Results Achieved from the Development and Operation of the Asteroid Probe MUSES-C (HAYABUSA)

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Abstract

The MUSES-C (HAYABUSA) is the first asteroid probe to have landed on a celestial body beyond the earth's atmosphere that is further out than the Moon and to have brought samples back to Earth. NEC coordinated the MUSES-C project, and it was in overall charge of the design, manufacture, testing and operations of the entire system as well as of much of the payload equipment, including the bus components and the ion powered navigation engines.
This paper provides details of the design and operation of the MUSES-C project. It also discusses the results achieved from its development and operation and the prospects for future commercial ventures.

Keywords

asteroid probe, MUSES-C, M-V, scientific satellite, HAYABUSA, swing-by
sample return, capsule, optical navigation, ion engines

1. Introduction

The MUSES-C (HAYABUSA) asteroid probe (**Fig. 1**) was launched using the M-V No. 5 carrier rocket on May 9th, 2003 (JST: All of the dates and times of day cited hereafter are those of Japan Standard Time.) MUSES-C was the world's first asteroid sample return technology, demonstration spacecraft. NEC acted as the systems coordinator of the MUSES-C probe and we were in charge of the design, manufacture, testing and operations of the entire system as well as of much of the payload equipment such as the bus components and ion engines.

The MUSES-C was assigned four engineering demonstration missions including; 1) demonstration of the ion engine as the main engine for interplanetary navigation, 2) demonstration of autonomous guidance control by means of optical navigation, 3) demonstration of sampling technology under trace gravity conditions and, 4) demonstration of the technology for the collection capsule to reenter from interplanetary orbit. Although each of these challenging issues was of extreme difficulty, we were able to complete all of them successfully with the return of the capsule on June 13, 2010.

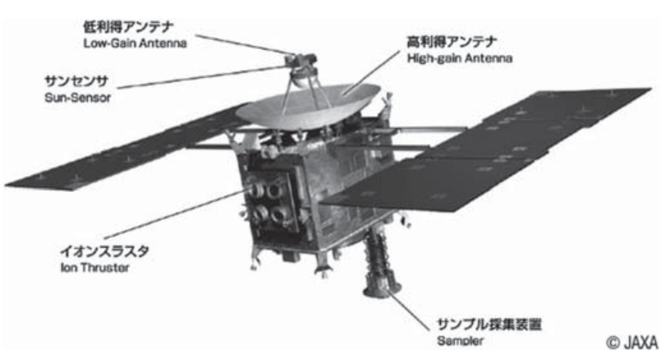

Fig. 1 External view of MUSES-C.

This has also led to a ground-breaking achievement in obtaining an asteroid sample for the first time. This advance is expected to contribute significantly to the study of the origin of the solar system.

The results obtained by the flight of the MUSES-C demonstrate not only the main engineering missions and other scientific results, but also include knowledge of the operations and system technologies. This was thanks to the experience gained from touchdown on an unknown asteroid and the overcoming of several difficulties encountered during the return cruise. Such knowledge will provide an excellent foundation for the solar system exploration technologies of the future.

The story of the MUSES-C's journey extended over 6 billion km and 7 years and the video of the return of the capsule was widely reported by the media. It not only helped deepen the national understanding of space development issues but also demonstrated the vigor of the challenging spirit, organizational power and human commitment of Japan as a technology-oriented nation. The very large numbers of enterprises that

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engaged in the MUSES-C project were able to celebrate the success with considerable satisfaction.

This paper gives an outline of the MUSES-C project, introduces the results achieved and discusses the prospects for future commercial ventures.

2. Mission Outline

Fig. 2 shows an outline of the mission sequence of the MUSES-C. The objectives of the MUSES-C were to touch down on the asteroid 25143 ITOKAWA, collect a sample and bring it back to Earth. Such a sequence of operations was a highly difficult one, because the missions would be terminated immediately unless there was a continuous series of successes, just like drawing a picture without lifting the brush from the paper.

