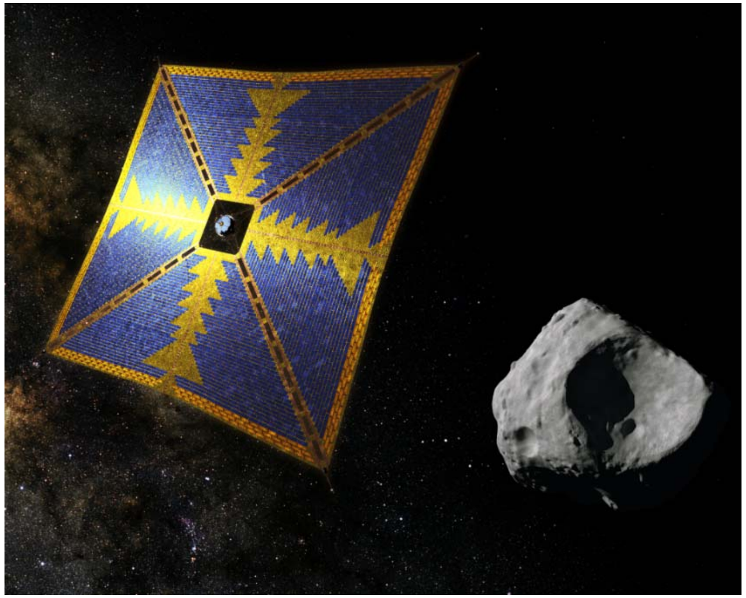
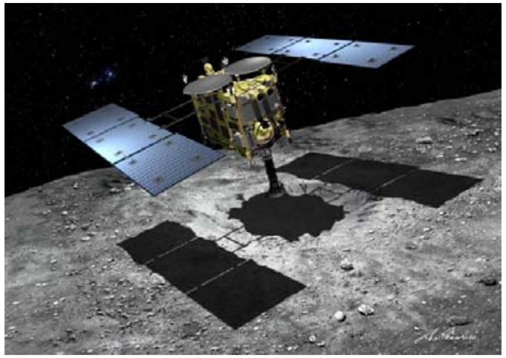
Direct Exploration of Jupiter Trojan Asteroid using Solar Power Sail

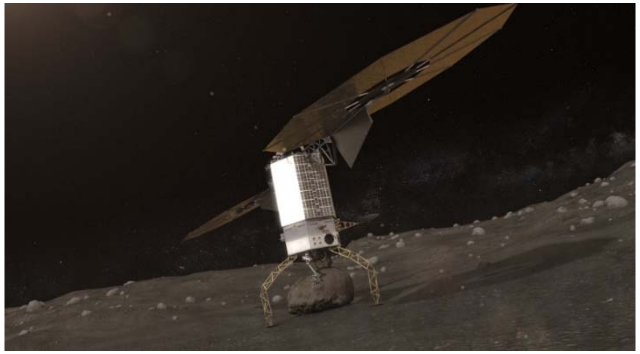


Osamu MORI*, Hideki KATO, Jun MATSUMOTO, Takanao SAIKI, Yuichi TSUDA, Naoko OGAWA, Yuya MIMASU, Junichiro KAWAGUCHI, Koji TANAKA, Hiroyuki TOYOTA, Nobukatsu OKUIZUMI, Fuyuto TERUI, Atsushi TOMIKI, Shigeo KAWASAKI, Hitoshi KUNINAKA, Kazutaka NISHIYAMA, Ryudo TSUKIZAKI, Satoshi HOSODA, Nobutaka BANDO, Kazuhiko YAMADA, Tatsuaki OKADA, Takahiro IWATA, Hajime YANO, Yoko KEBUKAWA, Jun AOKI, Masatsugu OTSUKI, Ryosuke NAKAMURA, Chisato OKAMOTO, Shuji MATSUURA, Daisuke YONETOKU, Ayako MATSUOKA, Reiko NOMURA, Ralf BODEN, Toshihiro CHUJO, Yusuke OKI, Yuki TAKAO, Kazuaki IKEMOTO, Kazuhiro KOYAMA, Hiroyuki KINOSHITA, Satoshi KITAO, Takuma NAKAMURA, Hirokazu ISHIDA, Keisuke UMEDA, Shuya KASHIOKA, Miyuki KADOKURA, Masaya KURAKAWA and Motoki WATANABE

Introduction (1)

Direct exploration mission of small celestial bodies, inspired by **Hayabusa**,
are being actively carried out ⇨ **Hayabusa-2, OSIRIS-REx and ARM etc**

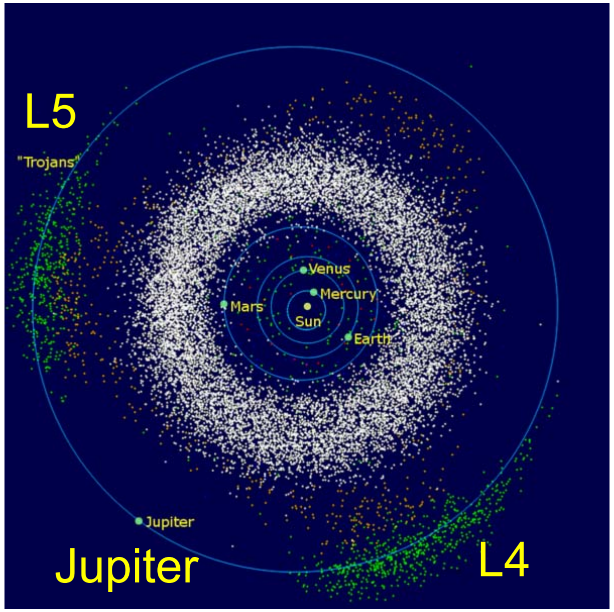




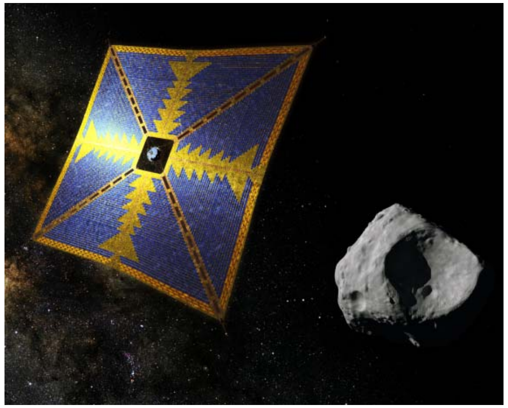
- Due to constraints of resources and orbital mechanics,
  the current target objects are mainly **near-Earth asteroids and Mars satellites**.
- In the near future, it can be expected that the targets will shift to
  higher primordial celestial bodies, located farther away from the Sun.

Introduction (2)

- In the navigation of the outer planetary region, ensuring electric power becomes increasingly difficult and ΔV requirements become large.
- It is not possible to **perform sampling (direct exploration) missions beyond the main belt with combination of solar panels and chemical propulsion system**.
- NASA selected **Jupiter Trojan multi-flyby** as Discovery mission.
- However, we propose **a landing and sample return of Jupiter Trojan using the solar power sail-craft**.



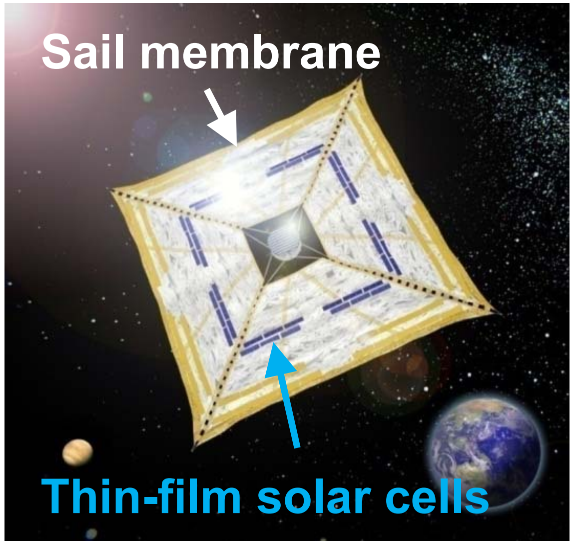
NASA

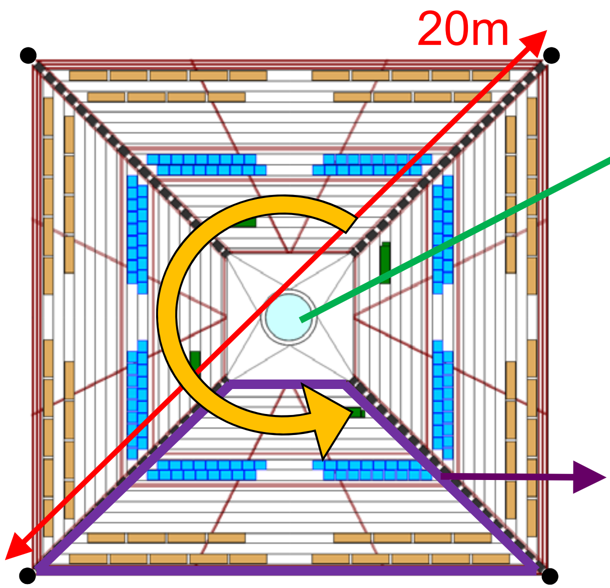


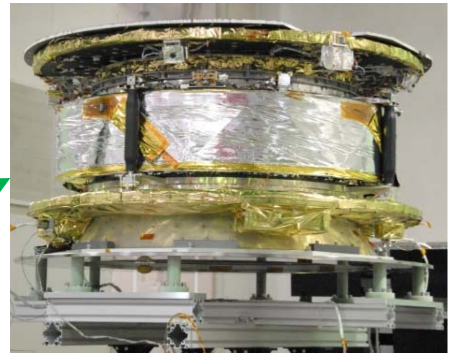
JAXA

What is Solar Power Sail ?

