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Achievement of IKAROS — Japanese deep space solar sail demonstration mission

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ABSTRACT

This paper describes achievements of the IKAROS project, the world's first successful interplanetary solar power sail technology demonstration mission. It was developed by the Japan Aerospace Exploration Agency (JAXA) and was launched from Tanegashima Space Center on May 21, 2010. IKAROS successfully deployed a 20 m-span sail on June 9, 2010. Since then IKAROS has performed interplanetary solar-sailing taking advantage of an Earth-Venus leg of the interplanetary trajectory. We declared the completion of the nominal mission phase in the end of December 2010 when IKAROS successfully passed by Venus with the assist of solar sailing. This paper describes the overview of the IKAROS spacecraft system, how the world's first interplanetary solar sailer has been operated and what were achieved by the end of the nominal mission phase.

1. Introduction

The Japan Aerospace Exploration Agency (JAXA) launched the solar sail demonstration spacecraft "IKAROS" (Fig. 1) 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 requisite 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 thrust by solar radiation pressure attracted on 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 then performed an interplanetary solar-sailing taking advantage of the Earth-Venus leg of the interplanetary trajectory. The initial spacecraft wet mass is 307 kg and is equipped with a rectangular solar sail which weighs 16 kg with the minimum thickness of 7.5 μm. 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 it to realize a very light and simple sail support mechanism. The deployment process was measured and recorded by several onboard equipment, such as cameras, attitude sensors and some surface sensor on the sail.

This paper describes the mission outline, spacecraft designs and achievements in the nominal mission phase completed in the end of 2010.

2. Mission and spacecraft design

2.1. Mission definitions

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

(1) Deployment of solar sail in space
(2) Solar power generation by means of thin film solar cells attached on the sail

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(3) Verifying solar radiation pressure (SRP) attracted on the solar sail
(4) Demonstrating guidance and navigation technique for solar sailing

The sail deployment, the power generation on the sail and the photon acceleration by the sail ((1)–(3) in the above list) were confirmed by the end of June 2010, which is approximately one month after the launch. The guidance and navigation testing by solar-sailing ((4) in the above list) was completed at the end of December 2010, when IKAROS made the closest approach to Venus at the distance of 80,800 km. As all of the four objectives were achieved, we declared the completion of nominal mission phase in the end of 2010. IKAROS was then authorized to proceed to the extended mission phase until March 2012.

Fig. 2 summarizes the mission sequence of IKAROS. IKAROS was to take advantage of the interplanetary flight environment of Earth-to-Venus trajectory for solar sail demonstration. First month was 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 were checked. Then IKAROS turned on all the science instruments, and continuously measured and controlled the SRP attracted on the sail and confirms the "solar sailing" performance of IKAROS.

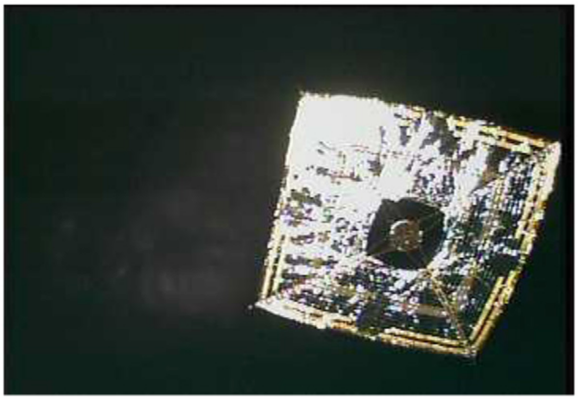


Fig. 1. Solar-sailing IKAROS in the interplanetary field. captured by Deployable Camera(DCAM) on June 14th, 2010.

2.2. Spacecraft design

IKAROS has a cylindrical body surrounded by the sail storage and deployment mechanism (Fig. 3). The attitude is stabilized passively by spinning. The centrifugal force generated by the spinning is a primary means of deployment and shape-keeping of the sail.

