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Flight status of IKAROS deep space solar sail demonstrator ☆

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ABSTRACT

JAXA launched the world's first deep space solar sail demonstration spacecraft "IKAROS" on May 21, 2010. IKAROS was injected to an Earth–Venus trajectory to demonstrate several key technologies for solar sail utilizing the deep space flight environment. IKAROS succeeded in deploying a 20 m-span solar sail on June 9, and is now flying towards the Venus with the assist of solar photon acceleration. This paper describes the mission design, system design, solar sail deployment operation and current flight status of IKAROS.

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1. Introduction

Japan Aerospace Exploration Agency (JAXA) launched a solar sail demonstration spacecraft "IKAROS" on May 21, 2010. IKAROS was launched together with JAXA's Venus climate orbiter "AKATSUKI (Planet-C)" as an interplanetary piggy-back payload. The launch vehicle was H2A and was launched from Tanegashima space center.

JAXA has been proposing a concept of "solar power sail" for future deep space exploration [1,2]. It combines the concept of solar sail (photon propulsion) with a larger power generation by flexible solar cells attached on the sail membrane. IKAROS is a precursor mission to demonstrate key technologies for the solar power sail concept, which are (1) deployment of large sail in space, (2) solar power generation by means of thin film solar cells attached on the sail, (3) confirming the acceleration due to the solar irradiance scattered by the sail and (4) demonstration of the interplanetary guidance and navigation of the solar sail spacecraft.

IKAROS successfully deployed a 20 m-span sail on June 9, and is now performing an interplanetary solar sailing taking advantage of the Earth–Venus leg of the interplanetary trajectory. The spacecraft mass is 307 kg and is equipped with a rectangular solar sail, which weighs 16 kg with the minimum thickness of 7.5 um. The solar sail is deployed and kept extended by centrifugal force of the spacecraft spinning. Thus it does not have any rigid member to support the extension of the sail, enabling to realize very light and simple sail support mechanism. The deployment process was measured and recorded by several onboard equipments, such as cameras, attitude sensors and some surface sensor on the sail.

This paper describes the mission design, system design and some results of the early mission phase, including the sail deployment and interplanetary solar sail operation. The flight results focusing on each subsystem of IKAROS can be found in another IAC papers [3–7] (Fig. 1).

2. Mission senario

2.1. Mission design

The objective of the IKAROS mission and its implementation to the spacecraft system are as follows [2]:

(1) Deployment of solar sail in space
- 200 m^2 square sail to be deployed by rotation.
- Behavior during and after the sail deployment is measured by attitude sensors and onboard cameras.

(2) Solar power generation by means of thin film solar cells attached on the sail
- 5% of the sail area is allocated for the a-Si flexible solar cells.

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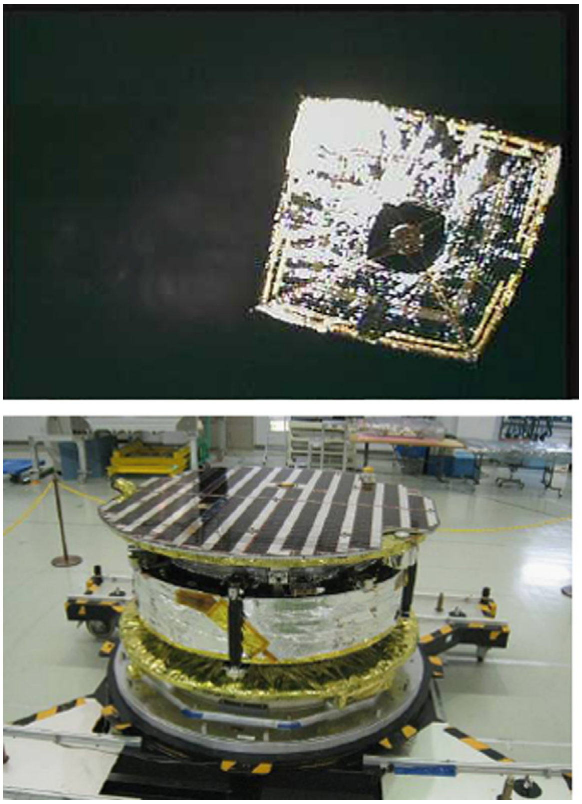

Fig. 1. (Upper) IKAROS with solar sail fully extended. This picture was taken by the deployable camera (DCAM) on June 14, five days after the deployment of the solar sail. (Lower) IKAROS flight model in final assembly phase.

