Development of Small Solar Power Sail Demonstrator IKAROS

UMESATO Masahiro, OKAHASHI Takakazu

Abstract

The solar power sail demonstrator is a probe that navigates by combining propulsion based on the momentum of photons from the Sun and an ion-propulsion engine. It is a middle-sized demonstrator spacecraft developed to demonstrate technologies that will be indispensable in the projected outer planetary exploration toward the Jupiter and its Trojan asteroid. The small solar power sail demonstrator IKAROS (Interplanetary Kite-craft powered by Radiation from the Sun) has been designed to reduce the risks of development in the middle-sized demonstrator program. It has succeeded in the first advanced demonstrations globally of the deployment a large membrane, power generation via power sail and photon acceleration/navigation using sail. This paper reports on the development of the bus technology of the IKAROS by NEC.

Keywords

solar sail, outer planet explorer, thin-film solar cell, spin satellite, deep space

1. Introduction

Although the use of chemical engines has a mainstream application in current rocket technology, it should be regarded as a secondary solution from the perspective of propulsion for space navigation systems. The solar sail navigation system based on solar energy simplifies the energy problem significantly and semi-permanent acceleration makes it possible to reach a high velocity in a relatively short time. The success of the IKAROS has established a new concept for solar system navigation. In this project, NEC supports the bus technology via telemetry commands, distance measurements, data transmission and attitude control of a deep space explorer. This paper summarizes the IKAROS system and innovative bus development devices.

2. Outline of the IKAROS System

Fig. 1 shows an external view of the IKAROS at the time of its launch. The IKAROS is a spin satellite and its form at the time of launch is like a metallic cylinder wrapped in a membrane. **Fig. 2** shows a view of the IKAROS accommodated in the adapter unit. The IKAROS is installed in the IKAROS installation adapter of the H-IIA No.17 launch vehicle and is launched together with the Venus climate orbiter PLANET-C (AKATSUKI). **Photo 1** shows an external view in orbit, shot from two ejected “deployable cameras.”

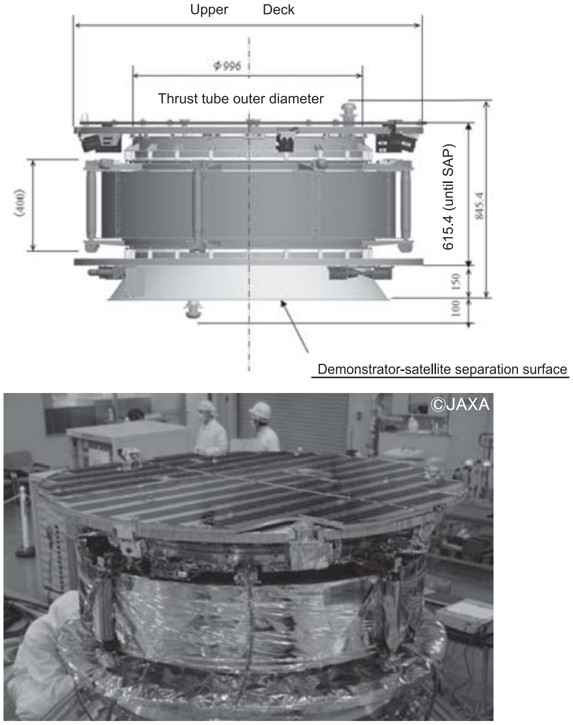

Fig. 1 External view of the IKAROS at launch.

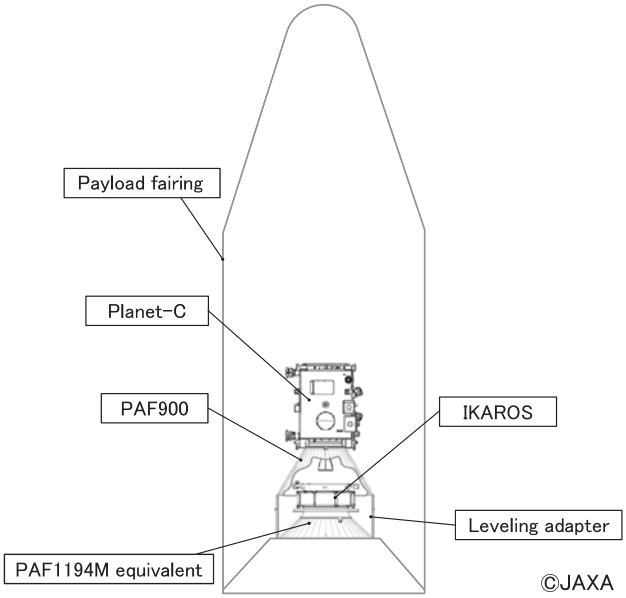

Fig. 2 Adapter accommodation status of IKAROS.