- **Solar Power Sail** is original Japanese concept
  in which electrical power is generated by **thin-film solar cells** on the sail membrane.
- JAXA developed the world's first solar power sail "**IKAROS**"
  which demonstrated for both its photon propulsion and thin-film solar power generation during its interplanetary cruise.
  - 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.

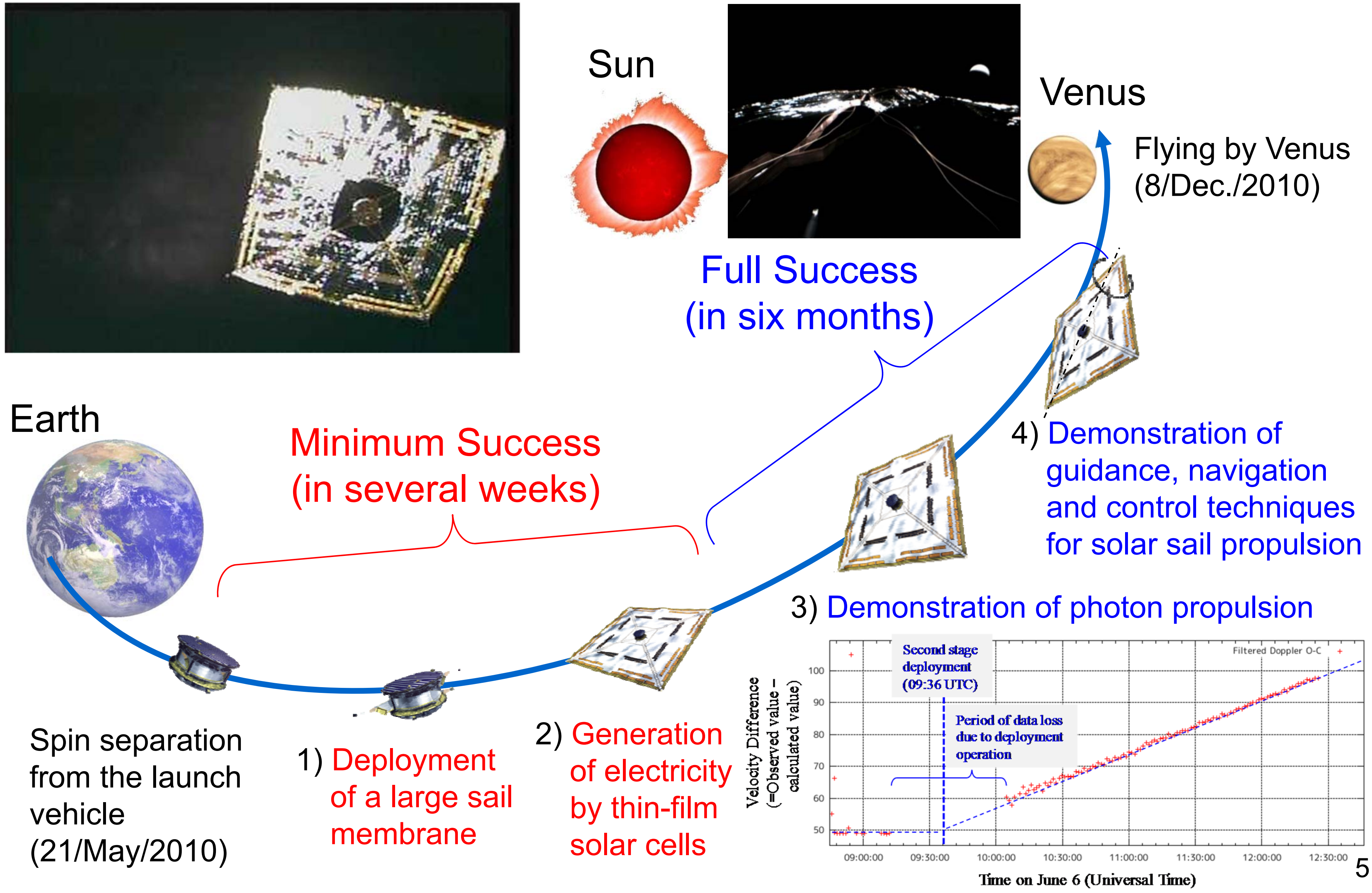






IKAROS = Interplanetary Kite-craft Accelerated by Radiation Of the Sun

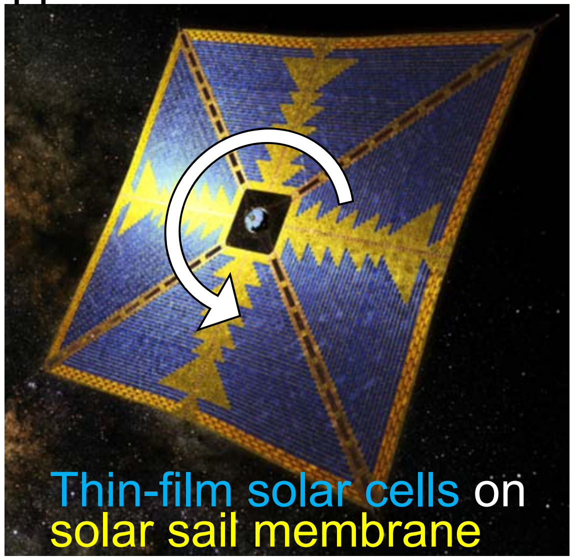
IKAROS Mission Sequence

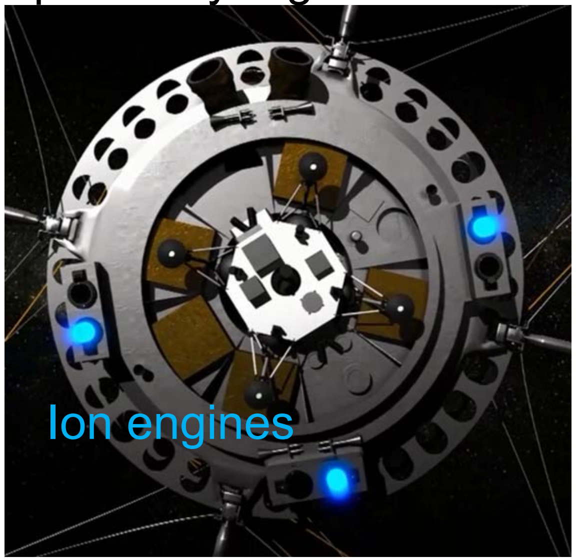


Next Solar Power Sail System

Solar power sail can generate the sufficient power by the large area thin-film solar cell to **drive the high specific impulse ion engine in the outer planetary region**.

⇨ It is applicable to missions to the outer planetary region.





<Thin-film solar cells>

•The area of spin-type solar sail is 2500m^2 (**10~15 times larger than that of IKAROS**).

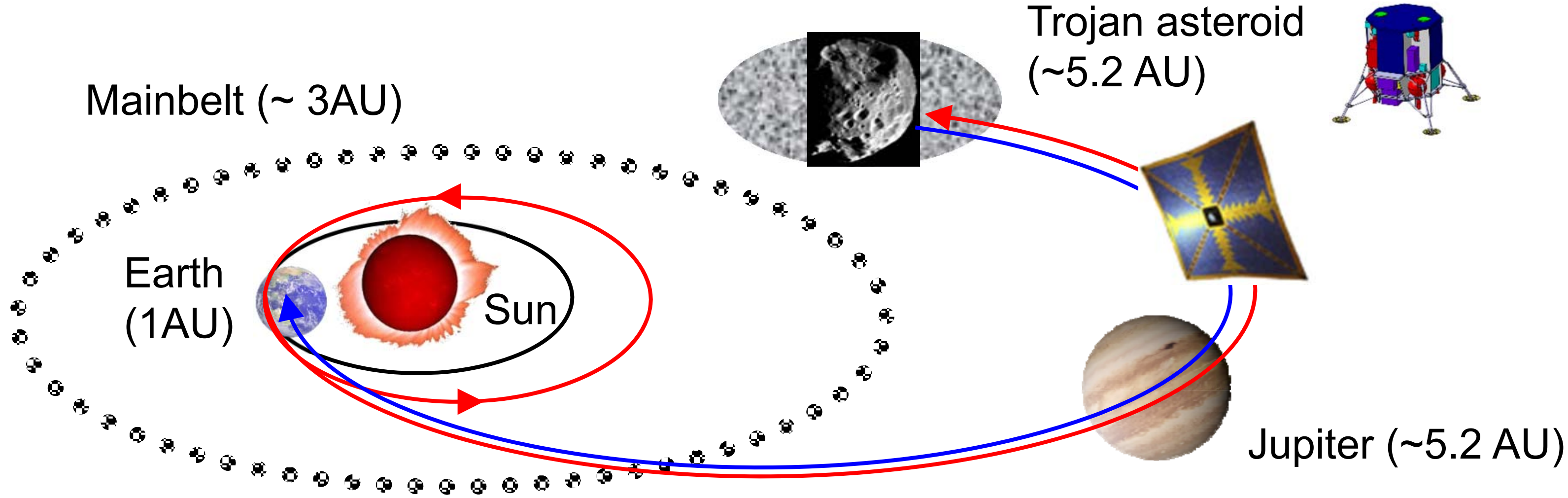
•It can be the **ultra-light power generation system (1kW/kg)** and **generate large electric power (5kW@5.2AU) in the outer planetary region** by attaching thin-film solar cells on entire surface of sail membrane.

<Ion engines>

•The Isp of ion engine is 7000 seconds (**2~3 times larger than that of Hayabusa**).

•It is capable of **getting a large ΔV in the outer planetary region** by this large power.