- The generated power is transferred by flexible cables on the sail, and *V–I* curve and several other characteristics are to be measured through these lines constantly.

(3) Measuring thrust due to the solar radiation pressure (SRP)
- 1–2 mN of SRP force is expected to act on the solar sail.
- The SRP acceleration is measured primarily by means of orbit determination (OD) process.

(4) Establishing guidance and navigation technique for solar sailing
- Steering the direction of the sail enables a continuous trajectory maneuver by SRP.
- Attitude control is achieved primarily by RCS. IKAROS is also equipped with a newly developed "reflectance control device" (RCD) attached on the surface of the sail.

The success criteria of the IKAROS project were defined so as to effectively contribute to accelerate the realization of the "solar power sail" concept. At the same time due to the IKAROS's very low budget, we have carefully tried to keep the mission goals as clear and straightforward as possible. The resulting success criteria we defined are composed of two categories. The first two objectives ((1) and (2)) are defined as "minimum success" of this mission, whereas the rest two ((3) and (4)) are defined as "full success" criteria. Minimum success must be fulfilled to declare the acquisition of solar sail technology by actual demonstration in space, and to step forward to the full-scale solar power sail mission in the future. Full success should be fulfilled to encompass all the essential technologies for interplanetary solar sailing.

2.2. Trajectory design

IKAROS trajectory was constrained by the primary payload, AKATSUKI, which aims at the Venus. It takes about 180 days to reach and fly by the planet, after which it continues its path by orbiting the Sun via solar sail. The original ballistic trajectory injected by launch vehicle was such that it exactly intercepts the Venus. IKAROS

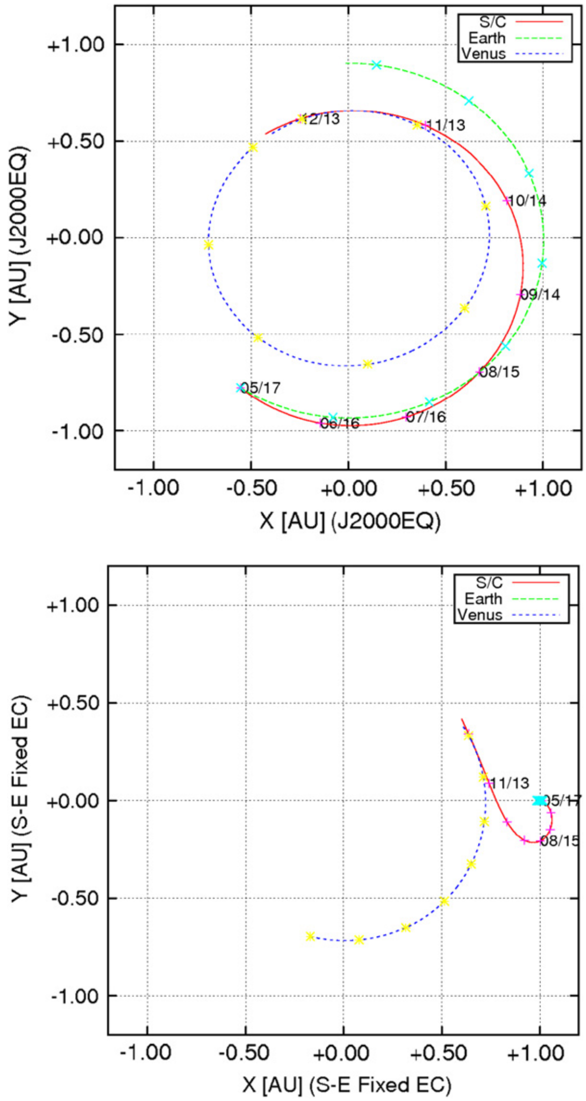

Fig. 2. IKAROS trajectory towards the Venus. Upper figure is drawn in J2000EQ inertial frame. Lower figure is drawn in the Sun–Earth fixed frame. IKAROS will continue interplanetary cruise after the Venus passage in December 2010.

attempts to escape from this Venus intercepting trajectory by means of solar sailing (Fig. 2).

To know the acceleration performance of the solar sail, it is important to precisely evaluate the optical parameters of the sail on orbit. Thus in the Earth–Venus leg, IKAROS is to attempt to steer its attitude so that it can experience various Sun angles.

