Solar power sail mission of OKEANOS

Osamu Mori[1] (✉), Jun Matsumoto[1], Toshihiro Chujo[2], Masanori Matsushita[1], Hideki Kato[1], Takanao Saiki[1], Yuichi Tsuda[1], Jun'ichiro Kawaguchi[1,4], Fuyuto Terui[1], Yuya Mimasu[1], Go Ono[1], Naoko Ogawa[1], Yuki Takao[3], Yuki Kubo[3], Kaoru Ohashi[4], Ahmed Kiyoshi Sugihara[1], Tatsuaki Okada[1], Takahiro Iwata[1], and Hajime Yano[1]

1. *Japan Aerospace Exploration Agency, Sagamihara 252-5210, Japan*
2. *Tokyo Institute of Technology, Tokyo 152-8550, Japan*
3. *The University of Tokyo, Tokyo 113-8654, Japan*
4. *Patchedconics, LLC, Sagamihara 252-5210, Japan*

ABSTRACT

The solar power sail is an original Japanese concept in which electric power is generated by thin-film solar cells attached on the solar sail membrane. Japan Aerospace Exploration Agency (JAXA) successfully demonstrated the world's first solar power sail technology through IKAROS (Interplanetary Kite-craft Accelerated by Radiation of the Sun) mission in 2010. IKAROS demonstrated photon propulsion and power generation using thin-film solar cells during its interplanetary cruise. Scaled up, solar power sails can generate enough power to drive high specific impulse ion thrusters in the outer planetary region. With this concept, we propose a landing or sample return mission to directly explore a Jupiter Trojan asteroid using solar power sail-craft OKEANOS (Oversize Kite-craft for Exploration and AstroNautics in the Outer Solar System). After rendezvousing with a Trojan asteroid, a lander separates from OKEANOS to collect samples, and perform in-situ analyses in three proposed mission sequences, including sending samples back to Earth. This paper proposes a system design for OKEANOS and includes analyses of the latest mission.

KEYWORDS

solar power sail
Trojan asteroid
landing
in-situ analysis
outer solar system
OKEANOS

Research Article

Received: 17 March 2019
Accepted: 13 September 2019

1 Introduction

For early missions with large solar distances, Galileo, Cassini, and New Horizons relied on radioisotope thermoelectric generators (RTG) to generate the required electric power, while chemical propulsion was used to generate the required delta-velocity (ΔV). As the performance of solar cells improved, Rosetta and Juno were able to instead rely on solar power even at these distances. Furthermore, Hayabusa and Hayabusa2 were able to generate enough power to operate their ion thrusters, generating enough ΔV for a return trip to small asteroids. It is key to note, however, that the power obtainable through solar panels reduces drastically beyond the asteroid belt, making the operation of ion thrusters challenging, while yet larger ΔV is required to reach these distances. These two factors make landing missions beyond the asteroid belt difficult with today's state of the art. The National Aeronautics and Space Administration (NASA) is currently considering exploring Jupiter Trojan asteroids through the Lucy mission, however, this mission aims to achieve multiple flybys over the target asteroids, and not landing.

The mission we propose uses the solar power sail-craft OKEANOS (Oversize Kite-craft for Exploration and AstroNautics in the Outer Solar System) to explore the Jupiter Trojan asteroids [1, 2]. Solar power sail-crafts are spacecraft equipped with a large number of thin-film solar cells attached on a solar sail with large surface area, generating enough power to operate high specific impulse (Isp) ion thrusters at Jovian distances and beyond (Table 1). Solar power sails are distinct from solar sails in that the majority of the thrust is generated through the high-Isp ion thrusters, rather

✉ mori.osamu@jaxa.jp

Table 1 Spacecraft power and propulsion systems

Power subsystem	Propulsion subsystem	Mission
RTG	Chemical propulsion	Cassini, New Horizons
Solar panel	Chemical propulsion	Juno, Rosetta, Lucy
Solar panel	Ion propulsion	Hayabusa, Hayabusa2
Solar power sail	High-Isp ion propulsion	OKEANOS

than from the sail itself. The sail instead serves as an extremely large platform to mount the necessary number of solar cells for power generation.

Table 2 shows the current status of outer solar system exploration. OKEANOS, with its new solar power sail, aims to extend the reach of sample return technology demonstrated by Hayabusa to distances beyond the asteroid belt. Potential target bodies can include the Jupiter Trojan asteroids, as well as Saturnian moon Enceladus and Centaurs (Fig. 1). In addition, the large cargo capacities anticipated for solar power sails can be used to transport and deploy multiple lander and explorer nanosatellites, where the main spacecraft may serve as a mother spacecraft (MSC) to relay the explorer probes' communications with Earth.

In 2017 NASA selected Lucy (multiple flybys for Jupiter Trojan asteroids) and Psyche (rendezvous with M-type asteroids) for its Discovery Program. This outcome comes to a close agreement with our long-held mission to conduct type-wise (S,C,M,D-P) asteroid exploration. The Lucy project in particular is very similar to the solar sailing project proposed in 2005 by our solar sail working group on Jupiter Trojan

Table 2 Status of outer solar system explorations

	Jupiter zone	Saturn zone	Uranus	Neptune	Pluto, EKBO
Flyby	●U ■U:Lucy	●U	●U	●U	●U:New Horizons
Orbit/ Rendez vous	●U ▲U:Juno ■U/J:Juice ■U:European Clipper	●U	■U		
Landing	●U ■J:OKEANOS	●U:Huygens	■U		
Sample return	■J:OKEANOS				