3. System Design Outline

3.1 Overall Design

The MUSES-C probe has a box-shaped body of 1m × 1.5m × 1.1m on which exterior equipment including a fixed high-gain antenna and fixed solar array paddles are installed. Its overall weight is 510kg (including 142kg of propellants). Attitude control is performed using reaction wheels (RWs). However,

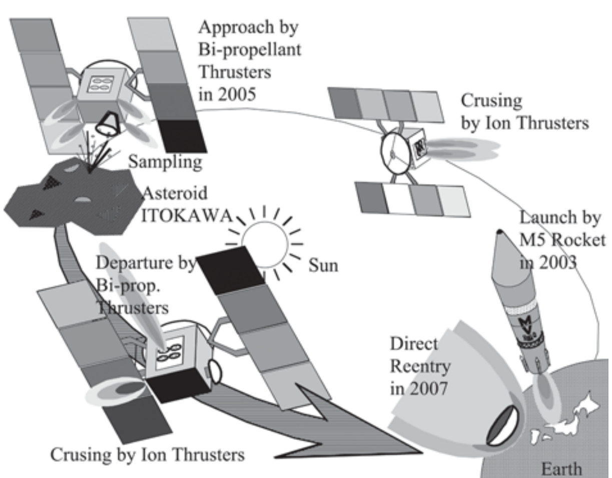

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Fig. 2 Mission sequence outline.

Table 1 Main system specifications.

Mission	Launch date	May 9, 2003
	Carrier rocket	M-V No.5
	Mission	Asteroid sample return technology demonstration
Overall system	Structure size	1 m × 1.5 m × 1.1 m (Height)
	Weight at launch	510 kg (including propellants)
	Propellant (RCS)	(69 kg)
	Propellant (Ion engines)	(73 kg)
	Generated power (Initial period after launch)	≥2.5 kW at 1 AU
	Communication frequency (Up/Down)	X-band
	Attitude control	Triaxial attitude control
	Propulsion subsystem (chemical fuel) RCS	20 N × 12 thrusters
	Ion engines (Xe) IES	8 mN × 4 engines (3 engines simultaneously)

at the time of touchdown on the asteroid, 12 thrusters of 20 N thrust force each of the RCS (Reaction Control Subsystem) of the propulsion subsystem (chemical fuel) are used in addition to the RWs for attitude/positioning control with six degrees of freedom.

Table 1 shows the main specifications of the typical MUSES-C system.

Issues of the MUSES-C system design can be grouped into the three topics of; 1) adaptation to environmental conditions that vary significantly depending on the distance to the Sun and the asteroid, 2) possession of advanced automation/autonomous control functions and, 3) use of system configuration and technology elements that can offer light weight and high reliability.

To solve these issues of the MUSES-C, we almost totally reviewed the bus modules used by previous scientific satellites. **Table 2** shows the design outline of the bus subsystems that were considered in dealing with the bus design issues.

(1) Power subsystem - Bus voltage control method

Since the on-orbit environment of the MUSES-C is one in which the distance to the Sun varies greatly, the bus power is controlled with a regulator system called the SSR-CV that is capable of obtaining the maximum possible power according to the solar light intensity at each point (**Fig. 3**).

(2) Power subsystem - Battery

To meet the severe weight reduction requirement imposed on the MUSES-C, the previously used NiMH (Nickel Metal Hydride) battery was replaced with a Li-ion battery (13.2 Ah). This was the first battery of this type to be developed for use by spacecraft.

Table 2 Design outline of bus subsystems.

Subsystem	Adaptation to Environment Change	Advanced Automation/ Autonomy	Weight Reduction, Reliability Improvement
Communication	X-band high-sensitivity reception, variable-depth modulation transmission		
Data processing	Transmission priority designation, report packet, multi bit rate	Automated autonomous command processing	
Attitude and orbit control		Autonomous touchdown GNC	
Ion engine	Variable number of working units, power throttling		Microwave discharge IES, IRS unloading of RW
Thermal control	Peak power suppression heater control, Smart Radiation Device	Prioritized heater control	C-C composite thermal doubler
Power	SSR-CV bus voltage control		Space use Li-ion battery
Solar paddles			High-efficiency 3-junction cells

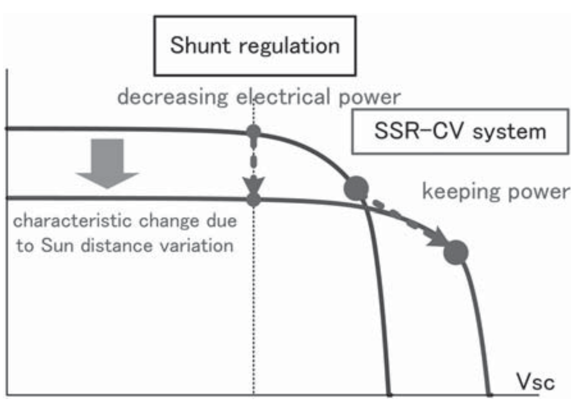

Fig. 3 SSR-CV power control.

(3) Communication and data process retaining subsystems

Deep-space communication subsystems until the PLANET-B (NOZOMI) Mars-orbiting probe used the S-band uplink and X-/S-band downlink system configurations, we newly adopted X-band uplink and X-band downlink (X-band transmitter/X-band receiver) systems.