2.3. *Launch and orbit insertion sequence*

IKAROS was launched as one of the piggy-back payloads of H-IIA flight #17, whose main payload was JAXA's Venus explorer AKATSUKI (Planet-C). To accommodate two large spacecraft, IKAROS and AKATSUKI, a new payload attach fitting (PAF) was developed. IKAROS was settled beneath this PAF, and was injected to a Venus transfer trajectory after AKATSUKI and the PAF were separated. IKAROS was released at 5 rpm spin with its spin axis pointed almost to the Sun. Three other small spacecraft developed by Japanese universities were loaded, among which two were LEO satellites and one was injected to the Venus transfer orbit. Fig. 3 shows the insertion sequence of the H-IIA flight #17.

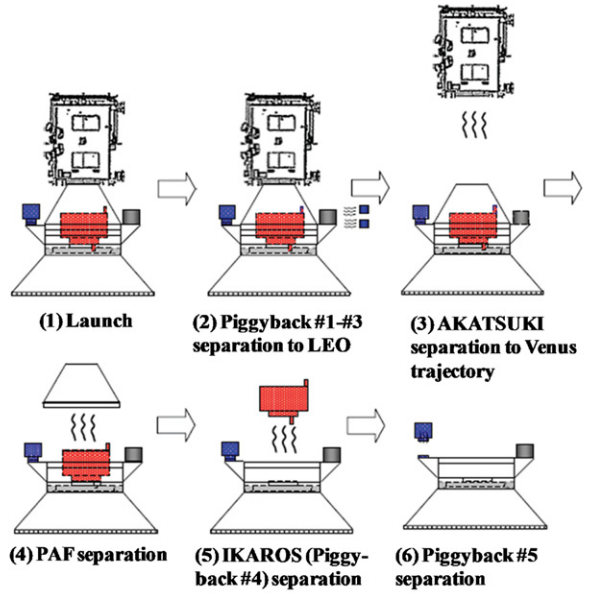

Fig. 3. Payloads injection sequence of H-IIA flight #17. IKAROS was one of 5 piggy-back payloads launched together with the Venus explorer AKATSUKI.

2.4. *Mission sequence*

Fig. 4 summarizes the mission sequence of IKAROS. IKAROS is to take advantage of the interplanetary flight environment of Earth-to-Venus trajectory for solar sail demonstration. First one month is to be used (and was actually used) for initial check-out, establishing the attitude and deploying the sail. After the sail deployment, all the functions of the sail, including the power generation of the thin flexible solar cells are checked. Then IKAROS turns on all the science instruments, and continuously makes measurements in order to confirm the "solar sailing" performance of IKAROS.

3. Spacecraft system

3.1. *Spacecraft specifications*

IKAROS has a cylindrical body surrounded by the sail storage and deployment mechanism. The attitude is stabilized passively by spinning. The related centrifugal force by the spinning is also used for supporting the deployment and shape-keeping of the sail.

The specifications of IKAROS are summarized in Table 1.

3.2. *Solar sail materials and configuration*

The main payload, solar sail, is made of polyimide. Two different types of polyimide are used; one is commercially available APICAL-AH, the other is ISAS-TPH. ISAS-TPH is a newly developed film, having thermal adhesiveness and is tolerant against space environment at the same time. Both films have thickness of 7.5 μm.

The solar sail consists of four trapezoidal petals (Fig. 5). Four petals are connected by "bridge" to form the rectangular sail. The sail and the hub body are connected by 8 tether lines. Four flexible harnesses also run between the

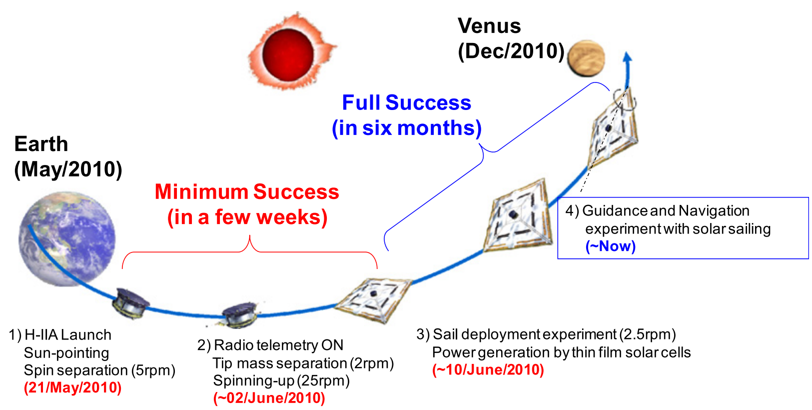

Fig. 4. Mission sequence of IKAROS. IKAROS already completed (1–3) by mid-June, 2010, and now in the sequence 4.