● Achievements
▲ Under operation
■ Under development
Under investigation
J = Japan; U = USA; E = ESA

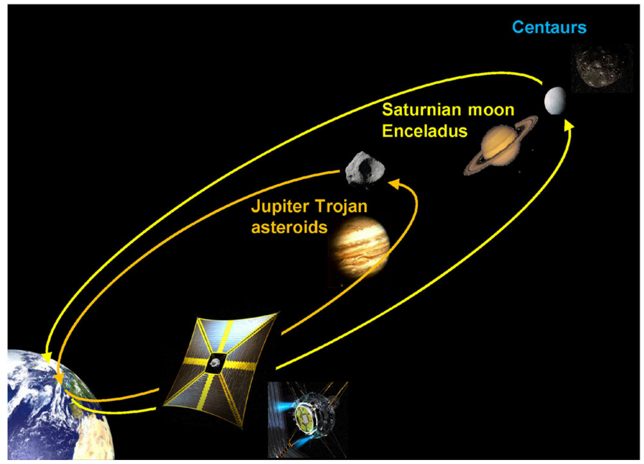


Fig. 1 Several application opportunities of solar power sails.

asteroid multiple-flyby mission (plus observation of Jupiter). This solar sailing project, unfortunately, was not selected as the key solar power sail technologies had not been demonstrated at that time, such as spin deployment of a large membrane sail, power generation with thin-film solar cells, and GNC of solar sail propulsion. In order to demonstrate these technologies, the IKAROS mission was later proposed and selected, followed by its launch and technology demonstration in 2010 [3–9]. Following this success, we have now further developed the concept for the much larger H3 launch vehicle, to perform direct observation (i.e., landing) on Jupiter Trojan asteroids. Since Lucy is a flyby mission to these asteroids, combining its observations with more detailed observations of the solar power sail probe will maximize scientific output. In other words, the two projects are thoroughly complementary endeavors, and key members of the two projects are in agreement with this direction.

In addition to asteroid exploration, OKEANOS will take advantage of its cruise flight environment to perform deep-space scientific observations. For past American and European exploration missions, long cruising phase (longer than a decade) has been seen in a negative light due to prolonged and costly operations, and hibernation periods were implemented. For our project on the other hand, we propose this as an advantage, because the interplanetary cruising phase can be deemed as 1) a laboratory for cutting-edge space science which benefits from long-term scientific observations and experiments, and 2) an opportunity to rapidly return scientific data immediately after launch.

OKEANOS cruise-phase operations will focus on the scientific missions which require consistent long-term observations, where the long distance to Earth is an advantage. Infrared telescope, gamma-ray burst polarimeter, dust detector, and magnetometer are considered as science payload candidates. Astronomy, historically, has always demanded better observation platforms, moving from land to mountain peaks, and eventually to space. The proposed mission will provide an unprecedented observation platform for new types of astronomy.

In this article, Section 2 outlines the trade-off process between various available types of power and the propulsion subsystems for outer planet exploration, and shows that sample-return missions to Jovian Trojans can be performed using solar power sail craft at under 1500 kg. Section 3 overviews three OKEANOS mission sequences, and Section 4 describes the orbit design and system design processes. Section 5 describes the proposed proximity operations upon asteroid arrival, namely the Home Position operation and descent/ascent operation. This section also proposes the image-based on-board GNC method for automated descent, and evaluates its performance via simulation.

2 First-order trade-off and design of power and propulsion subsystems

Power subsystem mass M_{p} relates to the power generated P and efficiency α, for four power generator types as follows:

1) Radioisotope Thermoelectric Generator (RTG)

$M_{\mathrm{p}} = 100$ kg, independent of P. Output power is limited to a few hundred watts.

2) Light solar panels

$M_{\mathrm{p}} = P/\alpha$ for $\alpha = 1.3$ W/kg (from Juno).

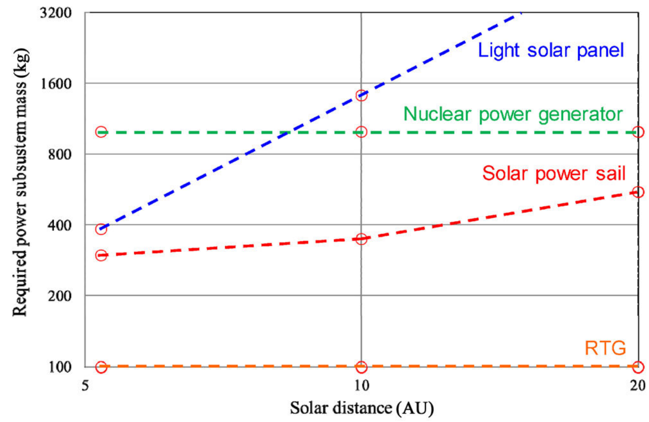
3) Solar power sail

$M_{\mathrm{p}} = P/\alpha + M_{\mathrm{d}}$ for $\alpha = 27$ W/kg at 5.2 AU. M_{d} is the structural mass of the sail deployment unit at 280 kg (both from OKEANOS).

