DEVELOPMENT OF FIRST SOLAR POWER SAIL DEMONSTRATOR - IKAROS

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ABSTRACT

The Japan Aerospace Exploration Agency (JAXA) will make the world’s first solar power sail craft demonstrate for both its photon propulsion and thin film solar power generation during its interplanetary cruise. The spacecraft deploys and spans its membrane of 20 meters in diameter taking the advantage of the spin centrifugal force. The spacecraft weighs approximately 315kg, launched together with the agency’s Venus Climate Orbiter, PLANET-C in 2010. This will be the first actual solar sail flying an interplanetary voyage.

1. INTRODUCTION

Solar Sail converts the sunlight to propulsion force by the large membrane. Solar Power Sail gets electricity from thin film solar cells on the membrane as well as solar sail. The Japan Aerospace Exploration Agency (JAXA) will make the world’s first solar power sail craft demonstrate for both its photon propulsion and thin film solar power generation during its interplanetary cruise.

The project code of it is named IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun). The spacecraft weighs approximately 315kg, launched together with the agency’s Venus Climate Orbiter, PLANET-C in 2010. Both spacecraft are boosted by the H-IIA vehicle directly on to their cruise orbit bound for the Venus. This demonstrator deploys and spans its membrane of 20 meters in diameter taking the advantage of the spin centrifugal force. It attempts further to deploy thin film solar cells on the membrane, in order to evaluate its thermal control property and anti-radiation performance in real operational field. The sail spacecraft steers its orientation in time-to-time to demonstrate managing photon acceleration in accordance with the guidance strategy. The flight hardware was fabricated and the integrated test was started in August, 2009. This will be the first actual solar sail flying an interplanetary voyage.

If the ion-propulsion engines are driven by the solar cells, solar power sail can be a hybrid engine and achieve various missions. JAXA has studied an extended Solar Power Sail craft toward the outer solar system via hybrid electric photon propulsion as shown in Figs. 1-3. The mission will take place in the late 2010s. It involves the solar power sail having a diameter of 50m, and integrated with ion-propulsion engines. The destination of the spacecraft will be Jupiter and the Trojan asteroids [1].

Solar sail missions are studied in many countries [2,3]. JAXA guides to the future solar system exploration by solar power sails. Our missions can also leads to low cost and large area solar cells. They are the key technologies of the anti-global warming. They are applicable to the solar cells of solar power satellite.

2. SOLAR POWER SAIL MISSION TO JUPITER AND TROJAN ASTEROIDS

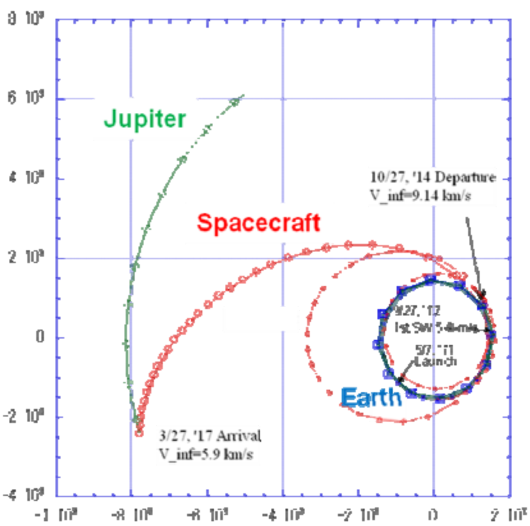
The Solar Power Sail spacecraft studied there uses a world's first hybrid photon / ion propulsions taking the advantage of thin film photo-voltaic technology. The mission has very new multi-purposes:
First of all, the mission aims at exploration of the Trojan asteroids for the first time. And it is simply the first spacecraft to the Jupiter's distance powered only by solar cells. Utilizing the power surplus available at the Earth distance, the spacecraft is supposed to drive its ultra-high specific impulse ion engines aboard with the combination of the Earth gravity assist. The intended specific impulse will be 10,000 seconds, almost as 3.3 times efficient as existing contemporary ion engines. Here are summarized major characteristics of the Solar Power Sail mission; It is

1. World's First Solar Powered Jovian Explorer,
2. World's First Combined Jovian Orbiter / Flyby Mission,
3. World's Highest Performance Ion Engines,
4. World's First Photon/Electric Hybrid Sail Propulsion,
5. World's First Background Emission Mapping,
6. World's First Access to Trojan Asteroids,
7. World's First Formation Flight in Jovian Magnetosphere.

The proposed Solar Power Sail craft is innovative as it carries the following new technology demonstrations.

1. A Large Membrane Space Structure including Deployment strategy,
2. A Hybrid Propulsion using both Photon and Ultra High Performance Ion Engines,
3. Thin Film Solar Cells,
4. Reaction Control functioning at very Low Temperature,
5. An Integrated Propulsion/Power System using Fuel Cells.
6. Formation Flight in Jovian system,
7. Electric Delta-VEGA technique for outer solar system,
8. Ultra Stable Oscillator for 1-way range or VLBI orbit determination,
9. Ka-band for Interplanetary Missions,
10. Radiation-Resistant Technology for Jovian Orbiter,

It is full of new technologies requisite for future solar system voyages.
Not only the technology demonstration, in addition to the Trojan asteroid exploration, there are still more new innovative science purposes carried by this spacecraft. Among them, what should be emphasized is a background emission mapping excluding ecliptic dust cloud, which is cleared beyond four AU distance from the Sun. This will reveal the fundamental questions as to the extraordinary young stars observed only in deep IR region. Furthermore, this single spacecraft carries both a Jovian orbiter and an atmospheric re-entry probe, both of which will constitute a spacious and simultaneous magnetosphere measurement at the Jovian polar region, via a formation flight. This is what has yet been tried so far in long solar planetary exploration history.
JAXA has been seriously investigating the spacecraft development and it now puts a technology demonstrator in 2010.