Table 1
IKAROS spacecraft specification.

Structure	S/C body: $\varphi 1.6 \times h0.8$ m cylindrical Solar sail: 14 m × 14 m rectangular
Mass	Wet: 307 kg Dry: 287 kg Solar sail: 16 kg
Attitude	Spin stabilized • Sun sensor • Earth angle measurement (by spin modulation on downlink RF) • 3 axis Gyro • Nutation dumper • Gas–liquid phase-equilibrium thruster (fuel: HFC-134A) $0.4N \times 8$ heads
Power	Body mount SAP 300 W
Comm.	X-band TT & C
Orbit determination	R & RR VLBI (experimental)
Solar sail support system	Deployment mechanism Solar sail-mount sensors • Flexible solar array (FSA) • Reflectance control device (RCD) • Dust particle detector (ALDN) • Surface charge sensor • Temperature sensor • Tip acceleration sensor
Other payloads	Solar sail mission • Onboard camera × 4 • Deployable camera (DCAM) × 2 Optional mission • X-band VLBI transmitter • GAmma-ray burst polarimeter (GAP)

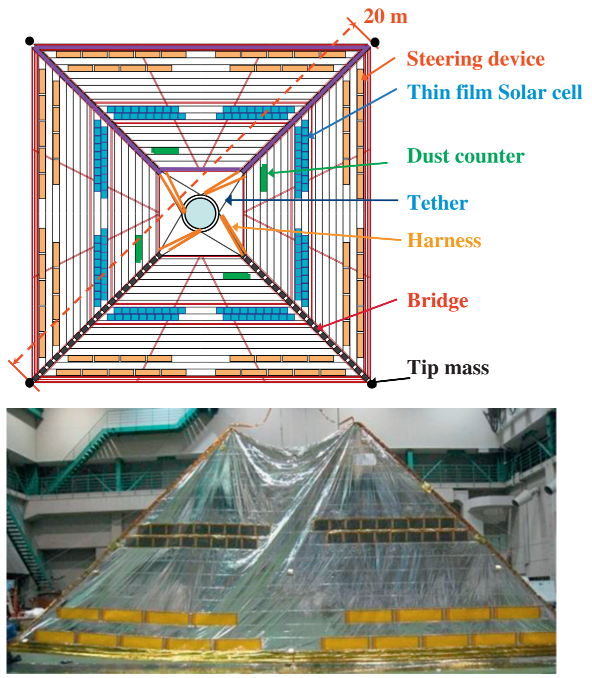

Fig. 5. (Upper) IKAROS solar sail and devices on the sail, (lower) one of four petals of IKAROS solar sail flight model.

sail and the hub. Tip masses are attached at four corners of the sail (0.5 kg each, 2.0 kg in total), which are to support the deployment and the extension of the sail by centrifugal force. An accelerometer is equipped in one of the tip masses to measure the centrifugal force during and after the deployment.

The solar sail is equipped with several devices. Flexible solar array (FSA) is an a-Si flexible cell with the total power generation of 300 W at 1 AU. FSA is to demonstrate the "solar power sail" concept by generating the power on the sail. *V–I* characteristics are to be constantly measured throughout the mission.

Reflectance control device (RCD) is a flexible layered sheet in which liquid crystal is encapsulated. Electrical voltage being applied, the sheet can change its optical reflectance (ON: specular, OFF: diffusive dominant). By synchronizing RCD ON/OFF with the spinning phase, the spacecraft can change its spin axis direction using SRP without consuming fuel.

Arrayed large-area dust detector for interplanetary space (ALDN) is a PVDF-based film sensor to detect particles impacting on the sail. The effective area of ALDN is as large as about 0.5 m^2.

3.3. *Sail deployment mechanism*

Fig. 6 shows the deployment sequence of the solar sail. The deployment sequence is divided into two phases. The first stage deployment is to extend the sail to a "cross-shape". The extension speed in this phase is controlled by four guide rollers moving along the surface of the sail. Thus the extension is done in completely quasi-static manner regardless of the flexibility of the sail.

