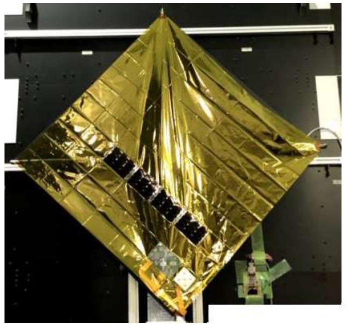
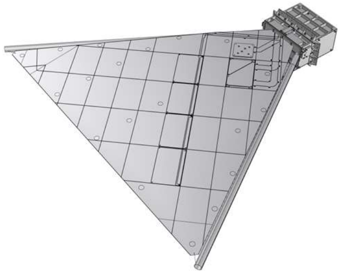
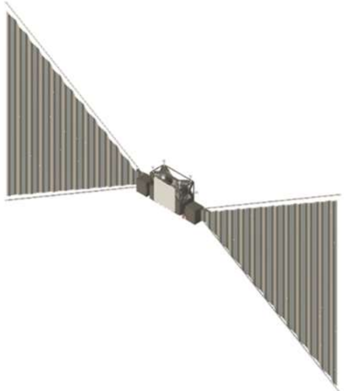
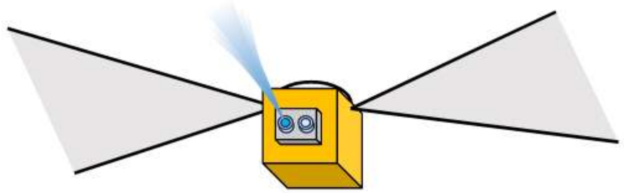
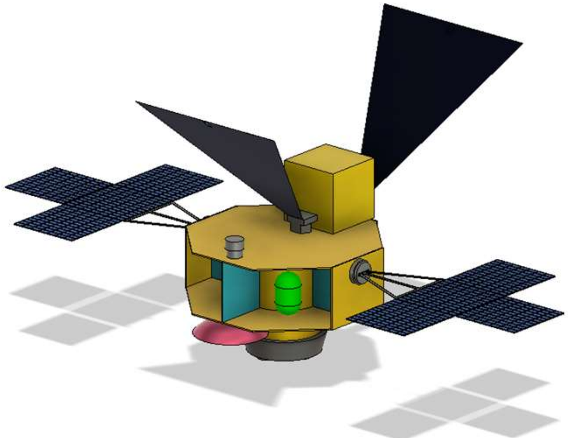
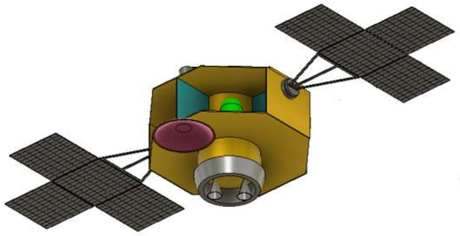
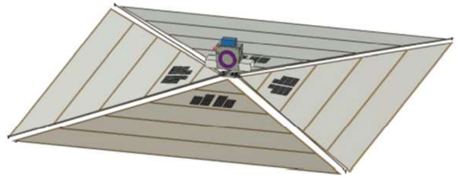
New Solar Power Sail Program in the Post-OKEANOS Era

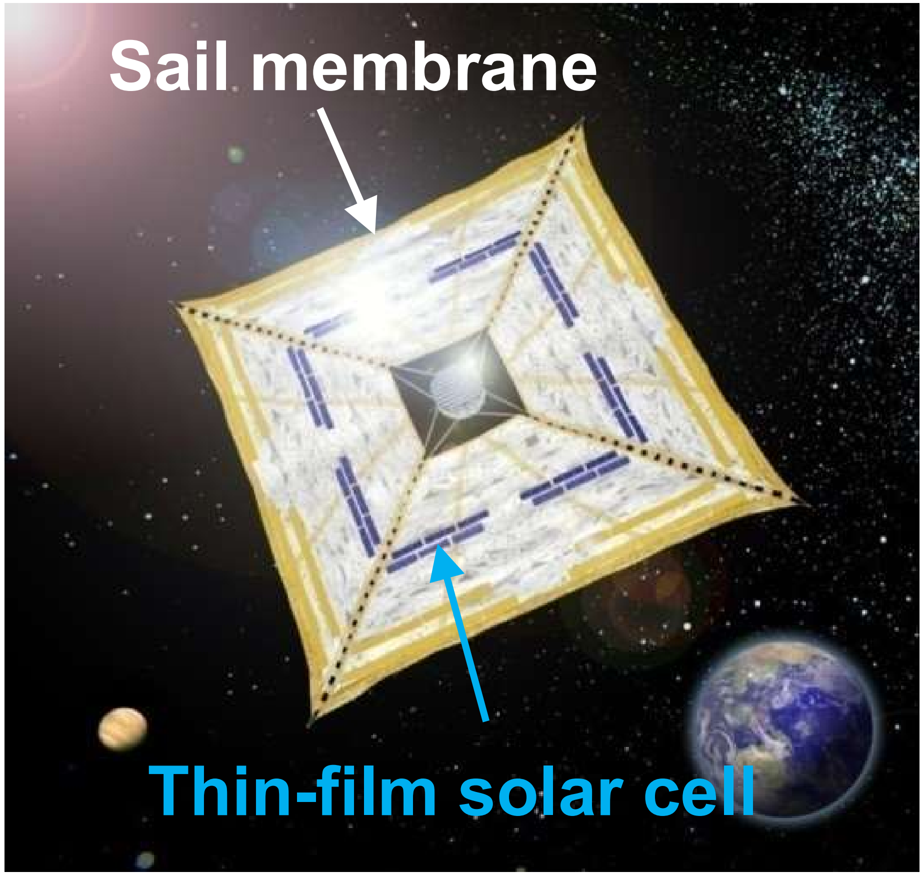






O. Mori, M. Matsushita, A. K. Sugihara, Y. Takao, T. Chujo, Y. Miyazaki, Y. Satou, N. Okuizumi, H. Sakamoto, R. Funase, N. Ozaki, Y. Kubo and A. Watanabe

What is Solar Power Sail ?

Solar Sail
Spacecraft can be propelled without fuel by SRP (Solar Radiation Pressure).

Solar Power Sail (original Japanese concept)
Electrical power is generated by thin-film solar cells on the sail membrane.



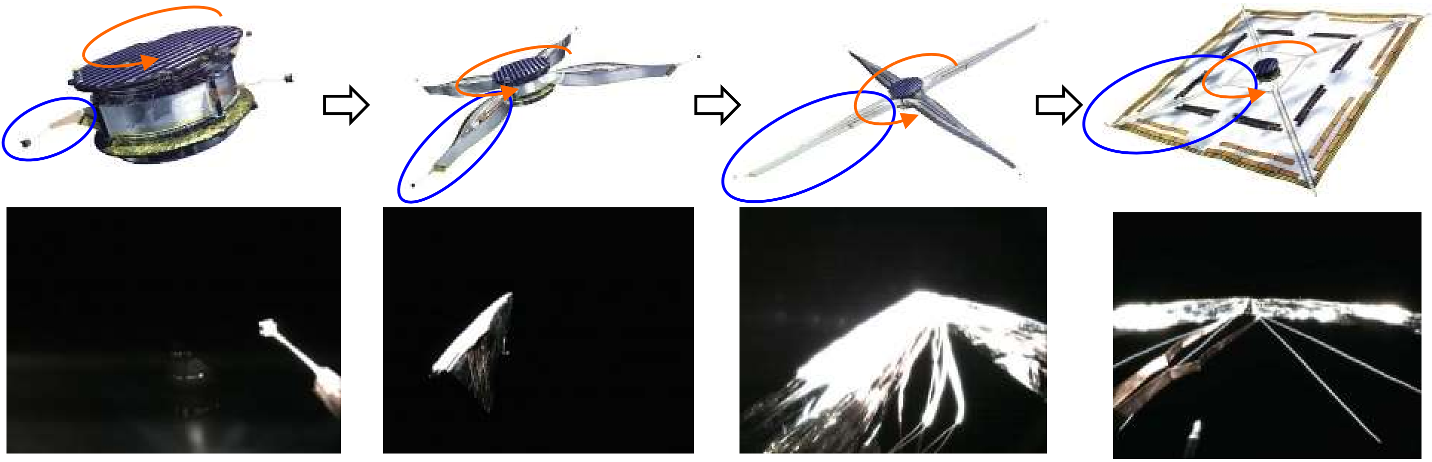
Solar power sail

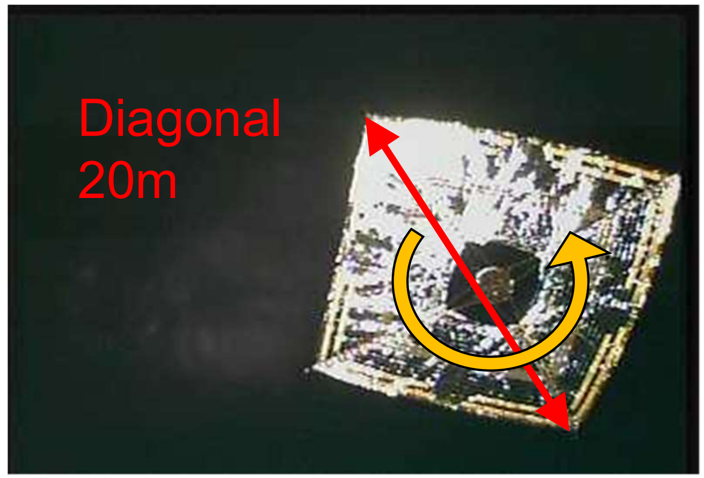
What is IKAROS ?

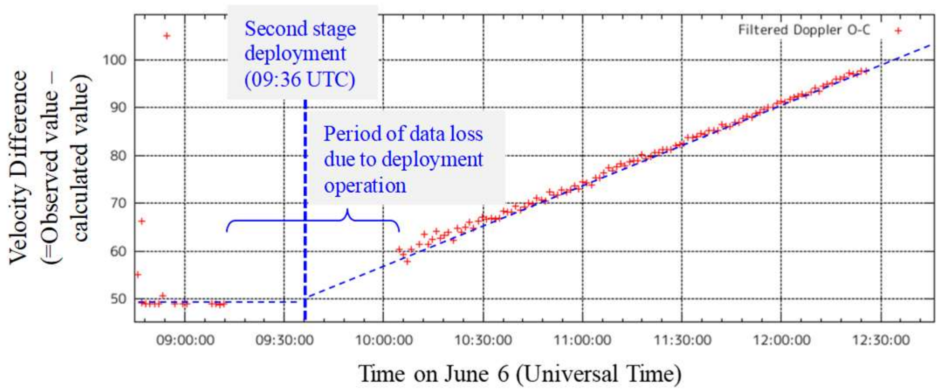
JAXA developed the world's first solar power sail-craft **IKAROS**.

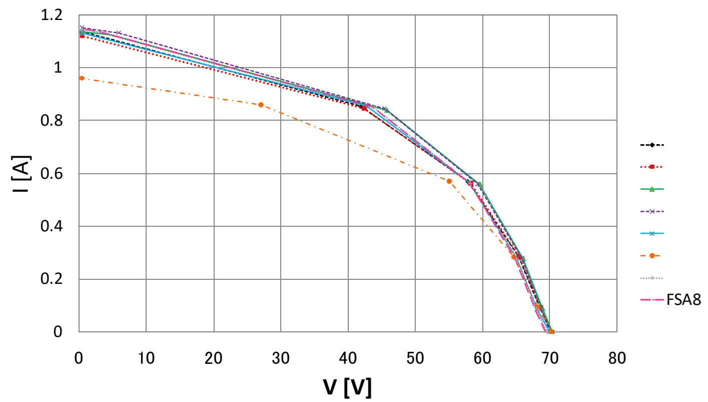
- The main body is a spinner and the shape is simply cylindrical.
- Taking advantage of centrifugal force, the main body extends a square membrane sail whose tip-to-tip length is 20 meters long.

IKAROS demonstrated for both its photon propulsion and thin-film solar power generation during its interplanetary cruise.



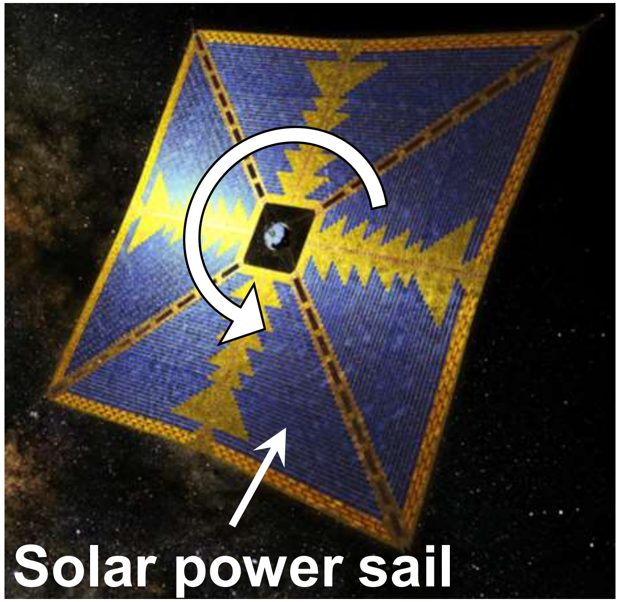






OKEANOS System

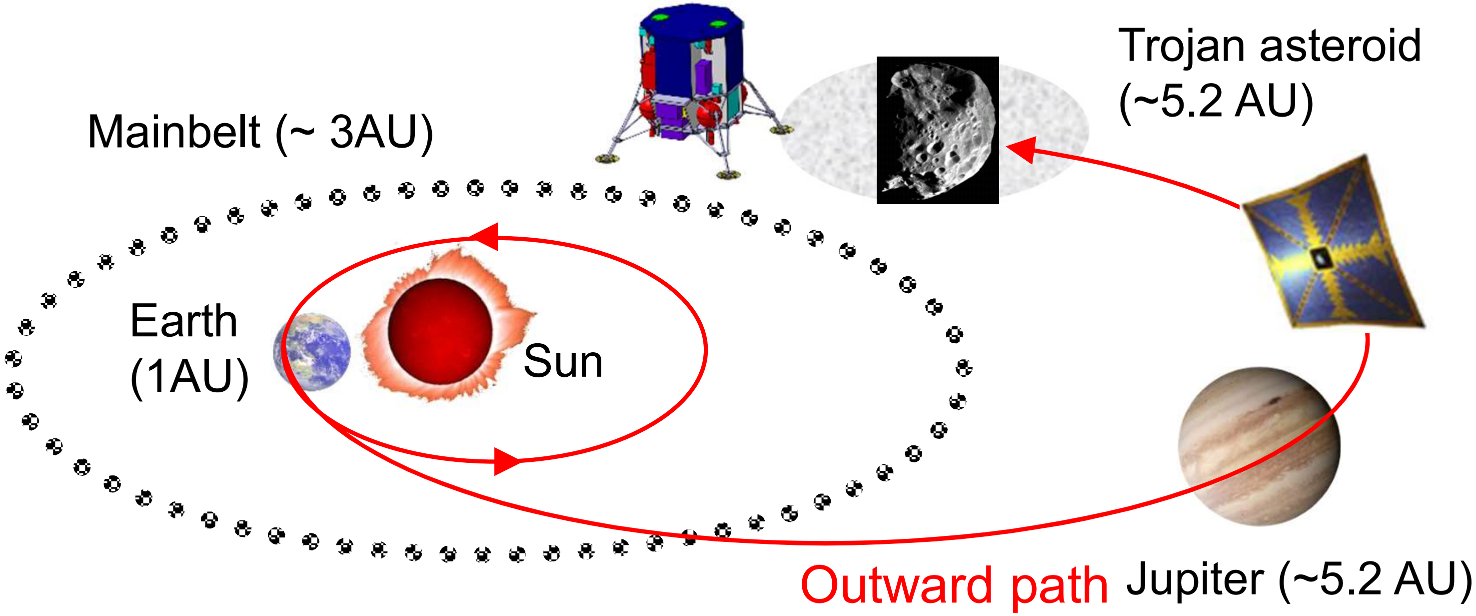
Solar power sail can generate sufficient power by large area thin-film solar cell to drive high-Isp ion engine in outer planetary region.
=> solar power sail-craft OKEANOS

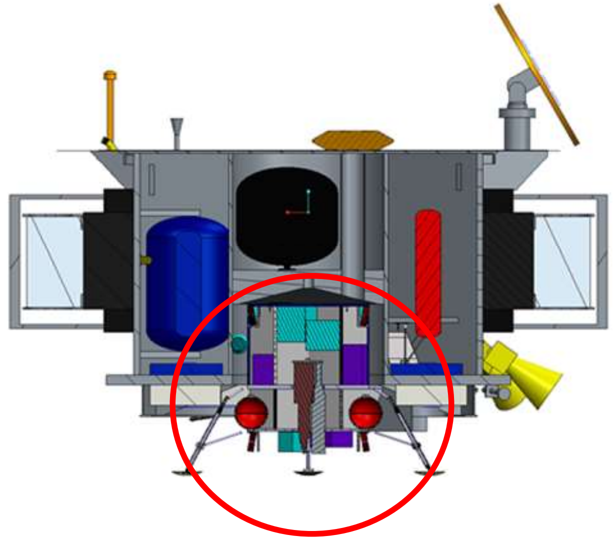


<Solar power sail>
- Spin-type sail: 2000 m^2 (10 times larger than that of IKAROS)
- Electric power: 5 kW @ 5.2 AU (10 times larger than that of Juno)

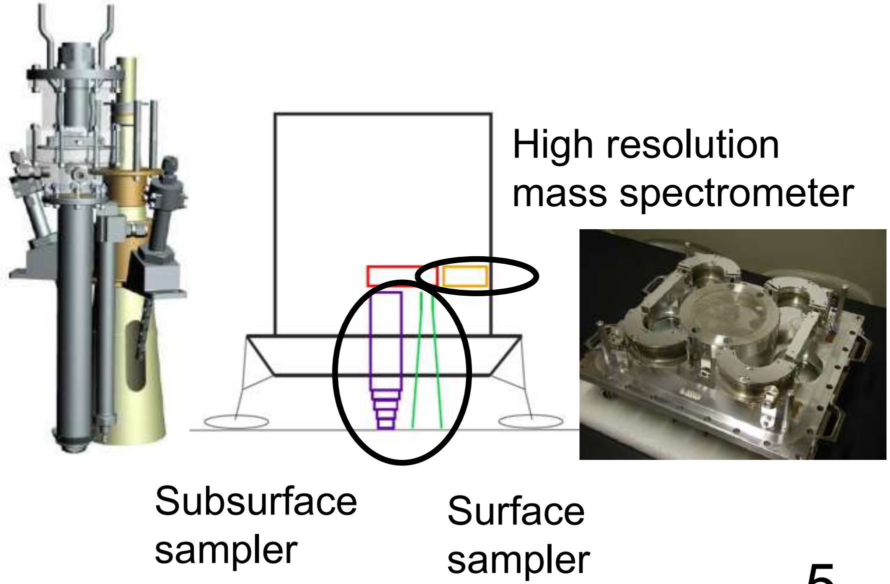
<High-Isp ion thrusters>
- Isp: 6800 seconds (2 times higher than that of Hayabusa2)
- ΔV: 4000~6000 m/s in the outer planetary region

