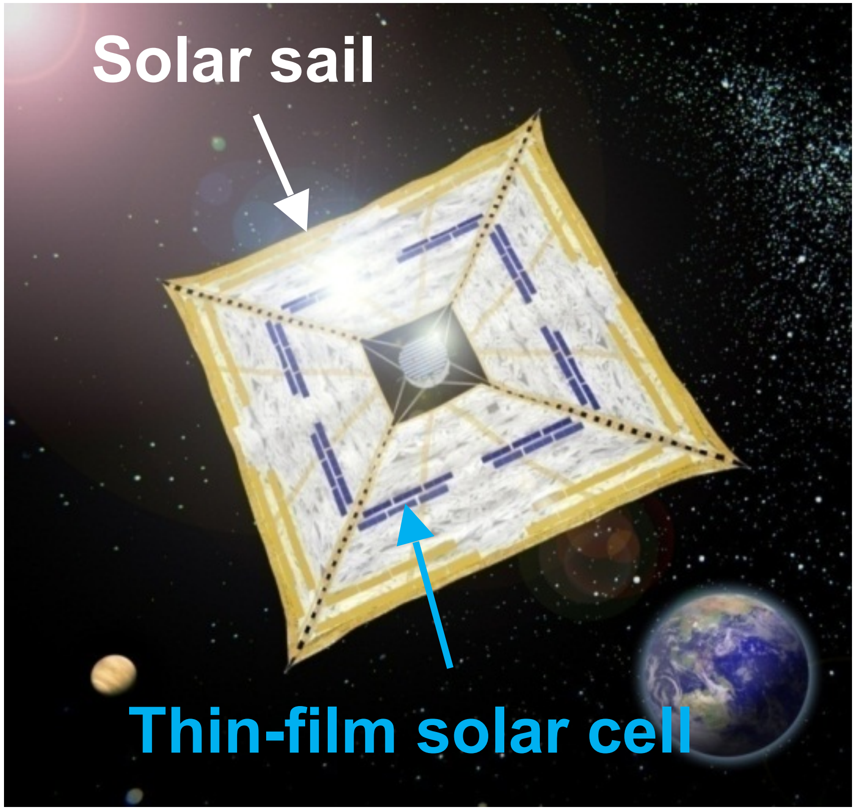
IKAROS and Solar Power Sail-Craft Missions for Outer Planetary Region Exploration

J. Kawaguchi (JAXA),

June 15, 2015

What is Solar Power Sail ?



A **Solar Sail** is a space yacht that uses the pressure of sunlight on a large membrane for propulsion.

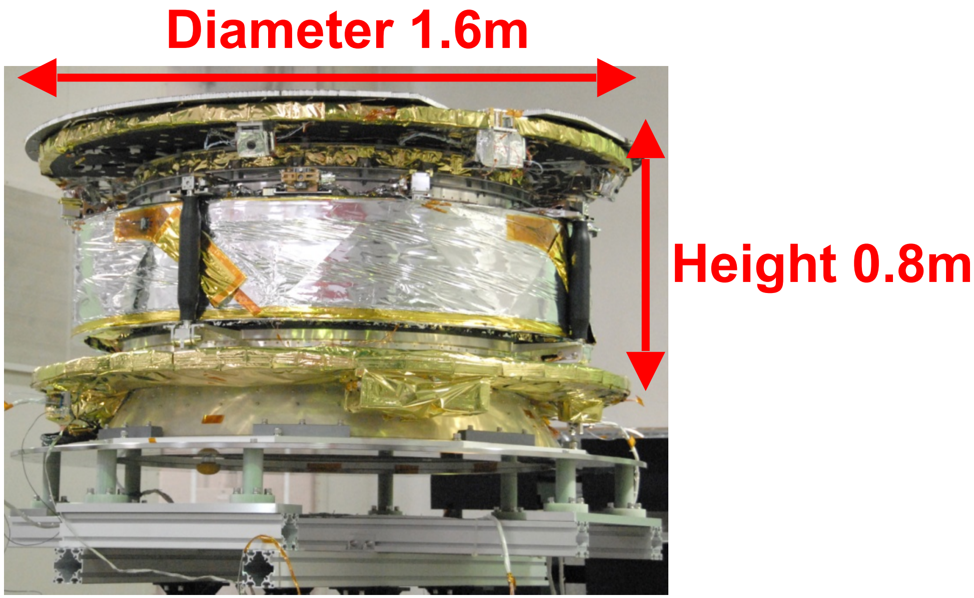
A **Solar Power Sail** is an original Japanese concept in which electrical power is additionally generated by **thin-film solar cells** on the sail membrane.

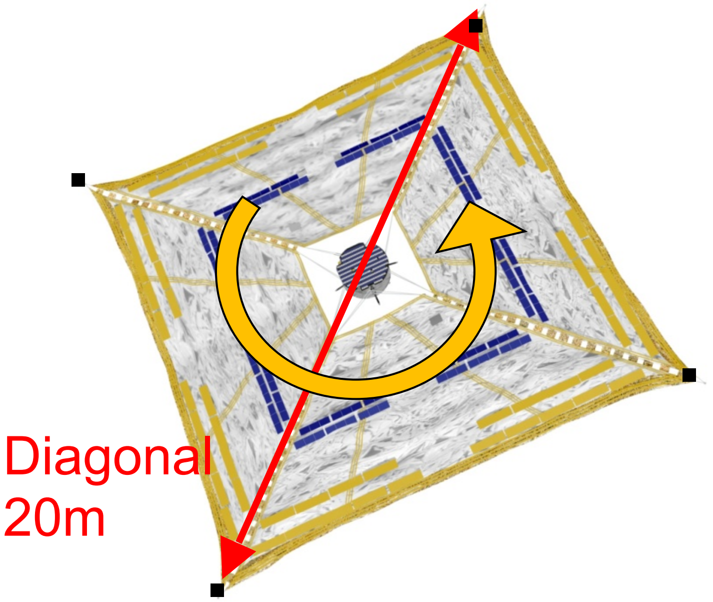
It is key technology for future outer solar system exploration, because it can **save fuel and generate high power at the point far from the Sun**.

What is IKAROS ?

JAXA developed the world's first solar power sail-craft which demonstrated for both its photon propulsion and thin-film solar power generation during its interplanetary cruise.

IKAROS = Interplanetary Kite-craft Accelerated by Radiation Of the Sun





- The main body is a spinner and the shape is simply cylindrical.
- Taking advantage of centrifugal force, the main body extends a square membrane sail whose tip-to-tip length is 20 meters long.