This has reduced the weight of the communication subsystem and has reduced the Solar corona interference on the uplink. This makes it possible to decrease the communication interference period produced during the conjunction in which the Sun is located between the MUSES-C and Earth, immediately before the rendezvous with ITOKAWA.

To utilize the communication capability limited by the resource at maximum, we adopted the multi-bit rate method that selects the downlink bit rate in 2-n steps in order to hold communications with the maximum available bit rate.

(4) Data processing subsystem - Telemetry/commands

The housekeeping data temporarily stored in the data recorder can be down linked by freely selecting the data from the sampling data of every 2 seconds to that of every 1,024 second.

This makes it possible to downlink only the necessary data, even in conditions allowing communication only at low speeds, by specifying the type and sequence of the data to be down linked in priority, according to the operation time and circuit situations. If data obtained in the course of time intervals or data skipped in the time domain is down linked and the result of a status check using it indicates the presence of an event that requires more detailed checking, it is possible to downlink the detailed data obtained in fine time intervals by specifying the required time zone.

Whenever the probe performs an autonomous operation based on its on-board judgment or if an irregularity occurs, a few bytes of code indicating the occurrence time and content of the event is formed into a very small packet called the report packet and is down linked in priority over other data. This makes it possible to check the most important information first, even when the available circuit capacity is small, and this function actually helped us to identify current situations with minimal delay in cases of irregularity.

(5) Data processing subsystem - Automation/autonomy

The data processing subsystem has various means of controlling the command sequences registered in the probe including; a macro function that encapsulates multiple commands, a timeline function that plans and controls the command issues based on absolute time designation, an autonomous function that monitors the telemetry data on the probe and issues commands autonomously, a request function that allows the payload equipment to request the subsystem to begin special autonomous control and the timer function that possesses a watchdog timer (WDT) and shifts to the backup mode autonomously in case the timer times out. By utilizing these functions at maximum, we executed the processing for allowing the probe to switch the standby mode autonomously and the communication for switching the telemetry circuit ON/OFF by the downlink carrier when the telemetry circuit is not established (1-bit communication).

(6) Thermal control subsystem

To supply all of the power generated by the solar array paddles to the ion engines, the thermal control subsystem incorporates the software-controlled HCE (Heater Control Electronics), which adjusts the ON/OFF timings of the 128 channels of the independent heaters to smooth the power consumption while reducing the peak power.

When the distance to the Sun is large, the probe supplies the maximum generated power to the ion engines. Consequently, if the On timings of the heaters of the multiple channels are overlapped and the power consumption rises instantaneously, exceeding the consumed power over the generated power will lead to the dangerous lockup mode, in which the operation voltage from the solar array paddles drops instantaneously to the BAT voltage and the BAT continues to discharge even after the overload is solved. To prevent this and to supply the maximum possible power to the ion engines, we newly developed a function for suppressing the heater peak power and incorporated it in this subsystem.

This function makes it possible to obtain power at the highest limit of the generation capability and to supply it to the ion engines.

Fig. 4 shows an example of the operations achieved with this function.

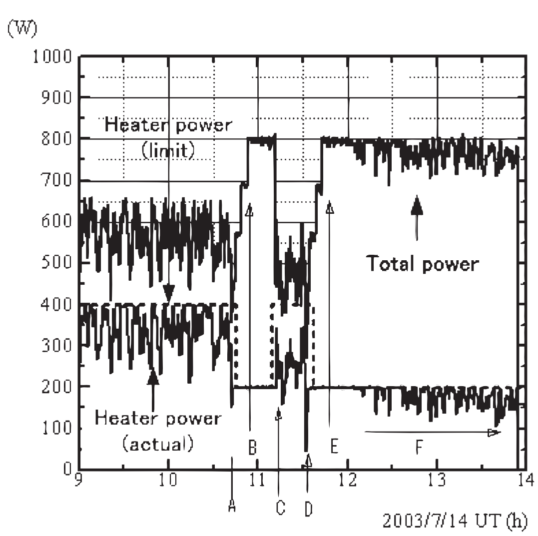

Fig. 4 Example of operation achieved with peak power-suppression heater control.

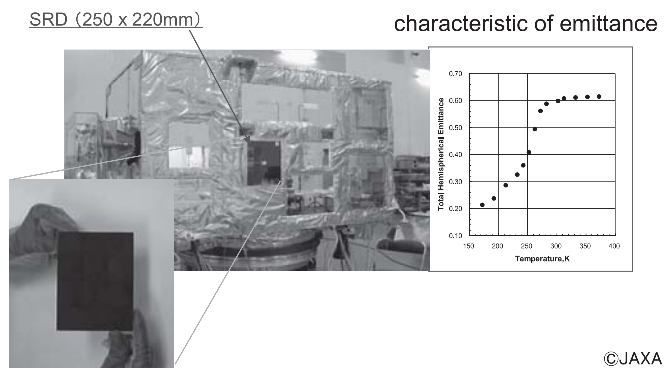

Fig. 5 Mounting of smart radiation device, its temperature characteristic.