OKEANOS Mission

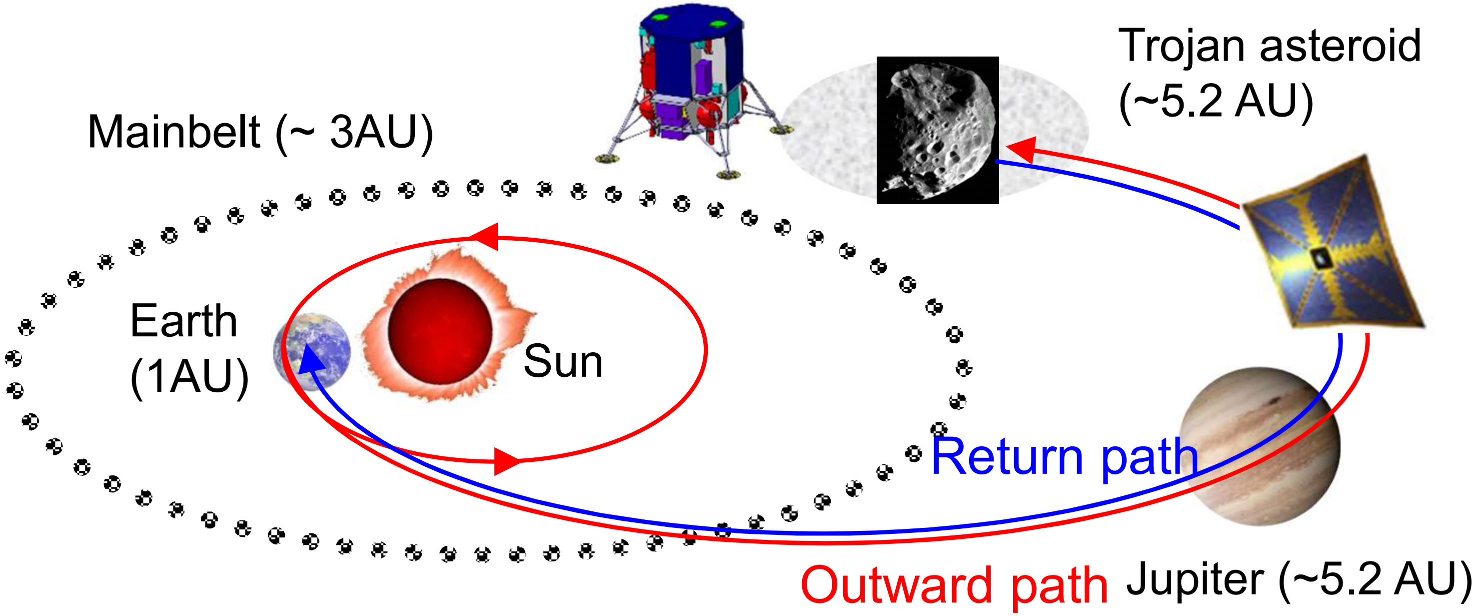


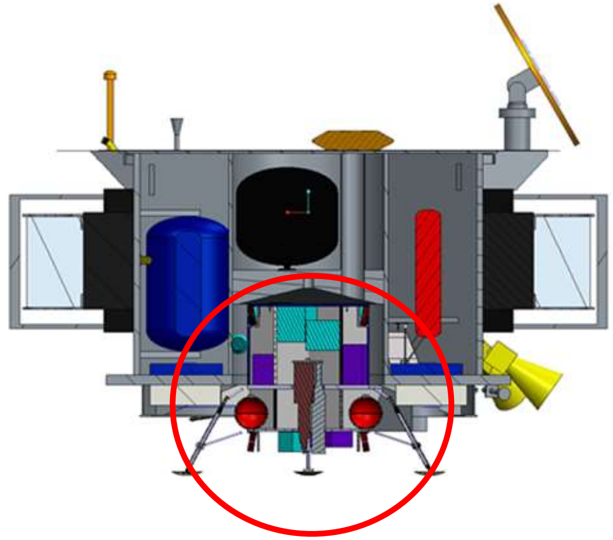


- A solar power sail-craft OKEANOS is supposed to rendezvous with a Trojan asteroid using both Earth and Jupiter gravity assists.
- It is difficult for the sail-craft, which has a large sail and spins, to land on a Trojan asteroid directly. A lander is separated from the sail-craft to land, collect surface and subsurface samples and perform in-situ analysis.



OKEANOS Mission





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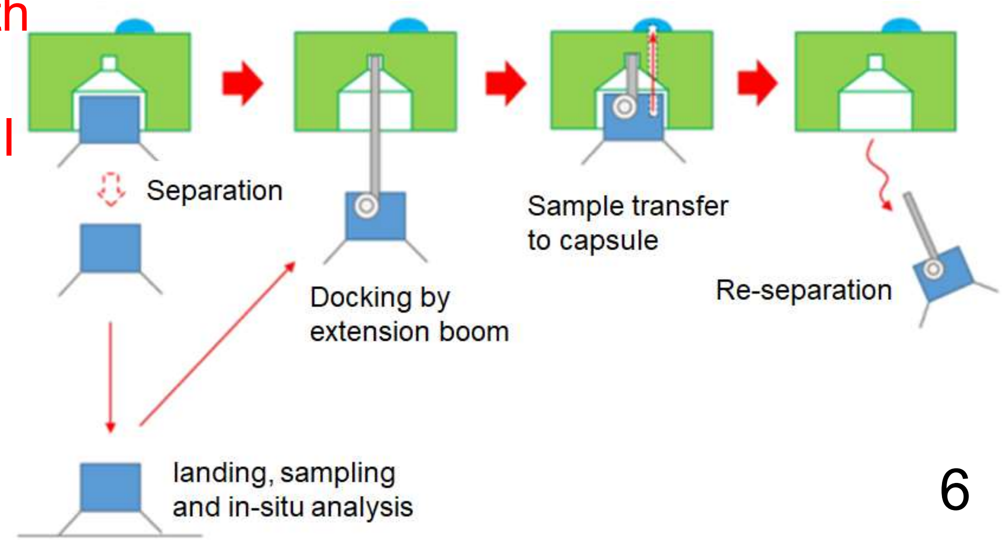
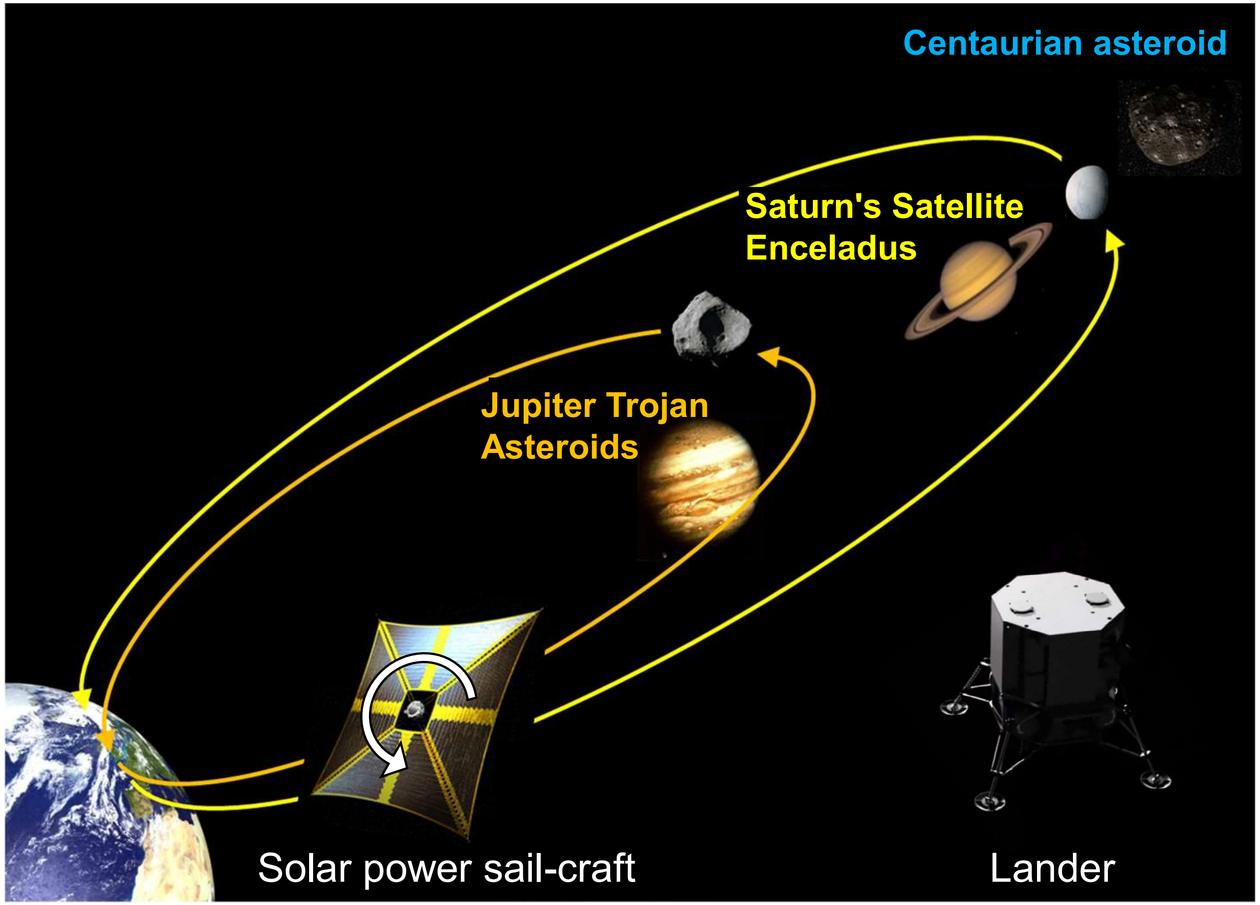
- It is difficult for the sail-craft, which has a large sail and spins, to land on a Trojan asteroid directly. A lander is separated from the sail-craft to land, collect surface and subsurface samples and perform in-situ analysis.
- The lander delivers samples to the sail-craft for sample return to Earth.



Solar Power Sail-craft and Lander



A solar power sail-craft: rendezvous and make a round trip to outer solar system
A lander: landing, sampling, in-situ analysis and delivering samples
=> The combination is the only solution for sample return from Trojan asteroids.
OKEANOS has not selected for JAXA strategic L-class mission due to cost issues.
The solar power sail and lander can contribute to the other exploration missions.
=> New solar power sail and lander concepts for new solar power sail program

New Concepts for Solar Power Sail

1) Boom-type sail methods for small spacecraft

- Central Hub Method
- Fixed Boom Method
- Coupling Boom Method
- Truss Boom Method
- Two Side Boom Method

The sail size is smaller than $100m^2$ due to the limitation of deploying boom. Even this size is large enough for small spacecrafts.

2) Attaching various devices to sail

- Thin-film solar cell (for thin-film solar array paddle)
- Array antenna (for high-capacity communication)
- Interferometer (for high-resolution observation)
- Reflective sheet (for deployable target marker)

3) Changing sail configuration for orbit and attitude control by SRP

- Gimbal
- SMA (Shape-Memory Alloy)
- Spin centrifugal force

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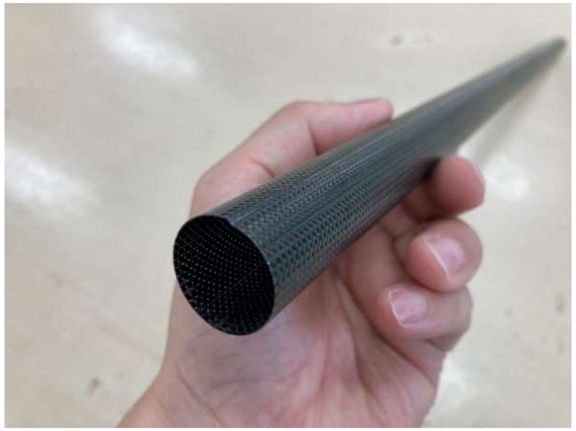
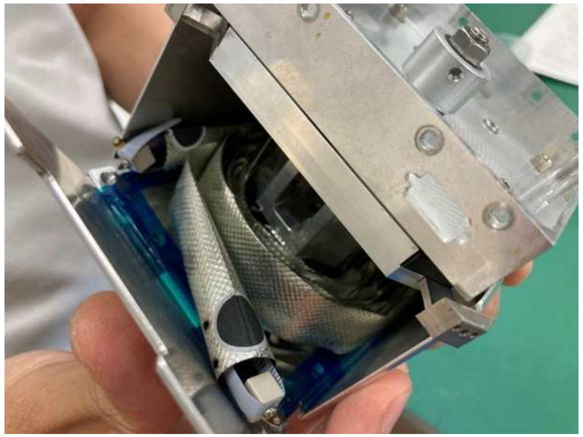
1-1) Central Hub Method

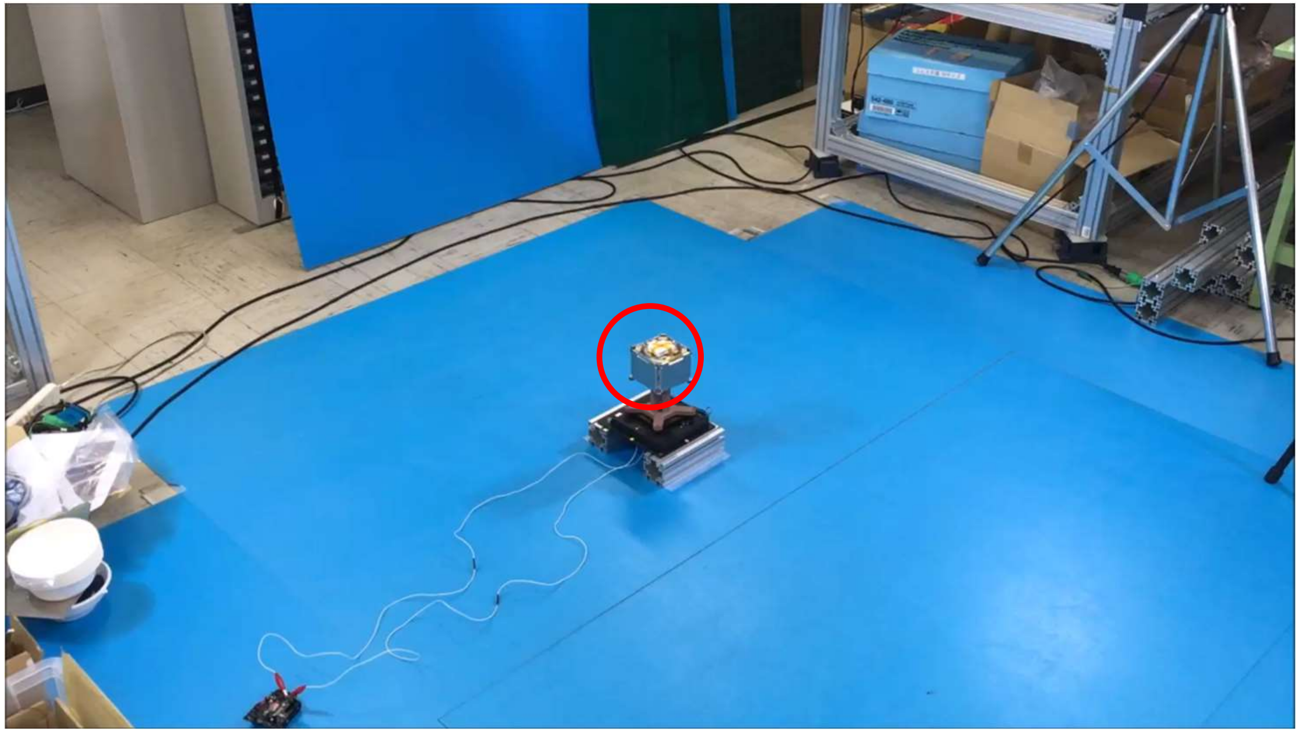
- Four CFRP cylindrical booms are wrapped around the central hub.
- These booms self-extend to deploy the sail quickly around the hub.

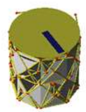


CFRP Cylindrical boom



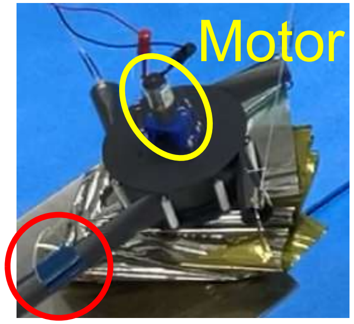
Central hub



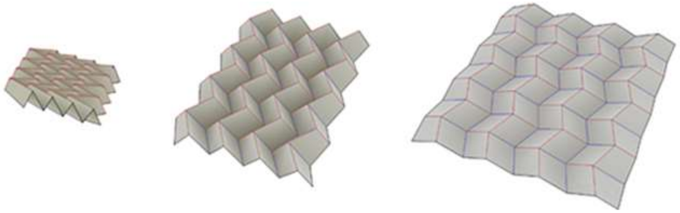


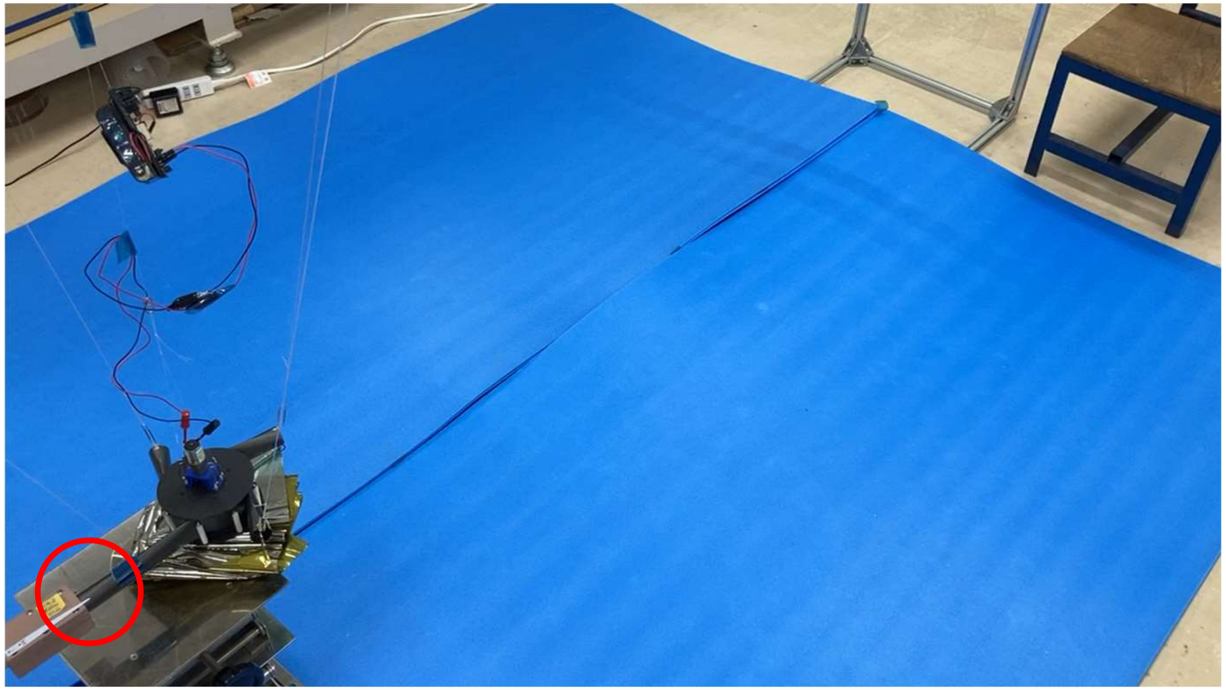
1-2) Fixed Boom Method

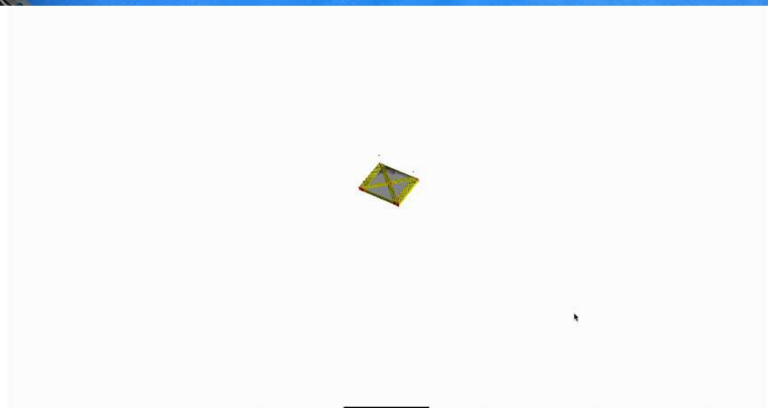
- One end of these booms is fixed.
- A motor extends four booms synchronously to deploy the sail quasi-statically.
- This method is used in the HELIOS mission.