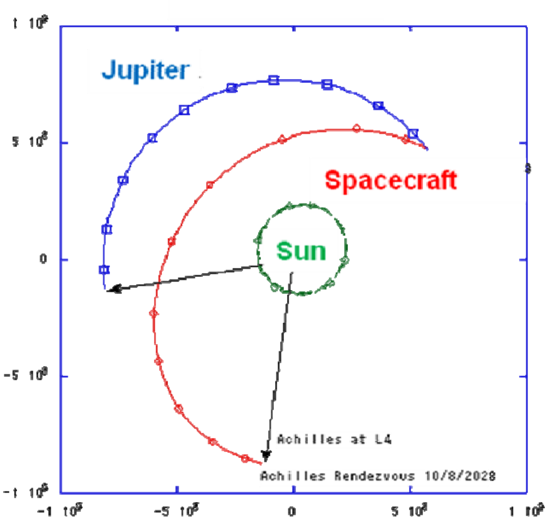
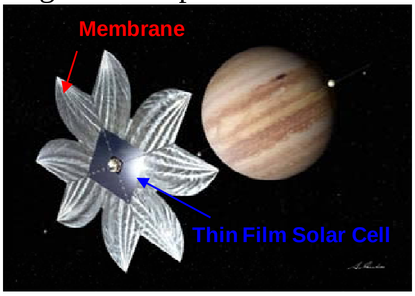


Fig. 1. Solar power sail mission to Jupiter and Trojan asteroids



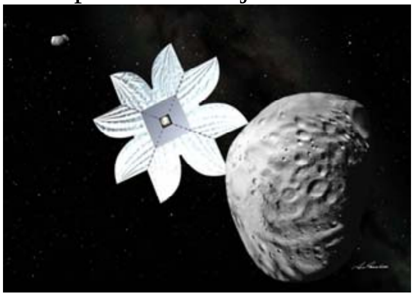


Fig. 2. Exploration of Jupiter and Trojan asteroids

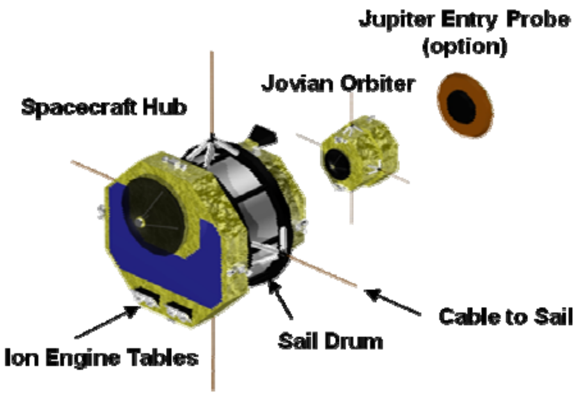


Fig. 3. Solar power sail spacecraft system

3. SMALL SOLAR POWER SAIL DEMONSTRATOR (IKAROS)

The outline of the IKAROS mission is shown in Fig. 4. The spacecraft spans a square membrane sail whose tip-to-tip length is 20meters long, and weighs about 315 kg. As its name infers, the sail spanned includes thin film solar cells which occupy approximately 5% to the total area. The success criteria of the "IKAROS" mission are summarized as follows;
(1) Deployment of Large Membrane Sail
- Deployment and Expansion of a Large Membrane in space using similar mechanical device and procedures to those in Solar Power Sail craft.
- Obtaining a number of data indicating the expansion status of the membrane.
(2) Generating Electricity by Thin Film Solar Cells
- Demonstrating Solar Power from Thin Film Solar Cells
- Evaluating performance of Thin Film Solar Cells on the membrane in space
These two items belong to the Minimum Success Criteria.
(3) Demonstrating Photon Propulsion
- Verification of Reflectance as well as Comparison of them with Diffuse & Specular Property.
- Measurement of overall Reflectance with the rigorous relation examination of the temperature and surface status
(4) Demonstrating Guidance, Navigation Control Skills for Solar Sail Propulsion
- Navigation / Orbit Determination under continuous and small acceleration
- Acceleration Direction Control via Steering via appropriate attitude control means
These latter two items belong to the Full Success Criteria.
IKAROS is stowed inside a PAF of the H-IIA vehicle when it launches a Venus Climate Orbiter, PLANET-C in 2010 as shown in Fig. 5.
The demonstration flight assumes an operation scenario described in the following figure, Fig. 6.
In IKAROS mission, not only just deployment of a sail but also steering capability is among of what it shall demonstrate. The attitude requirement most of all comes from radio communication constraints, while the attitude capability strongly relies on the Sun angle as shown in Fig. 7.
The flight period to the Venus is only half a year, during which IKAROS demonstrator is supposed to perform the above mentioned flight sequences. Fig. 8. also shows how the Sun acquisition and Sun-pointing control are performed. During the initial period, auxiliary solar cells atop the hub bus

portion and RCS thrusters are used to reorientation and deployment operation. The thin film solar cells are not actually relied on, since it is part of the mission to be demonstrated.