To perform robust temperature control, we provided smart functions with which the priority is set for each heater channel so that, in case the set heater power is insufficient, the temperature is maintained by putting priority on the propulsion system and BAT that should not be frozen, and that the control of the channel indicating abnormal thermometer values is switched autonomously to the open-loop duty control.

In addition, we recently developed and mounted an SRD (Smart Radiation Device) with variable thermal emittance as the heat radiation material for locations where the heat generation varies depending on the operation mode (**Fig. 5**). As shown in Fig. 5, the IR emittance of this material varies greatly depending on the temperature.

This characteristic increases the heat radiation capability at high temperatures and makes it more difficult at low temperatures, thereby enabling a reduction of the heater power required for temperature maintenance.

(7) Ion engine subsystem

The probe system is designed so that the +Z plane is pointed permanently to the Sun. Since the orbit control of a Sun-orbiting probe is efficient when the thrust force is exerted in the direction at right angle to the sun, the four ion-engine thrusters are mounted via a location that has a biaxial gimbal mechanism on the +X plane facing the right-angle direction to the Sun. Each thruster is mounted to point toward the center of gravity of the probe, and the deviation of the thrust force vector from the center of gravity is corrected by controlling the gimbal angle. The gimbal control can generate a torque for canceling external disturbance during operation of the ion engines so this function helps minimize the accumulated disturbance cancelation that would otherwise use the valuable chemical-fuel thrusters.

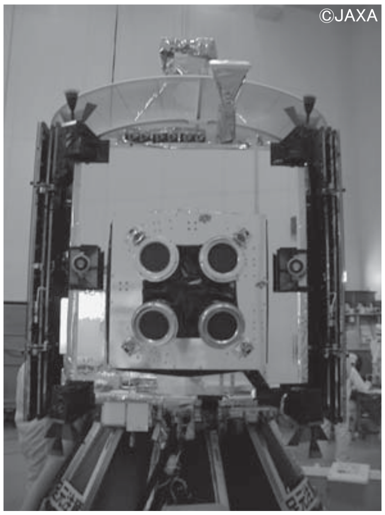

Photo 1 Ion thrusters mounted on the probe.

Photo 1 shows the mounting condition of the ion thrusters on the probe.

Since the ion engines are components for converting electrical power into the thrust force, they need a large amount of power. However, the power available from the solar array paddles varies greatly depending on the distance to the Sun from the orbit position of the MUSES-C during flight. Therefore, the ion engine subsystem is designed to be capable of switching the number of operated thrusters from the minimum of a single-thruster operation to the maximum of a simultaneous three-thruster operation according to the change in the power generated by the solar array paddles. In addition, the power supply design makes the thrust force of each thruster variable (by throttling) so that maximum power can always be invested at the limit as the ion engine propulsion force. The orbit design is also performed presupposing the use of this power supply design.

3.2 Mission Payload Design

Since the MUSES-C is used to perform observation of an asteroid, sampling and return of the sample, it carries payloads that are not found with ordinary satellites and are specific to its missions. The design strategies of these payloads are described in the following.

(1) Rendezvous/observation/touchdown-related equipment

During the rendezvous of the MUSES-C with ITOKAWA, the asteroid seen from the Earth is located on the other side of the Sun (superior conjunction location), and the Earth, Sun and ITOKAWA are positioned almost in a line. Because of the necessity of observing the bright side of ITOKAWA, we performed the position control (home-position keeping) so that the MUSES-C remains in a position (above ITOKAWA) on a line connecting the Earth, Sun, MUSES-C and ITOKAWA in this order.

At this time, the Sun and the Earth are located facing the +Z plane of the MUSES-C and ITOKAWA is facing the -Z plane. Therefore, we installed the solar array paddles and high-gain antenna so that they point in the +Z direction and the equipment for use in rendezvous with the asteroid in the -Z plane. **Fig. 6** shows the detailed installation situations of the equipment mounted on the -Z plane for use during the stay above the asteroid.

Specifically, the rendezvous equipment installed on the -Z plane includes the LIDAR (Light Detection And Ranging) using laser beam (**Photo 2** - Left), the ONC-T telescopic camera for detailed observation of the asteroid's surface topography (Photo 2 - Right) and the ONC-W1 wide-view camera for obtaining the information required for position maintenance above the asteroid (Photo 2 - Center).