Fixed boom

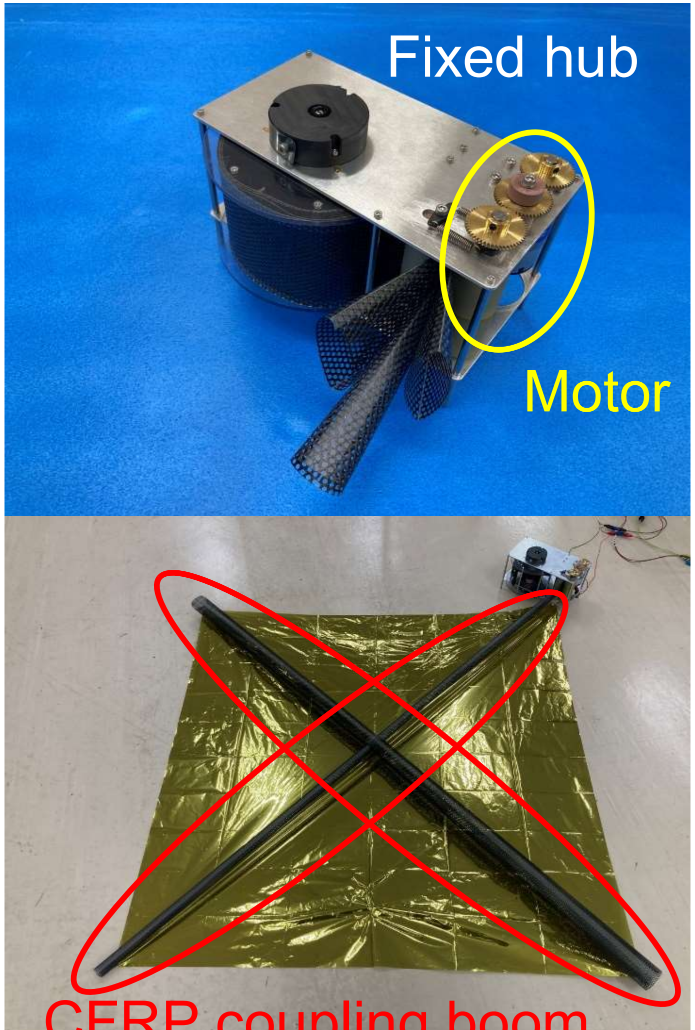






1-3) Coupling Boom Method

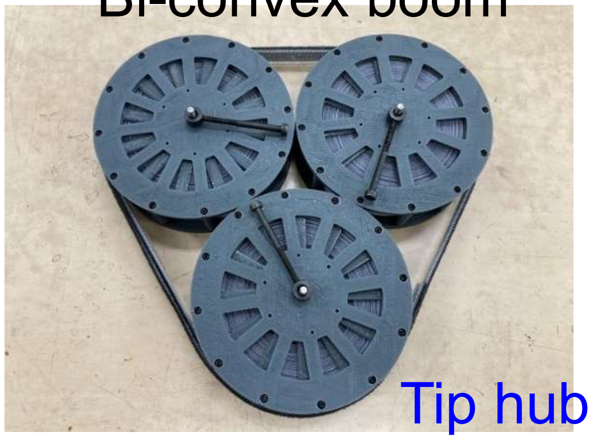
- A CFRP coupling boom is stored in fixed hub and a motor extends the boom to deploy the sail slowly.



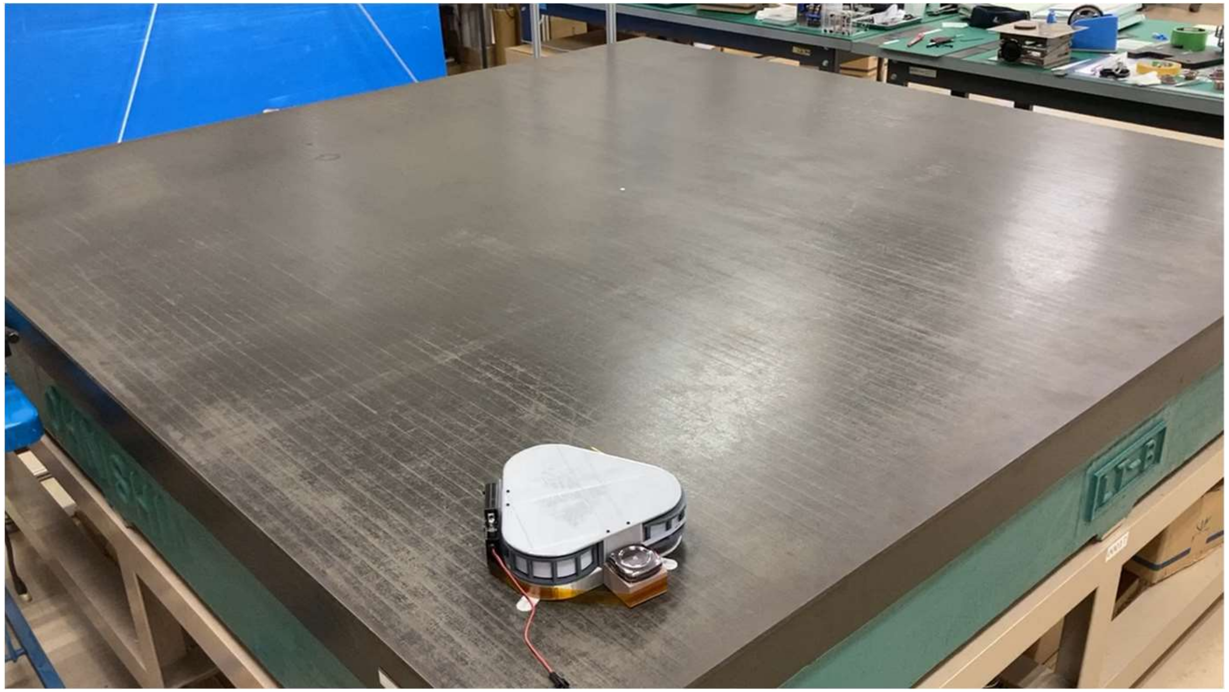
1-4) Truss Boom Method

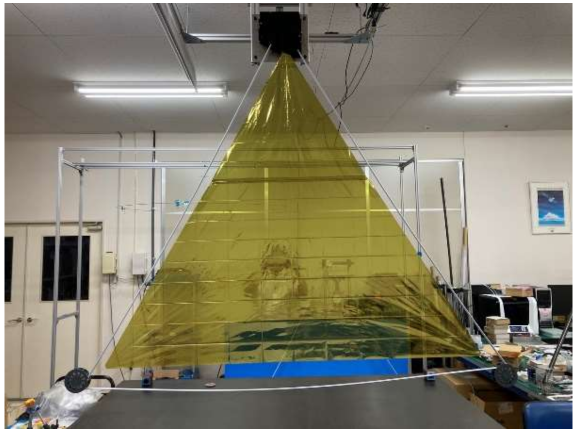
We are studying the triangular sails as well as square ones.
- Three bi-convex metal booms are wrapped around three tip hubs.
- These booms self-expand to form a truss.
- The truss keeps the triangular sail flat.

Bi-convex boom



Tip hub



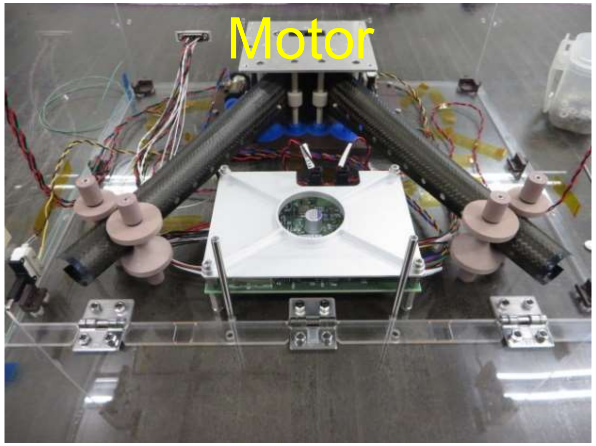


Triangular sail

1-5) Two Side Boom Method

- In two side boom method, a motor extends two side booms simultaneously.
- The booms deploy the sail.

Side boom



Side boom

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2) Attaching various devices to sail

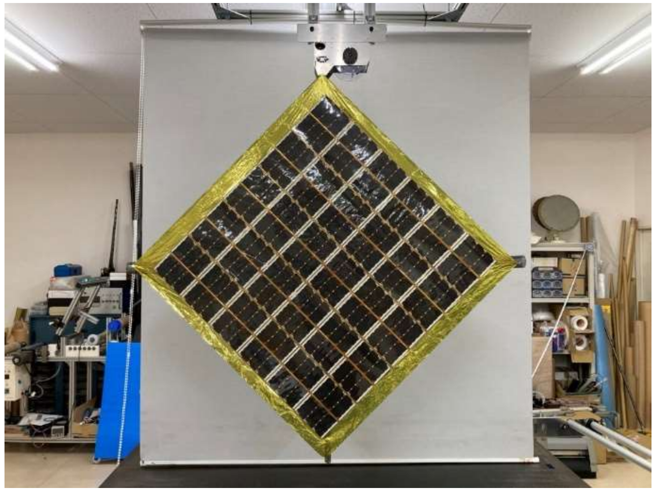
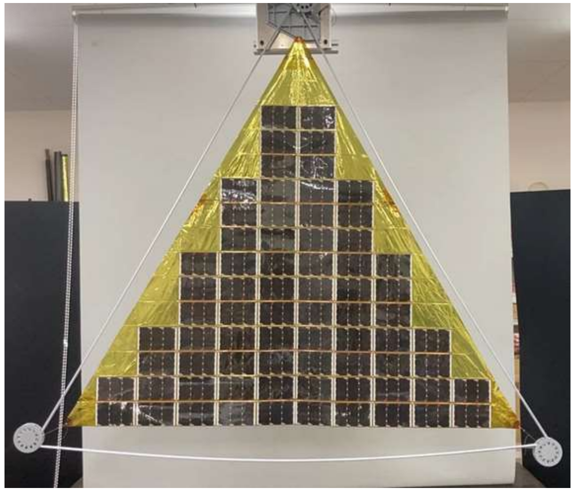
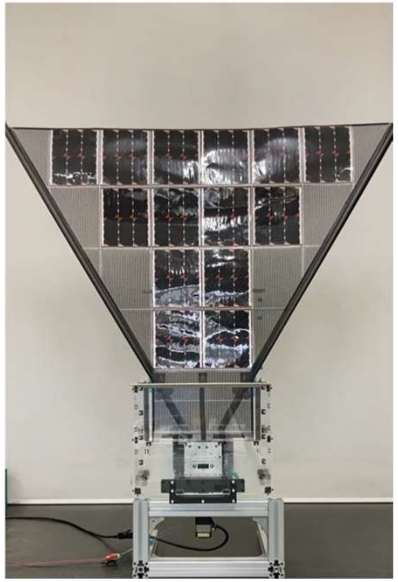
- Thin film solar cell (for thin-film solar array paddle)
- Array antenna (for high-capacity communication)
- Interferometer (for high-resolution observation)
- Reflective sheet (for deployable target marker)

3) Changing sail configuration for orbit and attitude control by SRP

- Gimbal
- SMA (Shape-Memory Alloy)
- Spin centrifugal force

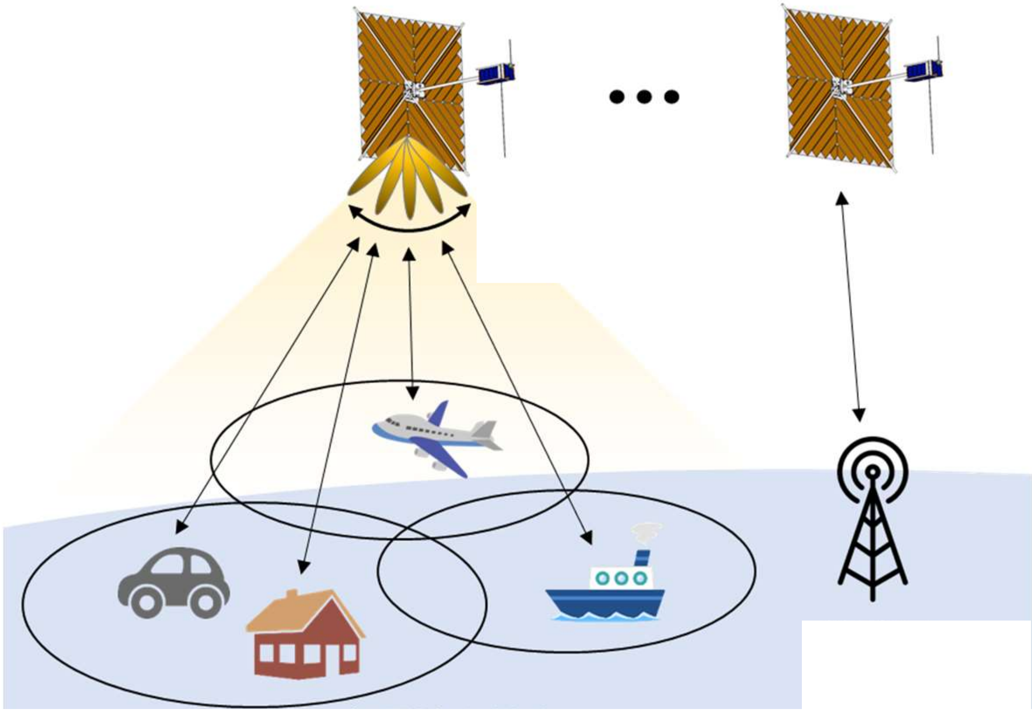
2-1) Thin-film Solar Cell

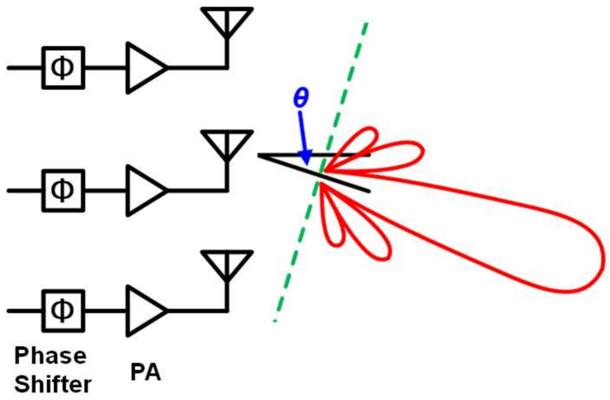
By attaching thin-film solar cells to a boom-type sail, we can
- create thin-film solar array paddle and
- achieve the world's highest power generation efficiency.

2-2) Array Antenna

A large number of array antennas are attached to the sail and beamforming is used to achieve high-capacity communications.





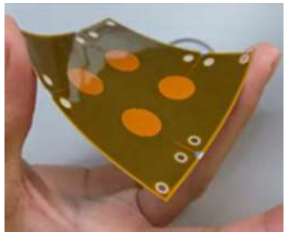
Beamforming

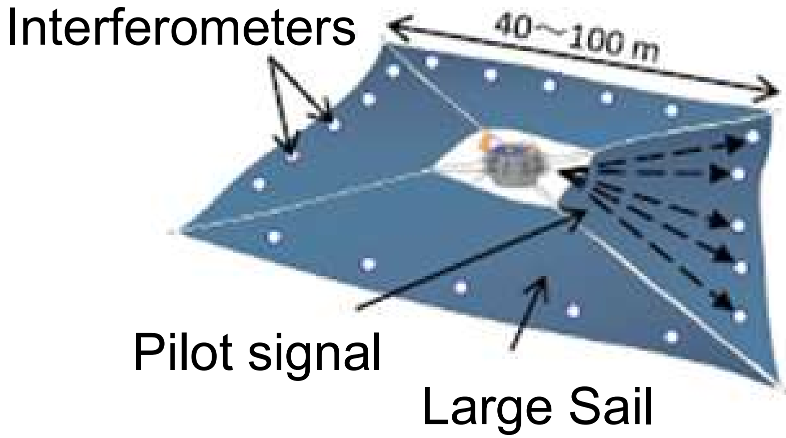
2-3) Interferometer

A large number of interferometers are attached to a large area sail to achieve the world's highest angular resolution observation

- for the earth's soil moisture and ocean salinity from high altitude, and

- for the deep atmosphere of gas giant planets such as Jupiter and Saturn.

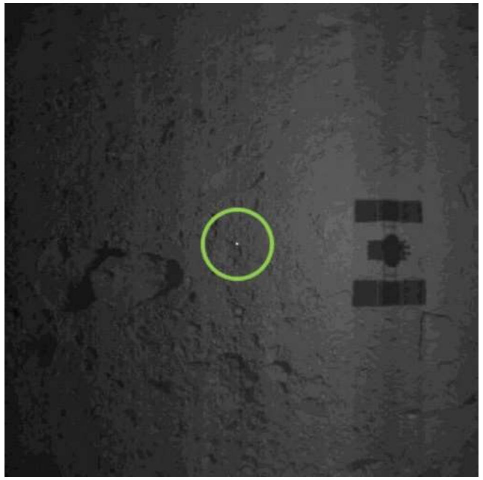


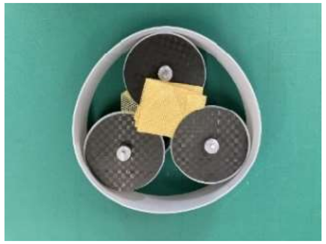


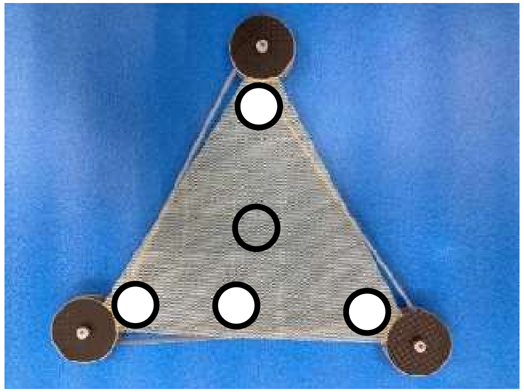
2-4) Reflective Sheet

Reflective sheets are attached to the sail to form a deployable target marker.


Diameter 100mm







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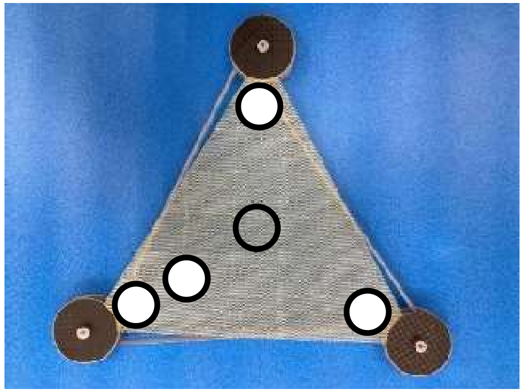

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Deployable target marker
- a membrane structure
- to identify multiple target markers with individual patterns
- to measure relative attitude as well as relative position

Conventional target marker
- a sphere
- to identify single target marker
- to measure relative position

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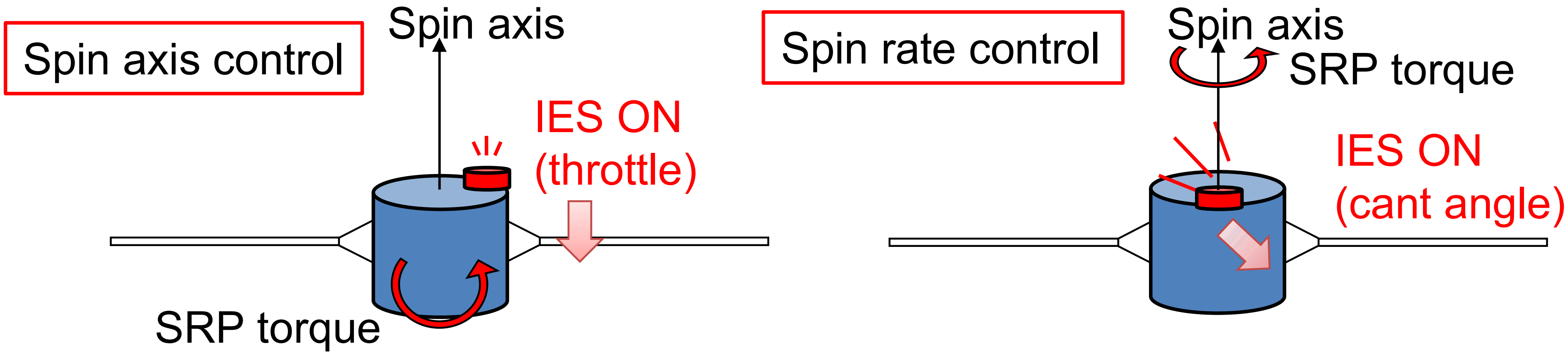
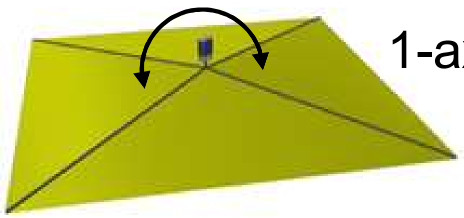
3) Changing sail configuration for orbit and attitude control by SRP
- Gimbal
- SMA (Shape-Memory Alloy)
- Spin centrifugal force

3-1) Changing Sail Configuration using Gimbal

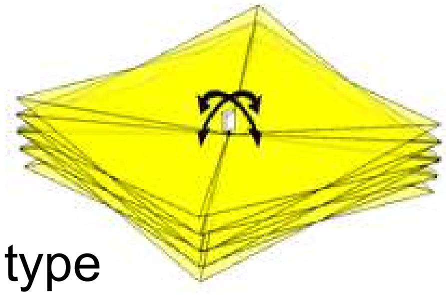
OKEANOS: attitude of the spin-type sail is controlled by ion thrusters.