Mission Sequence



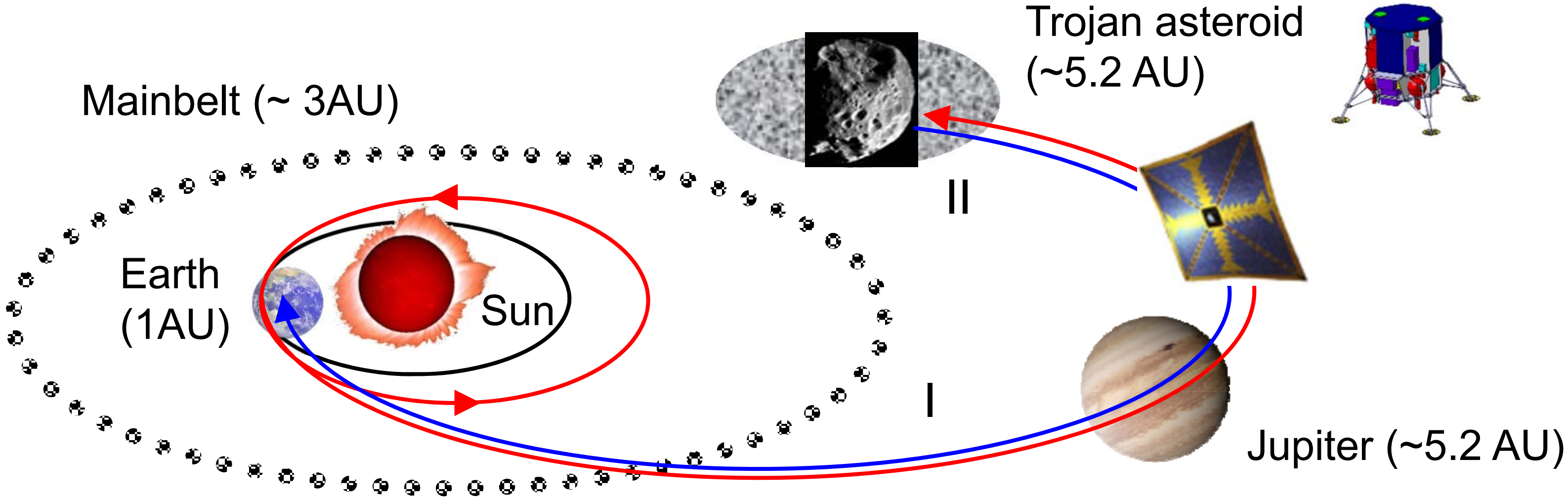
- The solar power sail-craft is supposed to rendezvous with a Trojan asteroid for the first time using both Earth and Jupiter gravity assists.
- After arriving at the Trojan asteroid, a lander is separated from sail-craft to collect surface and subsurface samples and perform in-situ analysis.
- The lander delivers samples to sail-craft for sample return to Earth.

<Event>

1) Launch
2) Earth swing-by
3) Jupiter swing-by
4) Arrival at Trojan asteroid
5) Landing, sampling and in-situ analysis (Lander)
6) Departure from Trojan asteroid
7) Jupiter swing-by
8) Return to Earth

Plan-A: One way
Plan-B: Round trip

New Innovative Scientific Purposes



- By probing the Trojan asteroids directly, it is possible to examine the planetary movement model of gas giants as the hypothesis of solar system formation theory.
- This mission aims to provide **several new innovative first-class astronomical science observations during the deep space cruising phase**. They can utilize features of cruising phase (long duration, long baseline and wide-area coverage) and contribute to the progression of planetary science, astronomy and space physics.

I. Cruising phase
(1) Infrared telescope (EXZIT)
(2) Gamma-ray burst polarimeter (GAP2)
(2) Dust detector (ALDN2)
(4) Magnetometer (MGF)

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

Plan-A: One way   Plan-B: Round trip

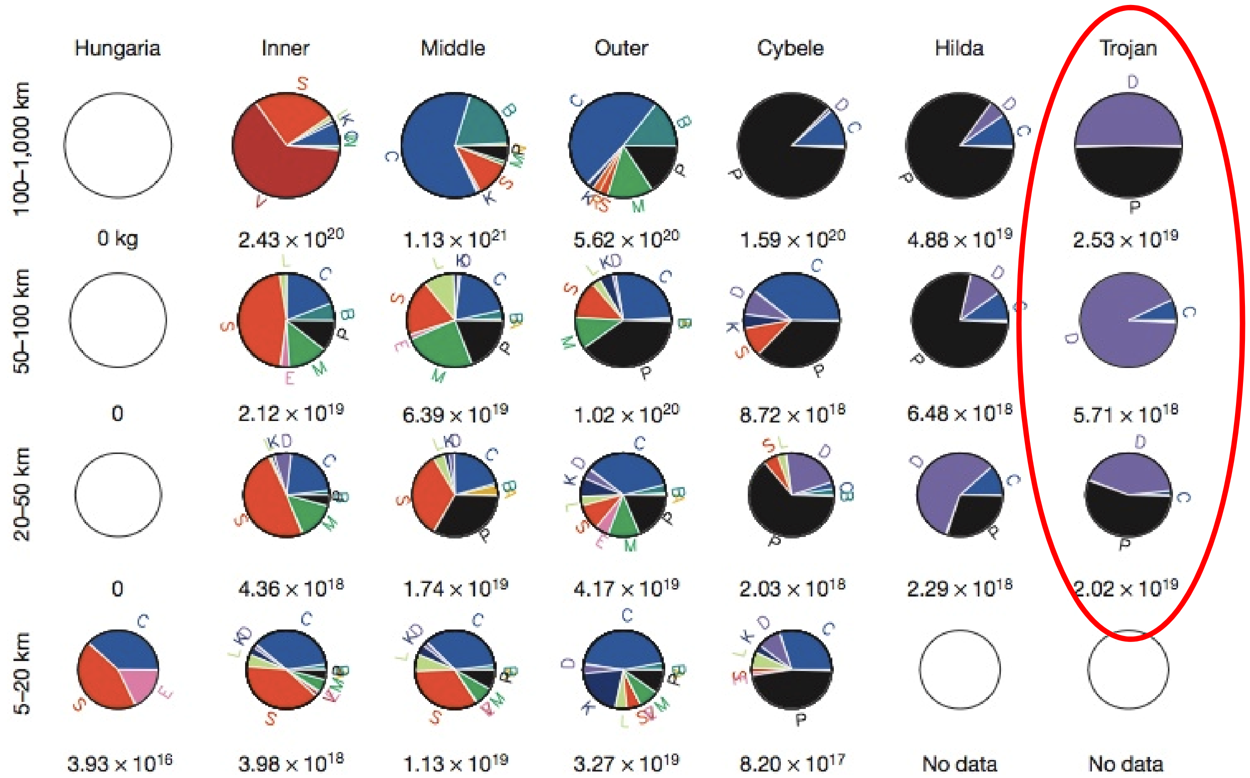
Mission Positioning

Spacecraft	Navigation	Landing	Sampling	Science
Hayabusa	Ion engine	Mother Spacecraft	Surface	ITOKAWA (S-type)
IKAROS	Solar sail	-	-	Cruising observation
Hayabusa-2	Ion engine	Mother Spacecraft	Surface and suburface	Ryugu (C-type)
Solar Power Sail-craft	High-Isp Ion engine Large solar sail	Lander	Surface and subsurface	Trojan Asteroid (D/P-type) Cruising observation

- Solar power sail-craft is composed of a high-Isp ion engine and a large solar sail which have been successfully demonstrated by Hayabusa and IKAROS respectively.
- The lander lands on the asteroid to collect surface and subsurface samples and carries out in-situ analysis, unlike Hayabusa and Hayabusa-2.
- S-type asteroid Itokawa and C-type asteroid Ryugu are the targets of Hayabusa and Hayabusa-2, respectively. A D/P-type Trojan asteroid is selected as the target.
- Solar power sail-craft performs cruise science observations as well as IKAROS.

Trajectory Design

There is a high probability of it being D/P type, if the diameter of the Trojan asteroid is more than 20km.



The gravity should be as small as possible, from the point of view of landing.

⇨ **The Trojan asteroid with diameters between 20~30km are selected as target candidates.**

Trajectory Examples

<Target>

•2001DY103 (L4)

<Result>

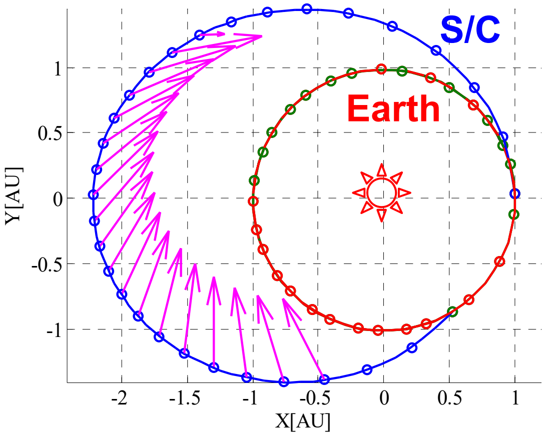
•In Plan-B, the outbound transfer period is about 13 years.

•In Plan A, it is about 11 years.
The flight time to the same asteroid can be shortened by using additional ΔV.