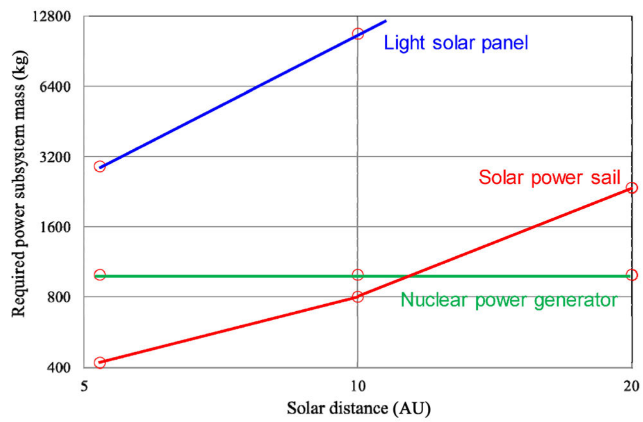
4) Nuclear power generator

$M_{\mathrm{p}} = 1000$ kg, independent of P. Multiple kilowatts may be generated (from TOPAZ reactors).

Figure 2(a) shows the required power subsystem mass M_{p} for the four generator types with $P = 500$ W (bus power only with chemical propulsion) and Fig. 2(b) shows $P = 3800$ W (bus and high-Isp ion propulsion).



(a) 500 W



(b) 3800 W

Fig. 2 Required power subsystem mass (M_{p}).

For 500 W option, M_{p} for RTG is the lightest, followed by solar power sail, then nuclear power generator for distances from 5.2 to 20 AU. For 3800 W, we find the solar power sail option to be the lightest for the 5.2 and 10 AU distances, while at 20 AU the nuclear power generator becomes the lightest option.

The specific impulse for the two considered options is as follows:

a) Chemical propulsion

Isp = 300 s

b) High-Isp ion propulsion

Isp = 6800 s

Spacecraft mass M_{s} is related to the total ΔV and bus mass M_{b} (M_{b} excludes power subsystem mass M_{p} and fuel mass) as follows:

$$M_{\mathrm{s}} = (M_{\mathrm{b}} + M_{\mathrm{p}}) \times \exp[\Delta V/(9.8 \times \mathrm{Isp})]$$

$M_{\mathrm{b}} = 900$ kg corresponds to a medium-sized probe. We take $\Delta V = 2$ km/s as a ballpark corresponding to a flyby mission, 4 km/s corresponding to a rendezvous mission, and 6 km/s corresponding to a sample return mission. For these three options, Figure 3 shows the estimated spacecraft mass M_s for the following five combinations of power and propulsion systems: 1a) RTG with chemical propulsion, 2a) light solar panel with chemical propulsion, 2b) light solar panel with high-Isp ion propulsion, 3b) solar power sail with high-Isp ion propulsion, and 4b) nuclear power generator with high-Isp ion propulsion.

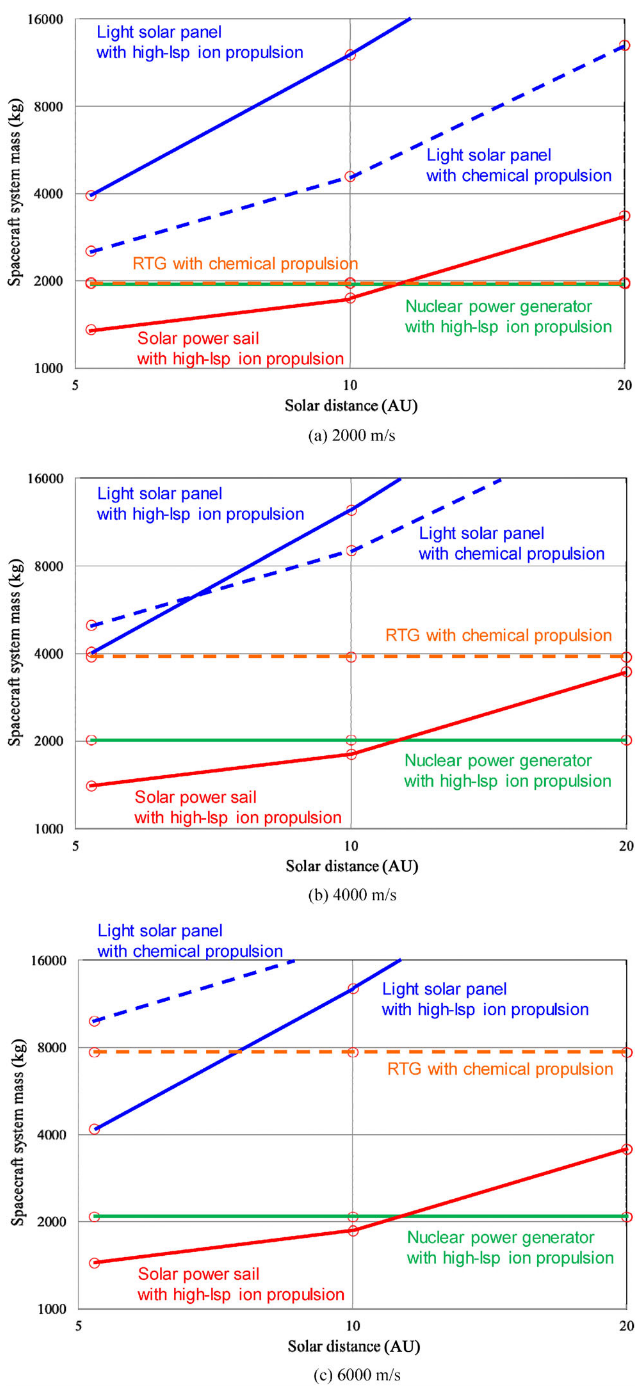


Fig. 3 Spacecraft system mass (M_s).