Orbit and attitude of the boom-type sail can be controlled using SRP by changing the orientation of the sail using gimbals.
=> propellant-free propulsion system can be established.



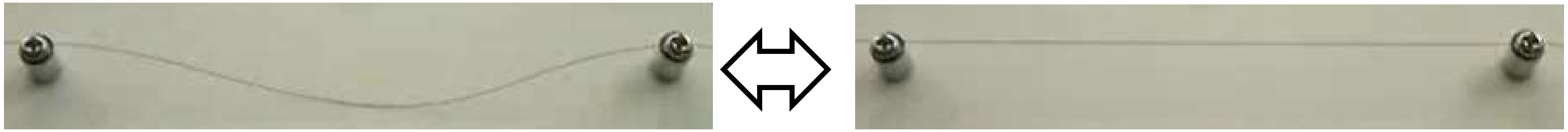
1-axis gimbal type



2-axis gimbal type

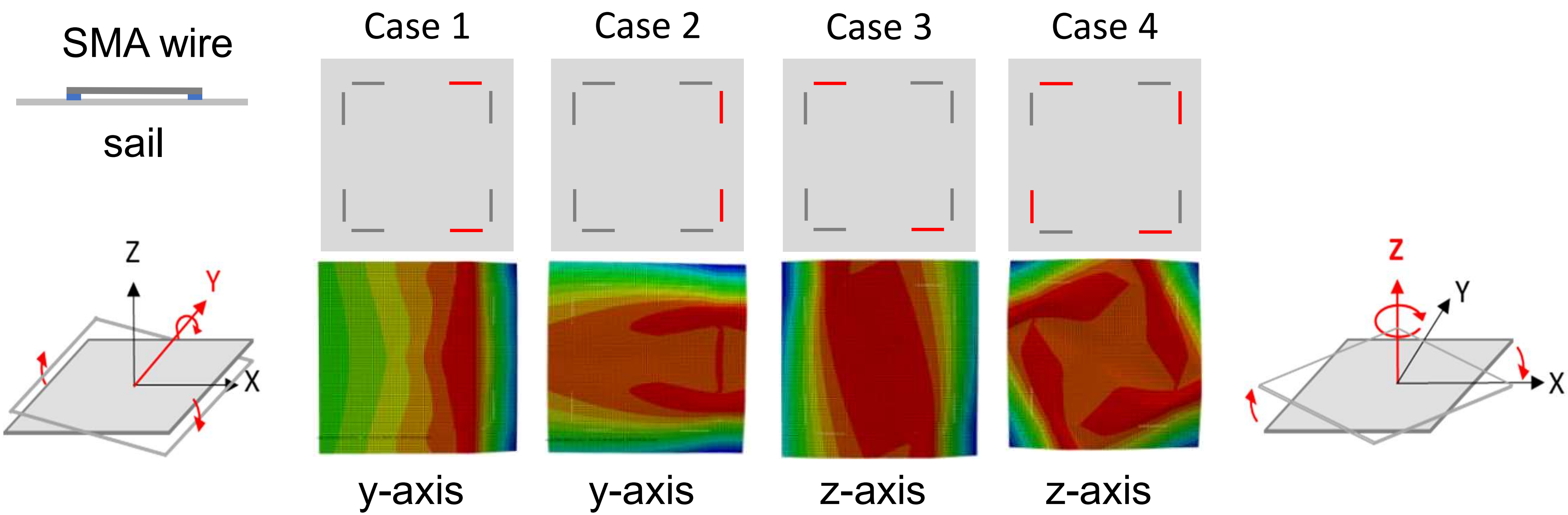
3-2) Changing Sail Configuration using SMA

SMA wire is an actuator that contracts when heated by energizing.



Energized heating

By contracting the SMA wire attached to the sail, the sail can be deformed.
SRP torque in any direction can be generated by selecting SMA wires to be energized.

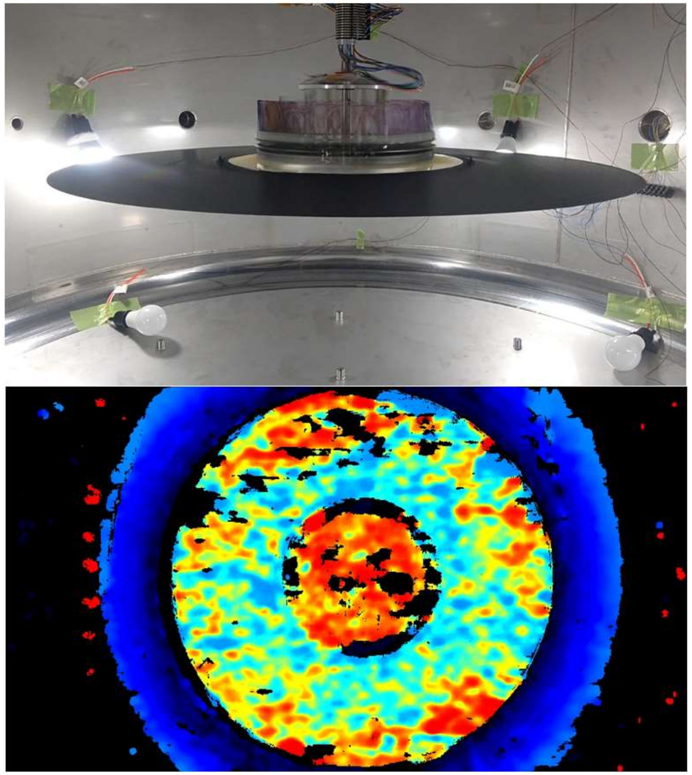


SRP torque around

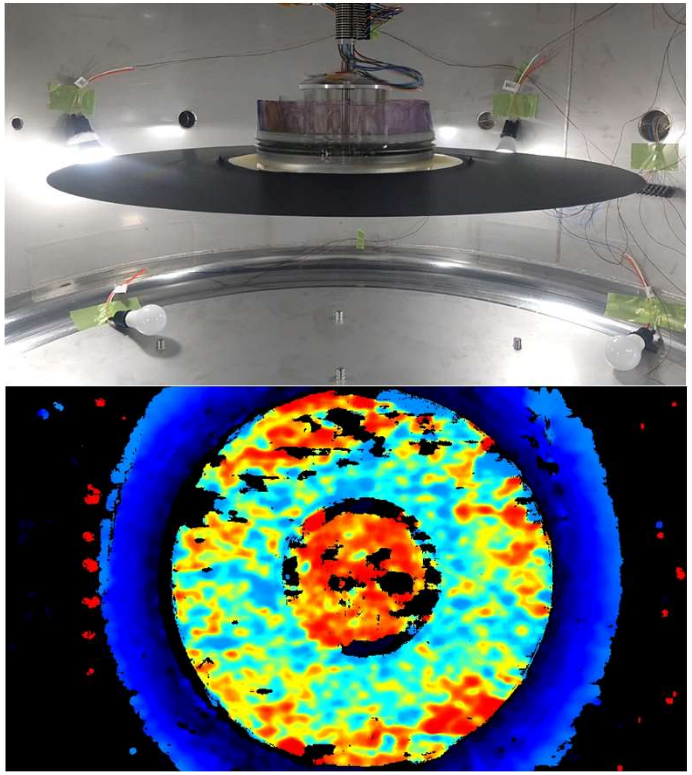
3-3) Changing Sail Configuration using Spin

This is a shape control method for spinning solar sails.
Continuous sail shape can be controlled by vibrating sail membrane.

1st-order static wave



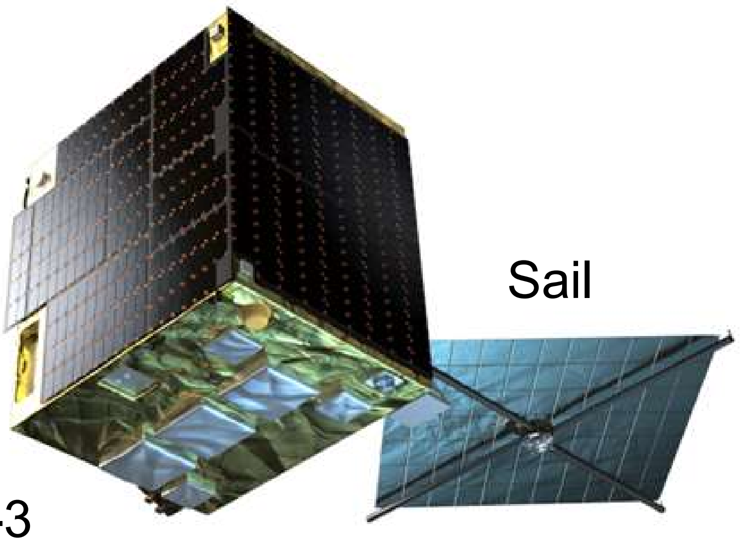
2nd-order static wave



Dr. Takao will present this topic on Friday morning.
“Constellation Around Small Bodies Using Spinning Solar Sails Under Simultaneous Orbit-Attitude-Structure Control”

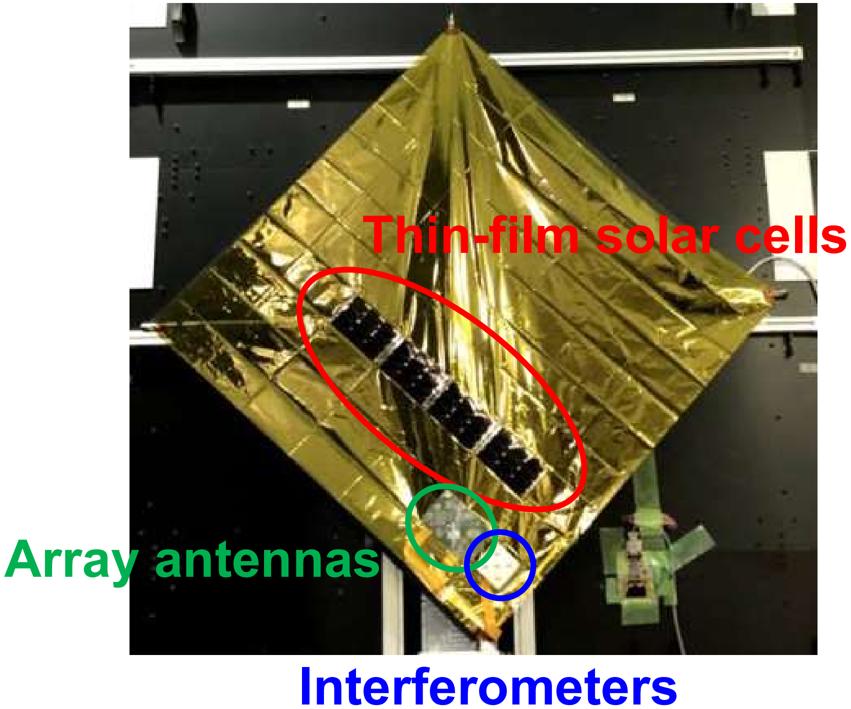
HELIOS

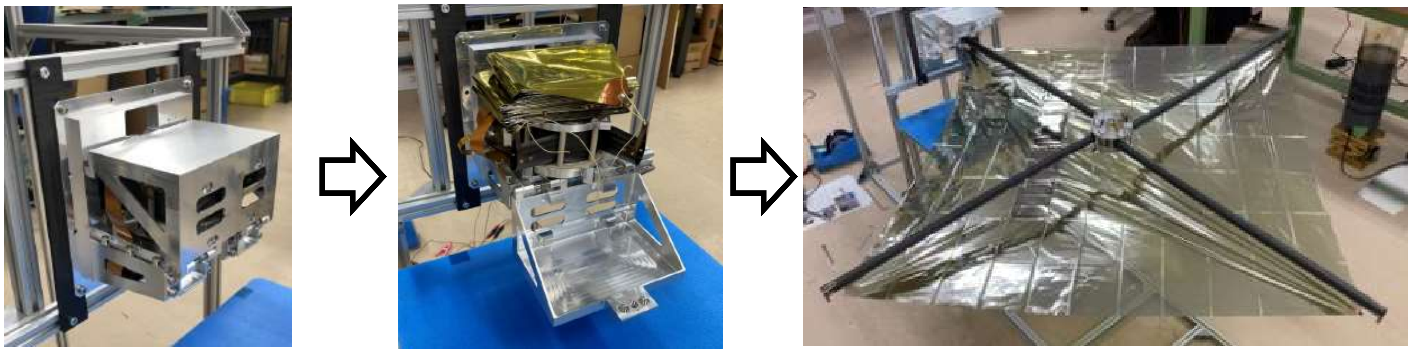
HELIOS, as a mission component onboard small demonstration satellite RAISE-3.
- 1m square boom-type sail with thin-film solar cells, array antennas and interferometers attached



Sail

RAISE-3

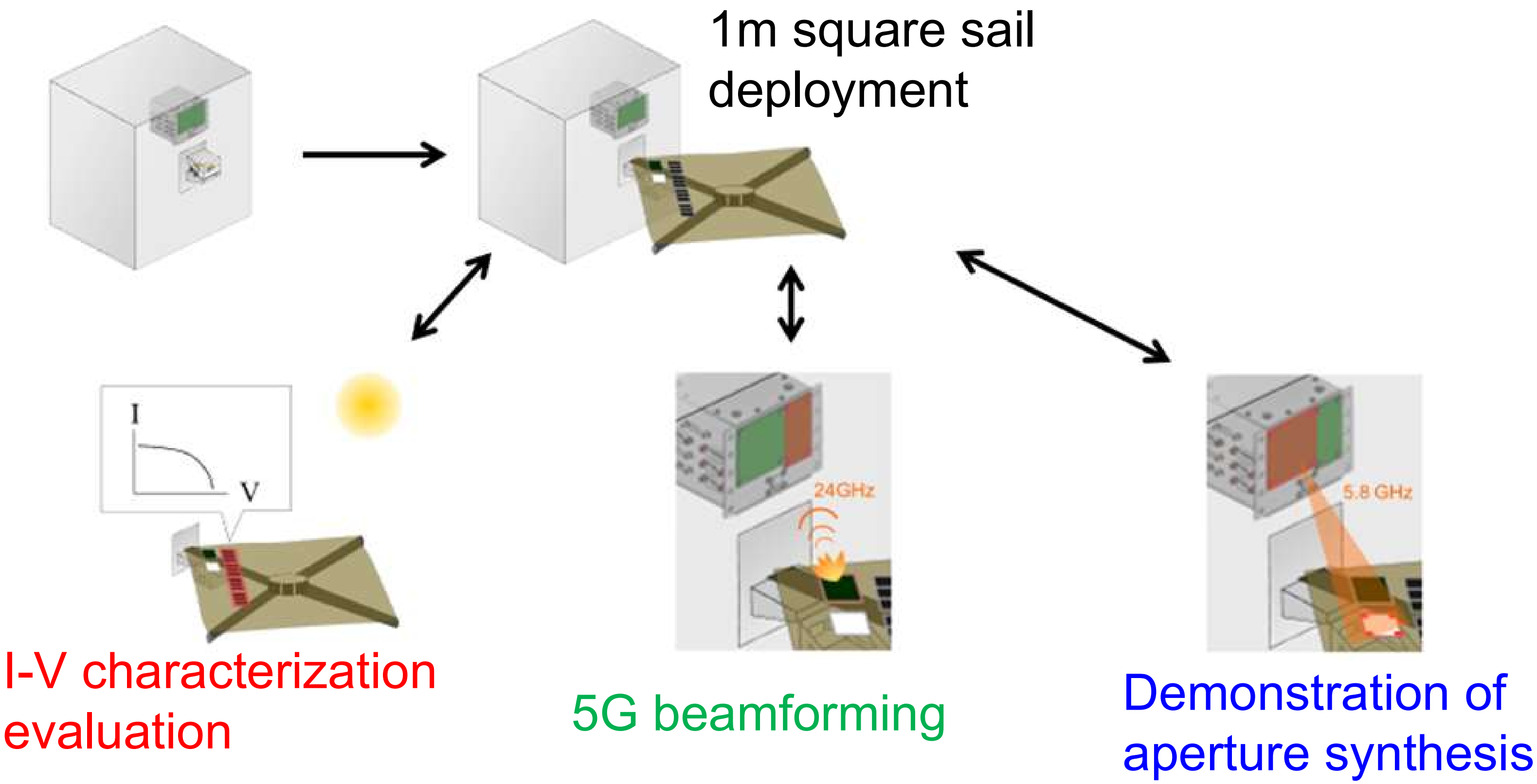




1m square sail deployment

HELIOS

- 1m square sail deployment by fixed boom method
- power generation by thin-film solar cells
- communication using array antennas
- observation by interferometers

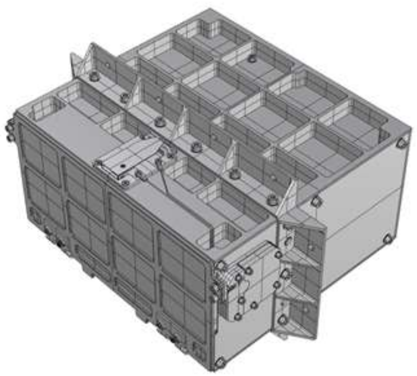


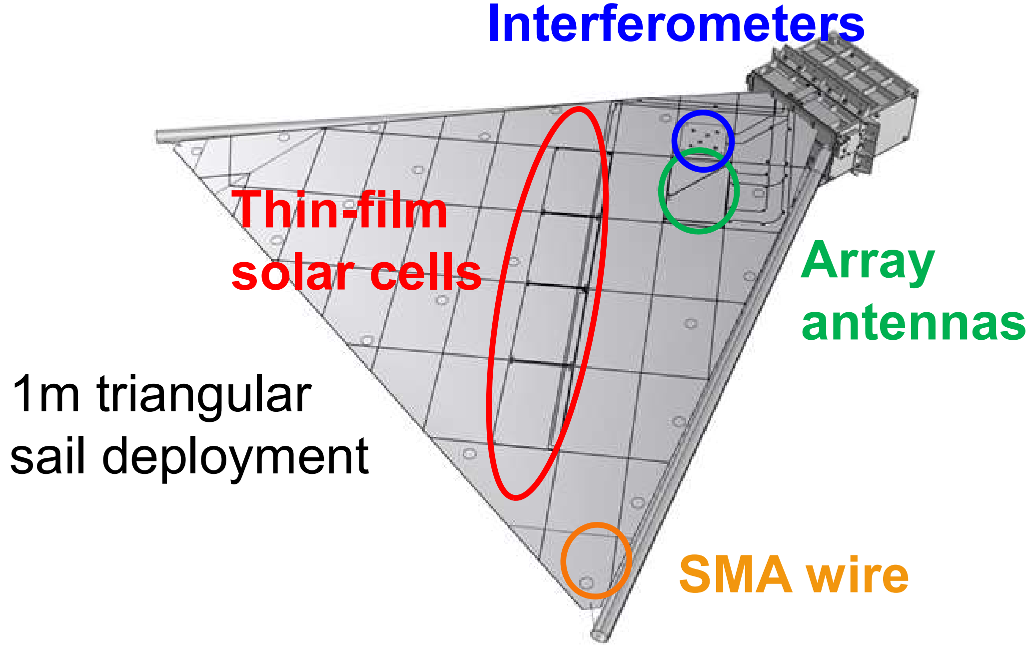
The launch of RAISE-3 by Epsilon-6 rocket failed on October 7, 2022,
HELIOS was unable to perform the missions, unfortunately.