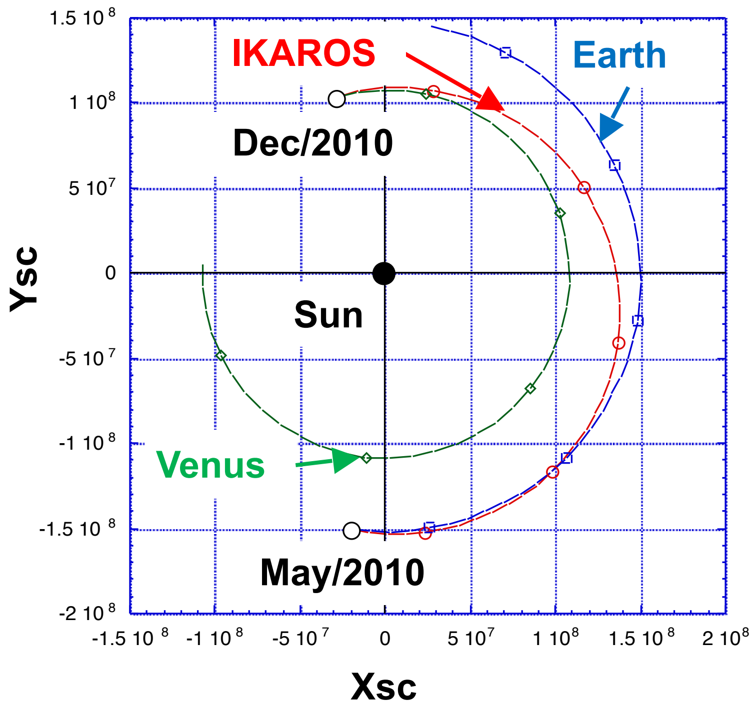
Total weight: 310kg (Sail: 15kg)

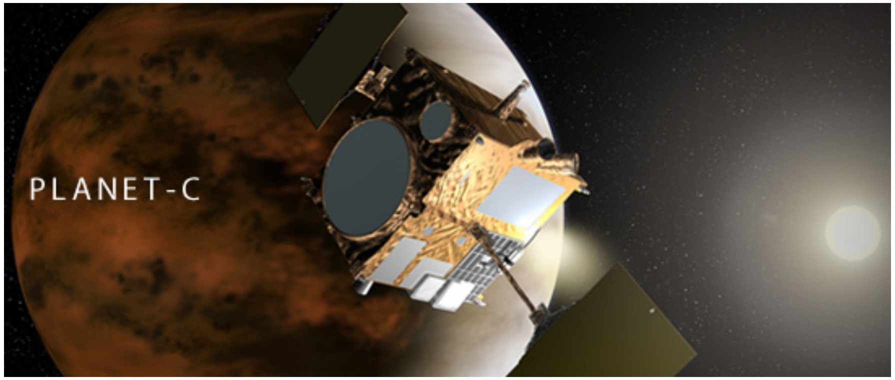
Trajectory

To achieve the missions 3 and 4,
air drag and gravity of the earth need to be ignored.

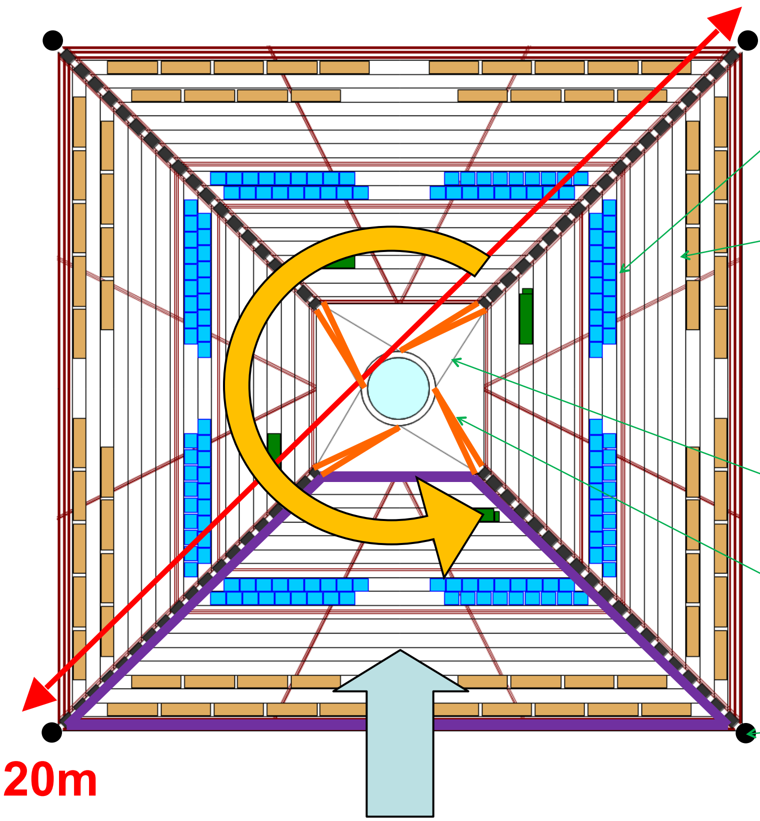
⇩

IKAROS was thrown into the interplanetary orbit
by launching together with the Venus Climate Orbiter "AKATSUKI".