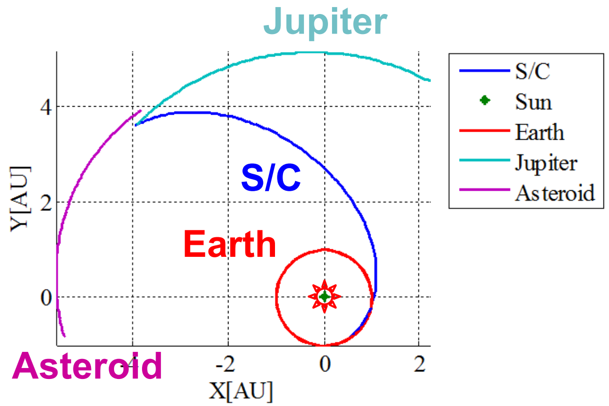
	Plan-B (round trip)			Plan-A (one way)		
Phase	Start	End	IES dV[m/s]	Start	End	IES dV[m/s]
2-year-EDVEGA	25/9/2022	24/7/2024	1442	20/9/2022	24/7/2024	1358
Earth to Jupiter	24/7/2024	22/12/2026	-	24/7/2024	22/12/2026	-
Jupiter to Asteroid	22/12/2026	1/1/2036	1471	22/12/2026	22/10/2033	4004
Rendezvous	1/1/2036	1/1/2037	-			
Asteroid to Jupiter	1/1/2037	12/9/2050	3686			
Jupiter to Earth	12/9/2050	29/7/2053	-			

***There are two or three target asteroids for every launch year.**

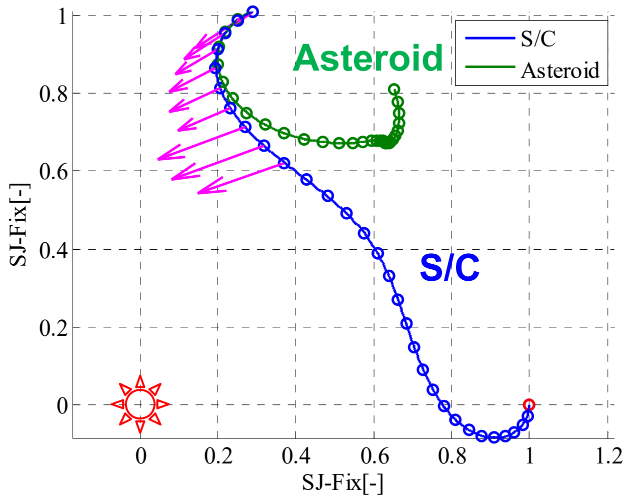
Orbit of Plan-B



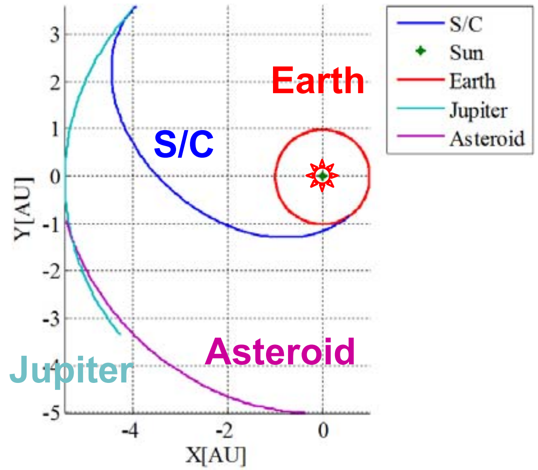
2-year-EDVEGA



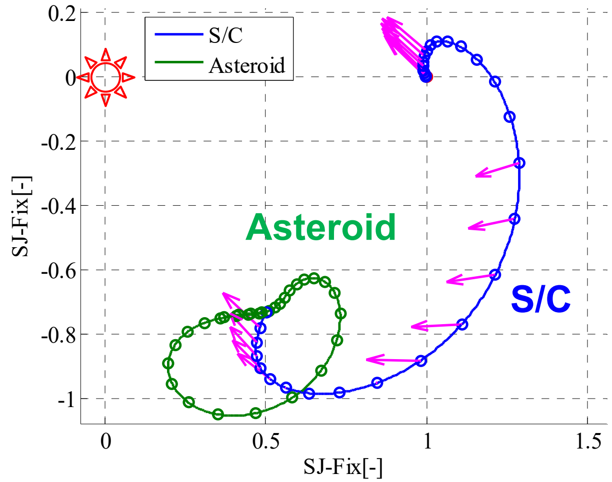
Earth to Jupiter



Jupiter to Asteroid

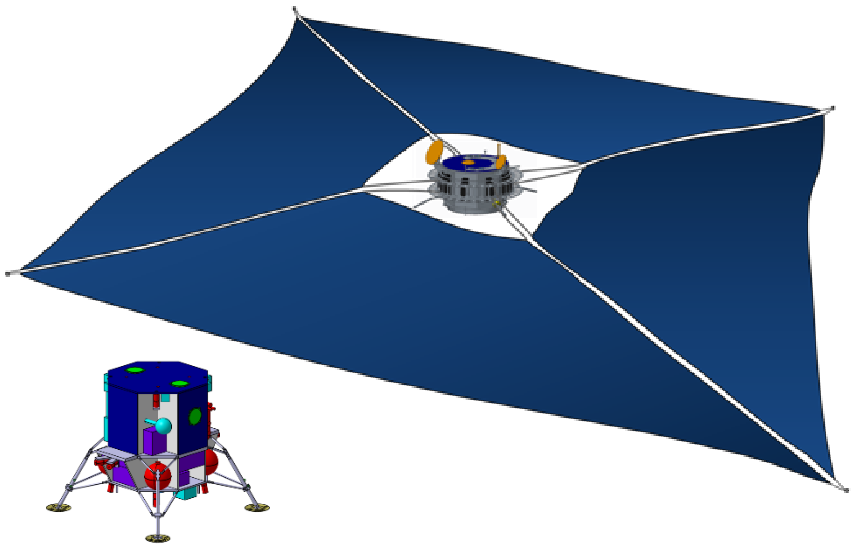


Jupiter to Earth



Asteroid to Jupiter

Initial Design of Solar Power Sail-craft

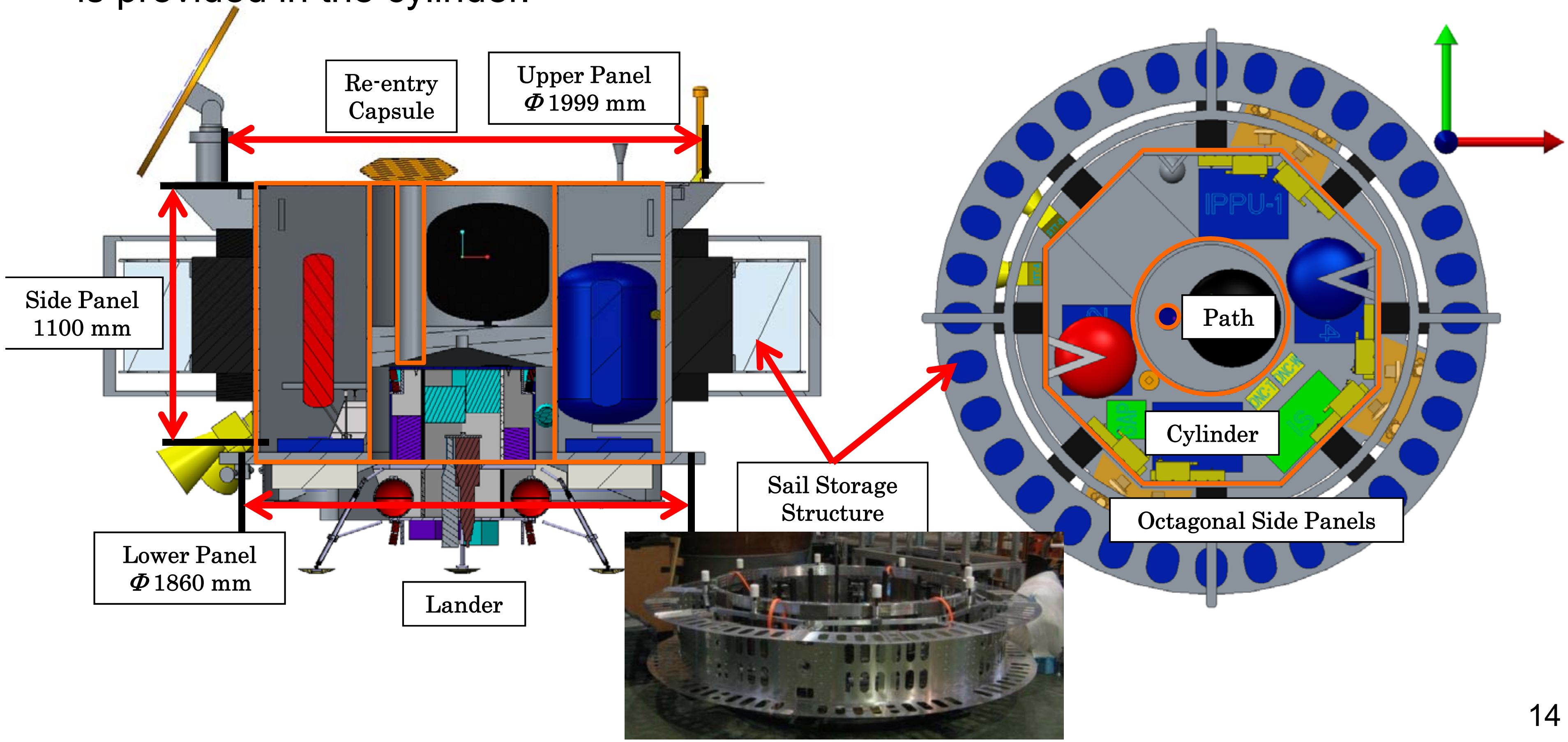


- Wet mass, which includes a 100kg lander, is 1285kg.
  - **The solar power sail-craft, with a mass of about 1.3 tons will be able to transport a 100kg lander to the Trojan asteroid and come back to the Earth.**
  - **Rosetta with its mass of 3 tons transported the Philae lander of the same 100kg mass to the comet, which is located closer than the Trojan asteroids.**

⇨ This difference indicates the superiority of the solar power sail.