HELIOS-R

HELIOS-R (Retry), as a mission component onboard RAISE-4.

- 1m triangular sail deployment by two side boom method
- power generation by thin-film solar cells
- communication using array antennas
- observation by interferometers
- changing sail configuration using SMA wire

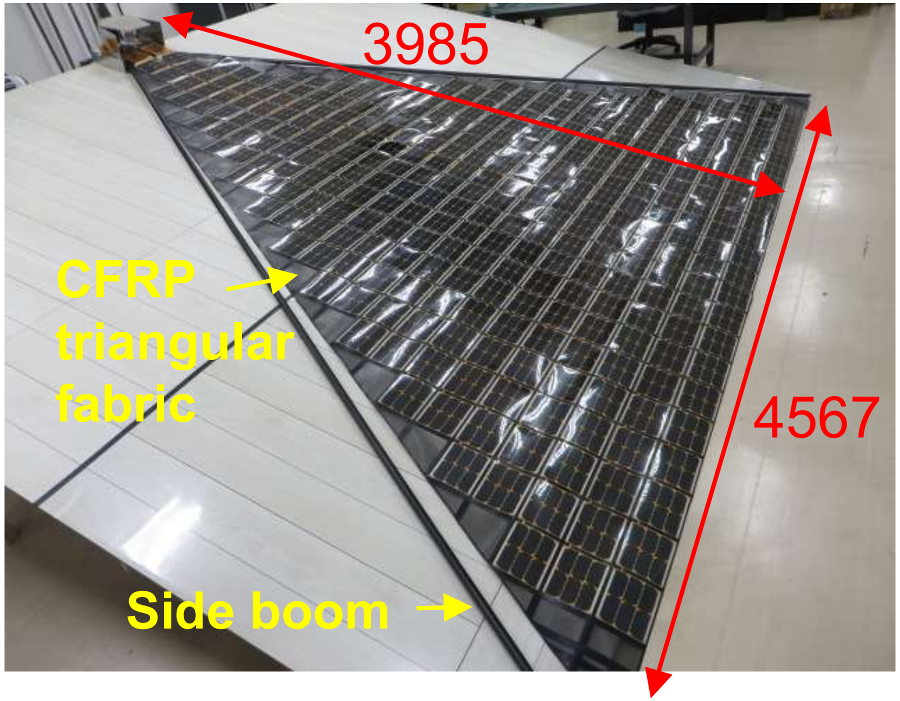




The RAISE-4 will be launched by Epsilon rocket in 2024.

Thin-film Solar Array Paddle

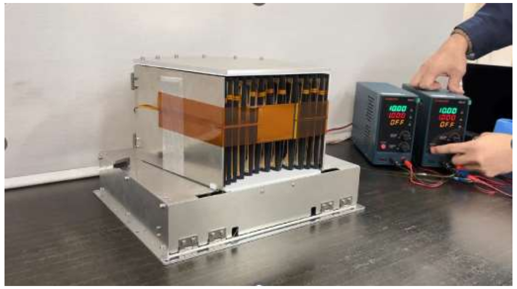
Thin-film solar array paddle
- attaching thin-film solar cells to CFRP triangular fabric with an area 9m²
- equipped with a torsion gimbal
- achieve the world's highest power generation efficiency 200W/kg
  (Power generation: 2428W, Mass: 12.2kg)

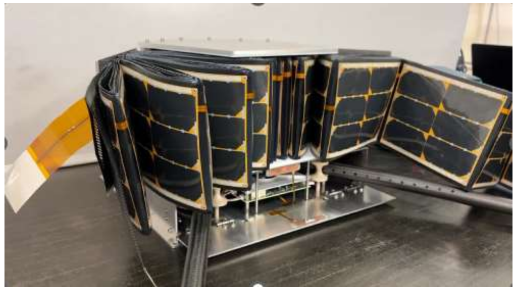


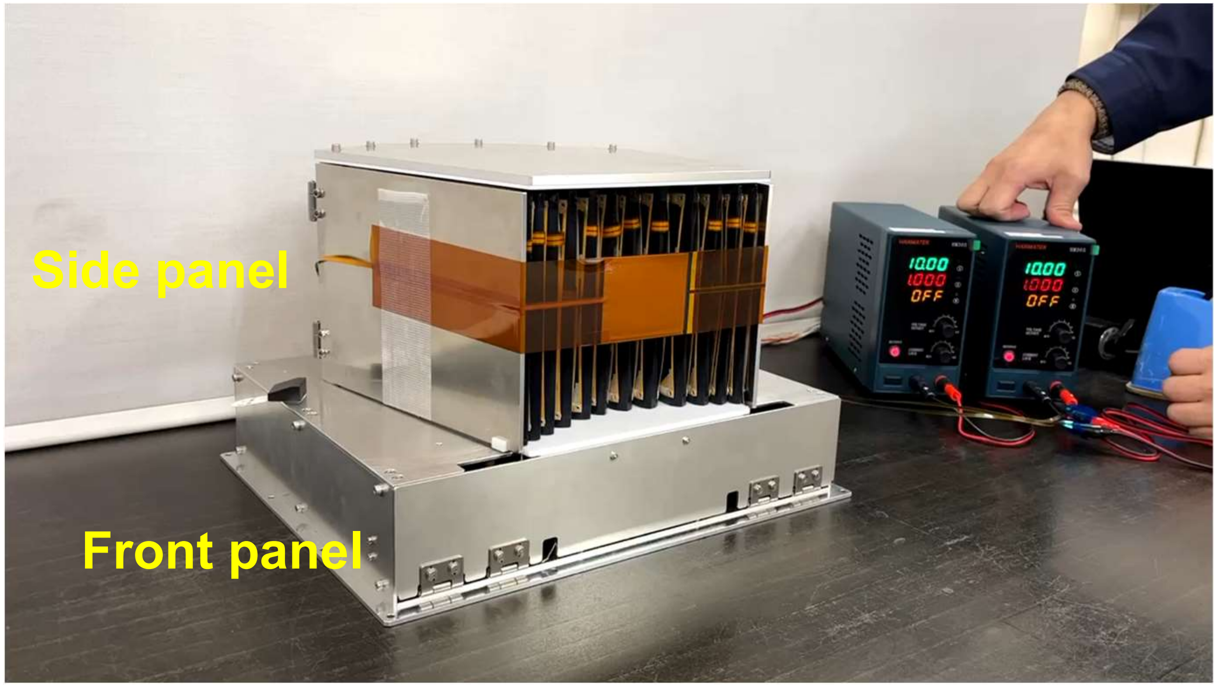
Ultraflex
(150W/kg)

Holding and Releasing of Front and Side Panels

The holding and releasing of the front and side panels with electrical release tape was verified.



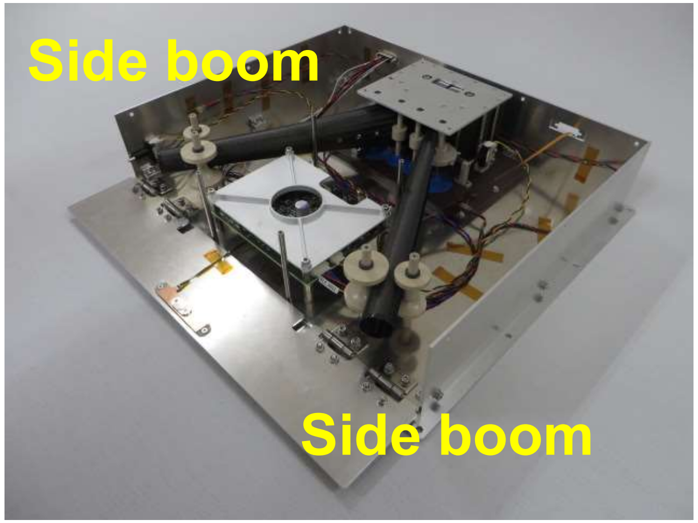


Triangular Fabric Deployment

Triangular fabric was deployed by two side booms.

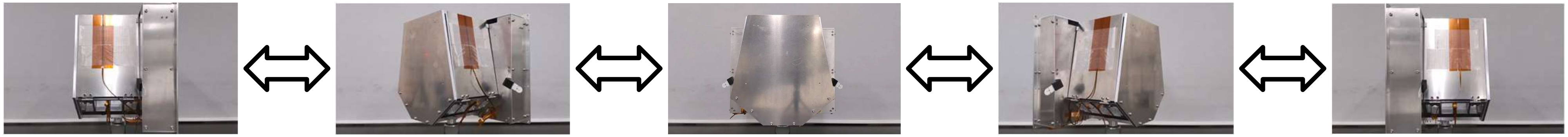


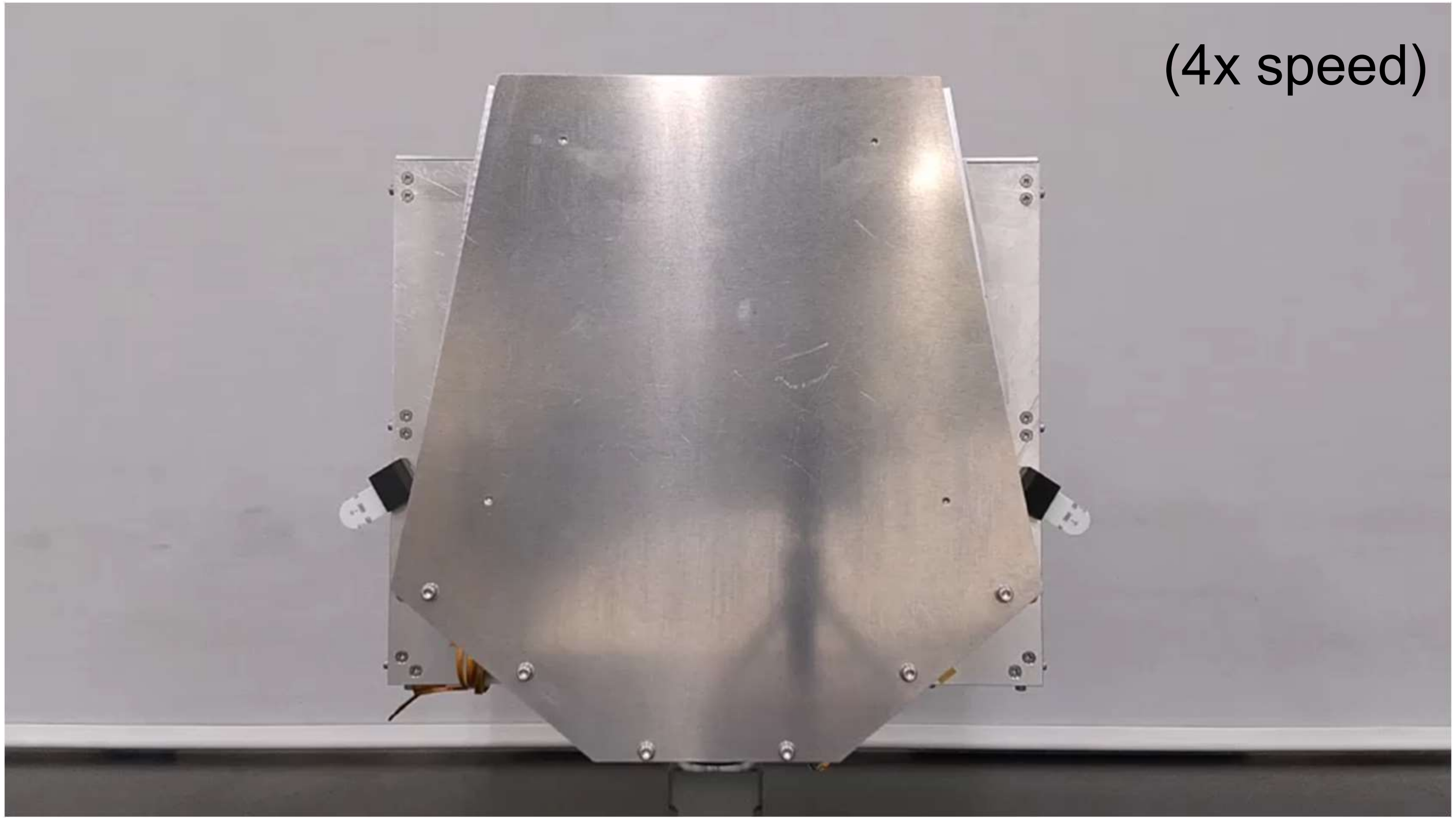


Gimbal Drive

Torsion gimbal drive enables ±90deg rotation.



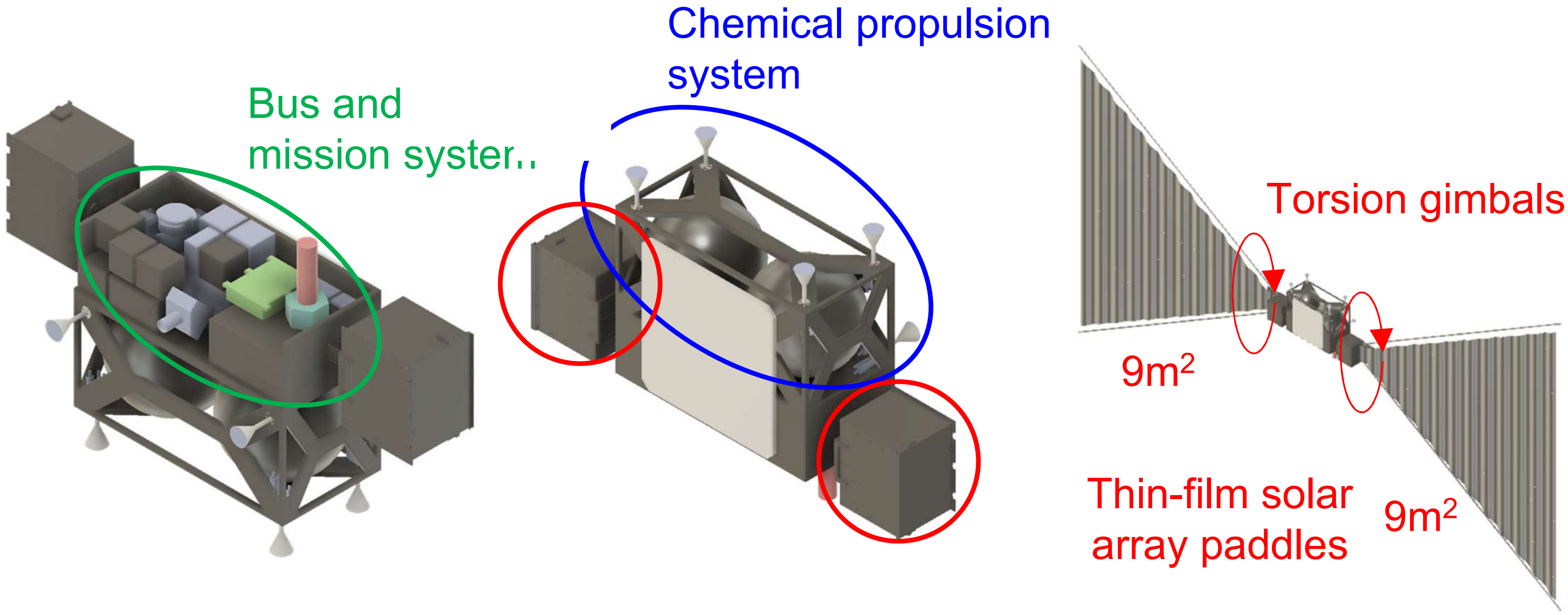


OPENS System

Saturn flyby mission OPENS using the thin-film solar array paddles.

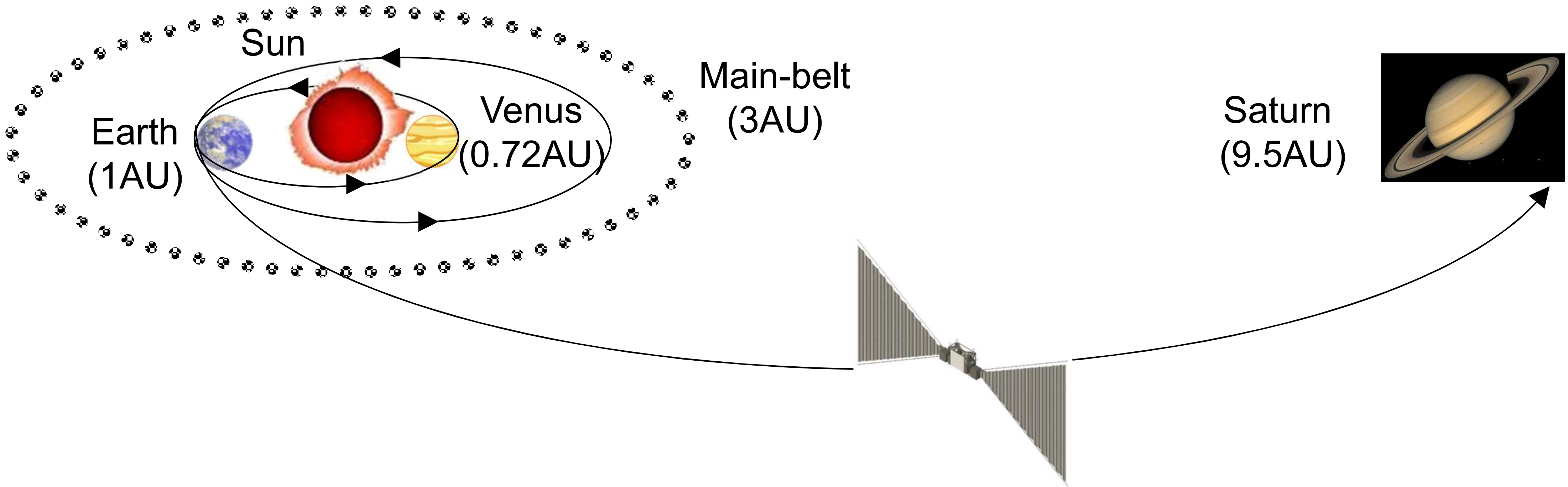
OPENS must be a small spacecraft to be launched by Epsilon S rocket.
- Wet mass: 140kg (fuel: 40kg, paddles: 24kg, the rest 76kg)

Each paddle has an area of 9m^2 and a torsion gimbal.
The ultra-light paddles make the OPENS mission feasible.



OPENS Trajectory

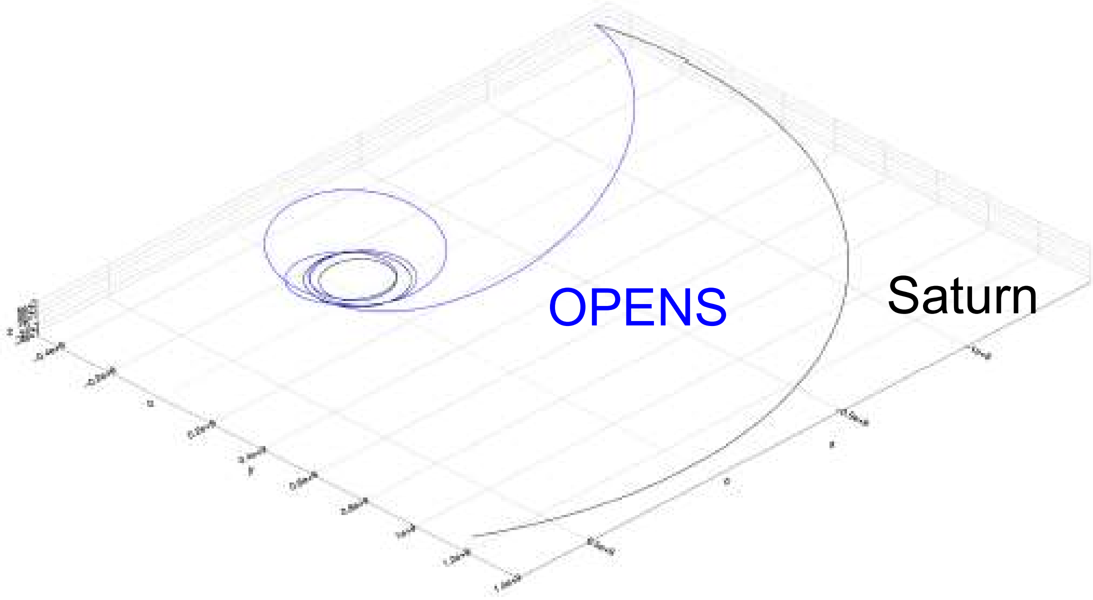
OPENS performs Saturn flyby with three Earth swing-bys and one Venus swing-by.