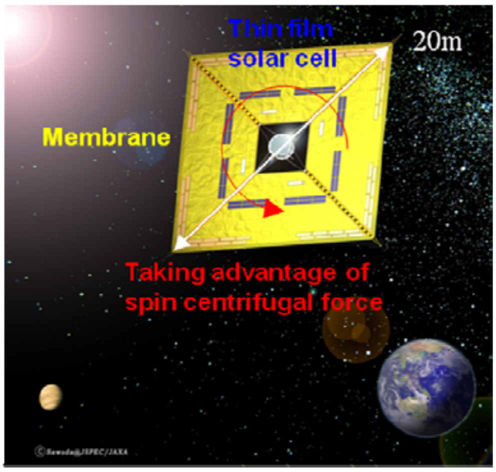


Fig. 4. Outline of IKAROS mission

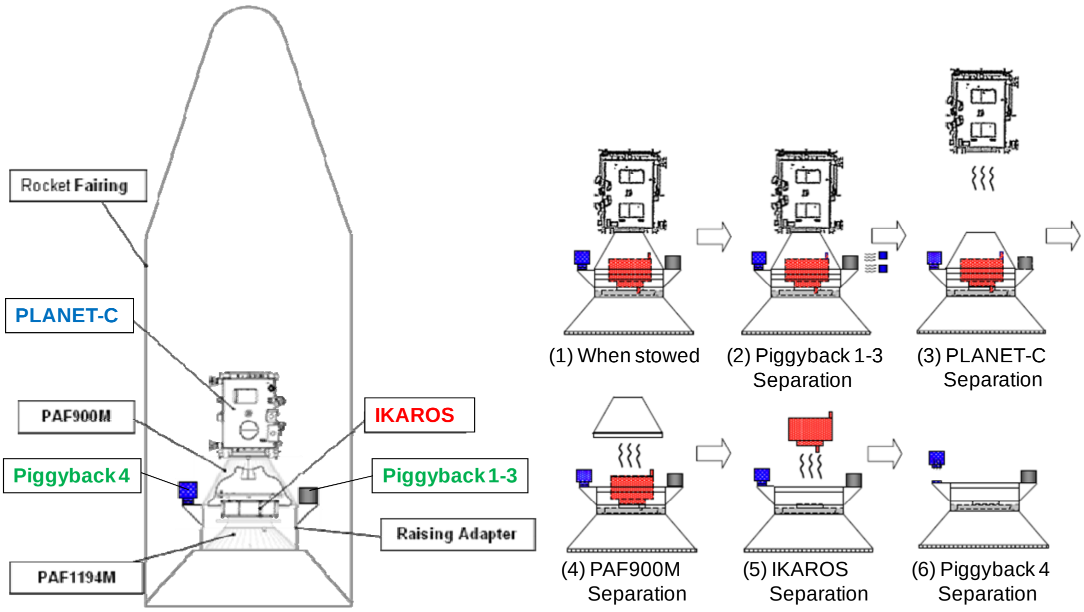


Fig. 5. Launch and separation of IKAROS

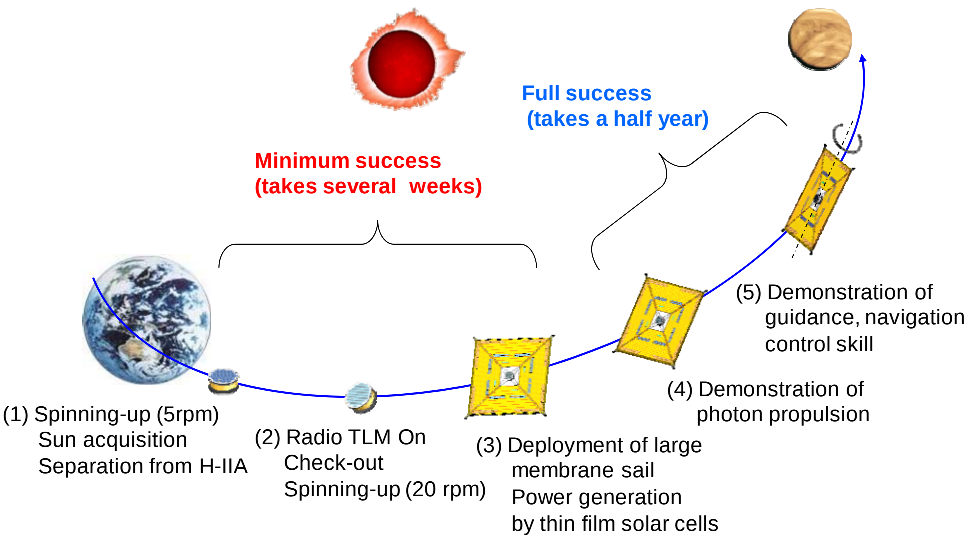


Fig. 6. Nominal operation sequence of IKAROS

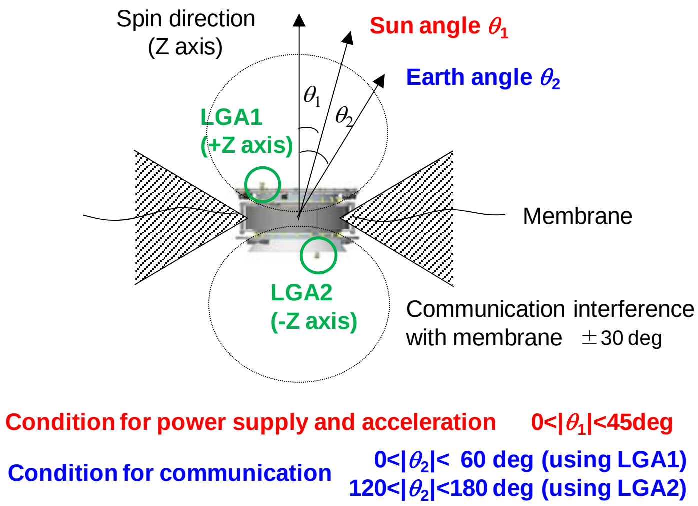


Fig. 7. Conditions of sun and earth angles

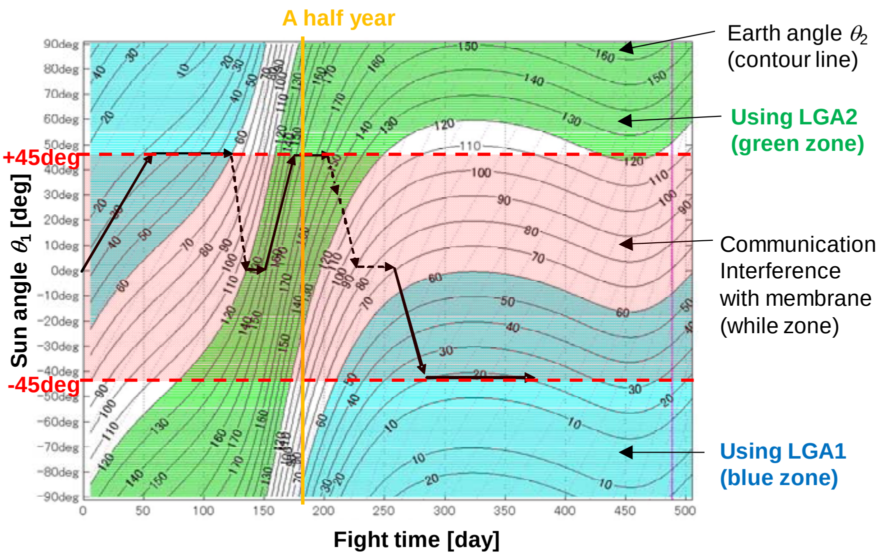


Fig. 8. Steering plan

4. IKAROS SPACECRAFT DESCRIPTION

IKAROS spacecraft is a spinner and the shape is simply cylindrical. It carries a drum around which a membrane is wound to be re-wound via a special mechanics aboard. Whole spacecraft view is presented below.

Where sail membrane is wound is Mission portion that is independent of the bus hub portion as shown in Fig. 9. The spacecraft design started from fall of 2007, just 2.5 years prior to the launch and the design process intentionally adopted No-EM development strategy taking the advantage of relatively enough mass margin indicated from the launch vehicle. Besides, the existing hardware surplus as well as reproduction of existing design are fully made good use of to shorten the development period as shown in Fig. 10.

This paper introduces the major development component: sail, deployment system, extra payload, reaction control system and antenna.