The second stage deployment is to extend the "cross-shape" to the final flat rectangular shape. This is done by unlatching the four guide rollers. By this action, the sail is extended dynamically in a few seconds by the centrifugal force. The spin rate before initiating the first stage is 25 rpm, and the final spin rate after the complete extension is 2.5 rpm.

3.4. *Attitude determination and control*

The attitude of IKAROS is determined by the Sun angle and the Earth angle. The Sun angle is measured by a spin Sun aspect sensor. The Earth angle is measured by Doppler modulation of the downlink RF due to the spacecraft spinning. For this purpose the antenna location is intentionally offset from the spin axis. The spin axis orientation can be determined by these two angles with the accuracy between 0.1 and 1 degree throughout the mission.

The attitude control is done primarily by RCS. IKAROS is equipped with a newly developed gas–liquid phase-equilibrium thruster. This system stores the fuel HFC-134a in a liquid phase, and at the injection it is in a gas phase. The temperature of the fuel tank and pipes are sophisticatedly controlled to keep this phase transition. As HFC-134a is atoxic and the whole system is constituted without using high pressure system, this RCS realizes an easy-to-handle system. IKAROS has 8 radial thrusters for

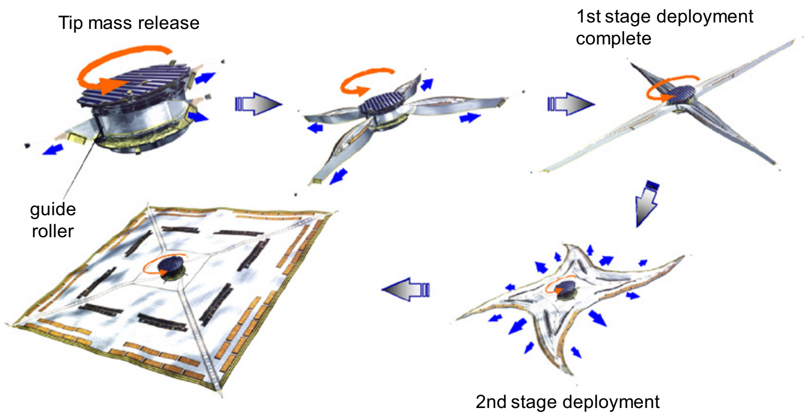

Fig. 6. Solar sail deployment sequence.

spin up/down and spin axis reorientation (no axial thruster available).

IKAROS ADCS supports Flex-RLC/Flex-ANC attitude control logics as well as the ordinary rhumb line control (RLC), active nutation control (ANC) and the spin up/down control. Flex-RLC and Flex-ANC are extensions of the ordinary RLC and ANC to suppress undesirable behavior of the sail due the flexibility [8,9]. RCD is a novel concept [8] adopted in IKAROS, which provides an alternative way to change the spin axis orientation. 72 sheets of RCDs are capable of changing the spin axis orientation by 1° at 1 AU at 1 rpm spin rate.

4. On-orbit operation results

4.1. Solar sail deployment

IKAROS started the sail deployment operation on May 22, and completed on June 9. The spin rate was changed several times during the deployment operation so that appropriate centrifugal force was applied to the sail at the each phase of the sail deployment. The actual sail operation proceeded as follows:

May 21	Launch, initial spin rate = 5 rpm
May 22	Launch lock released
May 24–25	Spin down to 2 rpm
May 26	Tip masses released
May 27–29	Spin up to 25 rpm
June 2	1st stage deployment #1, #2
June 3	1st stage deployment #3, #4, #5, #6
June 4	1st stage deployment #7, #8, #9
June 8	1st stage deployment #10, #11
June 9	2nd stage deployment
CAM operation	
June 14	DCAM2 release and operation
June 16–18	Spin down to 1 rpm
June 19	DCAM1 release and operation

The first stage deployment was divided into 11 subsequences, each of which were to radially extend the sail by a certain length. The result of each step was evaluated by onboard cameras and attitude status.