Phase	Start	End	ΔV
Earth – Earth	2030/May/10	2031/May/11	-
Earth – Venus	2031/May/11	2031/Nov./17	-
Venus – Earth	2031/Nov./17	2032/Oct./10	-
3-year DVEGA	2032/Oct./10	2035/Sep./17	540 m/s
Earth - Saturn	2035/Sep./17	2040/Dec./31	-

OPENS Trajectory

- Total flight time: 11 years
- Total ΔV: 540 m/s (using chemical propulsion system)



Phase	Start	End	ΔV
Earth – Earth	2030/May/10	2031/May/11	-
Earth – Venus	2031/May/11	2031/Nov./17	-
Venus – Earth	2031/Nov./17	2032/Oct./10	-
3-year DVEGA	2032/Oct./10	2035/Sep./17	540 m/s
Earth - Saturn	2035/Sep./17	2040/Dec./31	-

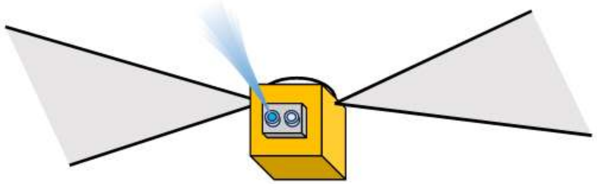
11 years

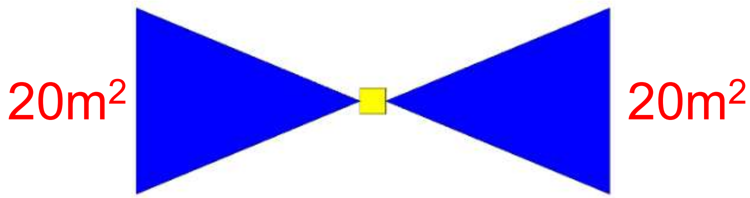
OPENS2

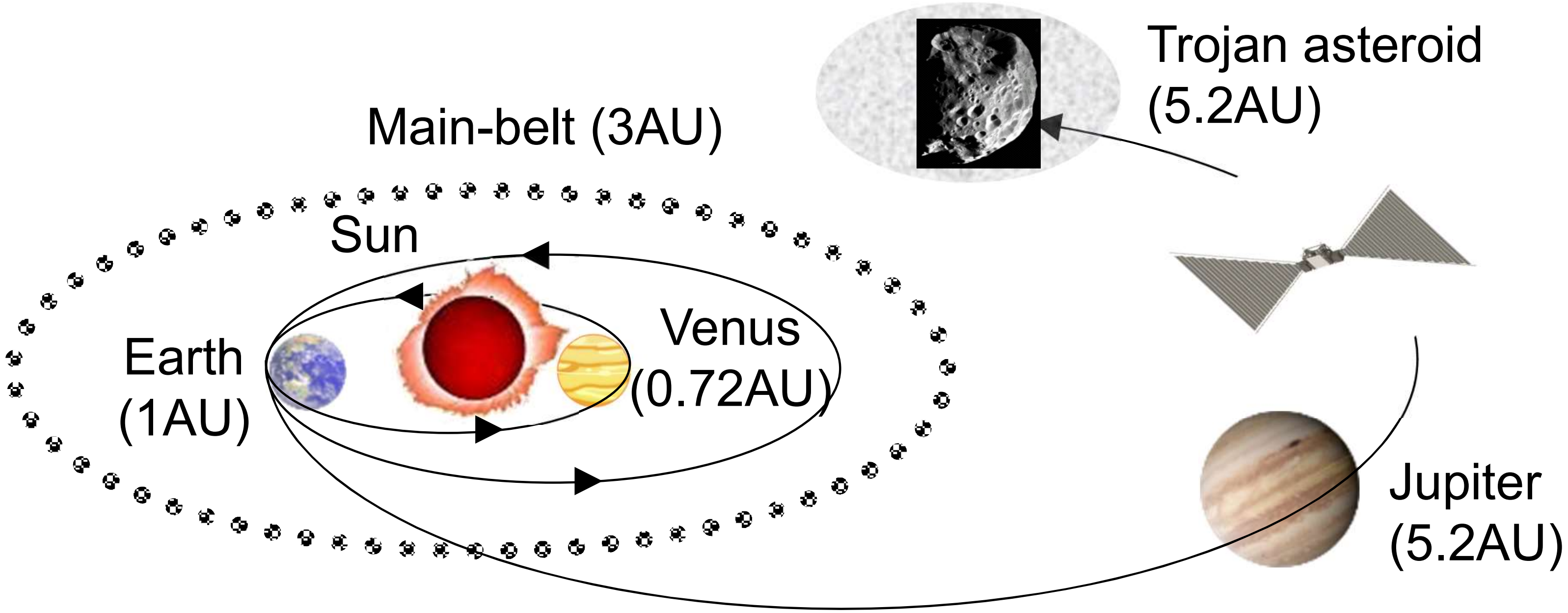
If the paddle area is increased from 9m² to 20m², the ion engine can be driven in the outer planetary region.

Trojan asteroid rendezvous mission OPENS2

- Wet mass < 200kg







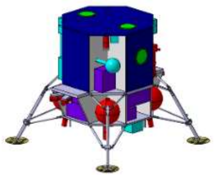
Dr. Takao will present this mission in detail tomorrow.
“A Rendezvous Mission to Outer Solar System Bodies Using a 100-kg-class Solar Power Sail”

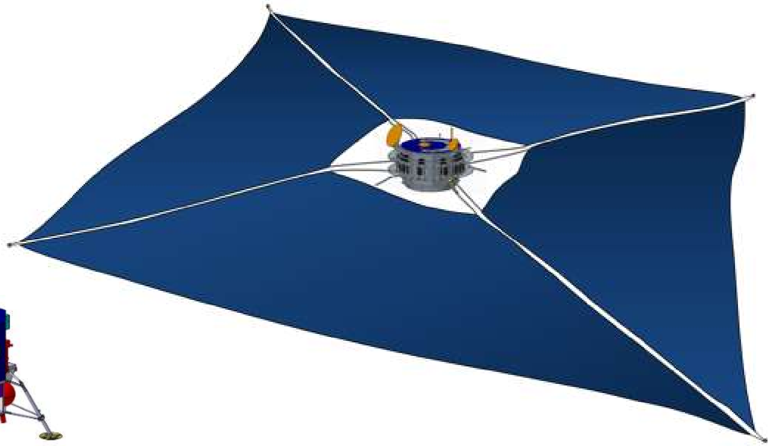
Sail-craft and Lander System

In OKEANOS mission, it is difficult for the sail-craft to land on Trojan asteroid directly, a lander is separated from the sail-craft to land.

This concept is applicable not only to sail-craft missions but also to landing missions in general for the reasons of

- Less fuel consumption
  Especially in case of landing on and taking off from large celestial bodies, smaller lander can consume less fuel than larger round-trip vehicle.
- Risk avoidance
  The use of a lander avoids total loss in case of landing or takeoff failure.
  The risk of losing the previously collected samples due to the second touchdown was discussed in Hayabusa2.

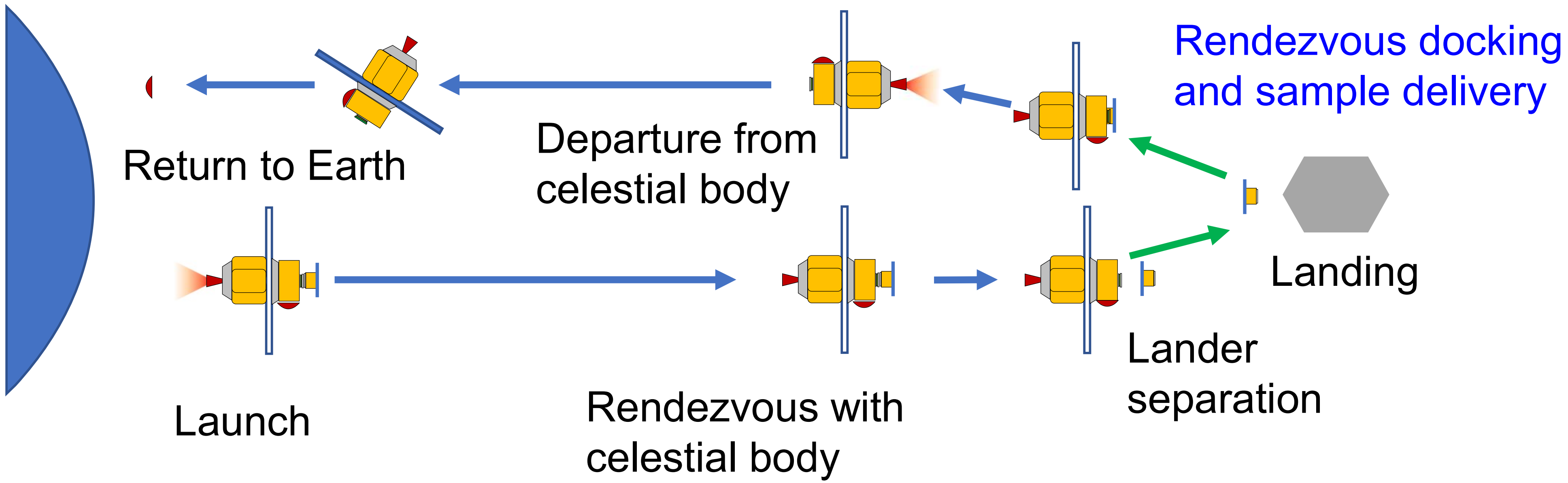




DSOTV and Lander System

DSOTV (Deep Space Orbit Transfer Vehicle) and lander system should be applied to sample return missions.

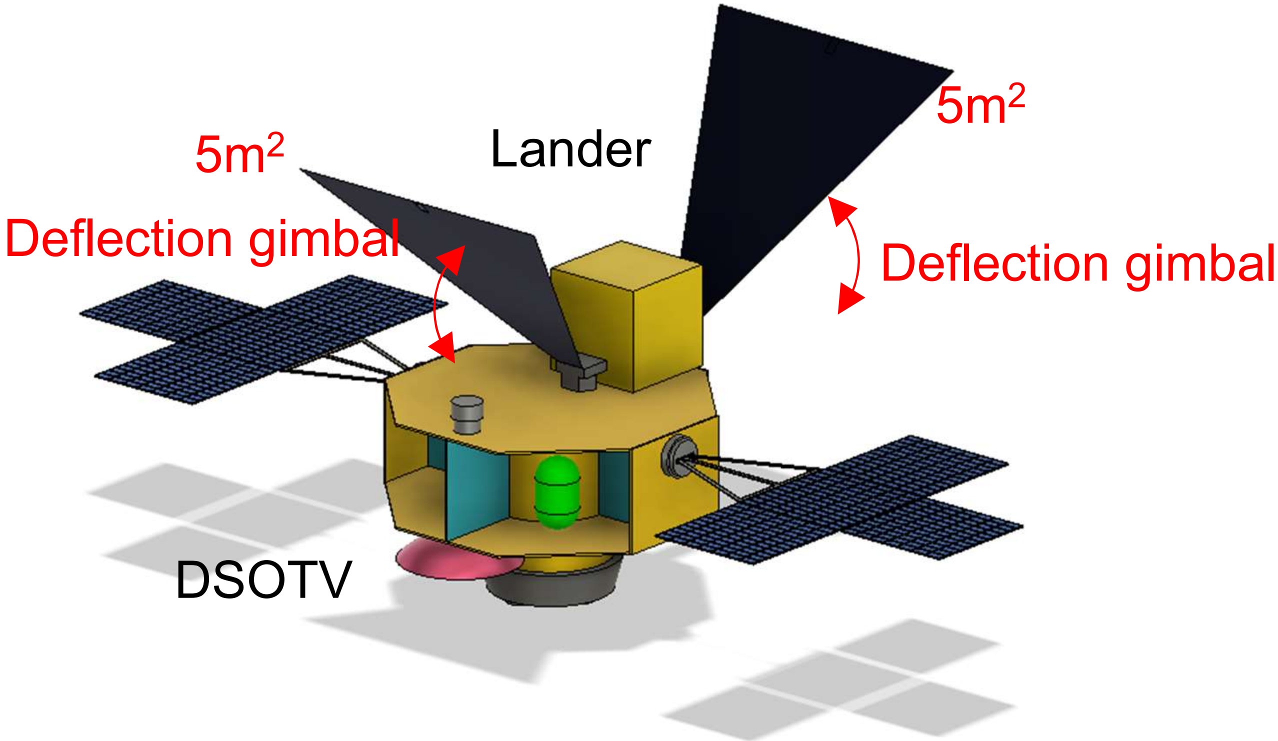
This system requires two key technologies:
- Rendezvous docking between a DSOTV and a lander in deep space
- Sample delivery from a lander to a DSOTV

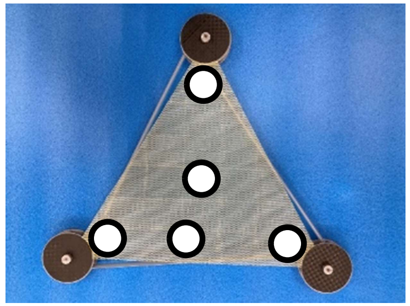


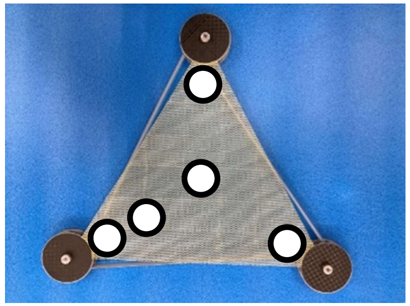
Next-generation Small Body Sample Return

Next-generation small body sample return mission, as a strategic L-class mission

Consist of a DSOTV and a lander.
- The lander performs multiple landings, samplings and takeoffs.
- The lander is 100kg class and has two thin-film solar array paddles.
- Each paddle has an area of $5m^2$ and is equipped with a deflection gimbal to avoid collisions during landing and rendezvous docking.
- The lander uses deployable target markers for pinpoint landings.

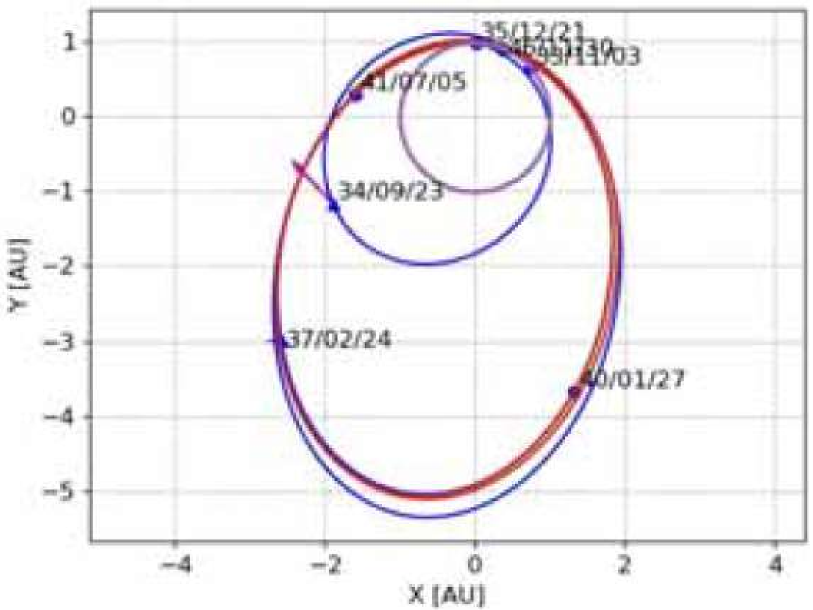






Next-generation Small Body Sample Return

Trajectory example to 289/target
- The target is a comet whose aphelion is above 5AU.
- Total flight time: 13 years
- Total ΔV: 1600 m/s (using chemical propulsion system)



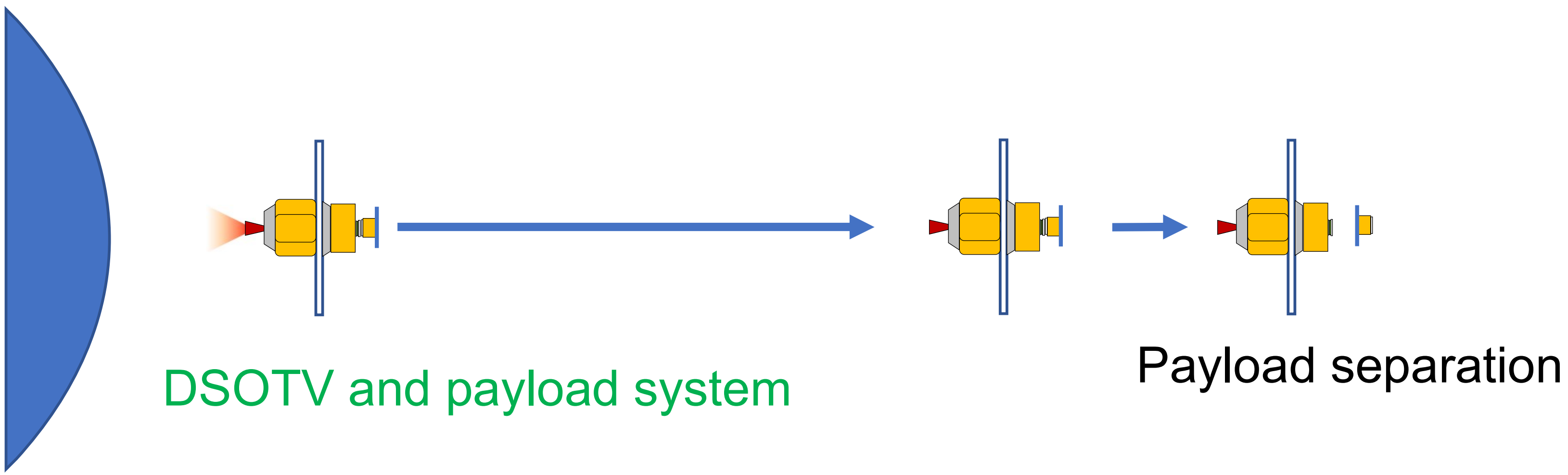
Aphelion > 5 au

2033/11/03 Launch
2034/09/23 Deep Space Maneuver (dV: 564.9m/s)
2035/12/21 Earth swing-by
2037/02/24 Deep Space Maneuver (dV: 545.3m/s)
2040/01/27 Rendezvous (dV: 78.6m/s)
2041/07/05 Departure (dV: 78.6m/s)
2046/11/39 Return to Earth
Total dV: 1591.5m/s

DSOTV and Payload System

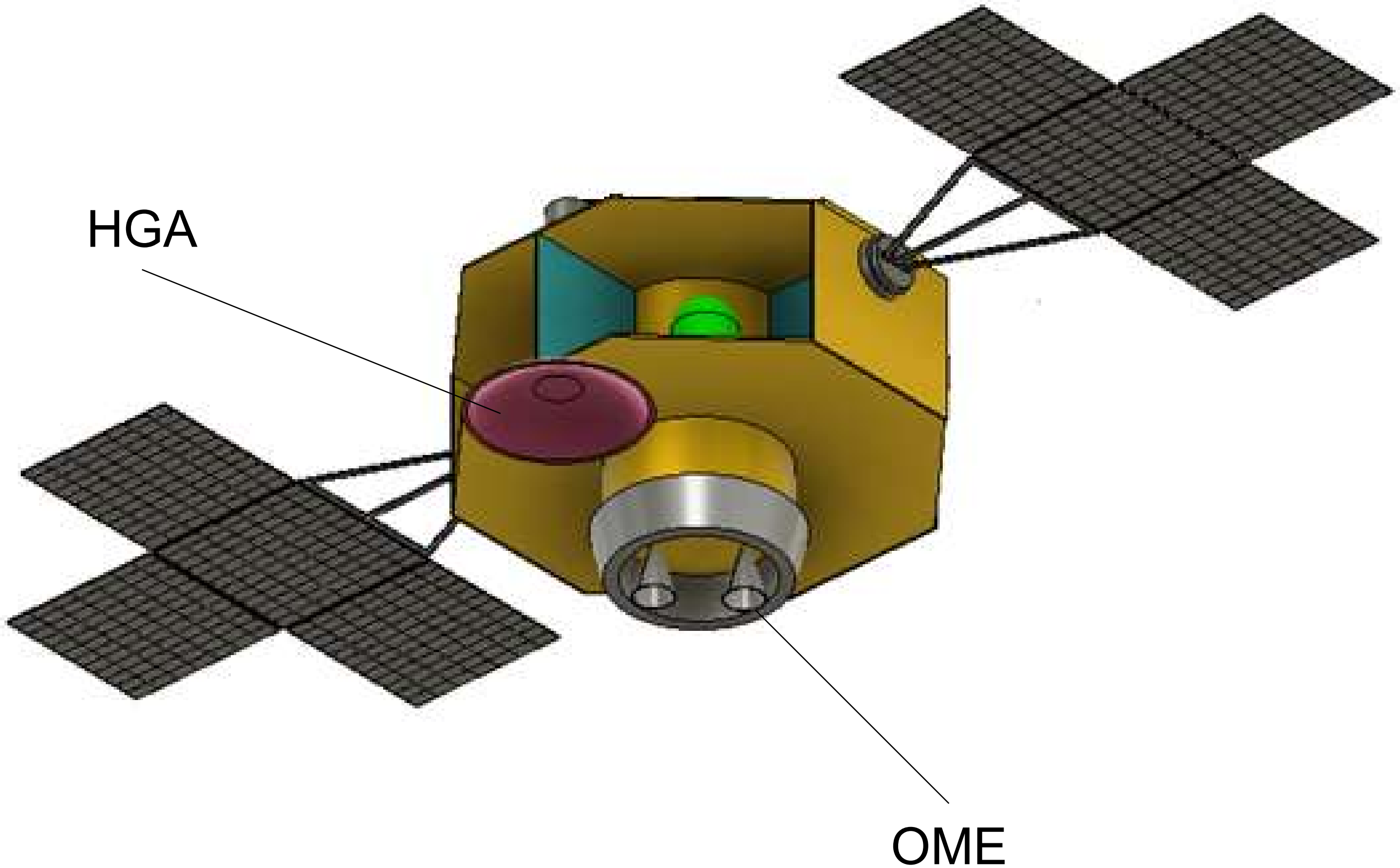
DSOTV and lander system can be extended to DSOTV and payload system.