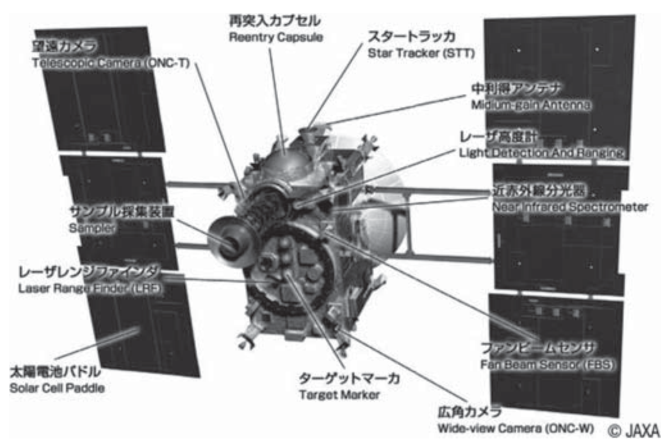

Fig. 6 Equipment mounting on the -Z plane of the probe.

Photo 2 LIDAR (Left), ONC-W1 (Center) and ONC-T (Right).

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In addition to the ONC-T described above, other asteroid observation equipment installed on the -Z plane includes the NIRS (Near-InfraRed Spectrometer) and XRS (X-Ray fluorescence Spectrometer) for observing the composition of the asteroid.
Similarly, all of the equipment for use in the touchdown is also installed on the -Z plane except for the fan beam sensor (FBS) that detects obstacles.
In the phase of approach to the asteroid, the camera for use in the rendezvous and the ranging equipment described above are the items that are mainly used. The target markers (TMs, **Photo 3**) for use as the landmarks on the asteroid surface and the flash lamps (FLAs) for illuminating them are used for guidance during the close approach to the asteroid surface at altitudes below 100 meters.
Photo 4 shows the TMs illuminated by the FLAs.
The camera used in detecting the TMs is the ONC-W1 mentioned above. The laser range finder (LRF-S1, **Photo 5** - Left) that measures the inclination angle and distance of ITOKAWA with respect to the local surface by measuring the distances between four points on the surface is also installed on the -Z plane.
The sampler (SMP) used in sampling during touchdown has a cylindrical shape with a length of 1 meter extended from the -Z plane of the satellite body toward the -Z direction. As it is the first part of the probe that comes in contact with the asteroid, it is given a coil spring structure for avoiding direct transmission of impact to the probe body. Another laser range finder (LRF-S2, Photo 5 - Right) for permanent monitoring of deformation of the distal end of the SMP via a laser is also installed on the -Z plane. The output of the LRF-S2 determines the timing of firing the projectiles for crushing the asteroid surface and that of the timing the probe ascends.
The FBS that detects harmful obstacles that may damage the probe during touchdown is installed on the ±Y plane to cover the bottom surfaces of the solar array paddles.

Photo 3 Target Markers (TMs).

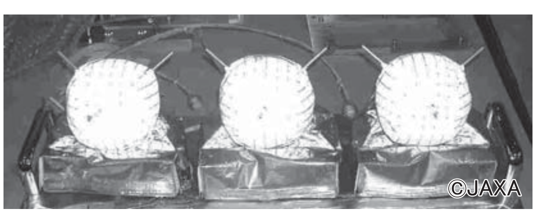

Photo 4 TMs lit with FLAs.

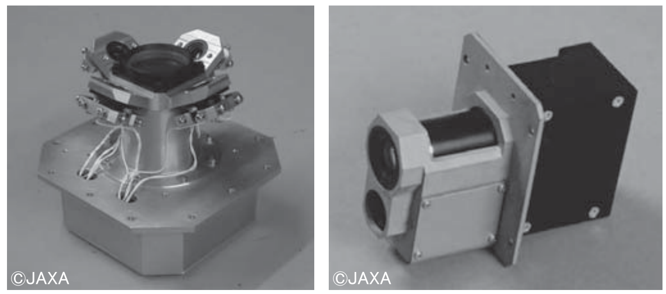

Photo 5 LRF-S1 (Left) and S2 (Right).

(2) Reentry capsule (CPSL)
To facilitate the transport of the sample collected with the SMP during touchdown to the reentry capsule and its storage in the container inside the capsule, the capsule is installed on the -X plane, in a position in close proximity to the SMP installation location and without any obstructions in the capsule release direction.