The base material of the solar sail membrane is polyimide with 7.5 μm thickness. 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 especially to meet our solar sail production and operation requirements [3].

The solar sail consists of four trapezoidal petals (Fig. 4). The four petals are connected by "Bridge" to complete the rectangular sail. Each petal is connected to the hub body with 16 tether lines. A flexible harness also runs between each petal and the hub to provide electrical connectivity. At the four tips of the sail are attached with 0.5 kg tip masses, which are to support the deployment and the extension of the sail by centrifugal force. An accelerometer is attached inside 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) [4] 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. The V–I characteristics are to be constantly measured throughout the mission.

Reflectance control device (RCD) [5,6] is a flexible multi-layered sheet in which liquid crystal is encapsulated. Electrical voltage being applied, the sheet changes its optical reflectance (ON: specular-dominant, OFF: diffusive-dominant). By synchronizing ON/OFF of the RCD with the spinning phase, the spacecraft can change its spin axis direction via SRP without consuming fuel.

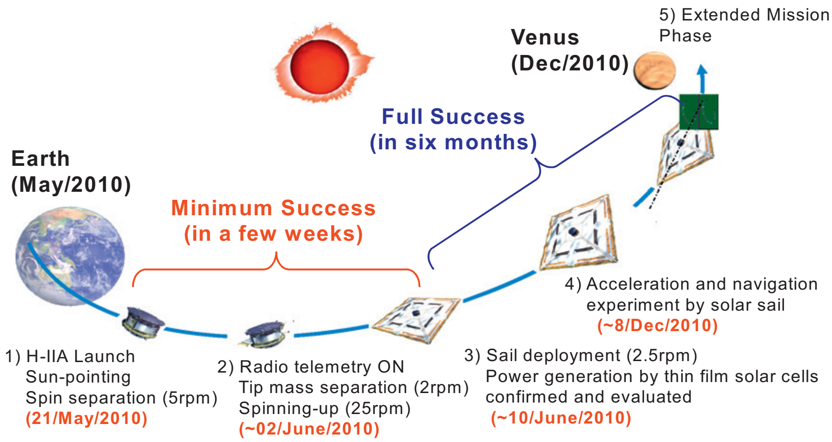


Fig. 2. Mission sequence of IKAROS.

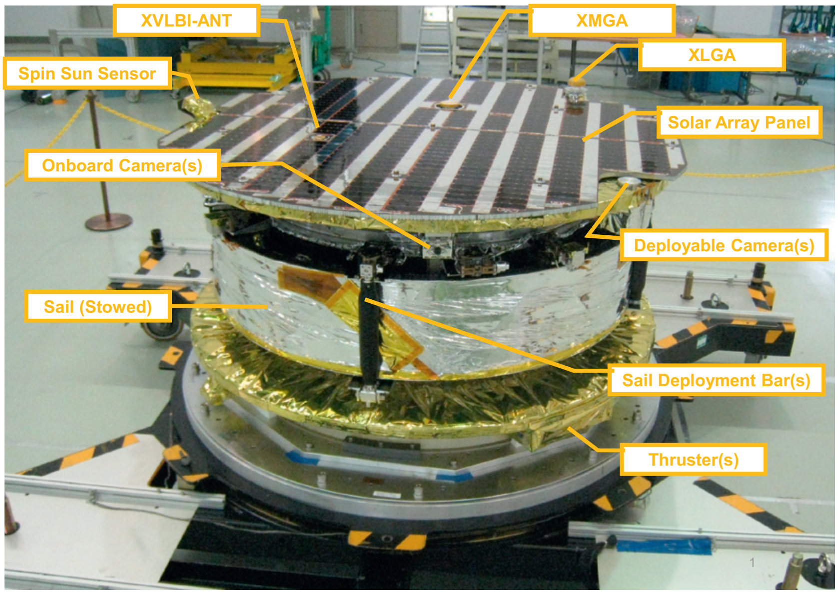
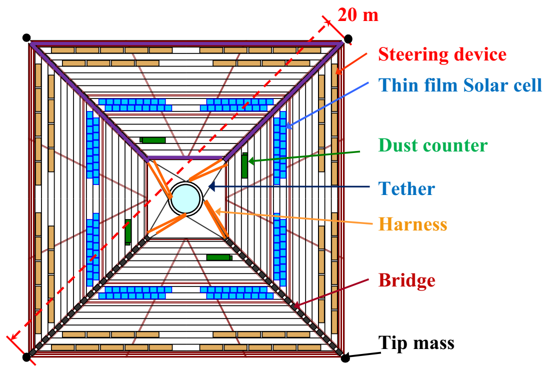