- DSOTV: a transportation system to deep space
  to require high reliability for long-term operations.
- Payload: small or micro probe to perform challenging missions
  not to require high reliability for short-term operations.



DSOTV and Payload System

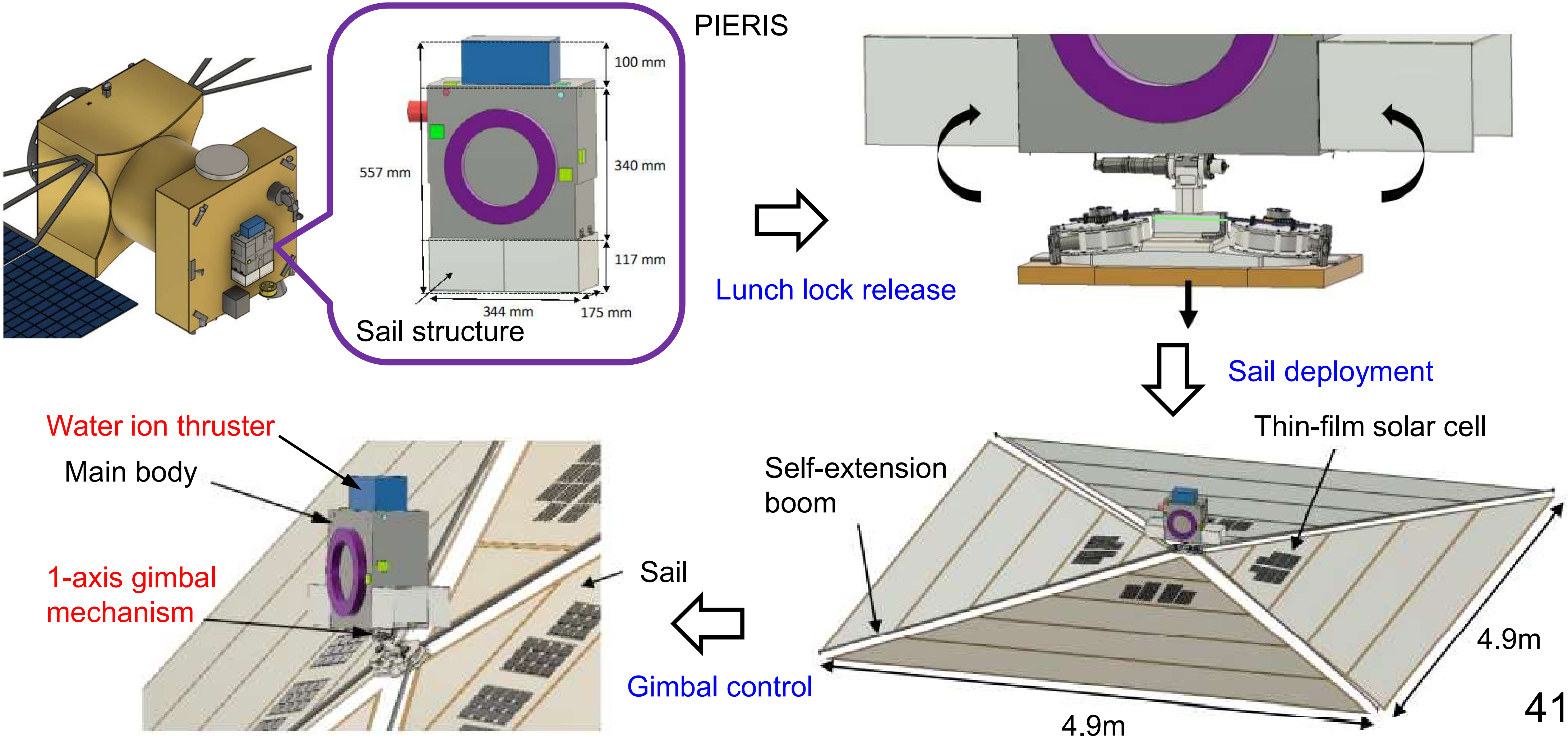
We are designing the DSOTV for the next-generation small body sample return mission to be widely used in Mars and outer planetary exploration.



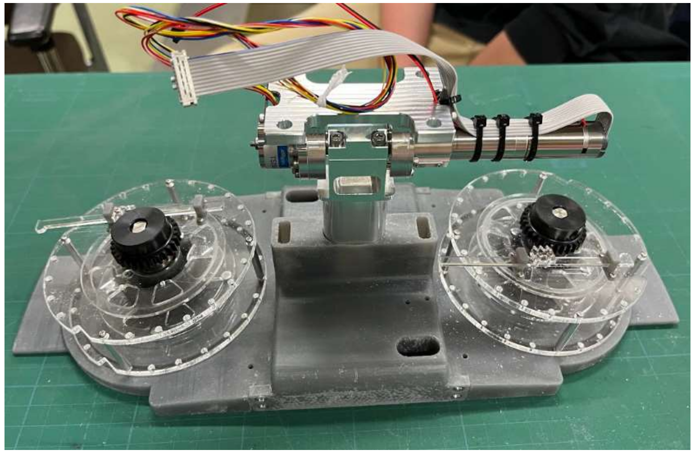
PIERIS System

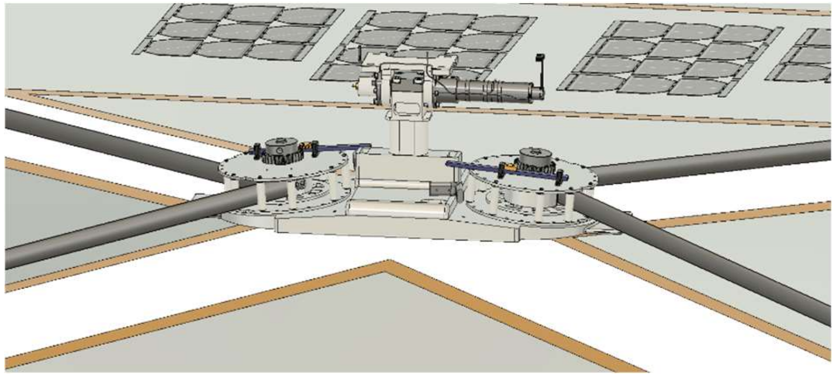
Micro solar power sail PIERIS < 30kg, as the payload of DSOTV

- Orbit and attitude simultaneous control using gimbal as reorientable boom-type sail
- Hybrid propulsion of photon acceleration and electric propulsion (water ion thruster)

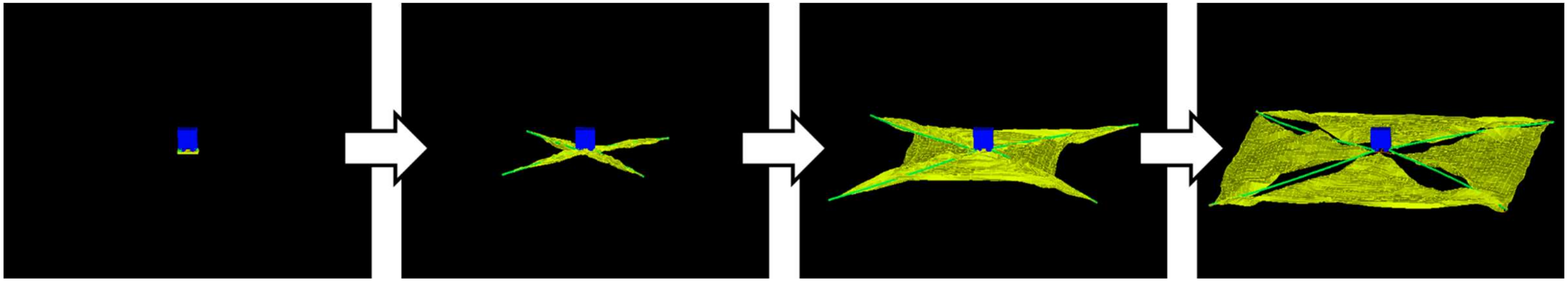


PIERIS Sail Structure





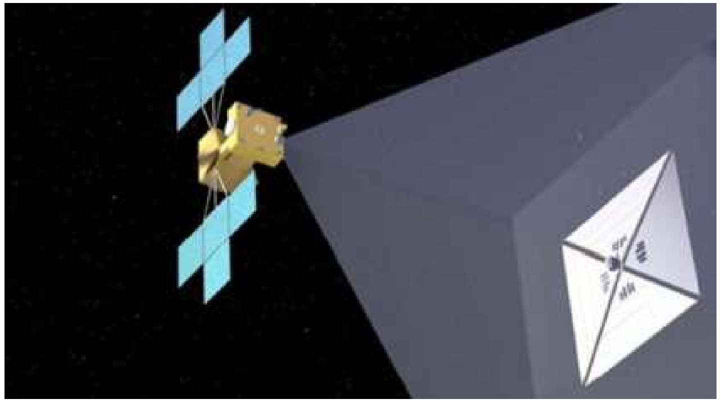
Gimbal and sail deployment mechanism



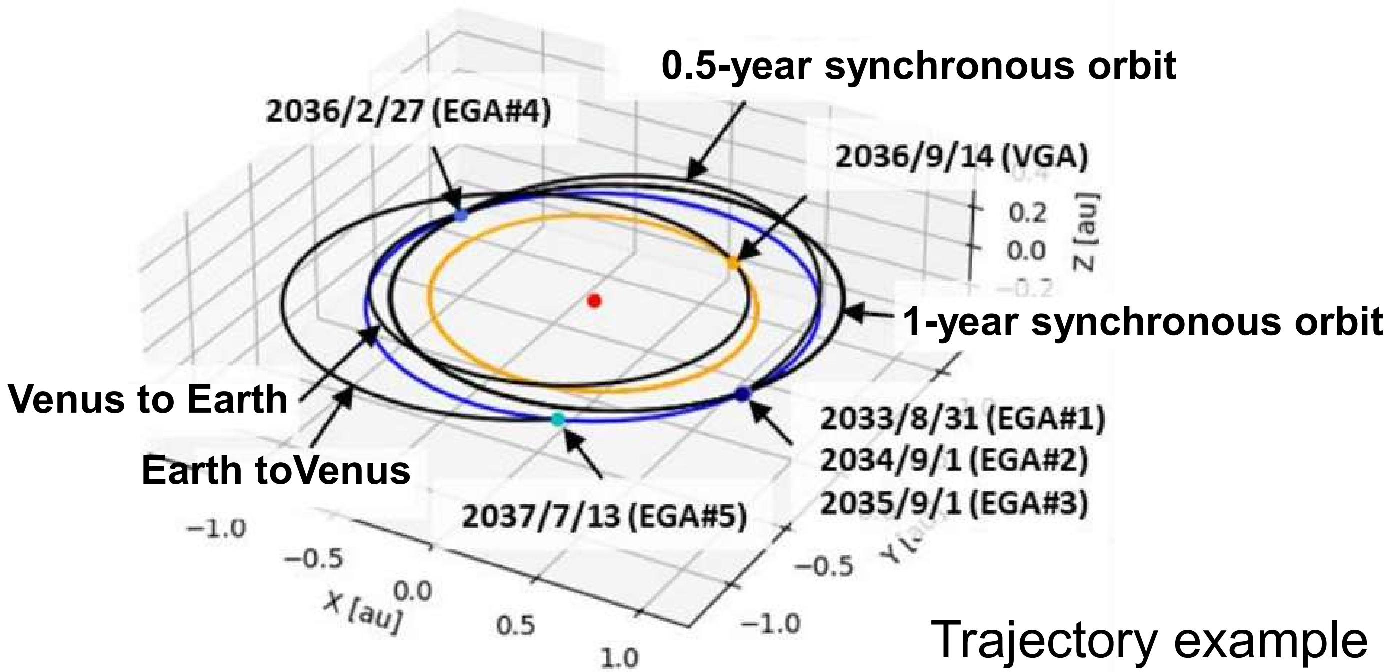
Sail deployment simulation

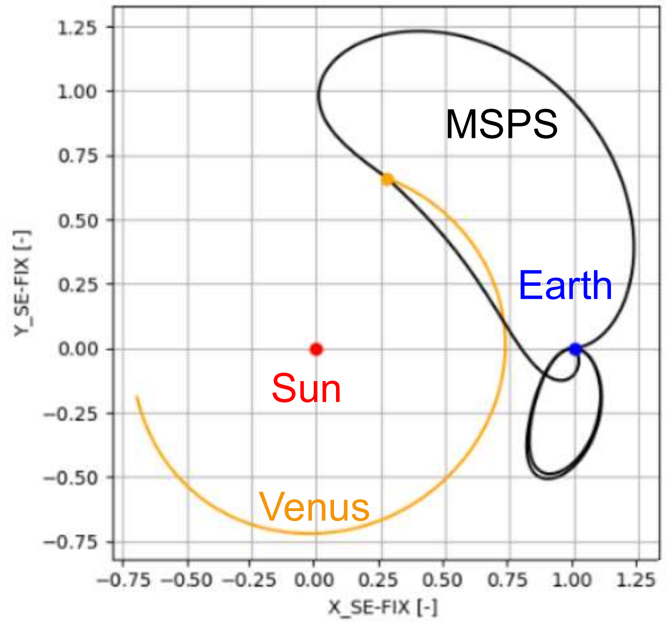
PIERIS Mission

- The sail deployment is imaged by DSOTV camera just after separation from DSOTV.
- PIERIS performs four Earth swing-bys, a Venus swing-by, and another Earth swing-by.



2032/11/30 Separation form DSOTV and sail deployment
2033/08/31 Earth swing-by #1 (Navigation, guidance and control)
2034/09/01 Earth swing-by #2 (DVEGA by hybrid propulsion)
2035/09/01 Earth swing-by #3 (DVEGA by solar sail)
2036/02/27 Earth swing-by #4 (Phase control using 0.5-year synchronous orbit)
2036/09/14 Venus swing-by
2037/07/13 Earth swing-by (Departure to outer planetary region)
2037/10/13 End of mission





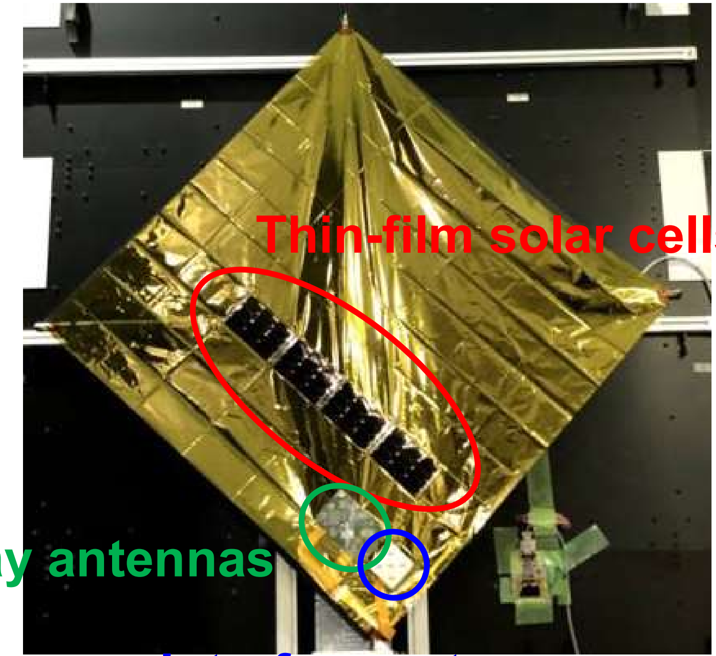
Trajectory example

New Solar Power Sail Program 1

New Concepts for Solar Power Sail

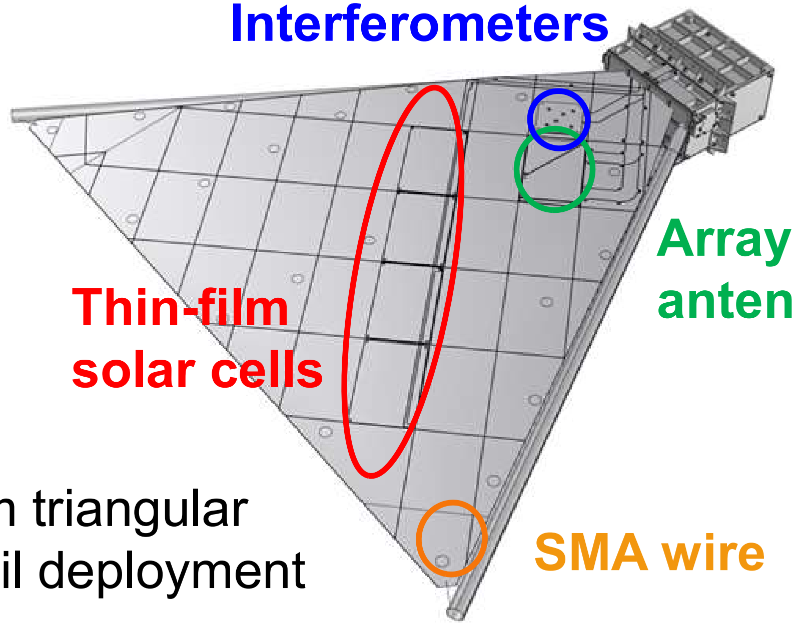
1) Boom-type sail methods for small spacecraft
2) Attaching various devices to sail
3) Changing sail configuration

HELIOS demonstrates 1,2).



1m square sail deployment

HELIOS-R demonstrates 1,2,3).