For high-Isp ion prolusion options, the required fuel mass is minimized, and the required power subsystem mass M_p instead becomes dominant. Minimizing M_p, therefore, is key for high-Isp ion propulsion options. At 5.2 and 10 AU distances, option 3b of solar power sail with high-Isp ion propulsion is the lightest option. At 20 AU, however, option 4b of nuclear power generator with ion propulsion becomes the lightest option, at the estimated mass of 2000 kg. Option 2b of light solar panel and high-Isp ion propulsion exceeds 4000 kg even at 5.2 AU.

Using chemical propulsion requires large fuel mass. On the other hand, the required power subsystem mass M_p is considerably reduced. For $\Delta V = 2$ km/s option, spacecraft mass M_s for chemical option is still workable, at about 2000 kg for the RTG and chemical propulsion option regardless of distances, and about 2500 kg for the light solar panel and chemical propulsion at 5.2 AU. At $\Delta V = 4$ km/s option; however, M_s for chemical propulsion option jumps beyond the other options.

Generally, spacecraft mass M_s correlates directly with mission cost. For $M_s < 1500$ kg, the mission can be categorized as a medium-class mission, and $M_s <$ 3000 kg can be categorized as a large-class mission. Therefore, we can categorize:

Medium-class mission:

– Solar power sail and high-Isp ion propulsion for Jupiter sample return mission.

Large-class missions:

– Solar power sail and high-Isp ion propulsion for Saturn sample return mission.
– Nuclear power generator and high-Isp ion propulsion for Jupiter, Saturn, and Uranus sample return missions.
– RTG and chemical propulsion for Jupiter, Saturn, and Uranus flyby missions.
– Light solar panel and chemical propulsion for Jupiter flyby mission.

As shown above, it is clear that with chemical propulsion, only flyby missions are feasible, regardless of mission class. If larger launch vehicles are used, asteroid rendezvous becomes a possibility; however, return missions still remain impractical. This finding is consistent with the Lucy project not attempting a rendezons, and selecting a flyby instead.

By introducing high-Isp ion propulsion to the mission, sample return missions become much more reasonably achievable. Particularly, introducing solar power sails to power these ion thrusters makes return missions to Jovian distances possible for a medium-class mission. This is the basis for the strategic medium-sized mission to conduct in-situ observations of Jupiter Trojan asteroids, as presented in this paper.

3 Mission sequence

Given the trade-off analysis presented above, this section now discusses the mission sequences proposed for OKEANOS. As shown in Fig. 4, three scenarios are proposed for further analysis: Plans A, B, and A'. Plan A is a landing mission, which is included in both Plans B and A'. This scenario applies Electric Delta-V Earth Gravity Assist (EDVEGA), as well as Jovian gravity assist to reach the Sun–Jupiter L4 point and achieving the world's first rendezvous with a Jupiter Trojan asteroid. At the asteroid, a lander is deployed to obtain samples for in-situ analysis.

EDVEGA is an innovative orbit maneuver applied to several past interplanetary missions, in which an electric thruster applies a small ΔV to the satellite immediately after leaving Earth, such that the remaining required velocity can be obtained through subsequent Earth gravity assists [10].

Plan B is a landing and sample return mission. In addition to Plan A, the lander leaves the asteroid surface and docks with the MSC, delivering a part of the collected samples. The lander is then jettisoned from the MSC, and the MSC returns to Earth through Jovian and Earth gravity assists.

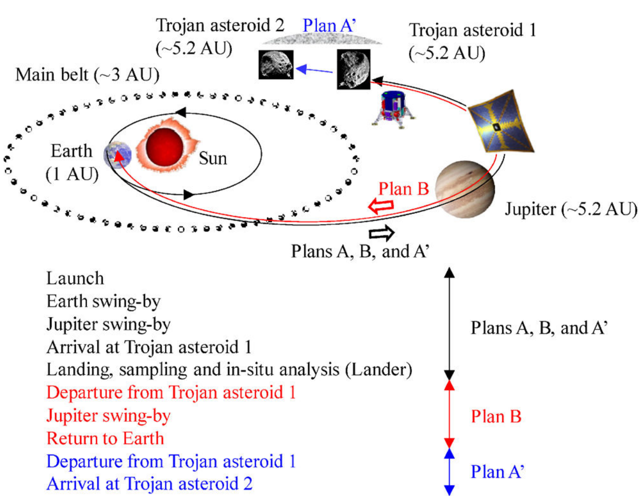


Fig. 4 Three proposed mission sequences.

Plan A' is a landing and multiple rendezvous mission, where in addition to Plan A, the MSC will rendezvous with other Trojan asteroids. In particular, if we can conduct detailed observations of P-type and D-type asteroids, we will have excellent compatibility with Lucy observations.

During the cruising phase, OKEANOS performs several innovative first-class astronomical science observations. The long distance and period from the launch to Jovian gravity assist provide excellent opportunity to explore the solar system between Earth and Jupiter, and to execute long-period and long-baseline observations for astronomy. Specifically, the GAP2 gamma-ray burst polarimeter will operate together with detectors near Earth, so that detection time differences will locate gamma-ray burst events at high precision. Further, the EXZIT infrared telescope, ALDN2 dust detector, and MGF magnetometer will utilize features of the cruising phase to make significant contributions to the progression of planetary science, astronomy, and space physics [11].