Structural Design

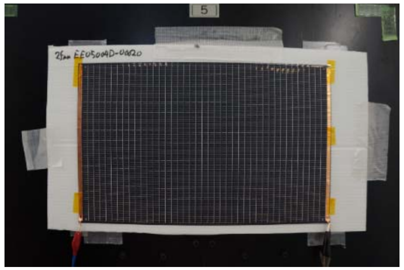
- <u>The entire structure is composed of octagonal side panels and upper / lower panels.</u>
- <u>A cylinder structure and sail storage structure is equipped inside and outside of the octagon, respectively.</u>
- Re-entry capsule and lander are located on +Z and -Z plane, respectively.
- A path for transferring the sample from lander to re-entry capsule is provided in the cylinder.

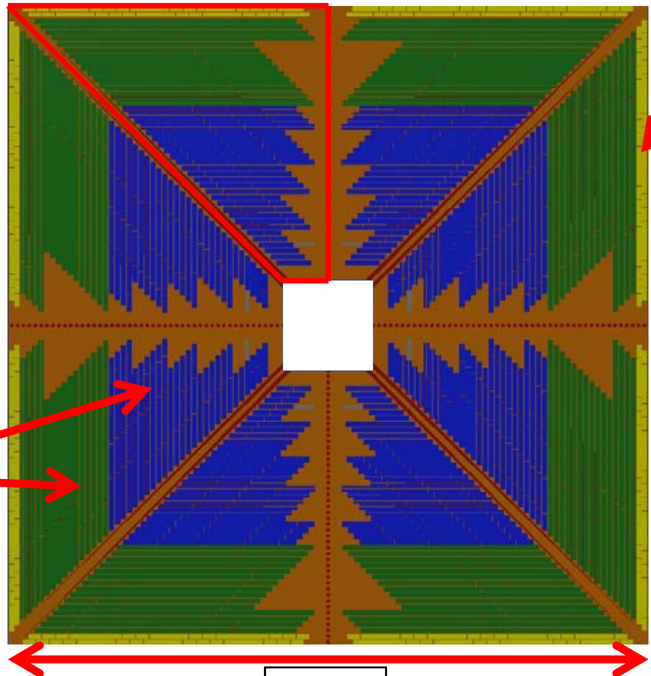


Power Sail Design

- <u>Large power sail is fully covered with thin-film solar cells (CIGS).</u>
- <u>Reflectivity control device (RCD) is also attached on the sail. It can change the optical properties using liquid crystal.</u> The attitude control toque can be generated by the solar radiation pressure.

Thin-film solar cell (CIGS)





48.7m

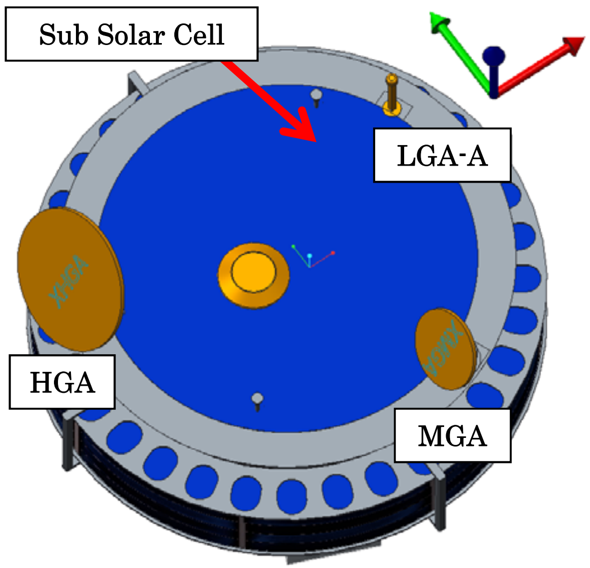
RCD

Power ON

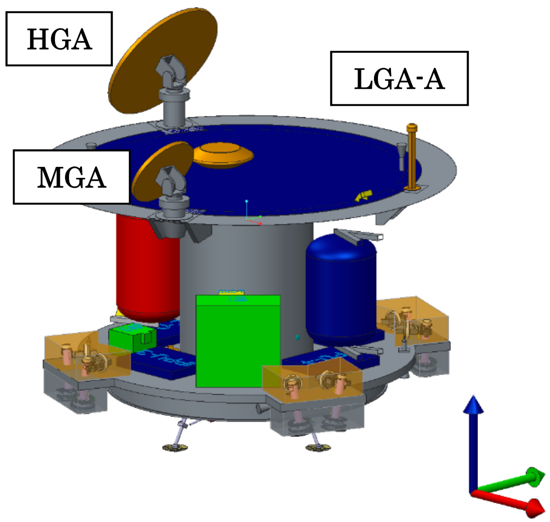
Power OFF

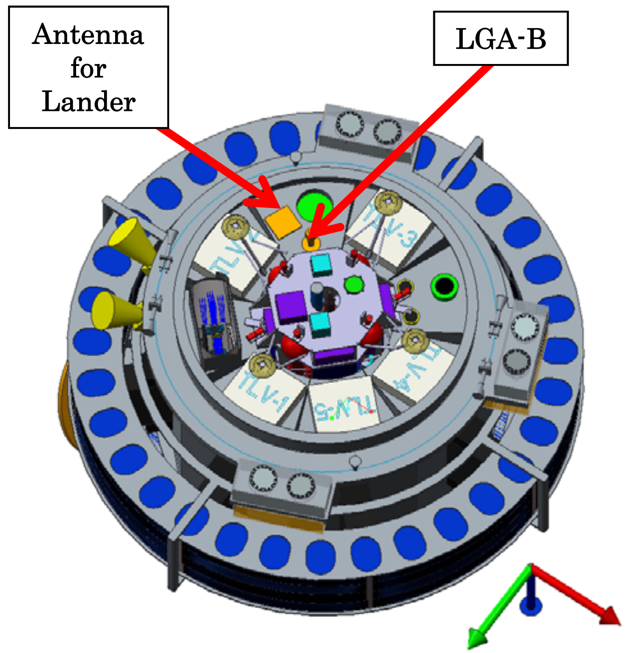
Overview of Sub-system (1)

- Electric power system (EPS): A sub solar cell mounted on +Z plane is used prior to deployment of the power sail.
- Communication system (COM): Two X-band transponders are equipped. LGA-A, LGA-B are used in the Earth neighborhood. MGA is mainly used during cruising phase. HGA is mainly used during the rendezvous phase. HGA and MGA can be point to Earth by a despun platform. The communication rate of the HGA is aimed 16Kbps in the Jupiter zone.



+Z plane

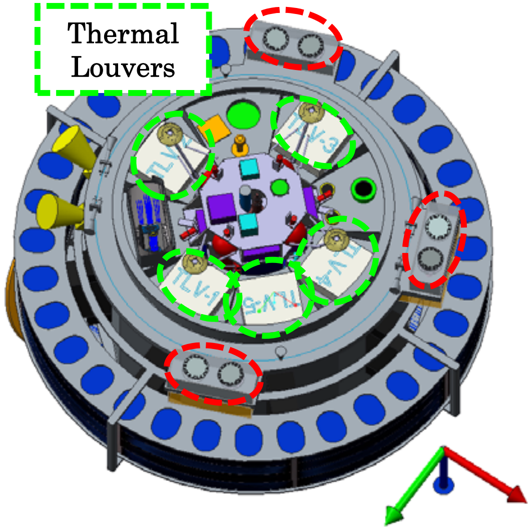




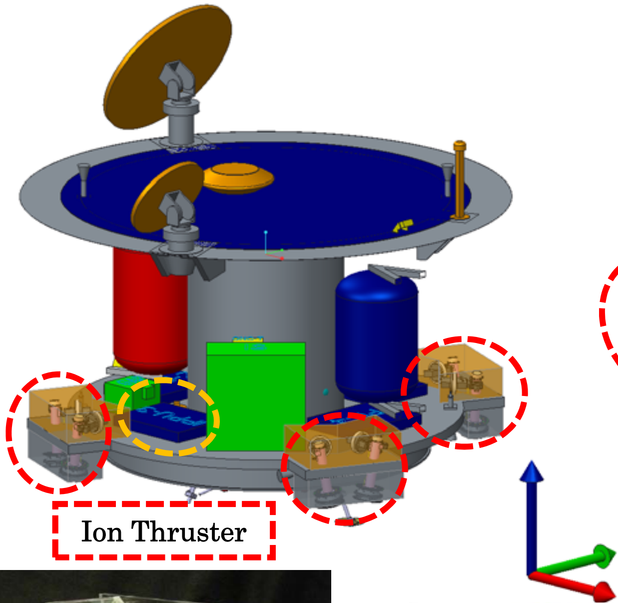
-Z plane

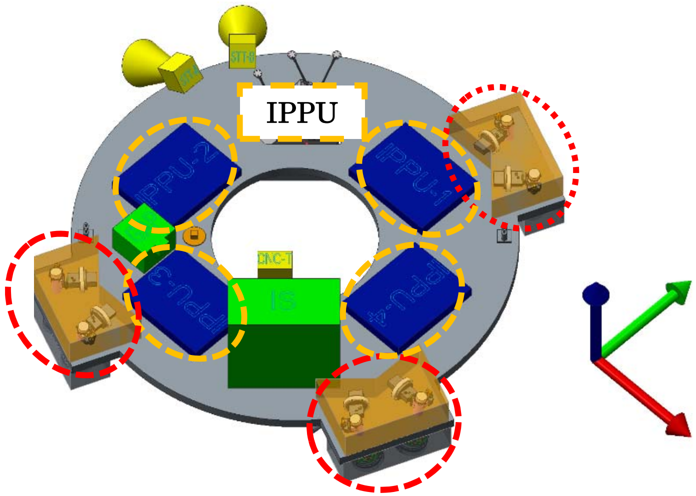
Overview of Sub-system (2)

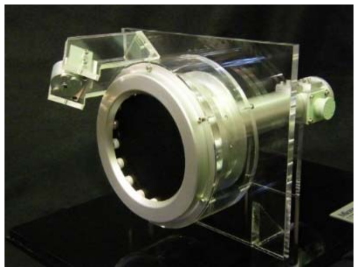
- Thermal control system (TCS): -Z plane is set as the main radiating face. In order to cope with significantly changing thermal environment and to reduce the heater power, thermal louvers and thermal switches are utilized.
- Ion engine system (IES): Six ion thrusters are mounted on -Z plane. In order to spin up / down, three thrusters each are inclined towards the spin up / down direction. Four IES power processing units (IPPU) are equipped account for redundancy.