4. Operations and Results Achieved with MUSES–C

The framework of the MUSES-C missions consists of a series of operations from the ion-engine navigation in the outward flight to the rendezvous with the asteroid, its observation, the touchdown and sample collection, return flight and reentry. The outlines and results of these operations are reported in the following.

(1) Ion engine-powered flight and swing-by
For the main engines for the interplanetary-orbit flight of the MUSES-C, we developed newly designed microwave discharge ion engine that features a 10X higher fuel mass efficiency than the traditional propulsion subsystem using chemical fuel. As the output power of each ion engine is as low as 8 mN, it is required to continue the operation for a

long period in order to change the trajectory gradually. Actually, after being inserted into a solar orbit almost identical to that of the Earth, the MUSES-C continued acceleration with the ion engines for a year.

When MUSES-C again approached the Earth and passed near to it, its orbit was bent significantly by the gravitation of the Earth and, at the same time, the orbit energy accumulated in a year of acceleration was converted effectively. This resulted in a successful transition to the orbit with an aphelion of about 1.4AU, which was almost identical to the orbit of ITOKAWA.

This maneuver is a kind of Earth swing-by called EDVEGA (Electric Delta-V Earth Gravity Assist). It was an effective orbit transfer method for an interplanetary flight by using ion engines that need sustained acceleration due to the low thrust propulsion forces. The MUSES-C became the first probe ever to have demonstrated and used this method.

This operation allowed us to acquire a promising deep-space exploration technology for performing large orbit transfer of a lightweight probe.

(2) Optical navigation demonstration and rendezvous

To perform the rendezvous of the MUSES-C with ITOKAWA, it is extremely difficult to obtain the required orbit determination information if only radio waves are used. Therefore, we performed the orbit determination technique called optical hybrid navigation, which utilizes both the results of radio wave measurement and the image information of ITOKAWA captured by the installed cameras.

This technique allowed us to determine the position of the probe with respect to ITOKAWA and the velocity with extremely high precision and to let the probe keep relatively stationary at an altitude of 20 km above the ITOKAWA's surface by means of precise control for guidance toward the asteroid. **Fig. 7** shows examples of camera images used as the optical navigation information.

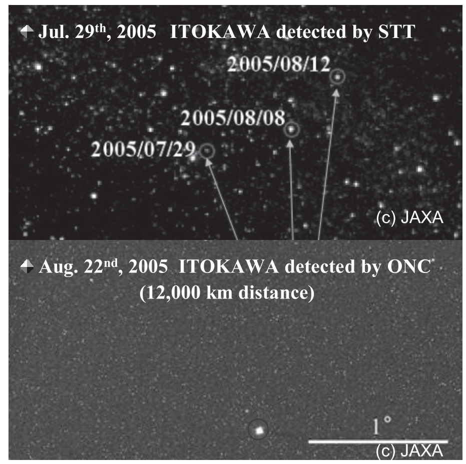

Fig. 7 Image information of mounted cameras for optical navigation to Asteroid 25143 ITOKAWA.

(3) Observation of the asteroid ITOKAWA

The MUSES-C stayed at a position at 20 km from ITOKAWA's surface (gate position) and another position at 7 km (home position) and acquired a large number of detailed surface images from all of the directions perpendicular to the asteroid's rotation axis using the mounted camera. **Fig. 8** shows examples of the images captured at different longitudes.

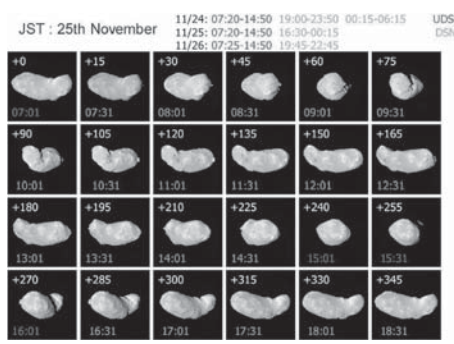

Fig. 8 Images of ITOKAWA per longitude.

Using this large number of images, we succeeded in modeling ITOKAWA's shape into a 3D model for use as a reference for selection of the points where touchdown would be possible and in studying the touchdown scenario. The 3D model was also used in the analysis for determining the density of ITOKAWA.

In addition, we also performed the composition analysis of the ITOKAWA's surface by means of remote sensing using the NIRS (Near-InfraRed Spectrometer) and XRS (X-Ray fluorescence Spectrometer) and obtained valuable results.

During the observations for the period of rendezvous, scientists and engineers cooperated together for observations and analyses. The achieved results were published as seven papers in the "MUSES-C" feature pages of the Science Magazine. Although this is a magazine specializing in science, seven engineers of the NEC Group had the honor of contributing to these papers as coauthors.