Fig. 3. IKAROS flight model in final assembly phase.



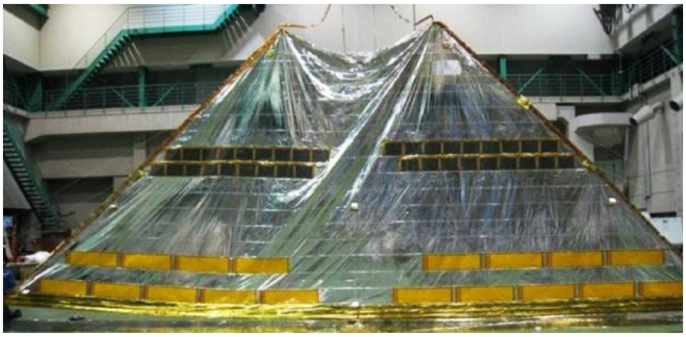


Fig. 4. IKAROS solar sail (left: Overall configuration, right: One of four petals of the sail flight model).

ALDN (Arrayed Large-area Dust detector for interplanetary space) 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 which is the largest detection area for this kind of particle detectors ever flown in the world.

Charge monitors and temperature sensors are also attached on the sail.

Besides elements attached on the sail, IKAROS equips two additional experimental components on the central hub. One is Gamma-ray burst polarimeter (GAP) and another is VLBI transmitter (VLBI-TX). GAP is a scientific instrument to observe gamma-ray bursts incoming from far galaxies and measures their polarization. VLBI-TX is an engineering experimental component to perform the Delta-Differential One-way Ranging (VLBI-based precise orbit determination) technique.

Fig. 5 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 around the spacecraft hub. Thus the extension is done in completely quasi-static manner so that the flexibility of the sail is suppressed as much as possible.

The second stage deployment is to extend the sail 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 reduced to 2.5 rpm just due to the law of conservation of angular momentum.

3. On-orbit results

3.1. Sail deployment operation results

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

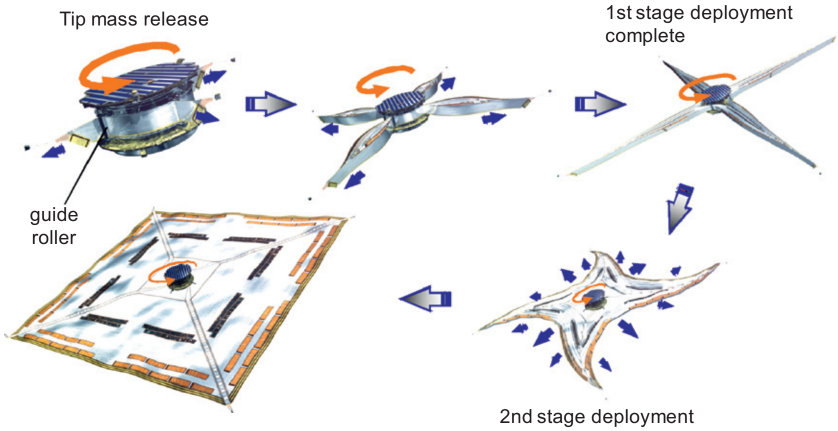


Fig. 5. Solar sail deployment sequence.

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 was to radially extend the sail by a certain length. The result of each step was evaluated by onboard cameras and attitude status.