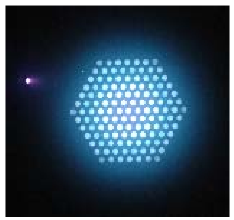


-Z plane



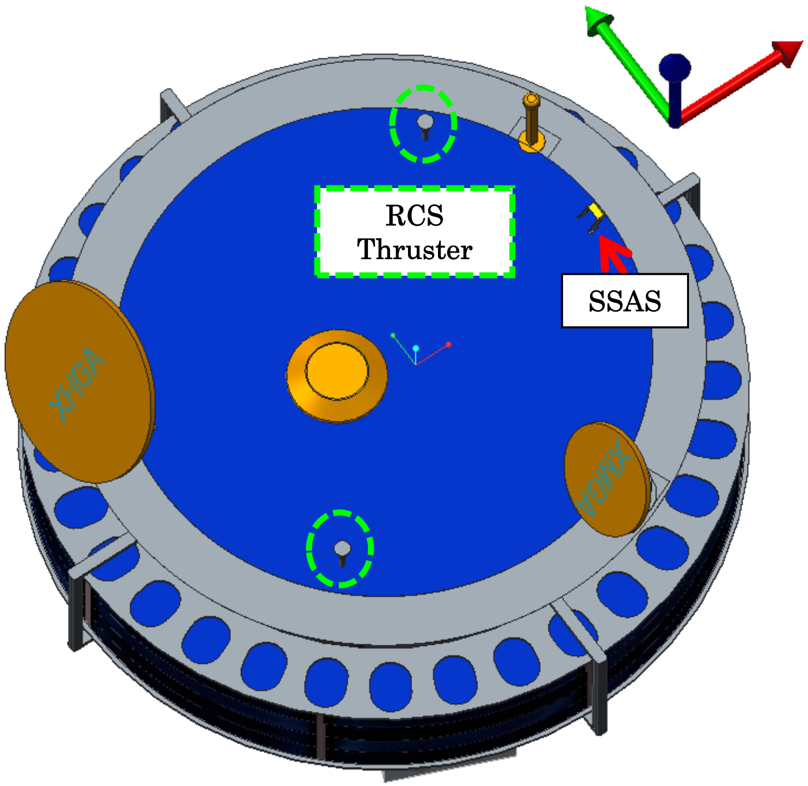




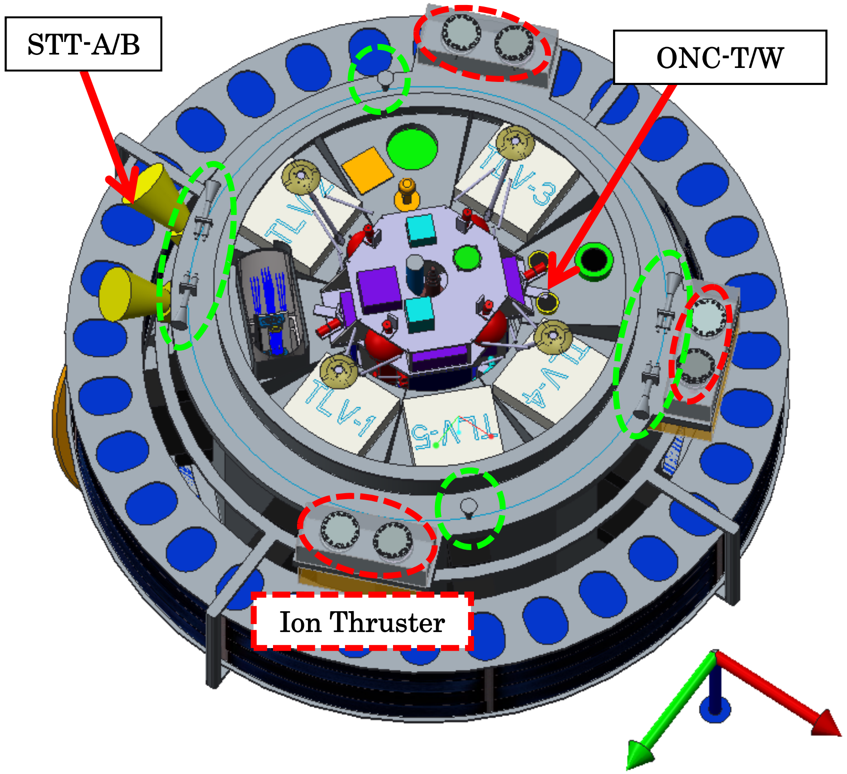


Overview of Sub-system (3)

- Reaction control system (RCS): A chemical propulsion system driven at ultra-low temperatures with much less heater power is adopted.
- Attitude control system (ACS): Spin type sun sensor (SSAS), star tracker (STT), inertial reference unit (IRU) and optical navigation camera (ONC) are equipped. IES, RCD and RCS are used to control attitude.



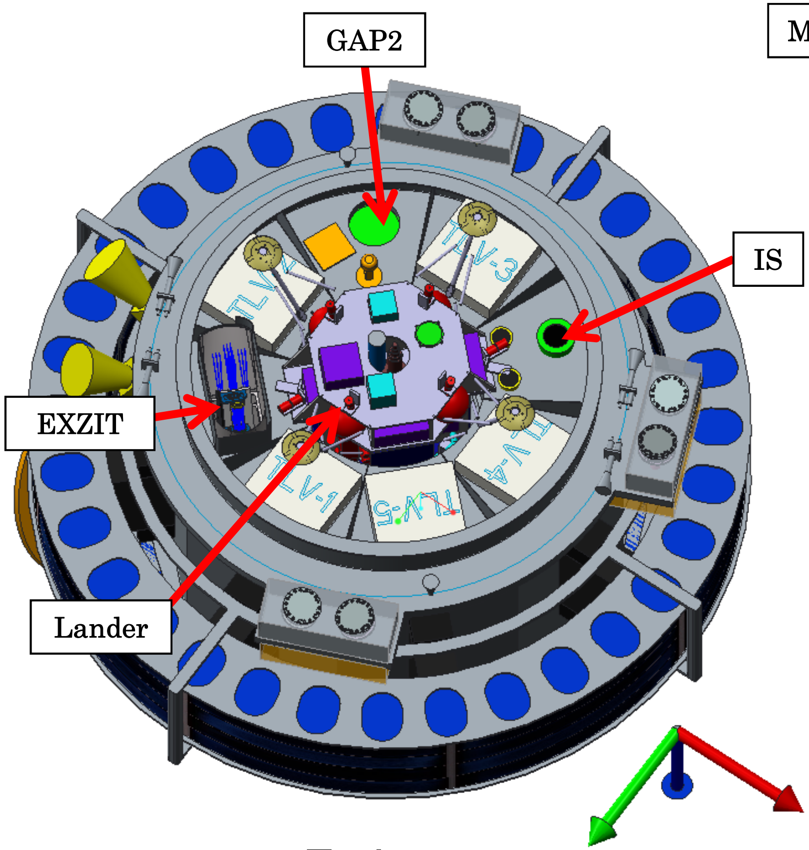
+Z plane



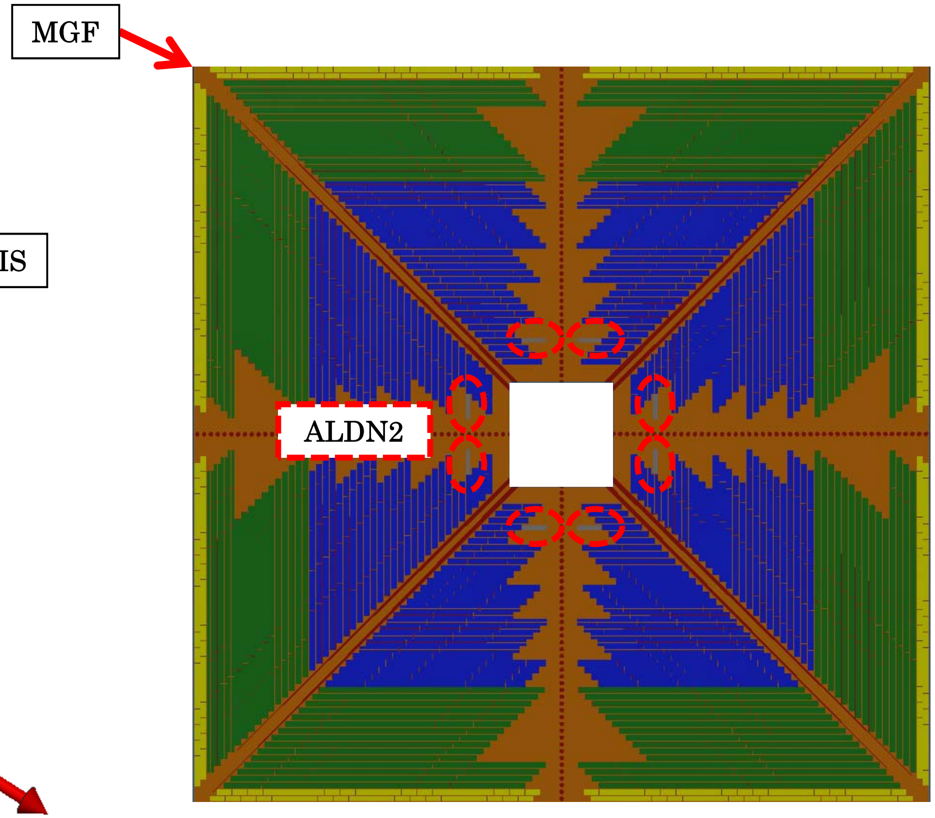
-Z plane

Overview of Sub-system (4)

- Mission system: Infrared telescope (EXZIT), gamma-ray burst polarimeter (GAP2), imaging spectrometer (IS) and lander are located on -Z plane. Dust detector (ALDN2) and Magnetometer (MGF) are attached on the sail.