Sail Design



Thin-film solar cells

Reflectivity control device

Liquid crystal is loaded near tips of sail to control the Sun angle

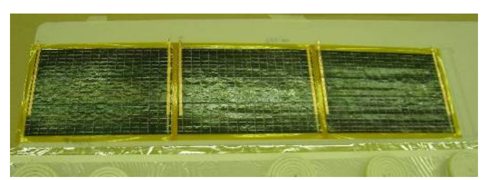
Tether

Harness

Connected main body and sail mechanically and electrically

Tip mass

A 0.5kg weight supports the spin deployment



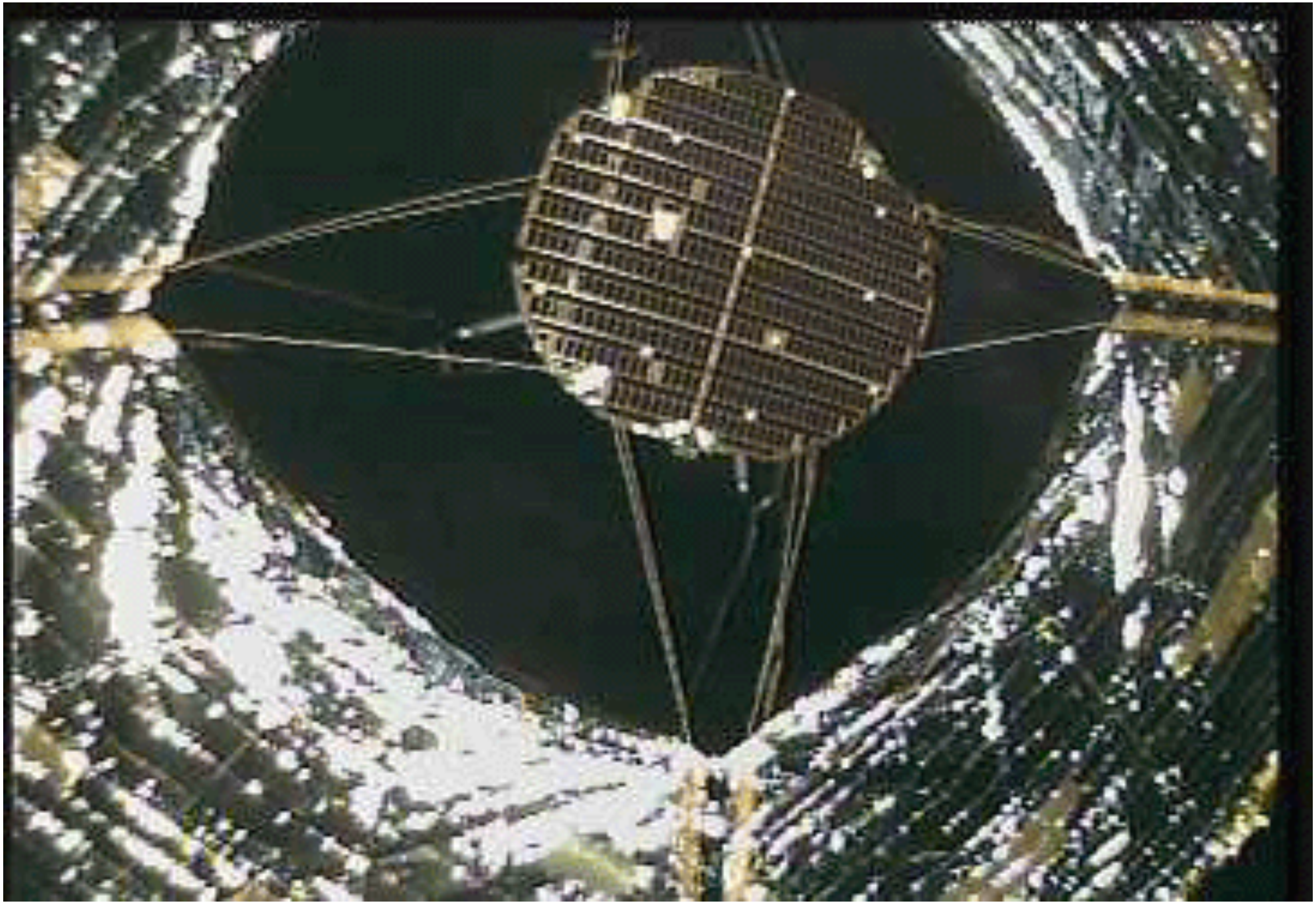
Amorphous silicon solar cells (25μm)

polyimide resin (7.5μm)

Summary of Operation Result

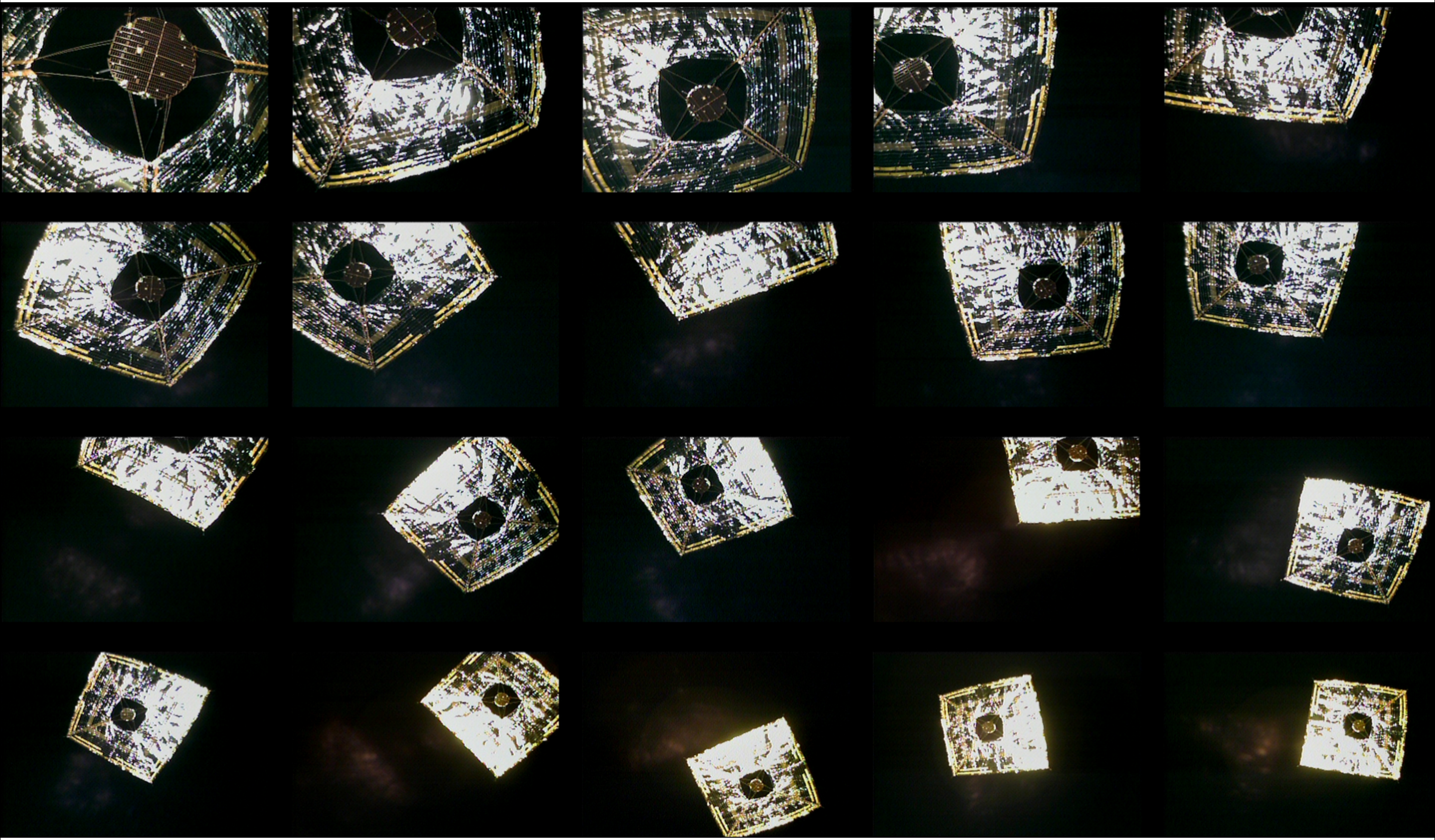
2010	May 21	Launch, Spin separation (=> 5rpm)
	May 23~25	Spin down (=> 2rpm)
	May 26	Tip mass separation
	May 27~31	Spin up (=> 25rpm)
	June 2~8	First stage deployment (=> 5rpm)
	June 9	Second stage deployment (=> 2.5rpm)
	June 10	Solar power generation through thin-film solar cells
	June 14	1st separation camera experiment
	June 16~18	Spin down (=> 1rpm)
	June 19	2nd separation camera experiment
	July 9	Demonstration of photon propulsion
	July 13	Attitude control experiment using reflectivity control devices
2011	December 8	Flying by Venus