4 Initial design

4.1 Trajectory design

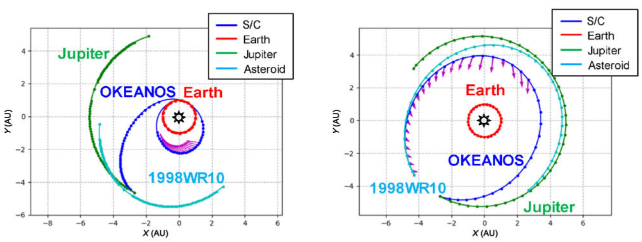
A spin-type large sail with an area of 2000 m^2 (ten times larger than that of IKAROS) can be applied as an ultra-light power generation system (1 kW/kg) to generate large volumes of electric power in the outer planetary region (5 kW at 5.2 AU), by attaching thin-film solar cells over the entire surface of the sail membrane.

The proposed mission applies this power to driving a set of high-performance ion thrusters with specific impulse of 6800 seconds (two times higher than that of Hayabusa or Hayabusa2), to achieve large ΔV in the outer planetary region.

Jovian trojans are asteroid located either in the L4 or L5 equilibrium points of the Sun–Jupiter system. From the scientific point of view, there is little difference between these bodies. From the point of view of trajectory design, however, there are important differences between L4 and L5 targets. If the target body is an L4 asteroid, the spacecraft approaches the asteroid from the sun side, and the thrust force can effectively cancel the relative velocity to the asteroid. As a result, the time of flight to the L4 target body is minimized [12, 13]. Choosing lighter asteroids will be advantageous from the point of view of approach and landing, since their gravity will be minimal. On the other hand, larger asteroids (20 km across or larger) are more likely to be D- and P-type asteroids, which are the prime targets for the proposed mission. Under the above conditions, we limited the target search space to a 20–30 km Trojan of the Sun–Jupiter L4 group, and conducted a target search assuming an H3 22S launch vehicle. We note that the launch date will have an effect on the target search space.

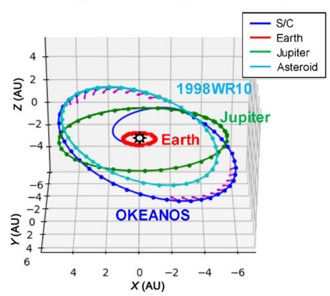
Figure 5 shows the trajectories we have designed for Plans A, B, and A' with 1998WR10 (and 2005LB37 for Plan A') set as the target asteroid. These calculations have been made with the probe's initial wet mass set at 1400 kg, three ion thrusters with maximum duty cycle of 80%, and initial specific energy (C3) of 36 km^2/s^2. For all cases we find 13-year trajectories single way. Considering that Rosetta required 11 years to reach comet 67P, which was located at a closer distance to Earth than Trojan asteroids at the time of rendezvous, it can be said that the proposed trajectories achieve return trips with reasonable time. We note that OKEANOS will have demonstrated key technologies soon after launch, thus will have achieved many of its objectives before its first Jovian gravity assist. Furthermore, it is also found that the required total ΔV found by these simulations agree with the estimations made in Figs. 3(b) and 3(c). The required ΔV for Plan A rendezvous, shown in Fig. 5(a), is approximately 3.5 km/s, while sample return in Fig. 5(b) requires further 2.2 km/s. Instead of sample return, a multi-rendezvous scenario shown in Fig. 5(c) requires further 1.9 km/s in addition to Plan A.

Phase	Start	End	ΔV (m/s)
2-year EDVEGA	20/1/2026	4/11/2027	954
Earth to Jupiter	4/11/2027	15/8/2030	—
Jupiter to 1998WR10	15/8/2030	20/1/2039	2498



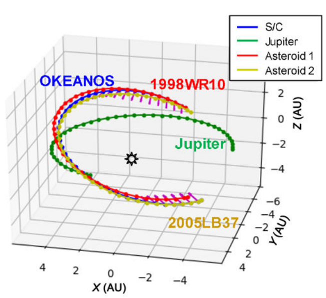
(a) Forward trajectory for Plans A, B, and A'

Phase	Start	End	ΔV (m/s)
1998WR10 to Jupiter	20/7/2040	6/5/2054	2209
Jupiter to Earth	6/5/2054	19/12/2057	—



(b) Plan B

Phase	Start	End	ΔV (m/s)
1998WR10 to 2005LB37	20/7/2040	20/7/2048	1895



(c) Plan A'

Fig. 5 Designed trajectories for the three proposed Plans A, B, and A'.

4.2 System design

Initial system design of OKEANOS has been conducted, giving a wet mass of 1351 kg, which includes a 100 kg lander. This means that the trajectory plans discussed above are feasible, as the estimated OKEANOS mass satisfies the upper limit of 1400 kg.

The structural design and equipment layout of OKEANOS in Plan A are shown in Figs. 6 and 7. The satellite structure is composed of octagonal side panels and upper/lower panels. A cylinder structure and sail storage structure are equipped inside and outside of the octagon, respectively. The overview of each subsystem is as follows.

Solar cell voltage generally decreases with rising temperature. Since this effect is severe for thin-film solar cells, a secondary solar panel is mounted on the upper panel, and power draw is switched between the main thin-film solar cell (CIGS) on the sail and the secondary panel, depending on the distance from the Sun.