-Z plane

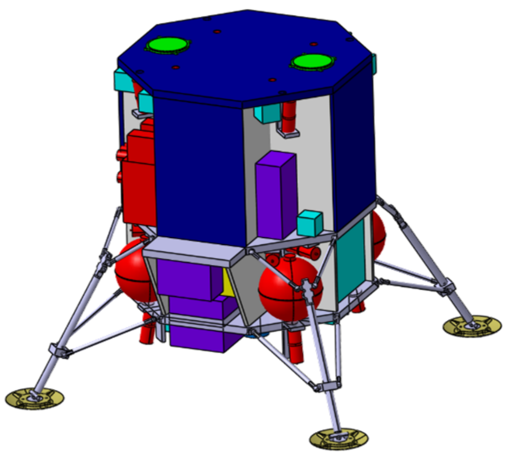


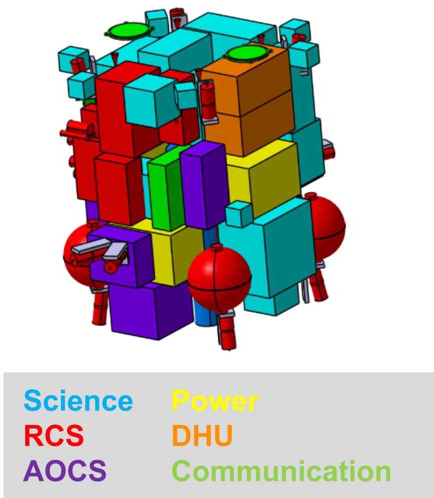
Initial Design of Lander

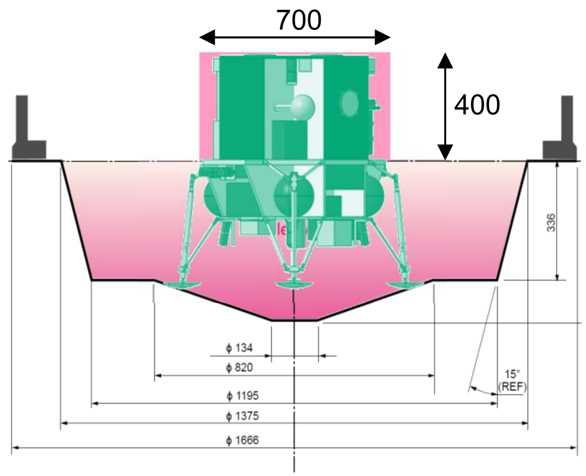
DLR and JAXA Joint study for a lander design started in 2014.

<System Requirements>

- The total lander mass (wet) shall not exceed 100kg.
- The payload mass including the sampling system shall not exceed 20kg.
- The allowed envelope inside sail-craft: diameter of 700mm and a height of 400mm
- The lander shall be powered by batteries during the descent and on asteroid phase.
- The lander shall be capable to perform an autonomously descent, hovering and landing using RCS.







Operational Policy at the Trojan Asteroid

1) Sail-craft is placed in a hovering home position (HP) above the asteroid. HP altitude is 250~1000km.

2) Sail-craft performs global mapping and scientific observations from HP.
These are used for the landing location site selection.

3) Sail-craft performs a rehearsal of the lander deployment by descending to a lower altitude and ascending again.
This makes it possible to investigate the asteroid surface around the selected landing point in detail.

4) Sail-craft descends again, and separates the lander at an altitude of 1km.

5) The landing method is not a free fall but a soft landing utilizing an RCS.

6) The lander collects the surface and subsurface samples and in-situ analysis is performed.

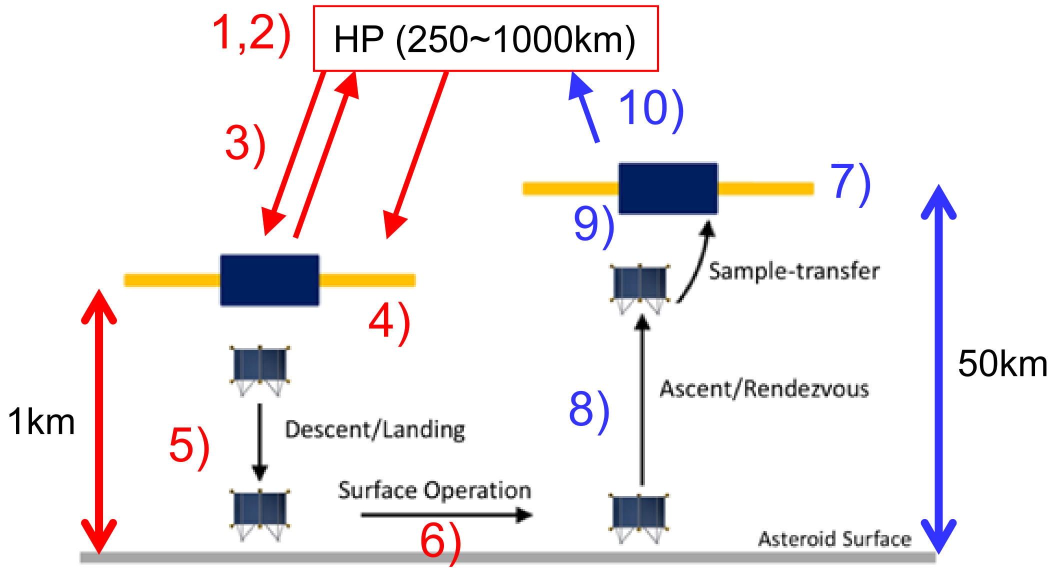
7) Sail-craft ascends to an altitude of 50km and waits for lander.

8) The lander takes off to rendezvous and be docked with sail-craft. Navigation is supported by sail-craft.

9) The lander delivers the sample and separated again and decommissioned.

10) Sail-craft returns to its original HP.

Plan-A: One way
Plan-B: Round trip

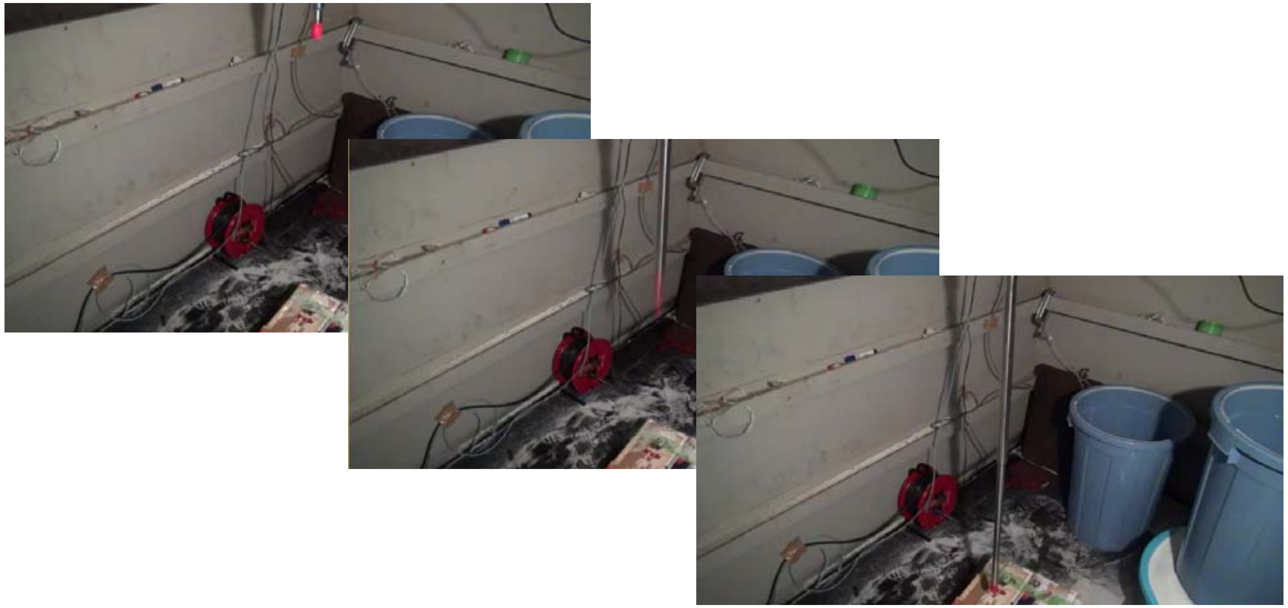


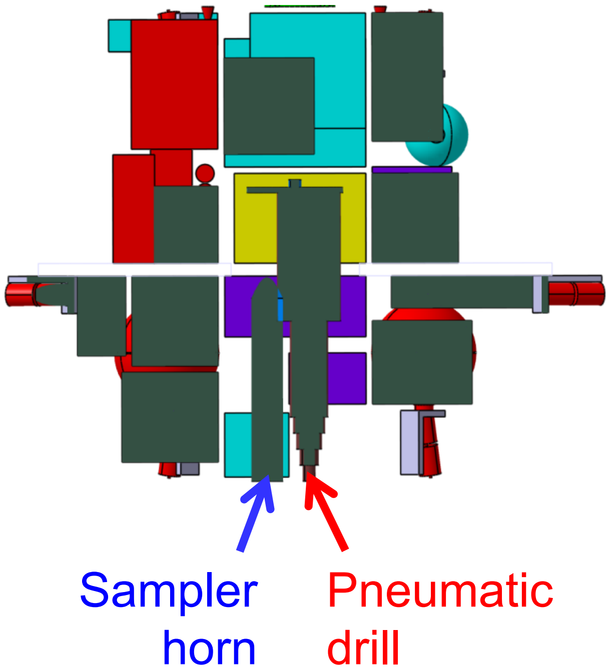
Sampling System (1)

The lander has two sampling devices to collect the surface and subsurface samples.

