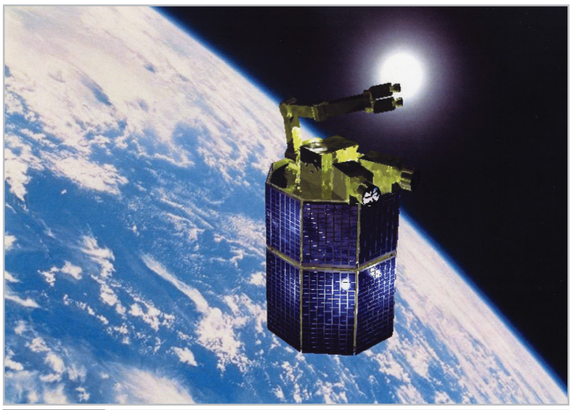

Fig.13 Illustration of an in-orbit validation experiment with a small satellite

5.3 L5 Mission Schedule

The L5 mission must be scheduled to allow joint observations with projects in Japan and foreign countries, which use satellites and spacecraft to observe the Sun, the inner heliosphere, and the magnetosphere. The mission needs to be scheduled during the solar maximum, since the frequency and scale of the space environment disturbances will peak during this period. The Inner Heliosphere Sentinel of NASA's "Living with a Star" project is currently scheduled for the period of 2011-2012. The Solar Orbiter, which will make observations of the Sun from an orbit inclined from the ecliptic plane, is currently scheduled for launch in 2011. The CRL is proceeding with plans to launch the L5 mission around 2011-2012.

6 Conclusions

Ever since its days as the Radio Research Laboratory, as CRL was formerly called, the CRL has been successful in turning observations of radio propagation and alert systems to practical applications, and operates systems as a part of its routine tasks. The CRL has played a central role in Japan in the study of monitoring, forecasting, and alert technologies related to space environment disturbances of solar origins. The expansion of human activity into space is accelerating as we enter the 21st century. From the perspectives of economy, industry, and national security, it will become increasingly important to establish a space infrastructure for communications and broadcasting and information technologies. Space development requires massive resources; international cooperation is essential. The building of a network for space weather forecasting and observation is a fundamental research field crucial for supporting safe and low-cost human activities in space. As a country that prides itself as one of leaders in space development, Japan has an obligation to take an active role in the project. With its long record of achievement in radio propagation, space weather studies, and space environment measurement technologies using electromagnetic waves, the CRL intends to play a central role in international efforts to construct the space weather observation network.

References

1 D. V. Reams, H. V. Cane, T. T. von Rosenvinge, "Energetic particle abundances in solar electron events", Astrophys. J., Vol.357, 259.

2 M. A. Lee, "Particle acceleration and transport at CME-driven shocks", Coronal Mass Ejection, 227, 1997.

3 N. Gopalswamy, A. Lara, P. Lepping, M. L. Kaiser, D. Berdichevsky, and O. C. St.Cyr, "Interplanetary accelaration of coronal mass ejetions", Gephys. Res. Lett., Vol.27, 145, 2000.

4 D. J. Schroeder, Astronomical Optics, P.317, 1987.

5 M. Akioka, H. Okamoto, and A. Nagata, "The availablility of COTS CPU in Space ─ The Results of the SEE Test ─", Proceedings of the 46th Space Science and Technology Conference, 91-96, 2002.

6 T. Fujita, T. Goka, M. Utashima, A. Tsuiki, M. Akioka, "Mission Study of L5 Fixed Point Sun Monitor Satellite", Proceedings of the 43th Space Science and Technology Conference, 99-1B6, 1999.

***AKIOKA Maki**, Ph. D.*

Leader, Solar and Solar Wind Group, Applied Research and Standards Division

Solar Physics, Optical System, Space Weather, Space Technique

OHTAKA Kazuhiro

Researcher, Space Weather Group, Applied Research and Standards Division

Space Weather

***NAGATSUMA Tsutomu**, Ph. D.*

Senior Researcher, Space Weather Group, Applied Research and Standards Division

Solar-Terrestrial Physics

***MARUHASHI Katsuhide**, Dr. Sci.*

Visiting Researcher, Solar and Solar Wind Group, Applied Research and Standards Division

Solar-Terrestrial Physics

***MIYAKE Wataru**, Dr. Sci.*

Senior Researcher, Space Weather Group, Applied Research and Standards Division

Space Weather