(4) Touchdown and sampling

Prior to the touchdown with ITOKAWA, the MUSES-C performed three approach/descent rehearsals, on November 4, 9 and 12, 2005. The first rehearsal made clear the following two important issues.

1) Two of the three reaction wheels failed one after the other before and after the rendezvous with ITOKAWA. As this made it necessary to use the RCS (Reaction Control Subsystem) for the attitude control, the thrusting for the attitude control interfered with the guidance for touchdown as a major disturbance factor.

2) ITOKAWA has an irregular shape, which had not been expected in advance, and its surface was like an agglomeration of stones. As a result, events that exceeded the control capability of the guidance control camera occurred, for example splitting of the asteroid image into two due to the shade or the appearance of more than the expected number of luminous dots.

Nevertheless, we were able to solve these problems by adding guidance from the ground during the descent to the 500-meter altitude above the landing point, by using tools that were quickly developed during the rehearsal period. These were a tool for position determination from the ground using the ITOKAWA images and one for guidance and control command generation from the ground.

On November 20 and 26, we performed landing/takeoff twice by using the new guidance and control methods as well as applying completely autonomous guidance and control in the proximity of the asteroid surface. With the touchdown on November 20, the guidance was performed very precisely by overcoming the above mentioned issues. However an FBS obstacle sensor output an obstacle detection signal immediately before the touchdown, which led to confusion of the autonomous attitude control and an unexpected landing causing the probe to stay on the asteroid for more than 30 minutes. Although we were able to let the probe take off by sending an instruction from the ground, we decided to cancel the autonomous operation based on the FBS obstacle sensor at the next touchdown. With the second touchdown on November 26, all of the guidance, landing and takeoff functions were performed almost exactly as expected. **Fig. 9** shows the planned and achieved paths of the guidance in the second touchdown.

Although we failed to fire the projectile for use in sample collection, we succeeded in collecting for the first time ever, fine particles from the asteroid surface that had been stirred up by the sampler on impact of touchdown.

This was the first direct sampling of the surface of an asteroid that retains primitive characteristics of the shape of the solar system, and which was expected to make a significant contribution to research into the evolution of the solar system.

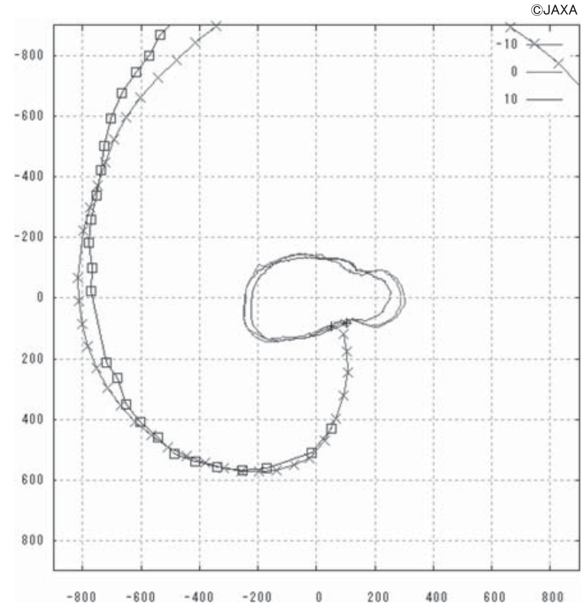

Fig. 9 Planned and achieved guidance paths for the second touchdown.

(5) Issues of the return cruise and recoveries

After takeoff from ITOKAWA, a loss of communication was produced due to a fuel leak from the RCS, but the probe succeeded in recovering communication by transferring to a safe attitude and re-stabilizing by the attitude control using the Xe gas from the neutralizations of the ion engines developed by NEC. However, on December 9, 2005, an important fuel leak occurred again, causing an altitude change and another loss of communication.

Assuming that there would be a timing in which the MUSES-C entered an attitude in which the solar light irradiated again on the solar array paddles, we created a tool that continues to send commands by encompassing all of the predictable case scenarios and tried to start the MUSES-C by sending commands every day so that they reached the MUSES-C without the power supply timing being recovered.

As a result, we were able to catch the MUSES-C again by receiving a signal from it on January 23, 2006. Subsequently, we tried to identify the probe status by means of the 1-bit communication that contained information of ON/OFF of the communication carrier, it was clarified that the RCS was unusable and that the batteries had also failed.

We then gradually changed the attitude to one suitable for communications by means of the Xe gas attitude control and succeeded in recovering the 32 bps communication via the medium-gain antenna on March 2006. We later succeeded in reigniting the ion engines so that we were able to perform orbit control into the return trajectory using these engines in 2007 and 2009.