For the former, the sampler horn, similarly to that of Hayabusa is used.

For the latter, a pneumatic drill excavates a 1m regolith layer using high-pressure gas.

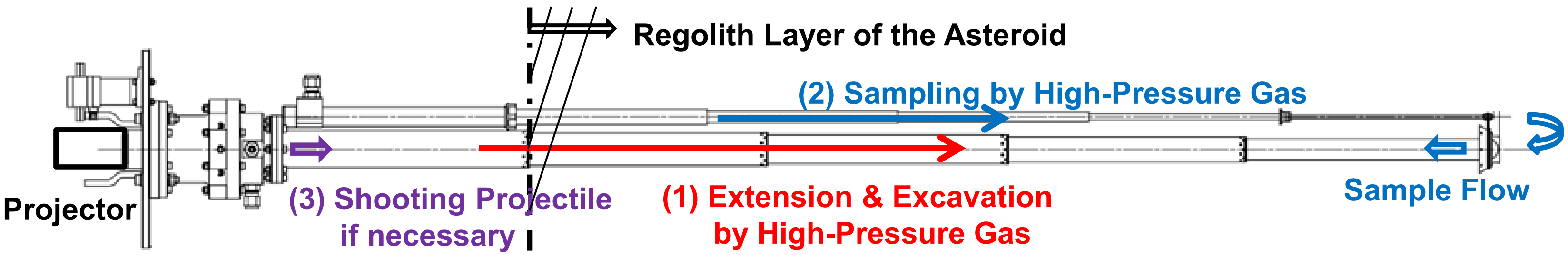




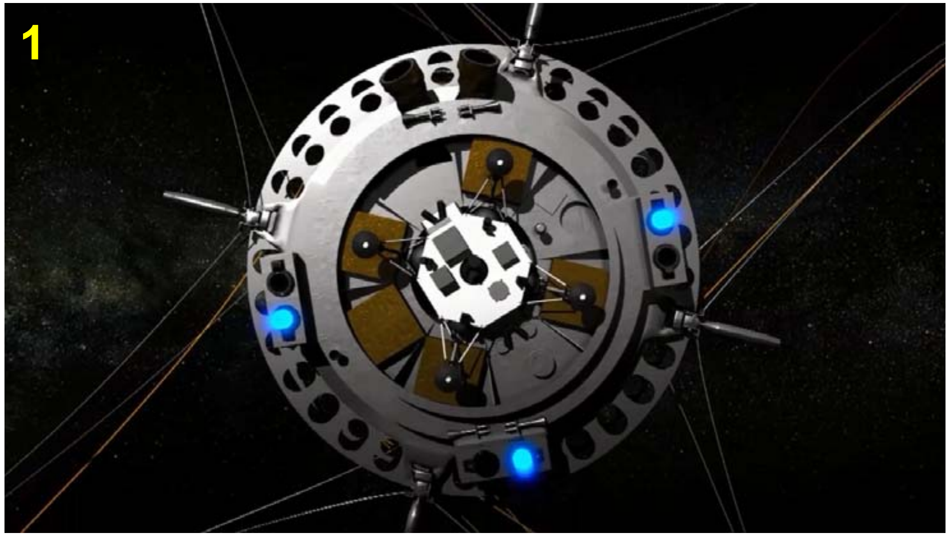
This device has a telescopic structure.

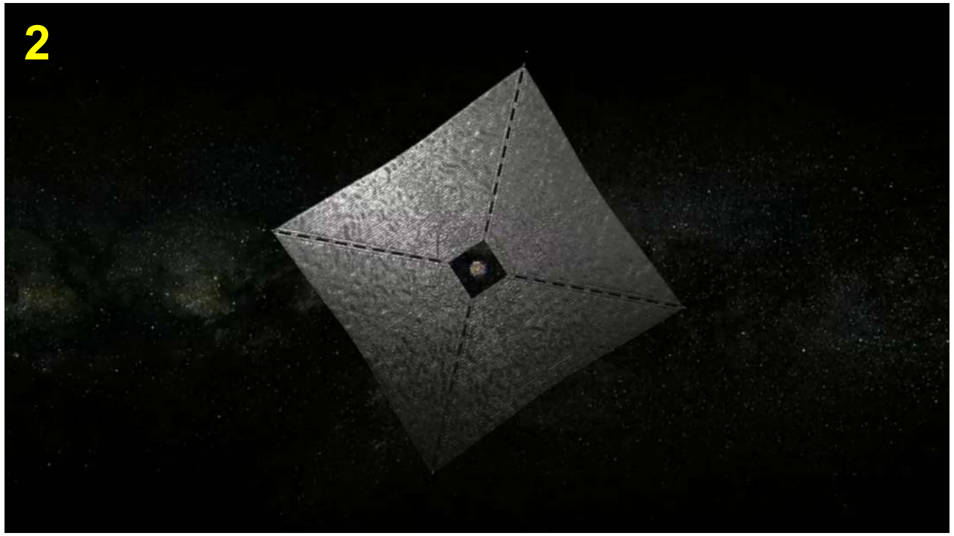
Sampling System (2)

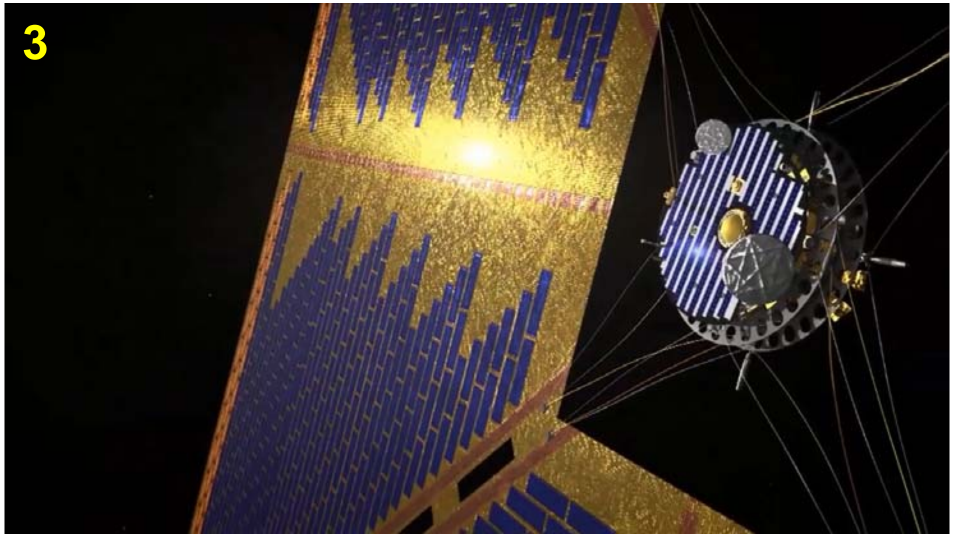
(1) Extension & excavation are performed at the same time.
(2) Additional high-pressure gas is released and subsurface samples are collected.
(3) If there is a rock, a projectile is shot to generate the fragments of the samples.

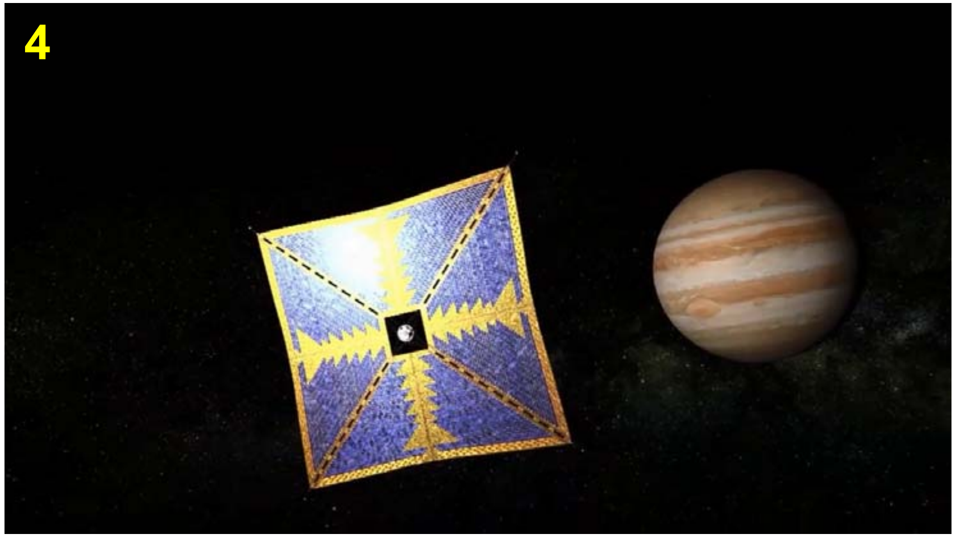


Mission Image (1)









Mission Image (2)

Conclusion

- In this presentation, a direct exploration mission of Jupiter Trojan asteroid by a solar power sail-craft was proposed.

- Mission Definition Review (MDR) was held in March 2015.
  This mission was selected as one of the two candidates.
- We will fix Plan-A or Plan-B in two years.
- System Requirement Review (SRR) will be held in December 2018.
  The final candidate will be selected.

- With this mission, **solar power sail can lead the future solar system exploration, as well as provide a breakthrough of space astronomy as a new scientific field.**