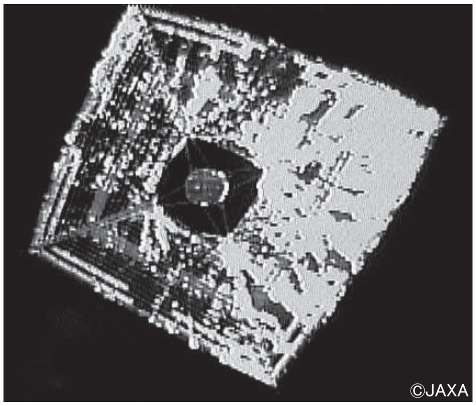

Photo 1 In-orbit external view of IKAROS.

The main specifications of the IKAROS are as follows.

(1) Structure subsystem

- Main body shape:
  Cylindrical (Diameter 1.6 m, height 1 m).
- Membrane shape:
  Square (Sides 14 m, thickness 7.5 μm).
- Weight:
  315 kg (Membrane 15 kg, propellant 20 kg)

(2) Temperature control subsystem

- Thermal insulation on the SAP, mission module and propulsion subsystem, heat is exhausted from the lower panel.
- Temperature gradient from the propulsion subsystem tank to the thruster module.
- Heater control and temperature management with HCE.

(3) Communication subsystem

- Xup/Xdown coherent transponder.
- Downlink bit rate:
  ≧ 512 bps (initial operation)
  ≧ 16 bps (regular operation)

(4) Antennas

- Whole range covered by LGA (× 2) and MGA (× 1).

(5) Power subsystem

- Series switching regulator, non-regulated 50 V bus.
- Power fed by SAP on the top panel.
- SAP generation power: ≧ 230 W (6 months)
- On-board secondary battery for use during peak power operation.

(6) Data processing subsystem

- Telemetry generation, command processing and DR.
- Autonomous control:
  Request commands, universal autonomy function.
- Automatic control:
  Timeline, macro commands, system timer.

(7) Attitude control system

- Single spin method, passive attitude stabilization (ND)
- Membrane deployment and extension by the centrifugal force of spinning.
- Control modes:
  Spin rate control,
  spin axis maneuver control,
  sun angle control, ANC.
- Attitude determination:
  SAS solar angle, RF Earth angle.
- Other sensor:
  Triaxial gyro (ANC, attitude measurement).

(8) Propulsion subsystem

- Vapor-liquid equilibrium thrusters.
- Thrust: 0.4 N. Specific thrust: About 40 s.

3. Mechanical Development Items

3.1 Rocket Interface

From the initial stage of development, the IKAROS was positioned as part of the dummy mass (800 kg) for attenuating the vibration environment of the PLANET-C, occupying 315 kg of the 800 kg dummy mass. However, since 70 kg of its weight corresponding to the mission module contains the sail membrane, it was difficult to predict how this weight would contribute to rigidity. Therefore, we proceeded to develop by assuming preliminarily that the mass serving effectively as a damper would be 230 kg. When a combined analysis of the "satellite adapter + IKAROS model" configuration was performed later in the launch vehicle study, it was found that the effective weight of 230 kg does not serve as a frequency damper unless the overall characteristic value is set between 40 and 45 Hz. A value below 40 Hz leads to deterioration of the environment of the IKAROS, and a value over 45 Hz deteriorates the environment of the PLANET-C. Consequently, we designed the satellite adapter and IKAROS so that their nominal characteristic value is 48.3 Hz and that a dummy mass of up to 74 kg can be mounted on the adapter if the value exceeds 45 Hz in a modal survey test of the combined status. As a result of the actual modal survey conducted in the general test, the measured value was 41.0 Hz, this confirmed that the requisite standard could be satisfied without mounting a dummy mass. **Photo 2** shows the testing conditions.