Figs. 7 and 8 show pictures taken by four onboard cameras (CAM) during and after the sail deployment

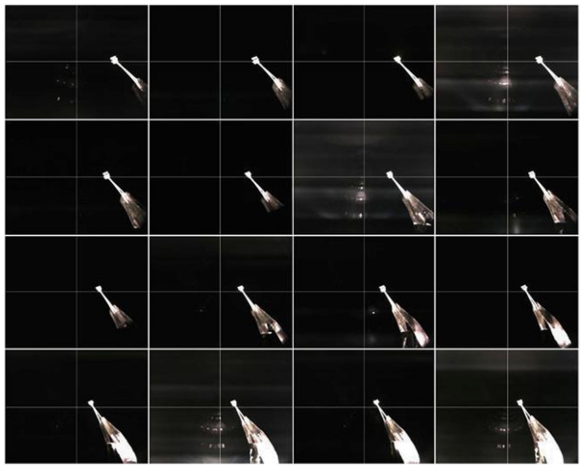

Fig. 7. CAM pictures of 1st stage deployment sequence #2. The pictures are taken every 3 s.

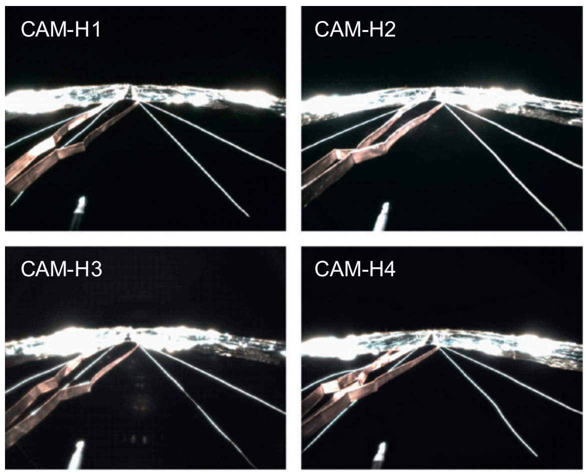

Fig. 8. CAM pictures after the complete deployment. Four pictures are viewing different portions of the sail.

operation. Four CAMs are located at the spacecraft body viewing toward radial direction to cover a whole area of the sail. Fig. 8 shows almost the same pictures taken by

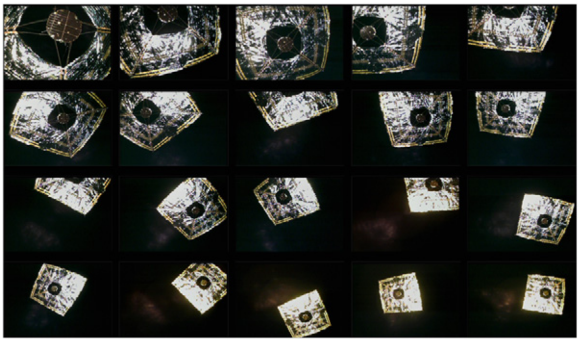

Fig. 9. DCAM2 pictures (every 1–3 s).

different CAMs at the same time, proving that the sail was deployed completely and uniformly towards four directions.

Fig. 9 is a result of the first DCAM operation on June 14. DCAM is a 280 g weight self-operating camera. Two DCAMs were deployed along the spin axis direction toward the Sun with some spin, and they transmitted real time images to IKAROS. IKAROS relayed the images to finally send them to the ground station. Two DCAMs operations were conducted successfully. They provided a whole view of IKAROS flying in the interplanetary space with its sail fully extended. The images provided precious information of the sail shape affected by the SRP in actual interplanetary flight.

The power generation of flexible solar array (FSA) on the sail was also measured nominally. We have been gathering *V–I* characteristics and several related data constantly since the completion of the sail deployment.

4.2. Photon acceleration measurement

We observed the solar radiation pressure on the sail right after the completion of the solar sail on June 9. An initial clue of the SRP acceleration was caught by real time Doppler observation minus calculation (O − C) measurement (Fig. 10 Upper). We saw from this data that the sail was deployed and the orbital acceleration changed appropriately. Precise evaluation of the SRP working on the sail has been conducted by means of orbit determination process. The sail receives the SRP force of 1.12 mN at 1 AU distance from the Sun. This value was almost as expected by design (Fig. 10 Lower). As is shown in Fig. 10 Lower, the measured thrust was 96% of the ideal (designed) thrust. Since the ideal thrust only accounts for flat surface with a corresponding solar incidence angle determined by attitude determination, this small error is due to the imperfectly-flat sail surface, which lowers the effective area and effective reflectance of the sail surface.