The spacecraft is equipped with 8 chemical thrusters forming the reaction control system (RCS), which are mainly used for position control during the proximity operations on the Trojan asteroid. The ion thrusters are used for attitude control as well as orbit control during the powered flight phase. Figure 8 shows the spin axis reorientation control using ion thrusters, where the

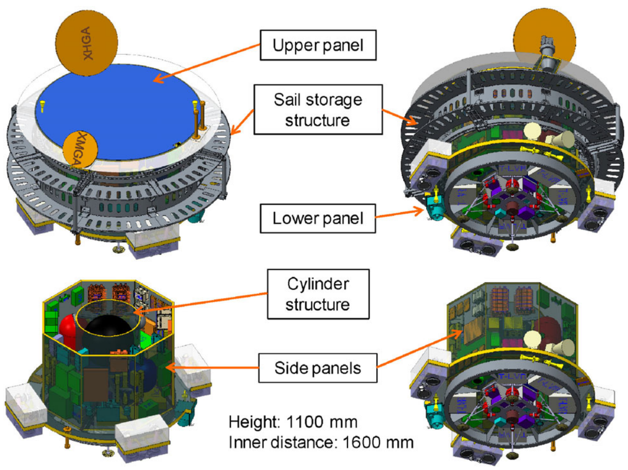


Fig. 6 OKEANOS structural design.

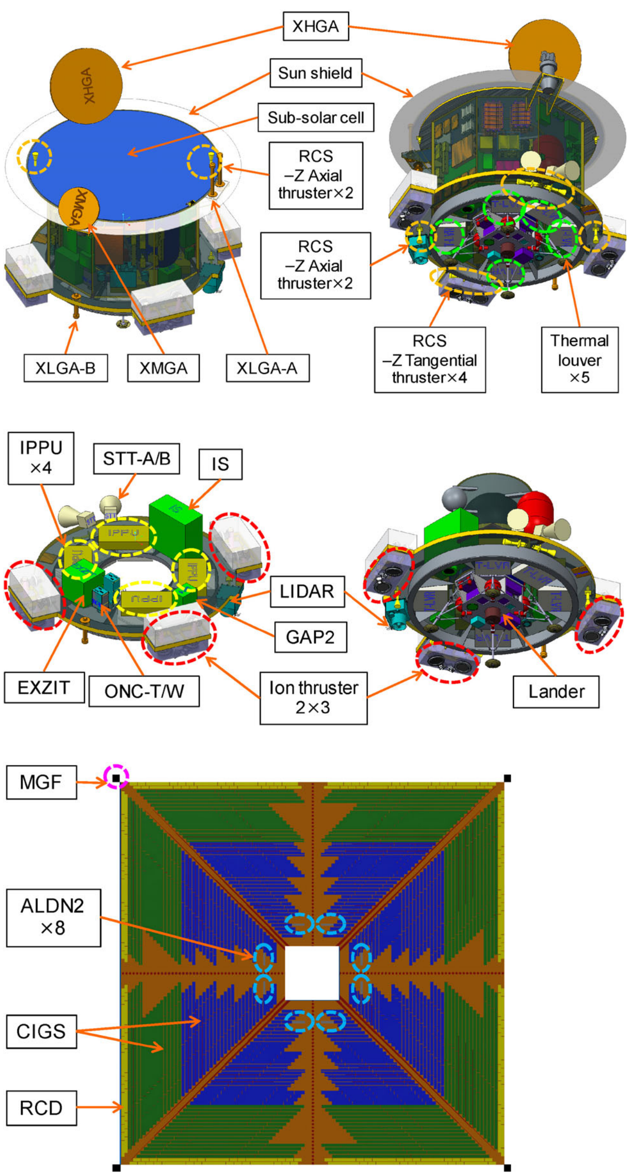


Fig. 7 OKEANOS equipment layout.

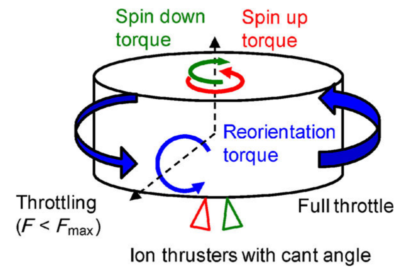


Fig. 8 Attitude control using ion thrusters.

reorientation torque is generated by throttling the ion thrusters synchronously with the spin period. The ion thrusters provide the spin up/down torque as well, by tilting the thrust vectors of the ion thrusters by several degrees from the spin axis [13].

The reflectivity control devices (RCD) are used to control the attitude under ballistic flight as shown in Fig. 9. RCDs consist of liquid crystal film and are capable of switching between specular and diffuse reflection by controlling the applied voltage (ON or OFF). By mounting the RCD near the sail membrane edge, and by periodically switching them ON and OFF synchronously with the sail spin rate, the RCD can control solar radiation pressure (SRP) torque for attitude control without fuel consumption, as demonstrated by IKAROS. However, since conventional

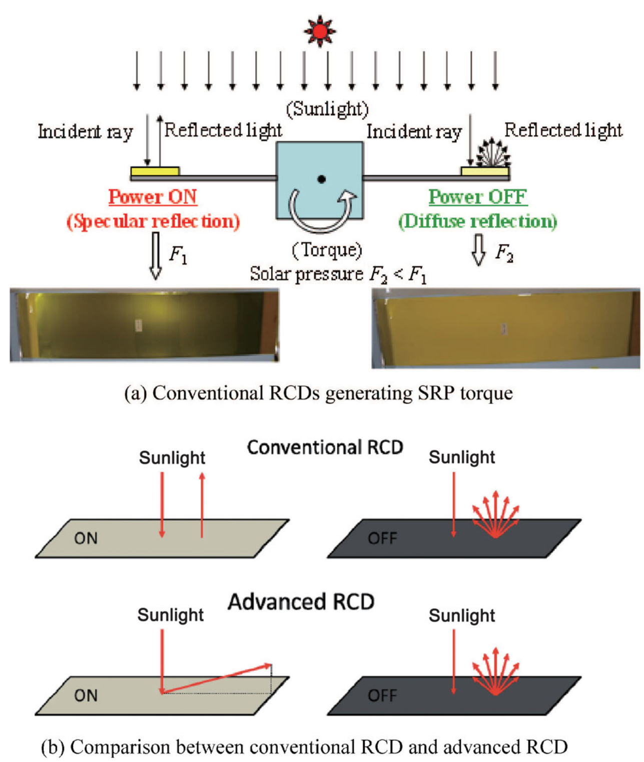


Fig. 9 Attitude control using RCD.