3.2 Satellite Mass Characteristic

The IKAROS deploys its membrane via the centrifugal force of spinning in orbit. To enable the complicated deployment sequence, the positioning tolerance of the center of gravity in the vertical direction from the geometric center of the membrane surface (Z = 380 mm) should be limited to Z = 380+30/-10 [mm]. Accordingly the restrictions imposed by the structural analysis of the launch vehicle is 47.5 less than Ixx and Iyy less than 51.5 [kg・m ^{2}]. In addition, as the specified mass of the launch vehicle interface is 315+0/-10 [kg] and the center of gravity in the lateral direction is SQRT(X ^{2} +Y ^{2}) less than 10 [mm] , it is deemed necessary to adjust the spinning axis inclination as closely as possible to zero under the above stated restrictions. As a result of the spin balance test conducted in the general testing for the spin adjustment, we adjusted the static/dynamic balance of the satellite by installing a balance weight.

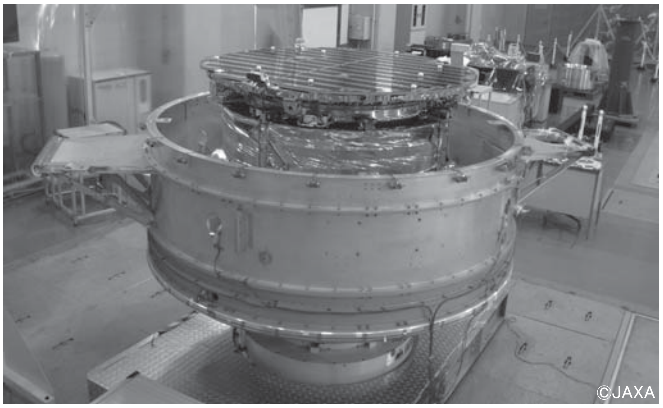

Photo 2 View of modal survey test.

4. Development of the Payload Equipment

This section describes the design and manufacture (procurement) of the payload equipment required for the IKAROS that is not normally used in a spacecraft.

4.1 Equipment Development Policy

As the IKAROS needed to be developed with a short lead time and at a low cost, we decided to minimize development of the equipment by utilizing equipment that had been previously designed, flight models from other projects and the prototypes of previous satellites.

Table 1 and **Table 2** list the main payload equipment and the previously designed payload equipment that was utilized by IKAROS. The equipment listed includes the main

Table 1 Payload equipment used.

Component	Source	Level
ND	LUNAR-A	FM (Flight model)
Battery	LUNAR-A	FM
SSAS-S	LUNAR-A	FM
SSAS-E	LUNAR-A	FM
SSR	MUSES-C (HAYABUSA)	FM

Table 2 Already designed payload equipment.

Component	Source
DHU	PLANET-C (AKATSUKI)
XTRP	PLANET-C (AKATSUKI)
SSPA	PLANET-C (AKATSUKI)
XDIP	PLANET-C (AKATSUKI)
XSW	ASTRO-F (AKARI)
XLGA	PLANET-C (AKATSUKI)
SCP	P-C or overseas

components of the power, communication, data processing and attitude control subsystems.

For the rate gyro (RG), we adopted a consumer product based on the R&D for a previous satellite (INDEX, or REIMEI). Limiting new developments to only two kinds of equipment the PCU and the DRU contributed to a significant reduction in the lead time and cost.

The PCU is the component that controls power distribution to the on-board equipment and to the BAT charge/discharge control. This device was newly developed because the power distribution method is specific to each satellite.

The DRU is the component that handles all of the functions that cannot be achieved with the above named equipment. Its multiple functions include; the launch sequence processing, telemetry/command processing for non-intelligent components, attitude control processing and heater control processing. Concentrating the newly developed items in a single component is advantageous for improving the development efficiency and for customizing functions for a small satellite. We attempted to improve the development efficiency of equipment for the IKAROS by focusing on its specific key technologies and by utilizing a wide range of existing equipment that has already been proven to have high reliability.