Images taken by the First Separation Camera

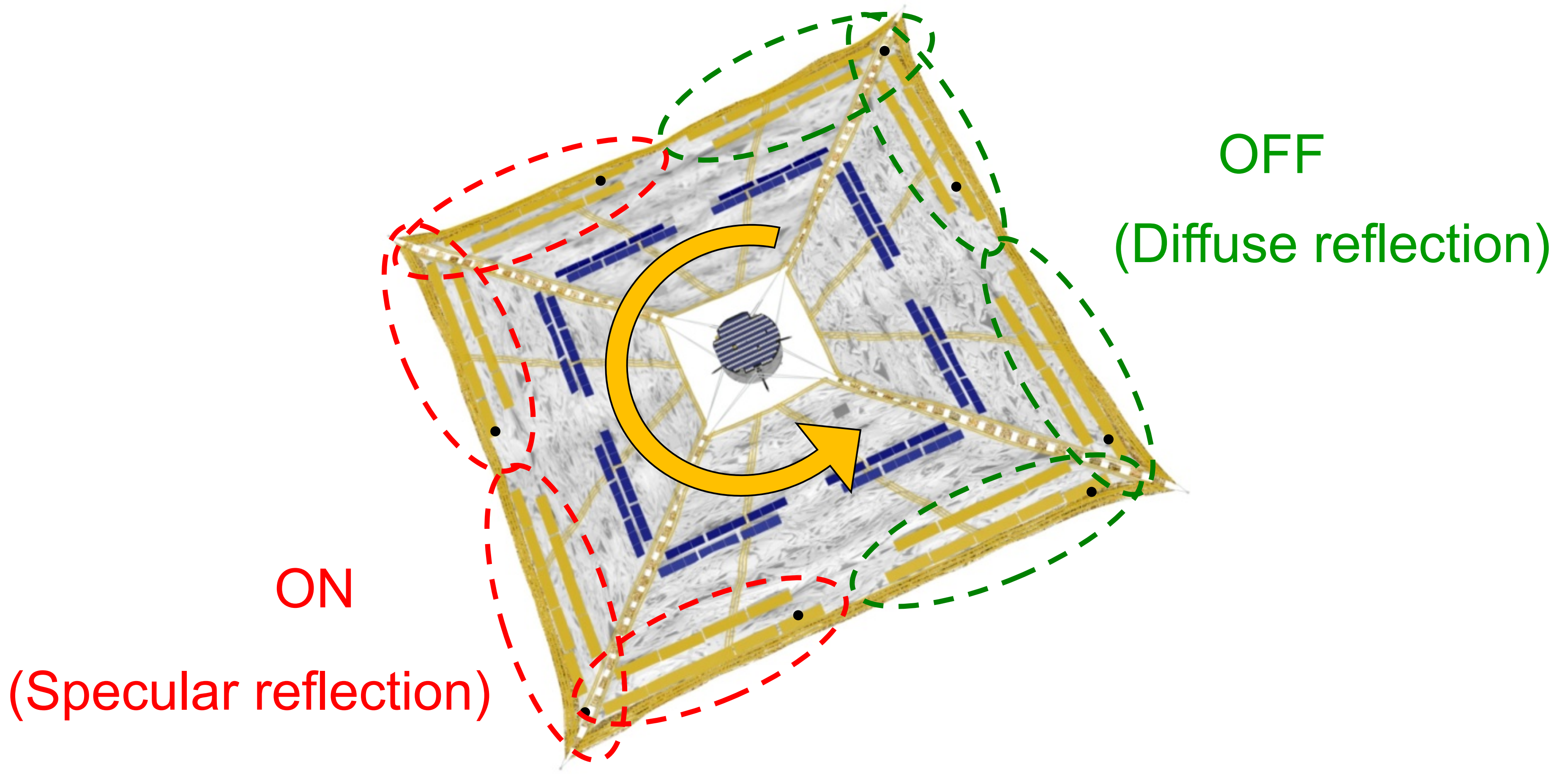


They are very impressive pictures.
The solar sail is shining in the dark space.

First Separation Camera Pictures

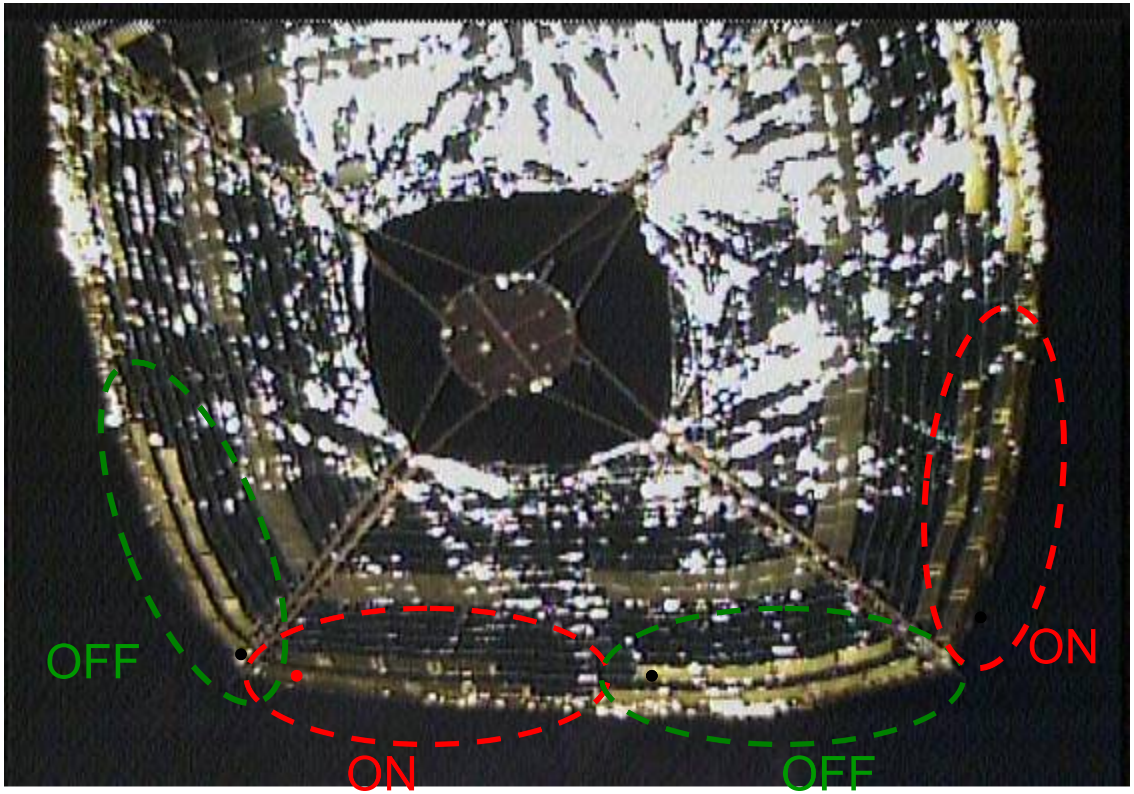


Attitude Control Method using Reflectivity Control Devices



To control the Sun angle, the reflectivity control devices need to be switched ON and OFF according to the spin rate.