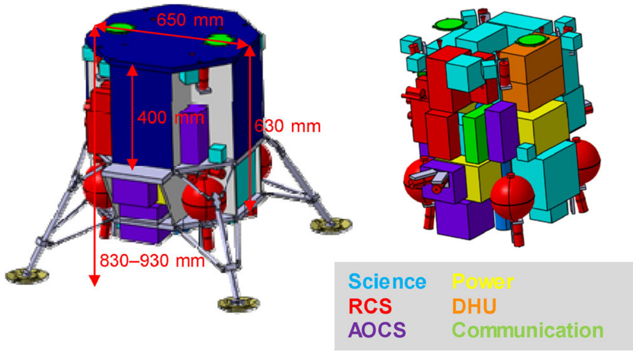


Fig. 10 Structural design and equipment layout of the lander.

RCD cannot generate torque along the spin axis (out-of-plane torque), IKAROS used thrusters for spin rate control. To address this challenge, the advanced RCD has been developed, which is capable of generating torque in the spin axis. Advanced RCDs have a sawtooth grating etched on the surface of the reflector, which alters the angle of specular reflection from the angle of incidence when the device is turned ON [14]. If this device is lit from the normal direction, for example, the light is reflected at some angle (determined by the grating) away from the normal vector, thus generating in-plane SRP, as well as out-of-plane SRP, which derive the torque around the spin axis (out-of-plane torque) of the spacecraft and the reorientation torque (in-plane torque), respectively [15].

The structural design and equipment layout of the lander is shown in Fig. 10. The lander is octagonal in shape with legs at the bottom. Unlike Philae, the lander is equipped with RCS consisting of 12 cold gas thrusters. Since the sun distance of Trojan asteroids is about 5.2 AU, meaningful power generation by solar cells cannot be expected. Therefore, the lander is exclusively driven by battery. Science equipment is assigned a mass of 20 kg, including sampling devices. The wet mass of the proposed design satisfies the 100 kg limit assigned to the lander [16, 17].

The lander has two sampling devices to collect surface and underground samples, as shown in Fig. 11. For the former, a sampler horn is used, which was selected for the Hayabusa missions. In Hayabusa and Hayabusa2, explosives were used as the projector driver. In contrast, high-pressure gas is used to drive the projector for OKEANOS to prevent contamination. For the latter sampling device, a pneumatic drill excavates a 1 m regolith layer using high-pressure gas. This device has a telescopic structure, as shown in Fig. 12. First,

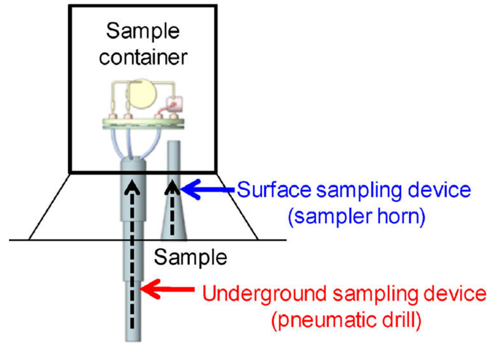


Fig. 11 Sampling devices and sample container.

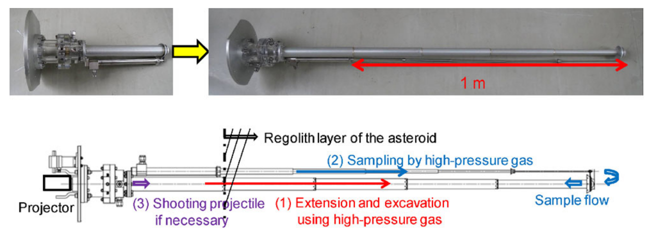


Fig. 12 Underground sampling device.

extension and excavation are performed simultaneously. Then, additional high-pressure gas is released to collect underground samples. If there is a rock at the sampling point, a projectile is shot to generate fragments of the samples [18].

The sample container is an interface device between the sampling devices and the High-Resolution Mass Spectrometer (HRMS), as shown in Figs. 11 and 13. On top of the sampler, a branch pipe is attached to distribute the collected samples into several sample boxes, which are attached compartments in the sample container. The sampling operation is designed to collect at least 1 mg sample in each sample box. After the sampling operation, the sample boxes are heated to vaporize the samples for processing by HRMS. The isotopic ratios of CHON elements, and organic molecules are investigated using HRMS.

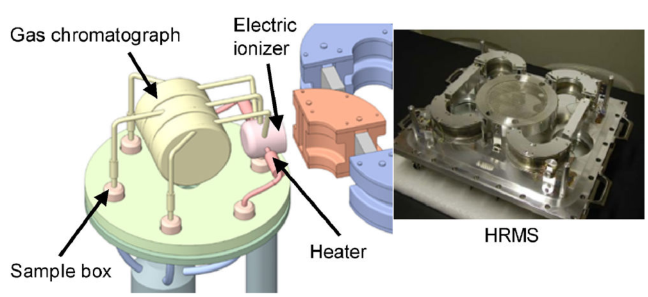


Fig. 13 Sample container.