Fig. 9. IKAROS spacecraft configuration

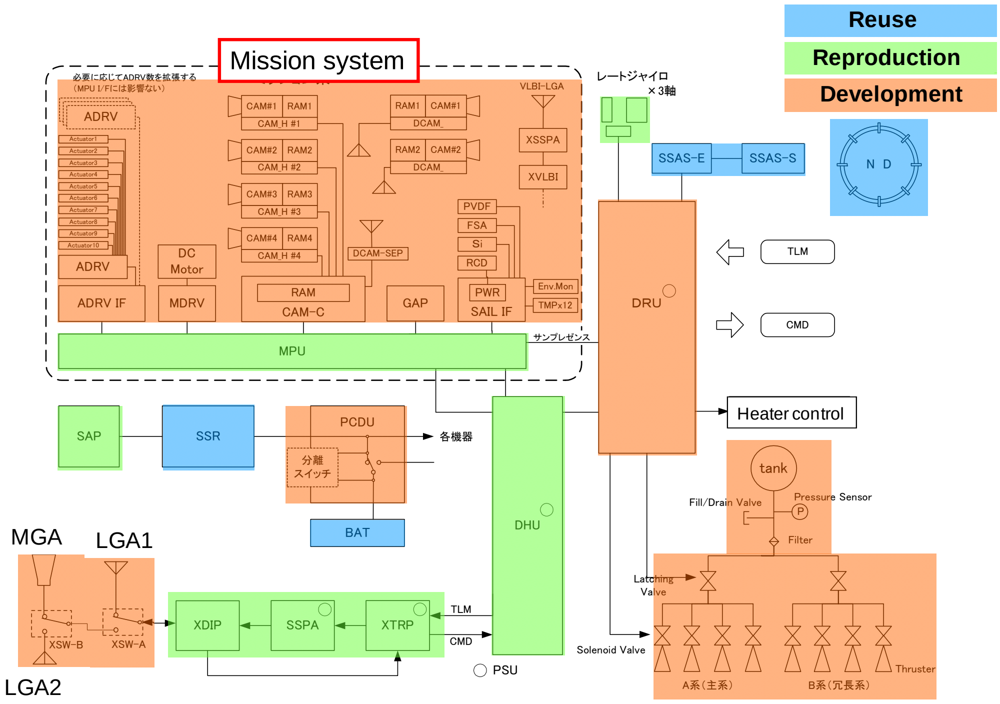


Fig. 10. Space system of IKAROS

4.1 Sail

The sail shape and equipment layout is shown in Fig. 11.
Membrane: The shape of the membrane is a square whose diagonal distance is 20m. Four trapezoid petals are connected by bridges as shown in Fig. 12. The direction of folded lines is perpendicular to the direction of the centrifugal force. It is made of two kind of polyimide whose thickness is 7.5μm. Polyimide2 is a-ODPA-PI, which is developed and manufactured by JAXA. It can be fused with each other by heater control as shown in Fig. 13.
Thin film solar cell: a-Si solar cells are attached to certain areas of the membrane. They generate almost 500W. The area ratio is 5%. The multilayer of the film prevents solar cells from curling because of symmetric mechanism as shown in Fig. 14. It also shields solar cells from radiation.
Steering device: Variable reflectance elements are loaded near the sides of the membrane. They can be used to control the spin direction as shown in Fig. 15.
Dust counter: PVDF film is attached for dust counter. It is extra success mission.
Tip mass: Four masses are attached to the four tips of the membrane. The tip masses adjust the centrifugal force and the inertial momentum of the membrane.
Tether and Harness: The membrane should not contact the main body after the deployment. It is connected to the main body by tether and harness.

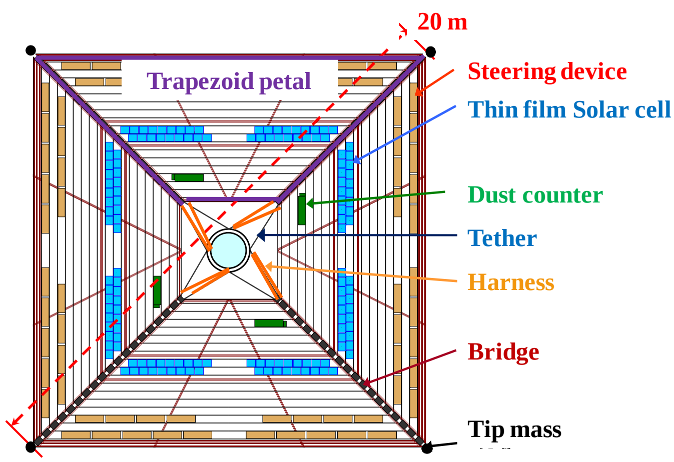


Fig. 11. Sail shape and equipment layout

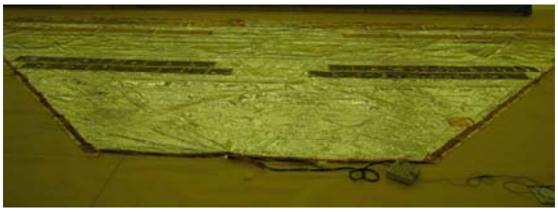
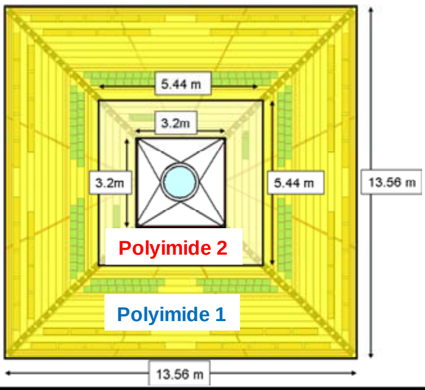
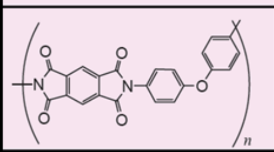
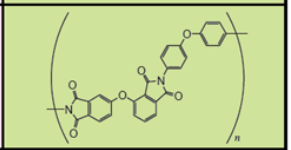


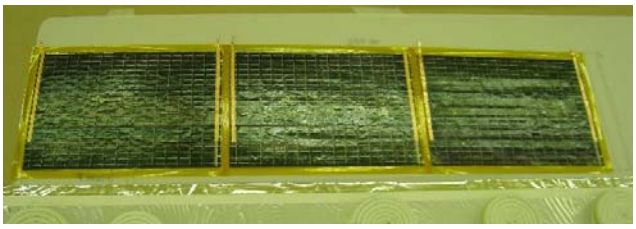
Fig. 12. Trapezoid petal



	Polyimide1	Polyimide2
Material	APICAL-AH 7.5 PMDA/4,4' ODA(㈱カネカ製)	ISAS-TPI熱可塑性ポリイミド a-ODPA/4,4'-ODA(ISAS開発)
Chemical formula		
Elasticity	3.8 GPa	3.2 GPa
Breaking strength	263 MPa	132 MPa
Breaking elongation	74%	90%
Thickness [μm]	7.5-8.5	7.5-8.5
Area	154.28(m^2)(膜面の88.9%)	19.35(m^2)(膜面の11.1%)
Weight	1.643 kg	0.206 kg
Al deposition	80 nm	80 nm<

Polyimide2 (a-ODPA-PI)

Fig. 13. Membrane material



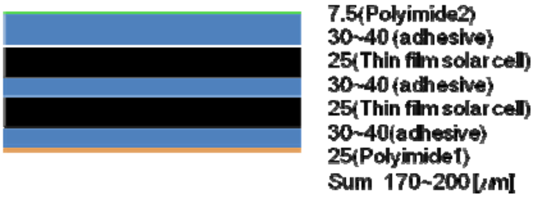


Fig. 14. Thin film solar cell (a-Si)