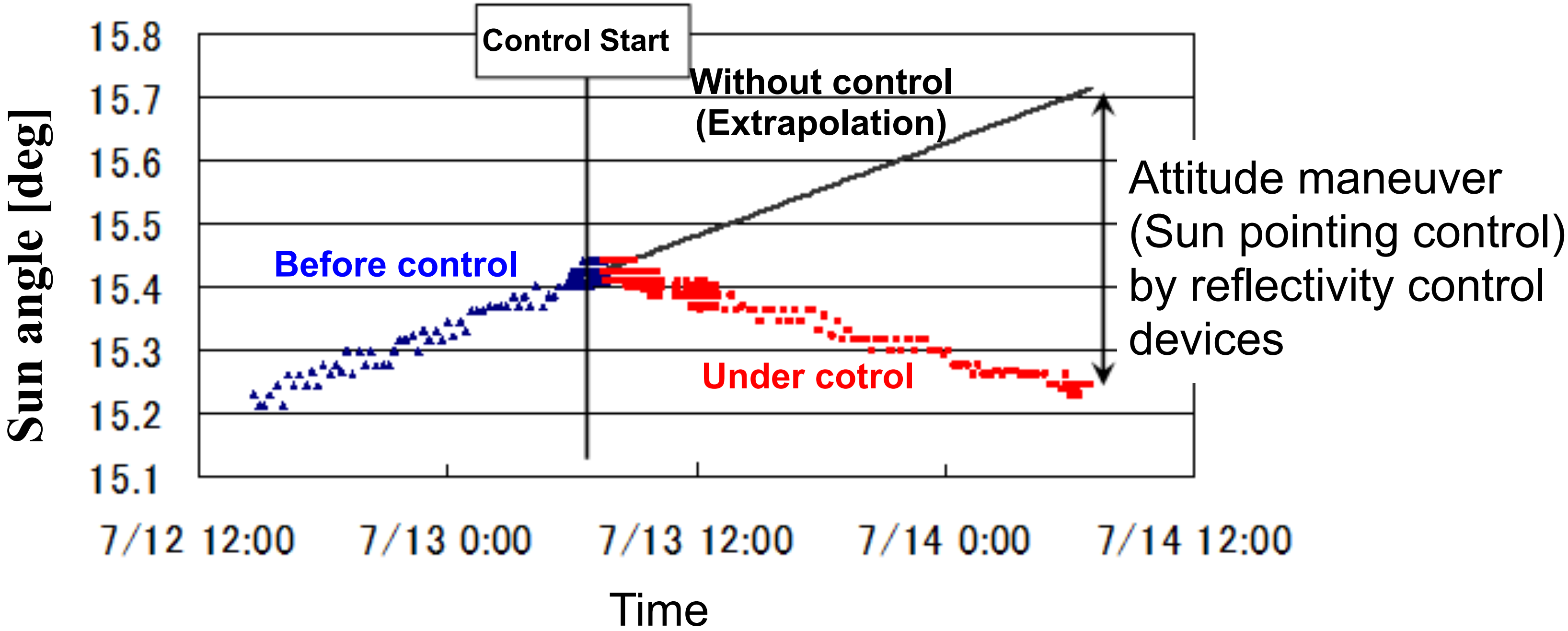
Reflectivity Control Test



(Specular reflection) (Diffuse reflection)

In this experiment, the appearance of the reflectivity control devices when they were ON and OFF on orbit was confirmed.

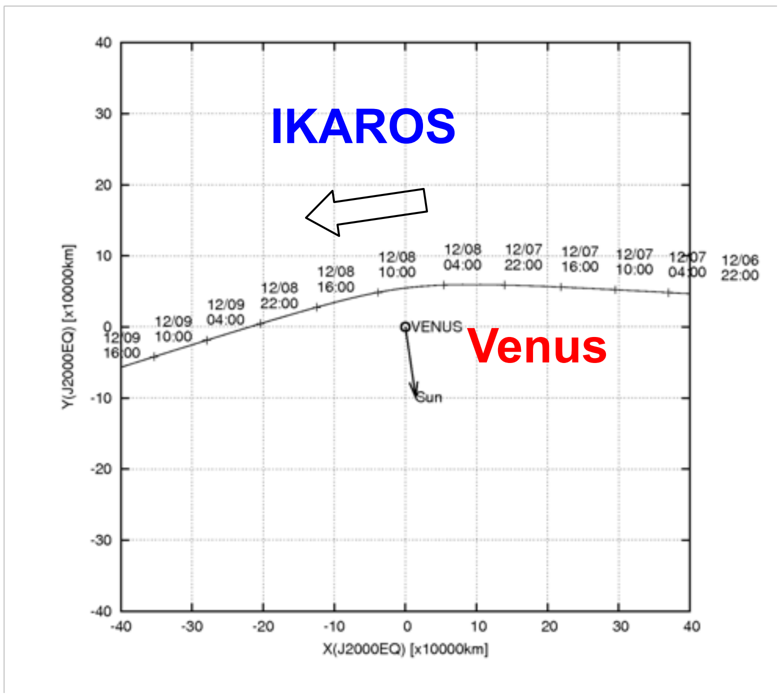
Attitude Control Result



- The Sun angle was gradually increasing without control, while it was decreasing when the reflectivity control devices were used to control the attitude toward the Sun direction.
- Very smooth attitude maneuver was achieved.

Flying by Venus

IKAROS flew by Venus on December 8, 2010.