The second stage deployment was conducted on June 9. The first implication that IKAROS was actually solar-sailing was observed by Doppler measurement. We observed acceleration due to the solar radiation pressure (SRP) via Doppler measurement right after the completion of the solar sail on June 9. The SRP thrust derived from the measurement is 1.12 mN, which is as exactly expected by design.

Another visual confirmation was performed by DCAMs (Deployable Cameras) on June 14 and 19. DCAM is a 280 g weight self-operating deployable 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 the ground station. The two DCAMs operations were conducted successfully. They provided a whole view of IKAROS flying in the interplanetary space with its sail fully extended (Fig. 1). The images provided precious information of the sail shape affected by the SRP in actual interplanetary environment.

The power generation of FSA (Flexible Solar Array) on the sail was also measured normally. We have been collecting V–I characteristics and related data constantly since the completion of the sail deployment.

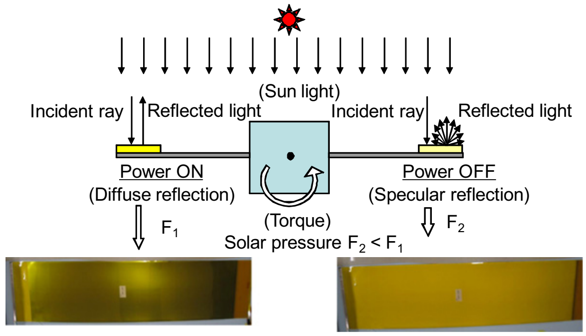


Fig. 6. Concept of reflectance control device operation.

3.2. Cruising phase results

The cruising phase operation was done for about six months from July until December 2010. Precise evaluation of the SRP attracting on the sail has been conducted by means of Range and Range Rate (RARR) orbit determination (OD) technique. Detail solar sail performance including optical parameters of the sail has been extracted through this OD campaign. Total of 21 OD processes were conducted in the cruising phase.

The RCD was first turned on on July 13. Fig. 6 shows the concept of RCD operation. Since then, we have extensively used the RCD for attitude maneuver in place of conventional thrusters (RCS) to save as much fuel as possible.

Although the spacecraft attitude is basically stabilized by spinning, the spin axis (both rate and orientation) always changes with respect to the inertial frame due to this SRP effect. Thus the trajectory guidance and attitude control are strongly coupled through the SRP effect.

The trajectory of IKAROS is exclusively controlled by thrust generated by the sail. In the early cruising phase, the attitude, which determines the orientation of the sail and consequently determines the thrust vector, is controlled via RCS and RCD. Quick analyses based on detailed in-flight SRP evaluation enabled us to develop a passive attitude control strategy which actively exploits the SRP torque [7]. Consequently IKAROS achieved almost 180 degree turn of the angular momentum vector with respect to the inertial frame without using much fuel (Fig. 7). Thus IKAROS was succeeded in utilizing SRP not only for the trajectory control but also for attitude control.

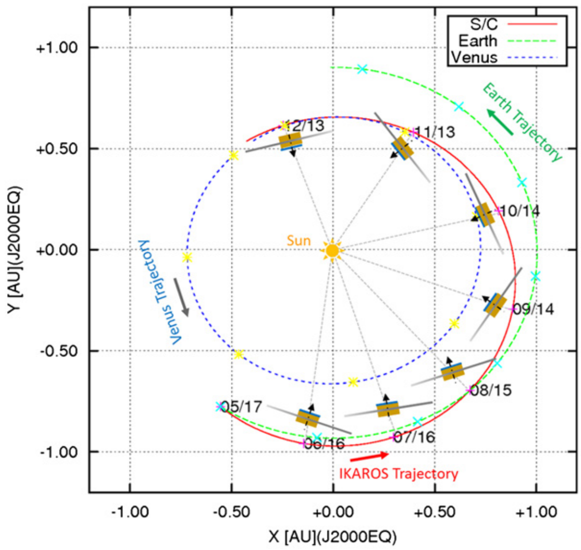


Fig. 7. Trajectory and attitude of IKAROS.