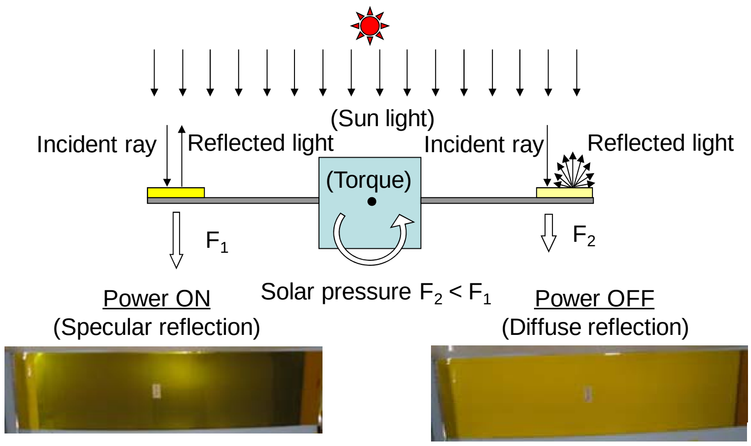


Fig. 15. Steering device

4.2 Deployment system

Some kinds of deployment methods have been investigated, and JAXA has studied the spinning type [4,5]. The membrane is deployed and kept flat by spinning motion. This method is expected to be realized with simpler and lighter-weight mechanism than other ways, because it does not require rigid structural elements [6,7]. The centrifugal force is used for membrane deployment at the initial sequence after the launch as well as shape maintenance during the cruise phase.

The proposed deployment method of the sail is shown in Fig. 16. It consists of two stages. In the folded configuration, each petal is line-shaped and rolled up around the main body. In the first stage, the rolled petals are extracted like a Yo-Yo despinner, and form a cross shape. The shape is maintained by stoppers. In the second stage, the stoppers are released and each petal expands to form a square shape. If the first stage of the deployment is performed dynamically, each petal would be twisted around the main body just after the deployment. Therefore, the first stage of the deployment needs to be performed statically. On the other hand, the second stage of the deployment should be performed dynamically as shown in Fig. 17.

The deployment sequence is defined as follows:

1) Separation from rocket with slow spin (5rpm)
2) Spin down using RCS (5rpm -> 2rpm)
3) Release of launch lock
4) Spin up using RCS (2rpm -> 20rpm)
5) First stage of the deployment (20rpm -> 5rpm)
6) Second stage of the deployment (5rpm -> 2rpm)
7) Spin down using RCS (2rpm -> 1rpm)
8) Control of spin direction and rate using steering devices

The spin rate is decreased in the first and second stages of the deployment because the inertial momentum of the sail is increased.

Fig. 18. shows the results of numerical simulations [8]. Fig. 19. shows the mechanism to wind the sail onto deployment system. Fig. 20. shows the deployment tests.