Orbit

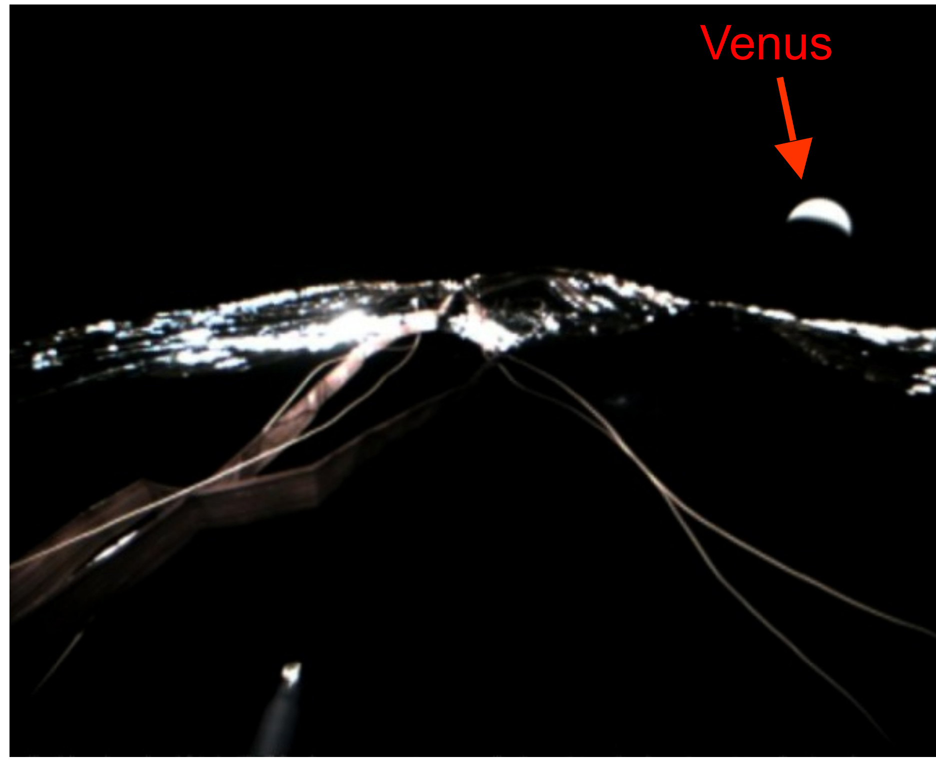
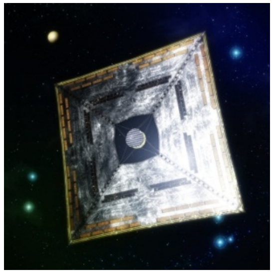


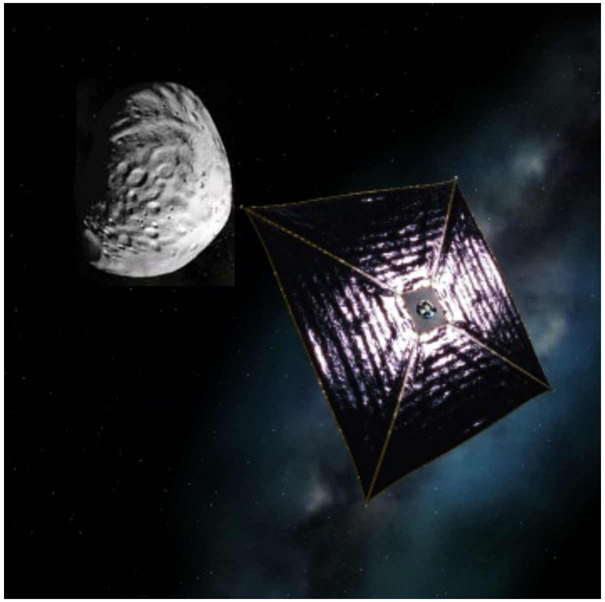
Image taken at the closest point by a side camera

Next Solar Power Sail Mission, Trojan Lander

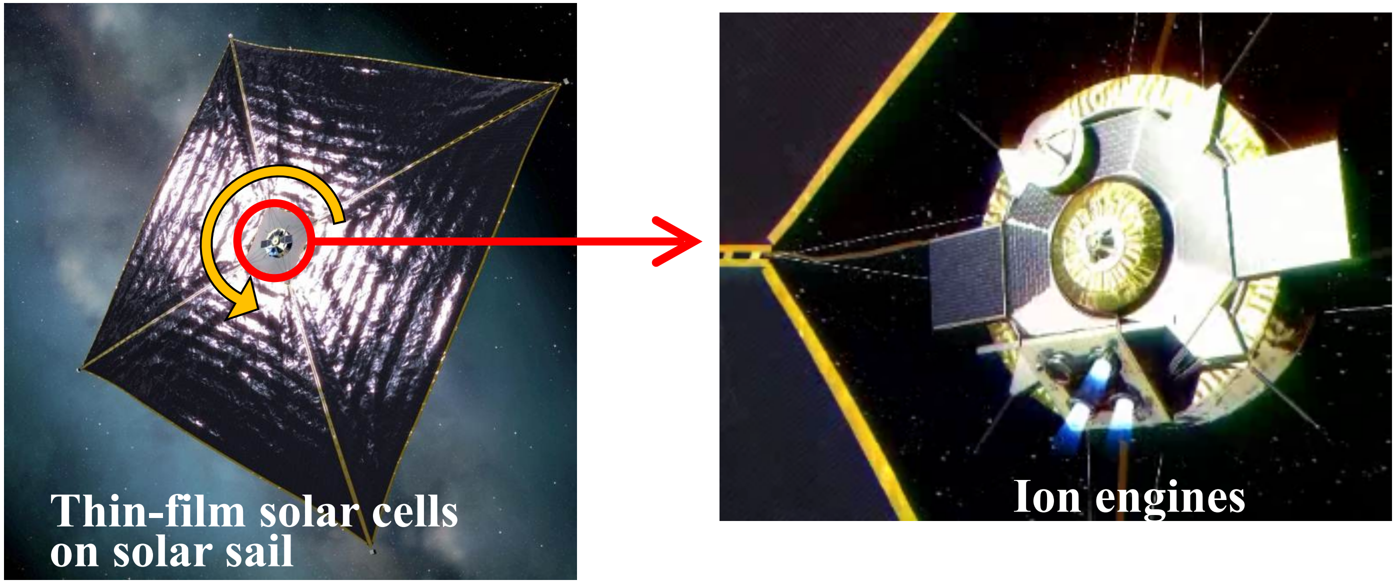
Solar power sail can be part of a hybrid propulsion system, with electrical power generated by thin-film solar cells being used to operate ion engines.
=> It is applicable to missions to the outer planetary region.

As a follow on to the IKAROS mission, we propose a demonstration mission of landing-round to Trojan asteroid using solar power sail.