4.3. Attitude control utilizing SRP torque

The first experimental operation of RCD was conducted on July 13. In this experiment RCD was operated so that IKAROS changed the spin axis orientation towards the Sun. Fig. 11 shows the result of this experiment. As is seen from the graph in Fig. 11, the attitude change was observed obviously by the Sun angle history, and the change rate by

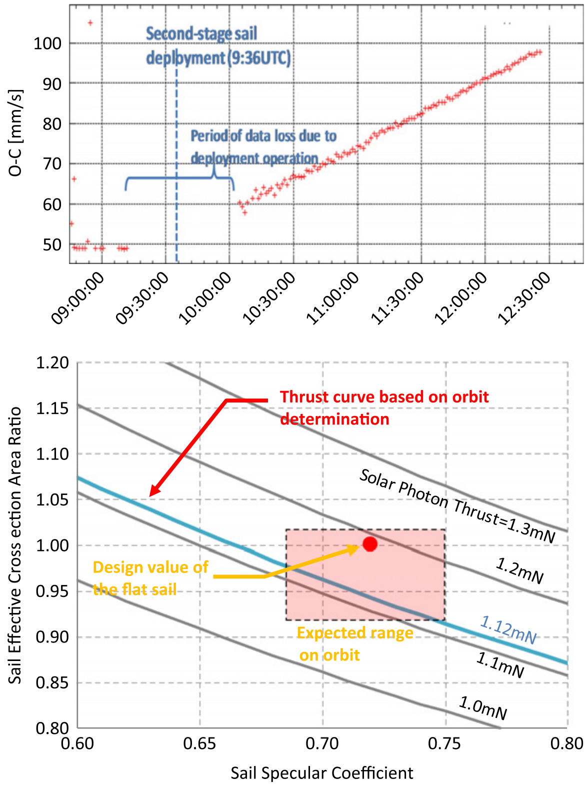

Fig. 10. (Upper) Doppler measurement at the 2nd stage sail deployment on June 9. (Lower) Estimation of solar radiation pressure by first precision orbit determination after the sail deployment.

the RCD operation was exactly as expected by the design. Since then we extensively use RCD for attitude manuever in place of RCS to save as much fuel as possible.

4.4. Trajectory guidance of solar sailing spacecraft

IKAROS experiences a severe disturbance on attitude due to the large solar sail. Although the spacecraft is spin stabilized, IKAROS changes both spin rate and spin axis direction with reference to the inertial frame because of the SRP.

Hence in the process of the trajectory guidance, we have built a SRP torque model and fitted the model parameters to the flight data. Then the trajectory guidance tool incorporates this attitude dynamics model to precisely output the maneuver plan.

Although IKAROS does not have a specific target to reach, we set several virtual targets so that we can evaluate the guidance performance of solar sailing spacecraft.

Fig. 12 shows an example of maneuver plan. If the SRP were not applied, the spin axis, spin rate and the ballistic projection point on the Venus B-plane should have been constant. Since large SRP is applied to the sail in reality, however, the attitude is variable and the RCS maneuver plan must incorporate and exploit the SRP torque in order to efficiently control the attitude. The result also affects the trajectory. Thus through IKAROS operation, we have