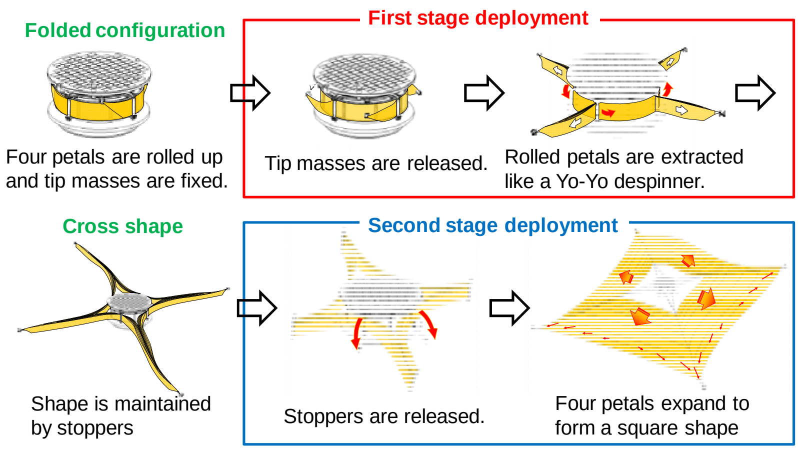


Fig. 16. Deployment method

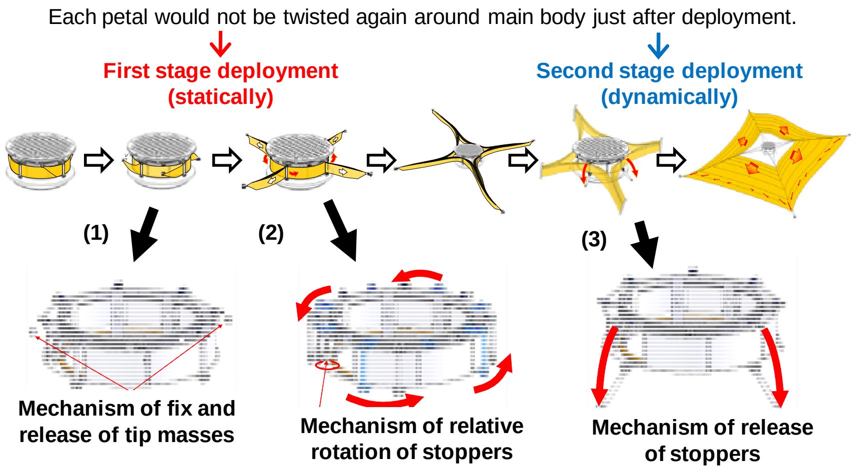
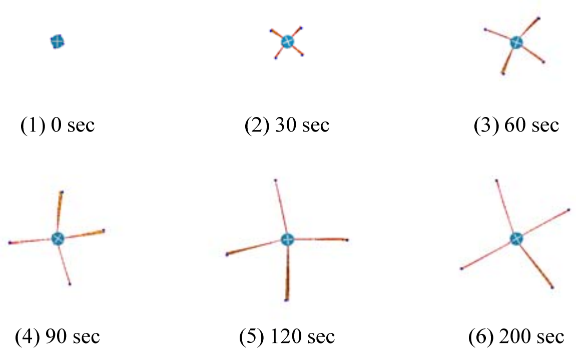
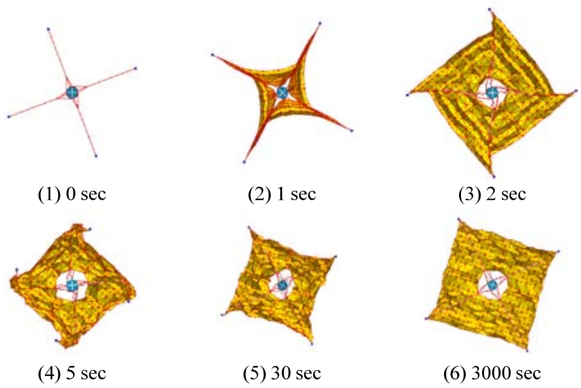


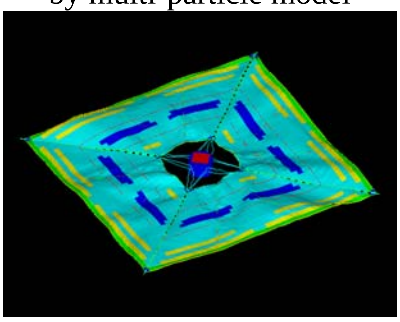
Fig. 17. Deployment mechanism



(a) Pictures of first stage of the deployment motion by multi-particle model



(b) Pictures of second stage of the deployment motion by multi-particle model



(c) Expansion state by finite element method model

Fig. 18. Deployment and expansion analysis

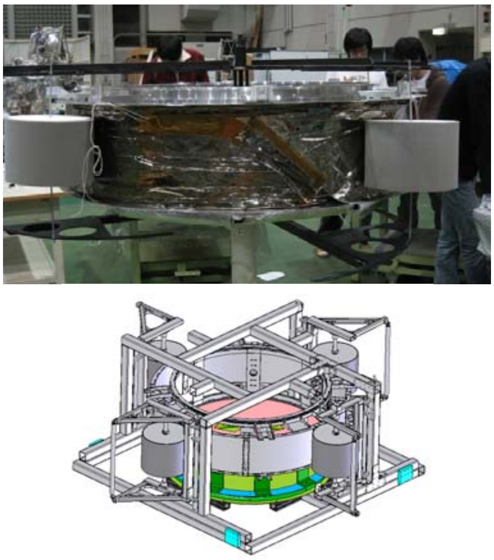
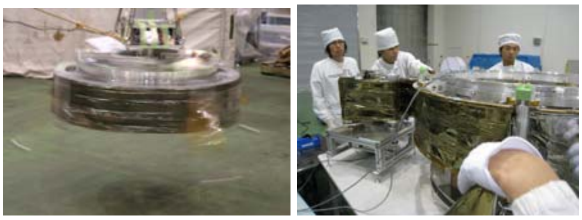
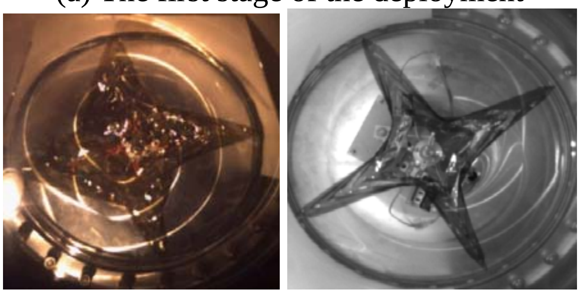


Fig. 19. Winding mechanism



(a) The first stage of the deployment



(b) The second stage of the deployment

Fig. 20. Deployment test

4.3 Extra payload

In addition to the components for the main mission, IKAROS has extra payloads for both science and engineering missions utilizing this interplanetary flight opportunity.
As science payloads, IKAROS has a gamma ray burst detector to observe polarization of gamma ray burst as shown in Fig. 21. and a dust detector to evaluate dust distribution in the inner planet region. As an engineering mission, IKAROS has a tone signal generator equipment to demonstrate the DDOR orbit determination technology. This is the key technology for the future deep space navigation.