IKAROS passed by Venus on December 8, 2010 at the closest distance of 80,800 km. IKAROS was successfully guided to the night side of Venus, which is opposite to the Akatsuki, which flew by the day side of the Venus one day before IKAROS's fly-by (Fig. 8).

The accumulated acceleration in the six months of nominal cruising phase is over 100 m/s (Fig. 9).

IKAROS is continuing its interplanetary cruise after the Venus fly-by. We are authorized to perform the extended mission phase until March 2012, in which we are planning to perform some "ambitious" experiments to better understand the ultimate performance envelope of IKAROS, and to extend the possibility of the spinner solar sailer system.

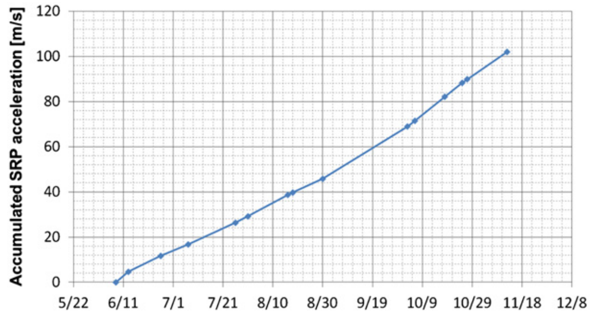


Fig. 9. Acomplishment of SRP acceleration.

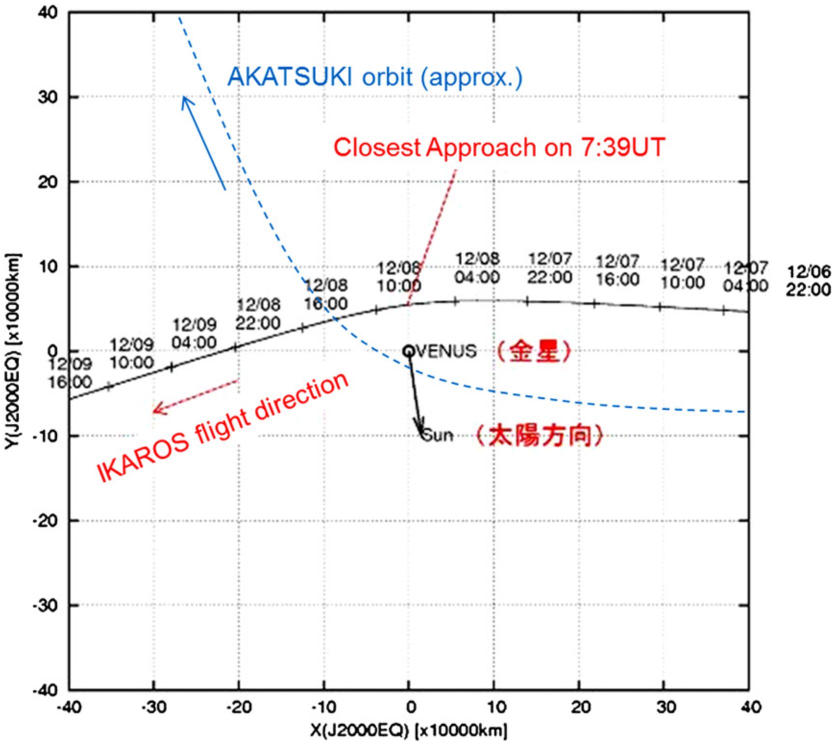


Fig. 8. Concept of reflectance control device operation.

4. Conclusion

This paper described accomplishments of the world's first interplanetary solar sail demonstration mission "IKAROS" in six months of the nominal mission phase. IKAROS successfully completed the sail deployment on June 9, 2010, and successfully passed by 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 all of the 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, and (4) acquisition of solar sail guidance and navigation technology. IKAROS is now flying under an extended mission phase operation. JAXA is pursuing the realization of the "Solar Power Sail" technology for future interplanetary explorations. IKAROS successfully undertook a role of the precursor for this new concept.

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