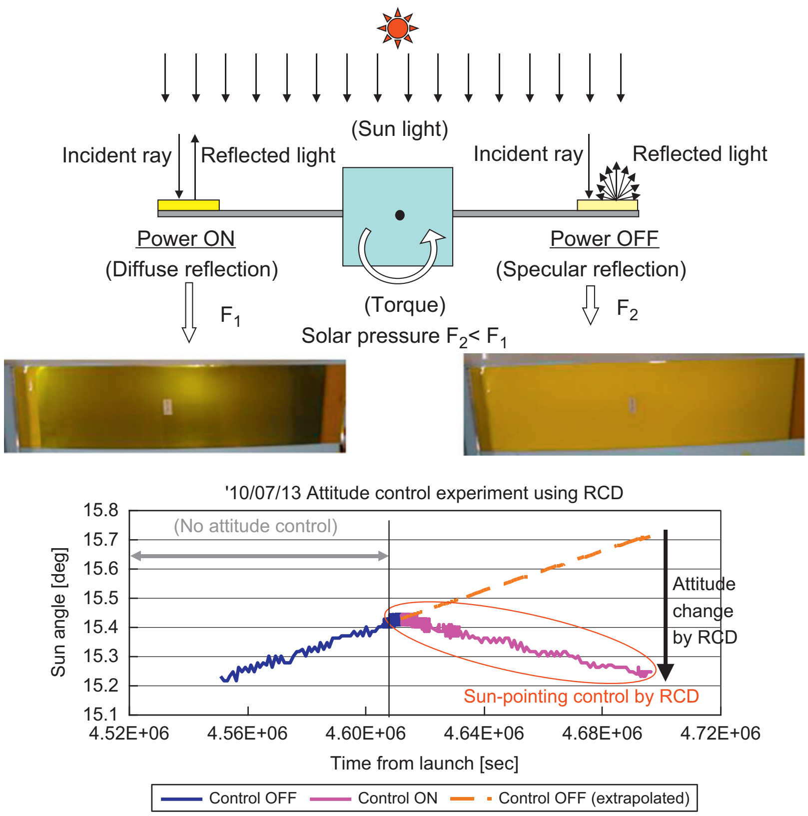

Fig. 11. (Upper) Operating principle of reflectance control device (RCD) aboard IKAROS. (Lower) First result of RCD operation on July 13.

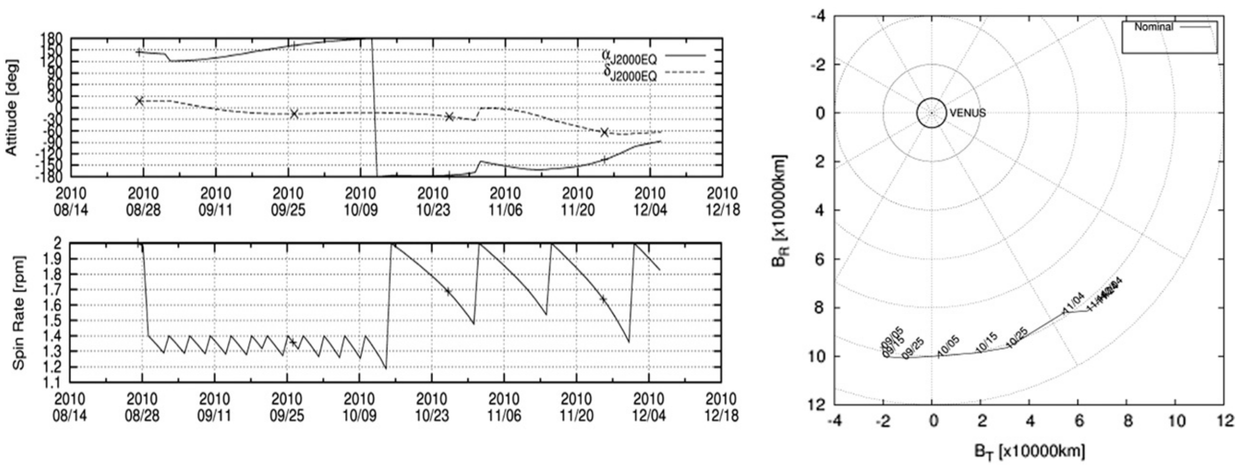

Fig. 12. Example of trajectory and attitude maneuver plan. (Upper left) History of spin axis direction w.r.t. inertial frame. (Lower left) Spin rate history. (Right) Venus B-plane and ballistic projection point history.

been acquiring fast and sufficiently precise modeling methodology of spinning solar sailor.

5. Conclusion

This paper described the initial three-month accomplishments of the world's first interplanetary solar sail demonstration mission "IKAROS". IKAROS successfully completed the sail deployment on June 9, 2010, and is now flying towards the Venus with the assist of solar radiation pressure. IKAROS spacecraft realizes many aspects of solar sail technology evaluations and validations, ranging from the sail deployment process, sail shape in space, SRP force and torque measurements and solar sail guidance and navigation to some new technologies such as the reflectance control device and the flexible solar array attached on the sail. IKAROS has achieved three out of four mission goals, which are (1) deployment of the sail,

(2) confirming power generation on the sail, (3) confirming and measuring orbital acceleration by SRP. The fourth objective, acquisition of solar sail guidance and navigation technology is now being performed. We are looking at realizing the "solar power sail" concept for the future interplanetary exploration, and IKAROS successfully undertook a role of the precursor for this new concept.

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