(1) GAP (GAmma-ray burst Polarimeter)
- observe polarization of gamma-ray burst (GRB)
- determine the direction of GRB

(2) ALADDIN (Arrayed Large-Area Dust Detectors for INterplanetary cruising)
- evaluate dust distribution in the region of inner planets by PVDF (Poly Vinylidene Di-Fluoride) Piezoelectric Film

(3) VLBI mission
- DDOR (Delta Differential One-way Range) orbit determination technology demonstration

Fig. 21. GAmma-ray burst Polarimeter

4.4 Reaction control system

IKAROS uses Reaction Control System for attitude control (spinning-up/down and steering) as shown in Fig. 22. The gas-liquid equilibrium thruster system is developed for IKAROS RCS newly. The fuel is stored in tank as liquid state, and it is emitted as gas state as shown in Fig. 23. It takes advantage of vapor pressure. HFC-134a is selected as the fuel, because it is noninflammable and nonpoisonous. The thrust level is 0.4N, and the specific Impulse is 40s. They are dependent on the temperature. The total fuel weight is 20kg, and the total impulse is 7000Ns. The tank is filled with metal foam as shown in Fig. 24

- To store liquid fuel in tank.
- To stop fuel from sloshing in tank.
- To increase thermal conductivity in tank.

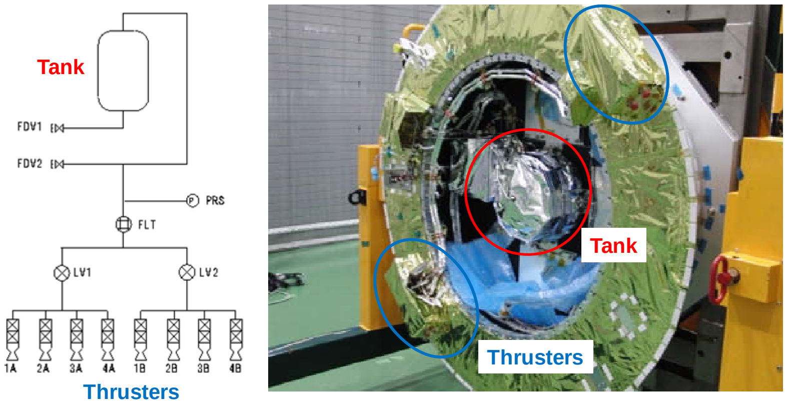


Fig. 22. Reaction Control System

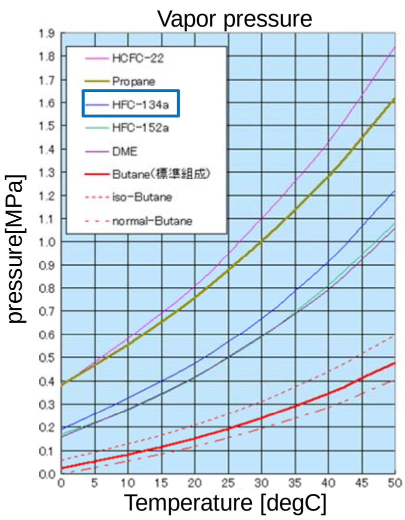


Fig. 23. Vapor pressure

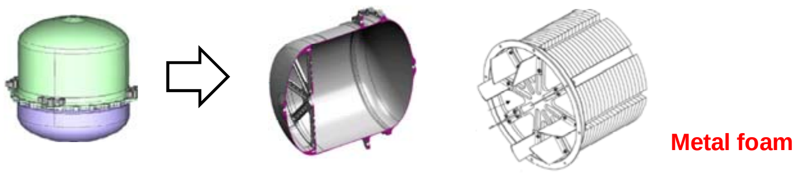


Fig. 24. Metal foam in tank

4.5 <u>Antenna</u>

IKAROS requires unique antenna pattern to avoid communication interference. Thus the antenna pattern was adjusted by reflection plate and height. The communication interference with the membrane was evaluated by the antenna pattern measurement using half size model as shown in Fig. 25.

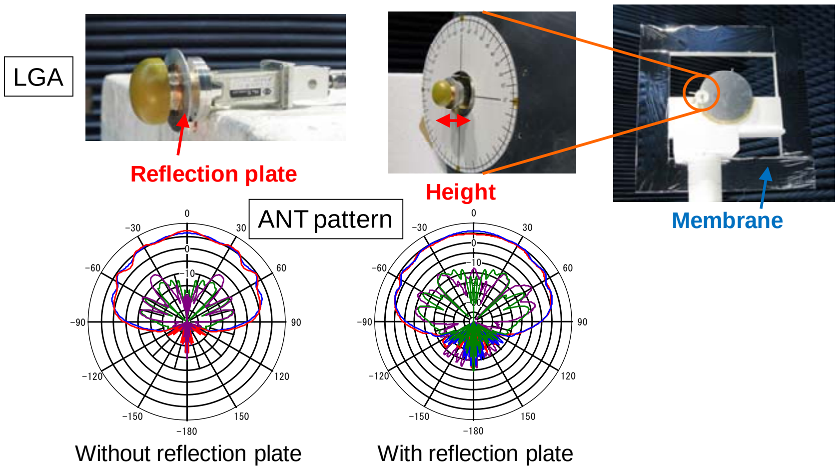


Fig. 25. Antenna pattern measurement

5. CONCLUSION

In this paper, it was reported that the Japan Aerospace Exploration Agency (JAXA) will launch the world's first solar power sail craft in 2010 together with its Venus Climate Orbiter, PLANET-C. It demonstrates both its photon propulsion and thin film solar power generation during its interplanetary cruise. This demonstrator attempts to deploy thin film solar cells on the membrane, in order to evaluate its thermal control property and anti-radiation performance in real operational field.

This paper introduces the major development component: sail, deployment system, extra payload, reaction control system and antenna. The flight hardware was fabricated and the integrated test was started in August, 2009. This will be the first actual solar sail flying an interplanetary voyage.

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