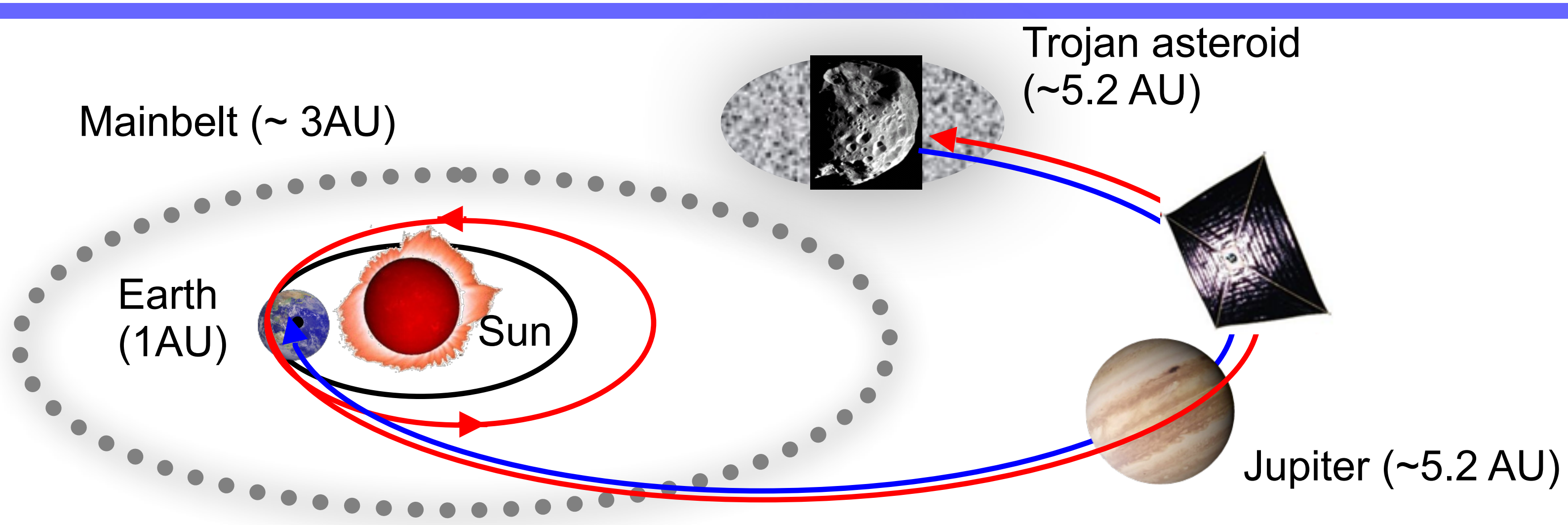


Solar Power Sail System



- The area of the sail is 2500 m^2,
  which is 10~15 times larger than that of IKAROS.
- To maintain the shape of sail membrane,
  spin rate is maintained at greater than 0.1 rpm.
- The spacecraft can generate large electric power
  using thin-film solar cells attached on entire surface of sail membrane.
- The specific impulse of the ion engine is 7000 sec,
  which is 2~3 times larger than that of the Hayabusa.

Mission Sequence



The spacecraft is supposed to be launched in early 2020s and make a world's first trip to Trojan asteroid using Earth and Jupiter gravity assist.
After arriving at Trojan asteroid, the lander is separated from solar power sail-craft to collect samples and perform in-situ analysis.
The lander delivers samples to solar power sail-craft for sample return mission (optional).

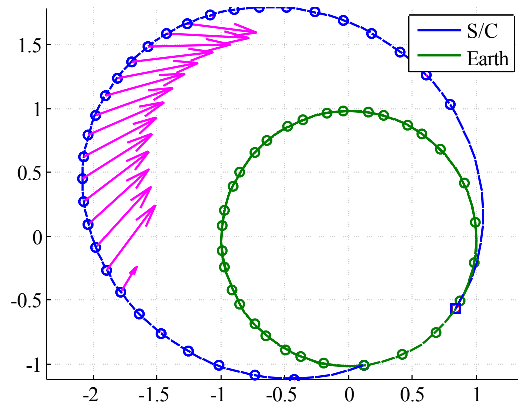
<Event>

1) Launch
2) Earth swing-by
3) Jupiter swing-by
4) Arrive at Trojan asteroid

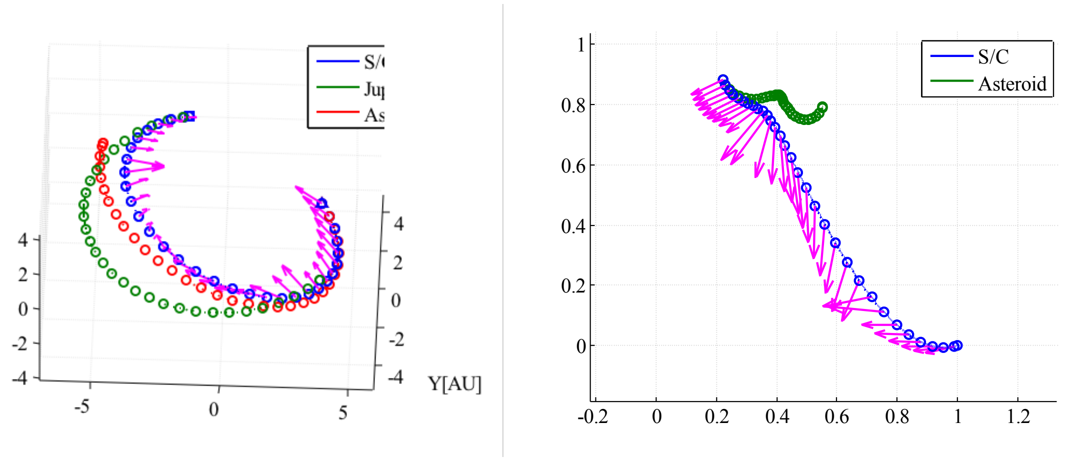
5) Depart from Trojan asteroid
6) Jupiter swing-by
7) Return to Earth

} optional

One Way Trip to 2007 RQ278 (L4)