For the attitude control during the return trajectory, we developed a new attitude control program that executes passive solar tracking using the pressure of solar light in order to reduce the Xe gas consumption, succeeding both in saving the fuel for the return and in maintaining the attitude.

In November 2009, immediately before the return, one of the ion engines stopped, which made us consider temporarily that the return to Earth might not be possible. However, we managed to combine the neutralizer of the ion engine thruster A with the ion generator of ion engine thruster B and succeeded in obtaining a thrust force corresponding to one thruster. This made it possible for the MUSES-C to re-enter the return trajectory toward the Earth (**Fig. 10**)

(6) Return and reentry

The completion of the guidance to the Earth return target position for the return path marked the end of the flight powered by the ion engines. Subsequently, the MUSES-C repeated the four trajectory correction maneuvers for precise guidance to the landing point, called TCM 0 -4, and the orbit determinations before and after each TCM. The guidance operation to the WPA (Woomera Prohibited Area) in the Woomera Desert, South Australia, was then completed successfully on June 9, 2010.

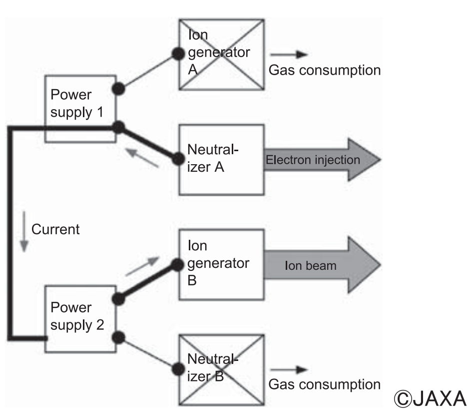

Fig. 10 Scheme of cross-operations of ion engines.

On June 13, 2010 at 19:51 the reentry capsule was released from the MUSES-C. This was the last function of guiding the capsule of the MUSES-C after a long journey of seven years.

At 22:51, the reentry capsule and the probe re-entered the atmosphere, in which the probe broke up and incinerated as a large fireball. But, due to the thermal protection of the ablator, the capsule succeeded in deploying its parachute, sending the beacon signal, and landed successfully for recovery.

5. The Results Obtained from the MUSES–C Missions

Because of the multiplicity and high difficulty of the newly developed demonstration items, all of the persons concerned in the MUSES-C project share the recognition of their challenging achievement.

To make this highly complex probe possible, it was necessary to advance from the standpoint of local optimization in which each subsystem is concerned only with what is allocated to it. We were only able to achieve the weight reduction target based on applying cooperation between subsystems, in which a failure to reduce weight in one subsystem was compensated for by the weight reduction of another subsystem.

This strategy was enabled only because we shared the final target with a very high level of commitment and maintained high motivation towards its achievement. It was because we were able to maintain the high motivation and teamwork that crossed company and organization barriers from the early stages of development to completion, that the missions were completed seamlessly in the eventual return of the probe.

As the success of the probe was widely acknowledged by the general public, the recognition and understanding of MUSES-C and space projects in general was raised inside as well as outside the corporation. Our experience in this project has taught us that our unswerving commitment has been the key to our success.

One of the new technologies developed for and demonstrated in MUSES-C, namely the microwave-discharge ion engine, is under preparation for commercialization. This is typical of the achievements of this project that are bearing fruit and leading to the expansion of our space business.

With the NEXTAR compact satellite bus being developed by us as a standard satellite bus, the exploration automation/autonomy program, demonstrated by the MUSES-C, is being integrated in order to improve the operational reliability and robustness as well as to reduce the labor input. In addition, the

Results Achieved from the Development and Operation of the Asteroid Probe MUSES-C (HAYABUSA)

on-demand telemetry method that has demonstrated impressive information transfer efficiency for MUSES-C is being adapted for and packaged in the new SpaceWire high-speed satellite networking system.

Following its demonstration over the seven years of a demanding flight schedule that was full of hardships, the variety of technologies that were ambitiously developed for the MUSES-C are going to be steadily utilized as the foundations of the projected satellite technologies of the future.

Deep-space exploration is one of the main pillars of the Science/Technology Demonstration SBU. We believe firmly that the development of more technologies in support of deep-space exploration will make a significant contribution to the expansion of the future space development business.

In closing, we would like to express our gratitude to the Japan Aerospace Exploration Agency (JAXA), the Institute of Space and Astronautical Science (ISAS) and all of the persons concerned from the participating universities for their generous guidance and support. We also thank the many enterprises engaged in this project for their enthusiastic cooperation in dealing with our sometimes seemingly impossible requests and by sharing in our final objectives.

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