1m triangular sail deployment

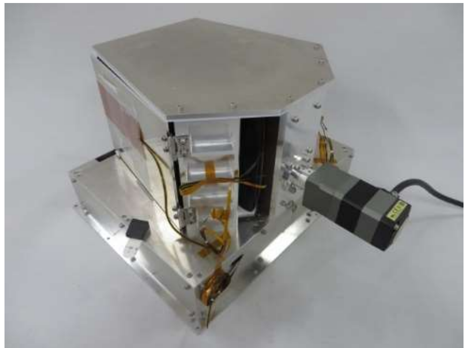
New Solar Power Sail Program 2

New Concepts for Solar Power Sail

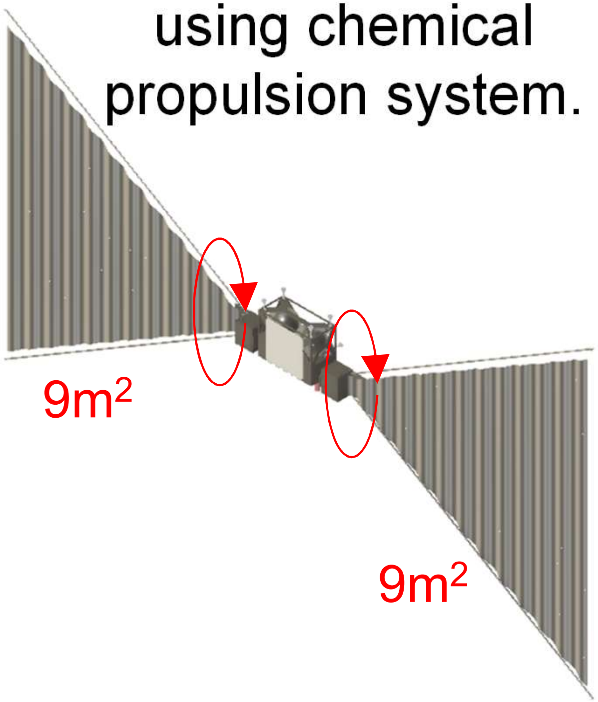
1) Boom-type sail methods for small spacecraft
2) Attaching various devices to sail
3) Changing sail configuration

Thin-film solar array paddle uses 1,2,3).

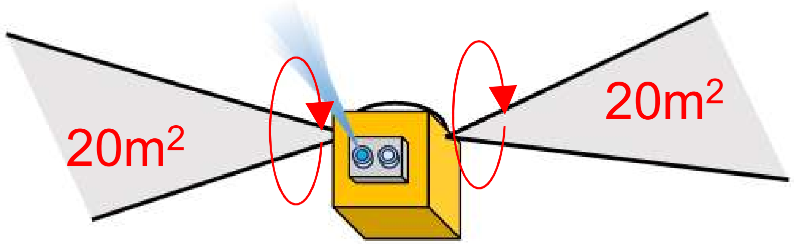
OPENS and OPENS2 utilizes thin-film solar array paddles.



OPENS performs Saturn flyby using chemical propulsion system.



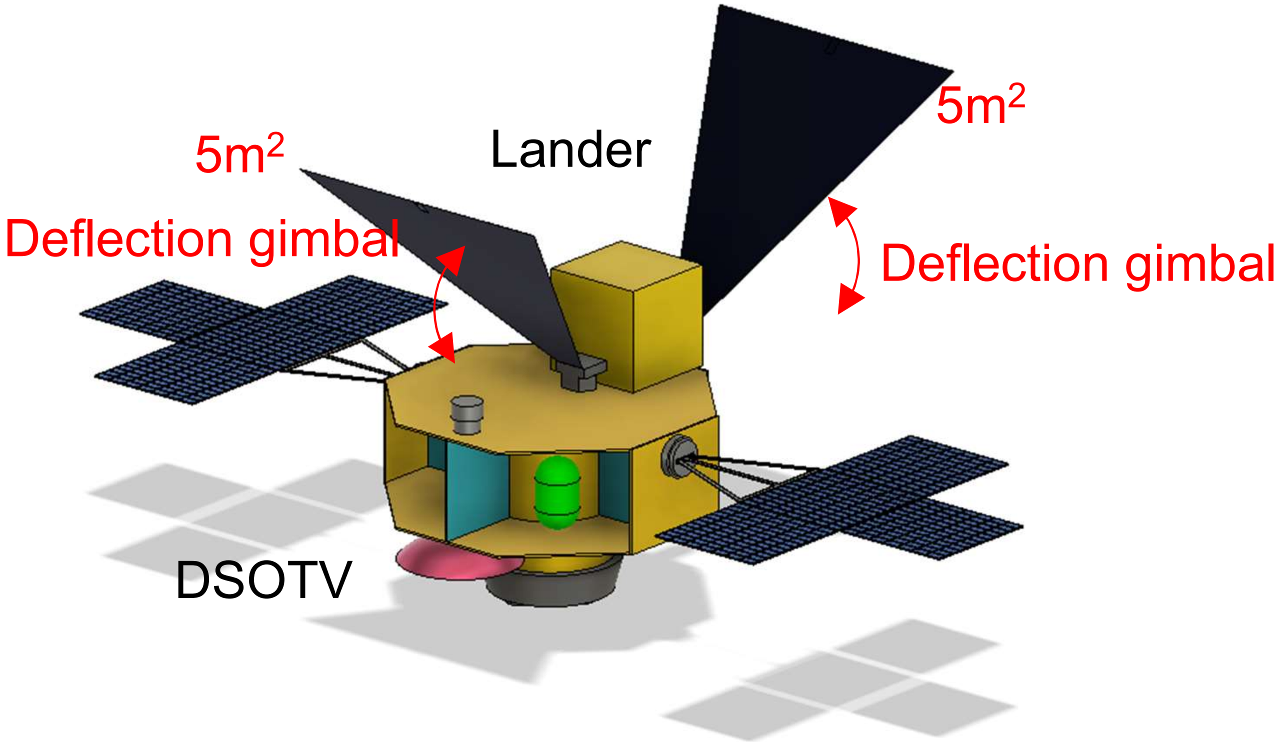
OPENS2 performs Trojan asteroid rendezvous using ion-engine.

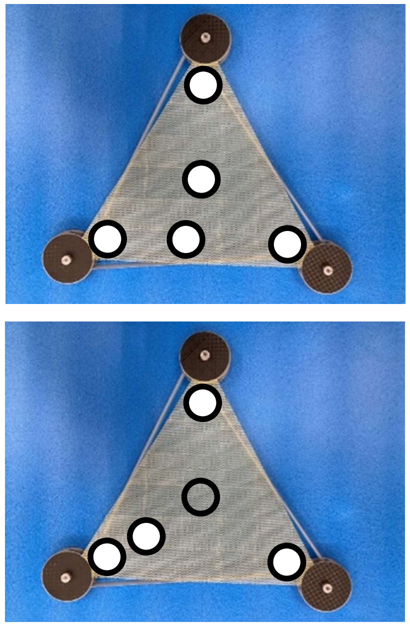


New Solar Power Sail Program 3

Sail-craft and Lander System ⇨ **DSOTV and Lander System**

The system concept is applied to next-generation small body sample return mission.
The lander uses deployable target markers for pinpoint landings.

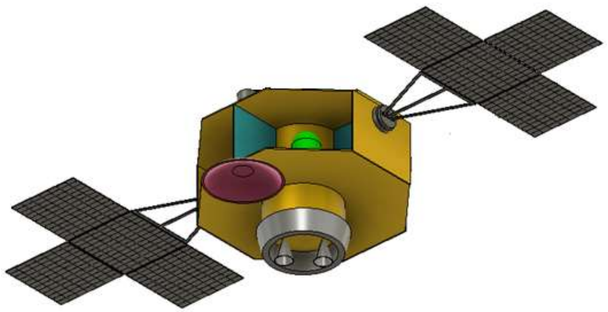


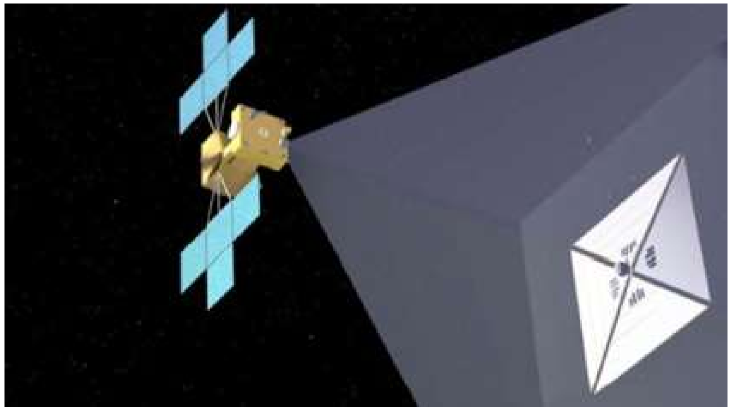


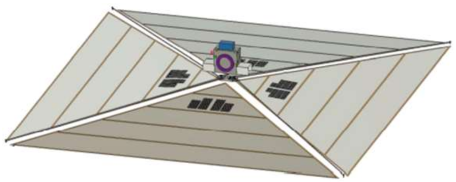
New Solar Power Sail Program 4

DSOTV and Lander System ⇨ **DSOTV and Payload System**

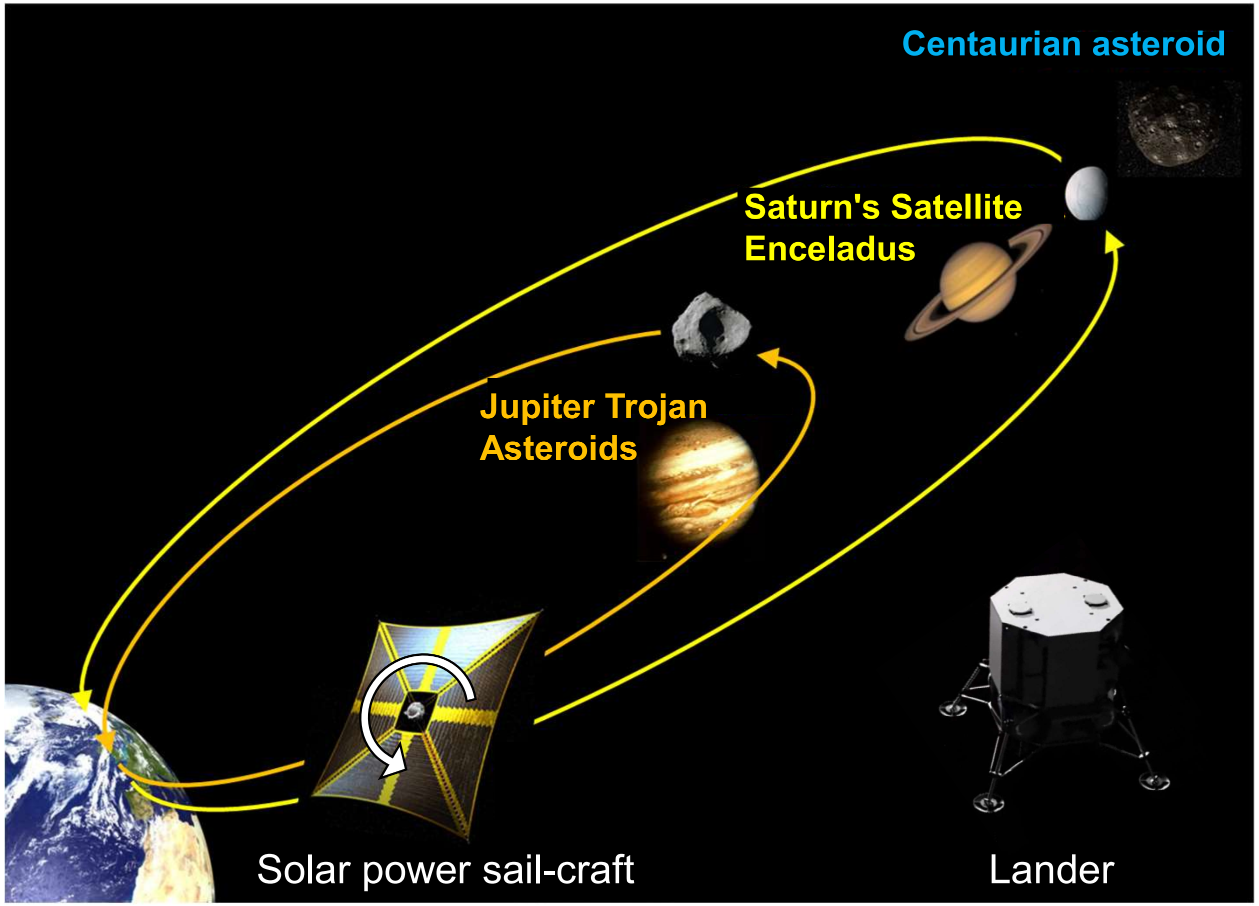
This system concept is applied to DSOTV and PIERIS.
PIERIS demonstrates hybrid propulsion of photon acceleration and electric propulsion (water ion thruster).







New Solar Power Sail-craft and Lander Mission



We are convinced that new solar power sail program leads to new sample return mission from outer planetary region using solar power sail-craft and lander.

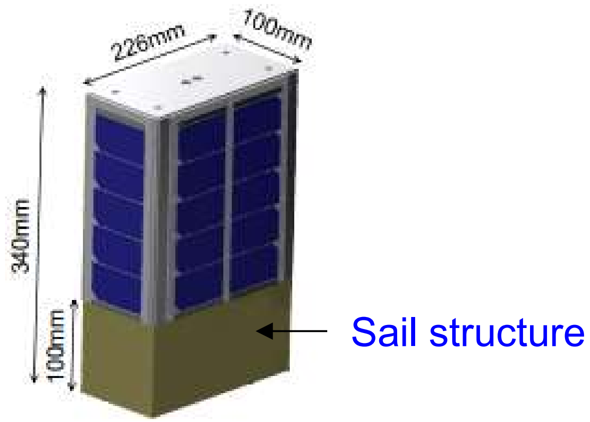
6U Solar Sail System

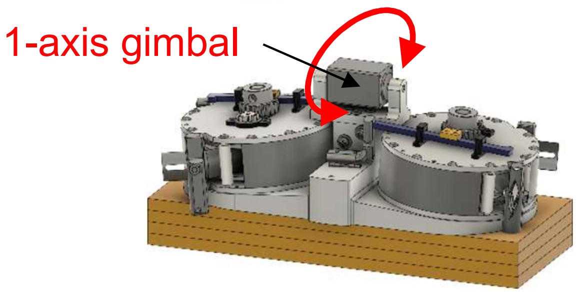
6U solar sail, as a piggyback payload for Lunar program

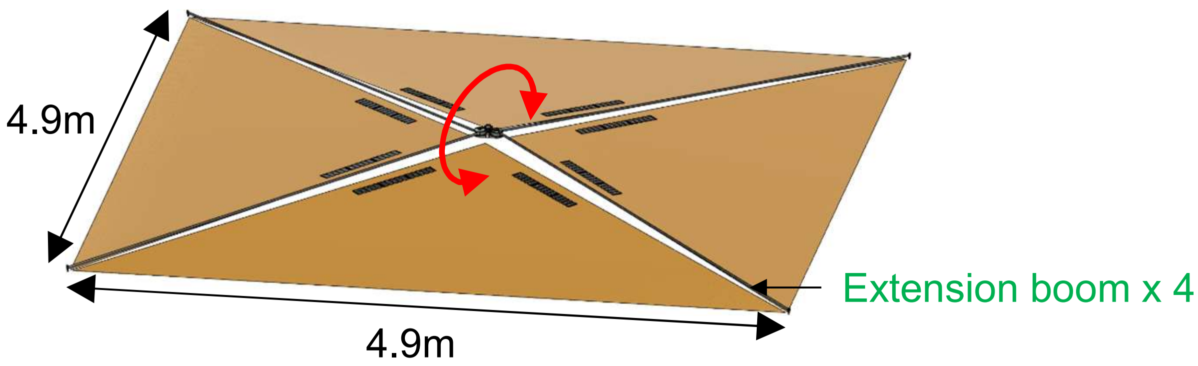
Size: 6U total (including 2U sail structure, not including ion thrusters)

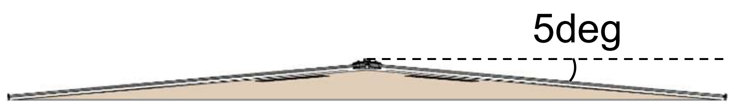
Sail configuration: the same of PIERIS

- The sail is deployed by the four self-extension booms.
- The shape is a square with 4.9m sides.
- The sail is canted 5deg to stabilize the attitude against SRP.
- The sail is reorientable using 1-axis gimbal.





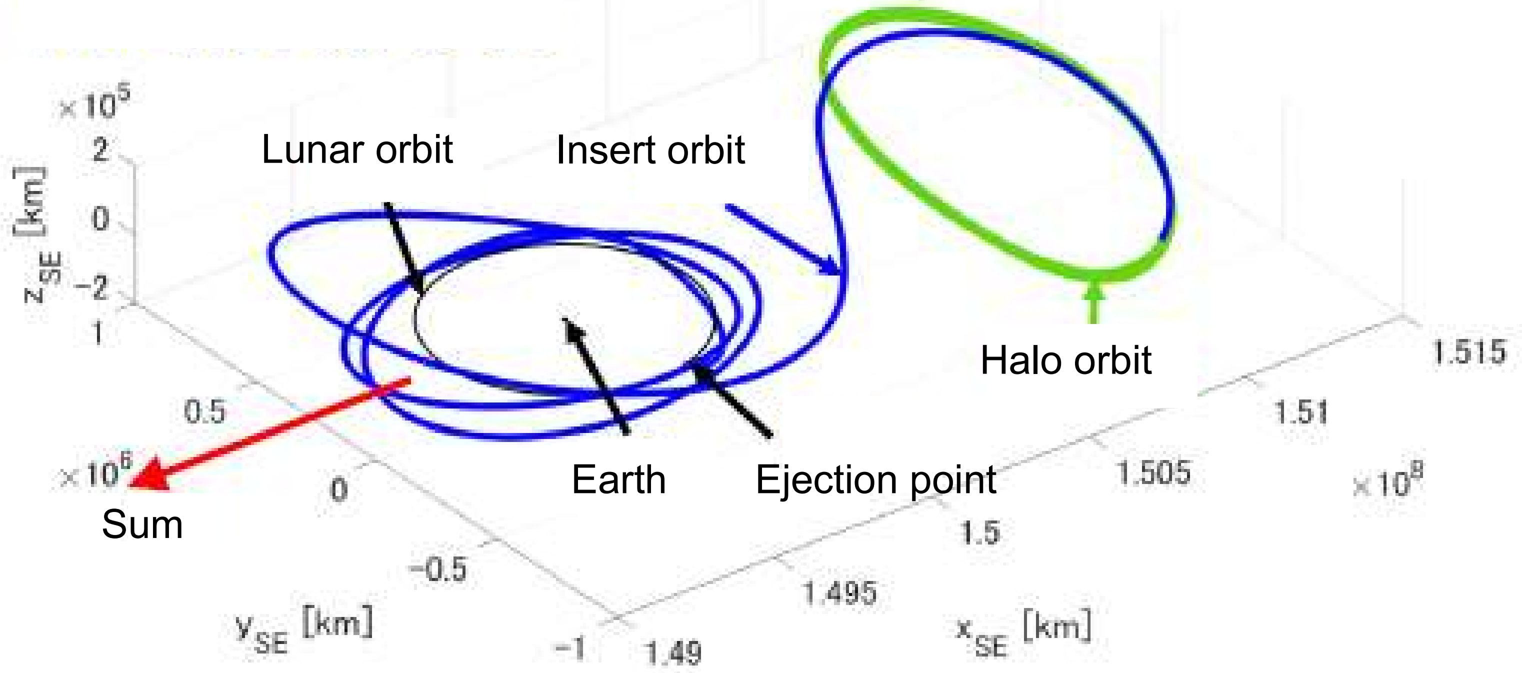




PIERIS Mission2

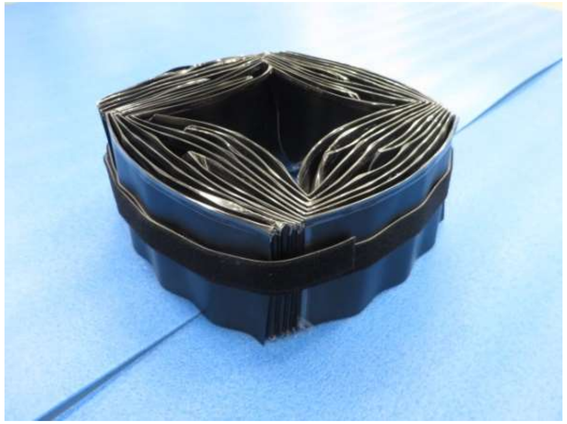
1. It will be ejected from lunar orbit and injected into a halo orbit around the Sun-Earth system L2.

2. It will maintain a <u>halo</u> orbit for a long ti<u>me</u>.



1-6) Wave-shaped Panel Method

Wave-shaped panels self-expand to form a paddle without booms.



Wave-shaped panels