2 yr EDVEGA



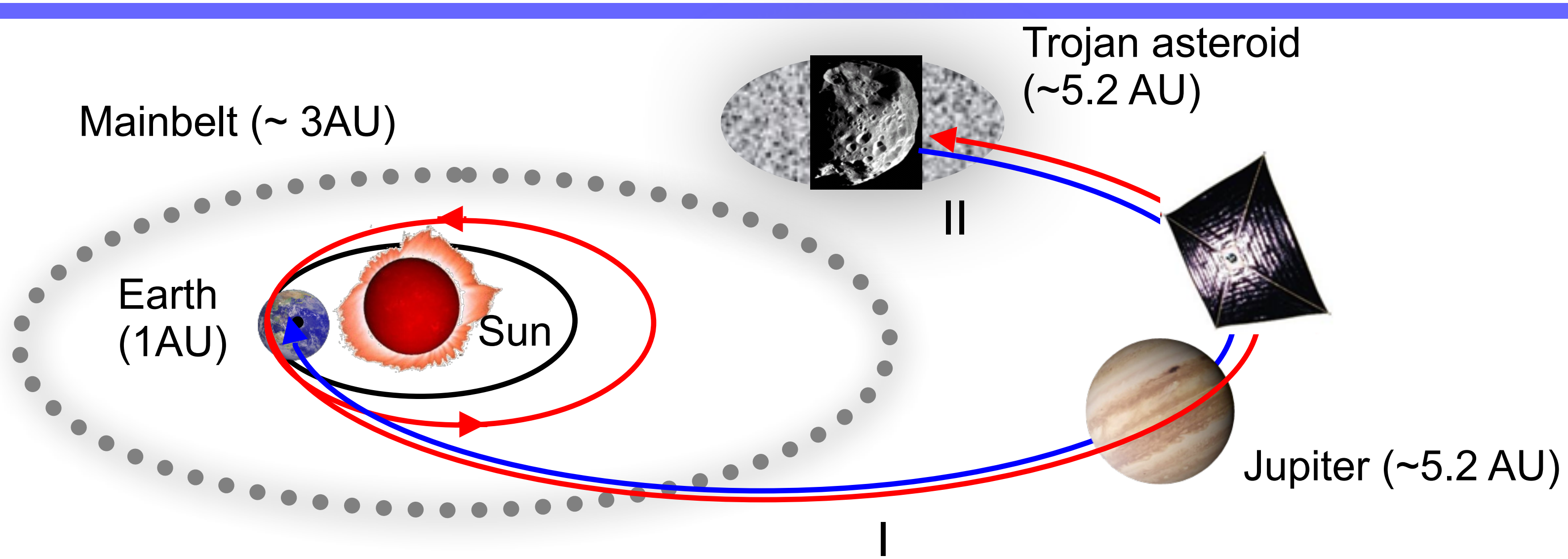
J2A

Phase	Start	End
2yr EDVEGA	9/8/2021	29/6/2023
Earth to Jupiter	29/6/2023	10/12/2025
Jupiter to Asteroid	10/12/2025	5/4/2033

In this case, it takes 11.7 years for arriving at Trojan asteroid.

The flight time can be reduced drastically by cancelling optional mission.

New Innovative Scientific Purposes



The mission has several **new innovative first-class planetary science and space physics objectives**. This spacecraft will perform infrared astronomy observations together with dust observation and will detect gamma-ray burst during its interplanetary cruise, as well as direct exploration of Trojan asteroid.

I. Cruising phase
(1) IR astronomy (CIB and zodiacal light obs.)
(2) Dust observation
(3) High-E astronomy (Gamma-ray burst)

II. at Trojan asteroid
(4) Rendezvous observation
(5) Sampling and in-situ analysis
(6) Sample return (optional)

New Technology Demonstrations

The solar power sail-craft will carry demonstrations of **new technologies that will be required for future solar system exploration**.

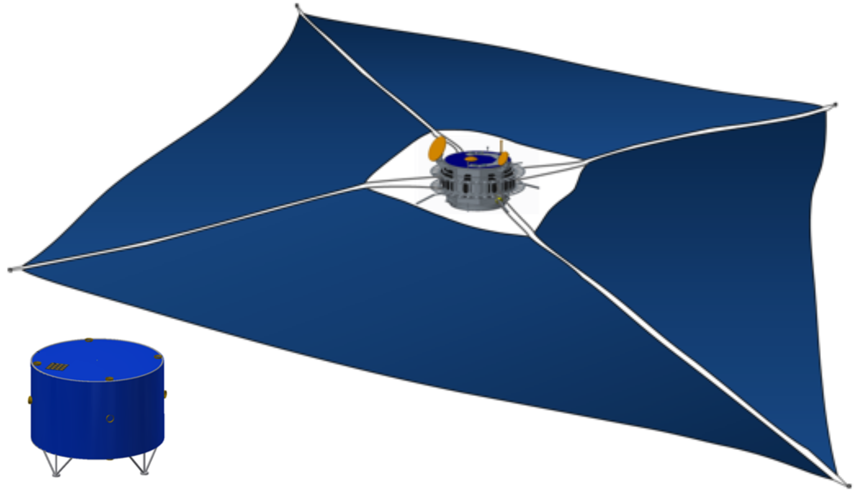
1. A large membrane space structure including deployment strategy,
2. Thin-film solar cells,
3. Reflectivity control device,
4. Hybrid propulsion using both solar sail and ion engines,
5. Ultra-high specific impulse ion engines,
6. Reaction control system capable of operation at very low temperatures,
7. Surface and underground sampling and in-situ analysis,
8. Rendezvous, berthing and handing over the asteroid sample (optional),
9. High speed re-entry capsule (optional)

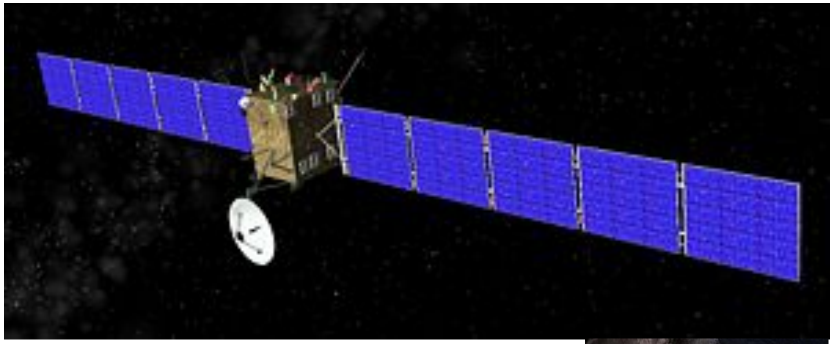
Summarized Major Characteristics

1. World's First Photon/Electric Hybrid Sail Propulsion,
2. World's Highest Performance Ion Engines,
3. World's First Background Emission Mapping,
4. World's First Access to Trojan Asteroid,
5. World's First Sample Analysis of Trojan Asteroid,
6. World's First Round Trip to Outer Solar System (optional)
7. World's Highest Speed Re-entry Capsule (optional)

Design of Solar Power Sail-craft

Minimum Delta-V Case(2002 VH107)			remark
Isp of ion engine system	sec	7172	
IES thurust	mN/unit	26.1	
Number of ion thruster	unit	6	
IES power(5.2AU, sun angle = 0deg)	W	2600	
Required power (5.2AU, sun angle = 0deg)	W	6494	
Delta-V(EDVEGA)	m/s	1500	2002 VH107
Delta-V(J2A)	m/s	1500	2002 VH107
Delta-V(A2J)	m/s	2000	2002 VH107
IES operation time	hr/unit	11588	
Ion engine system	kg	80.0	
Ion engine system tank	kg	6.8	
Sail deployment structure	kg	118.7	D=1.6m
Solar power sail & tip mass	kg	204.6	
Bus instrument	kg	150.0	
Chemical engine system(RCS)	kg	30.0	
RCS tank	kg	17.5	
Lander	kg	100.0	include margin
Mission instruments+Re-entry capsule	kg	50.0	
Structure	kg	180.0	wet * 0.15
Option	kg	47.8	
IES propellant	kg	85.2	
RCS propellant	kg	129.4	
Dry weight	kg	985.4	
Wet weight	kg	1200.0	





Solar power sail-craft of about 1.2 ton will transport the lander of 100kg to Trojan asteroids.
On the other hand, Rosetta of about 3 ton transported the Philae of the same 100kg to the comet, which is closer than Trojan asteroids.
→This difference indicates the superiority of the solar power sail.