4.2 Control During Carrier Rocket Separation

As the IKAROS is deployed as a piggyback satellite, it adopts the cold launch method with which it is powered ON after the launch of the carrier rocket. The IKAROS is turned ON by starting the BAT power supply upon reception of a pulse command from the H-IIA that is issued before separation. Due to a request from the H-IIA, the IKAROS is inhibited to output RF for 200 seconds after the separation from the H-IIA. For this purpose, the IKAROS begins the timer sequence after it has detected the separation from the H-IIA. **Fig. 3** shows the timer sequence immediately after the separation of the IKAROS from the H-IIA. The timer sequence is controlled by the DRU as described above.

4.3 Heater Control Method

The orbit of the IKAROS is fully sunlit so the power is permanently fed from the solar cells. However, the power balance is so tight that, if more than the specified number of heater CHs are ON, an insufficiency of power may cause lock-up, making it impossible to feed sufficient power from the solar cells. To prevent this happening, we adopted the duty control for limiting by time division of the number of heater CHs that can be turned ON at a time. The duty control directs the heaters ON/OFF by registering the patterns of the heater CHs to be turned ON in the satellite and by switching the patterns at certain intervals. The heater function used for controlling the temperature over a certain range is calculated from thermal analyses made in advance. This method is variable as long as it can control the temperature stably over a range, even when the temperature varies periodically. However, certain countermeasures are required in case the function needs to be changed depending on the value of the highest and lowest temperatures.

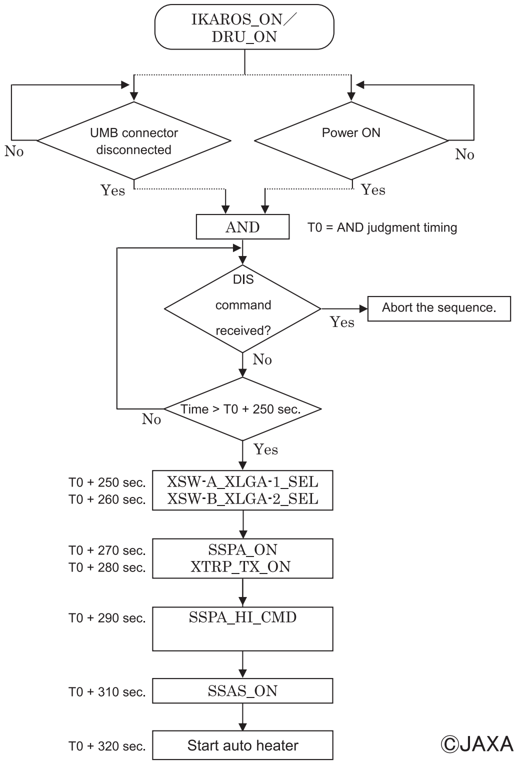

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Fig. 3 Timer sequence immediately after separation.

Since the temperature environment inside the IKAROS varies depending on the orbit and attitude and that the temperature range to be controlled is narrow, the function needs to be optimized according to each event. However, it is actually a difficult task to change this frequently due to the restricted availability of the communication circuit.

As a result, while the ordinary function control switches the heater CHs ON and OFF according to time division, we designed the duty control of the IKAROS so that it permits or inhibits the heater CHs to turn ON. When a heater CH is permitted to go ON, the temperature is detected and the CH is turned ON only when the detected temperature is below the specified temperature. With this method, when the duty for the case of lowest temperature is set to the CHs, the temperature controls of both low/high temperature sides is possible with a single function because the heaters of these CHs are not turned ON even if the temperature rises. This heater control is also executed by the DRU.

5. Conclusion

The success of the IKAROS project has proven the reliability of NEC's core bus system technology supporting deep space explorers that began with MUSES-C (HAYABUSA). In addition, we also consider that it contributes to the creation of key technologies that lead directly to the deployment of space solutions business enterprise, which is an important goal of NEC.

Authors' Profiles

UMESATO Masahiro
Engineering Manager
Space Systems Division
Aerospace and Defense Operations Unit

OKAHASHI Takakazu
Assistant Manager
Space Systems and Public Information Systems Division
NEC Aerospace Systems, Ltd.

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