5 Mission analysis at Trojan asteroid

5.1 Home Position and descent/ascent

Since OKEANOS has a large sail that spins, it is highly risky for itself to land on the asteroid. A lander will therefore separate and perform the landing, sampling, and in-situ analysis. The lander then delivers a sample back to the MSC by rendezvous and docking for sample return in Plan B.

The operational plan after arrival at the Trojan asteroid is shown in Fig. 14. During the proximity phase, the spacecraft maintains Earth-pointing attitude at a specified altitude, which is called the Home Position (HP), in the same manner as Hayabusa and Hayabusa2 missions. To maintain the altitude, the spacecraft must counteract the gravity of the asteroid, and the high-Isp ion propulsion system attached on $-z$ plane of the body is utilized instead of the chemical propulsion system to minimize fuel consumption. The thrust of a single ion thruster on arrival at the asteroid is estimated at 19.3 mN, and the HP altitude is set where this thrust equals the gravitational force of the asteroid. This altitude is 350 km if the diameter of the asteroid is 30 km, and 192 km if it is 20 km, where the asteroid sizes are selected in Section 4.1 for their potential for being D- or P-type. Note that solar radiation pressure forces at these distances will be negligible compared to the thruster output. In both cases, the altitude is much higher than that in previous missions, which is 20 km for the Hayabusa2 mission, as the selected asteroid is much larger.

When the lander separation operation starts, OKEANOS descends to an altitude of 1 km via free-fall to deploy the lander. After separation and landing, the lander starts to conduct sampling and in-situ analysis. In Plans A and A', MSC returns to HP. In Plan B, MSC ascends to an altitude of 50 km (docking altitude) and keeps that position until rendezvous docking with the returning lander is completed. After finishing the in-situ analysis of the samples on the asteroid, the lander starts ascending toward OKEANOS, and performs rendezvous and docking. Then, the samples inside the lander are transferred to the re-entry capsule held by the MSC. Finally, the lander is again separated from MSC to reduce the system weight during the return trip to Earth.

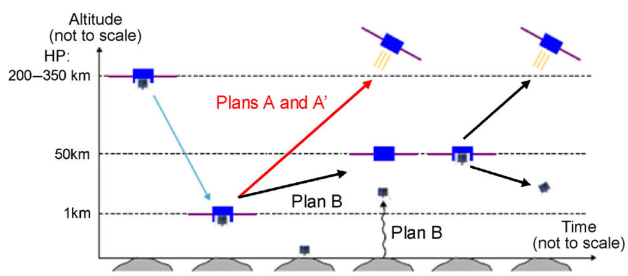


Fig. 14 Operational policy at the Trojan asteroid.

5.2 Image-based on-board GNC method using AIT and OF

The diameter of the target asteroid is 20–30 km, which is much larger than the target asteroids of Hayabusa/Hayabusa2. Its gravity is also larger, thus the spacecraft needs more propellant to perform the landing. In addition, OKEANOS must maintain its spin in order to maintain tension in its membrane; therefore, as stated earlier, it is highly risky for the MSC to perform the landing itself. A lander, which has less GNC sensors and instruments, has to aim for safe landing. To enable this, a GNC method which can be executed autonomously by the lander is needed.

This paper proposes an image-based on-board GNC method using AIT (Asteroid Image Tracking) and OF (Optical Flow) [19]. Table 3 shows the provisional descent scenario for OKEANOS using these two techniques. At high altitude, AIT calculates the centroid of the asteroid from the captured images to estimate the lateral position of the spacecraft. As the spacecraft approaches the asteroid, the camera's field of view will be filled by the asteroid, at which point AIT will be unable to calculate the asteroid centroid. From this point forth until 1 km altitude (about 20–1 km), the spacecraft will use only LIDAR to numerically propagate its estimation. At 1 km, the spacecraft emits a jet to stop, which is impulsive and may destabilize the satellite attitude. In such case, we propose to use OF for navigation, which is in general used to calculate the amount of movement of the observer. For example, optical mice apply OF to detect their movement against the surface. In this descent scenario, OF is used for two purposes. One is to reduce the wobble caused by large jets. The other is to match the lateral velocity of spacecraft with the velocity of asteroid surface. OF is used from 1 km before separation to 10 m.

To conserve fuel, constant-velocity descent is only proposed in phase (5) of the descent scenario. For

Table 3 Provisional descent scenario of OKEANOS

	Altitude	Agent	Descent velocity	Lateral measurement	Height measurement
(1)	350–20 km	MSC	Free fall→Stop@1 km	AIT	LIDAR
(2)	20–1 km			Propagation	
(3)	1 km		Hovering (separation)	OF @Inertial frame	
(4)	1 km–50 m	Lander	Free fall→Stop@50 m	OF @Asteroid fixed frame	OF
(5)	50–10 m		0.1 m/s		OF+LRF
(6)	10 m		Free fall		

the remaining phases (from (1) to (4), as well as (6)) the lander conducts a series of free-fall descent and impulsive velocity-cancellations.

5.3 Simulation

In this section, using extended Kalman filter, a simulation campaign is conducted with 100 simulations with random initial conditions to evaluate the performance of AIT and OF. Position and velocity errors of each descent phase ((2), (3), and (5)) are evaluated. For image processing in the simulation of phase (1), asteroid model from NASA is used, and in the simulation from phase (3) to phase (5), surface model from Geospatial Information Authority of Japan is used because NASA's asteroid model is too coarse for the application.

The parameters of the asteroid and camera are set as in Table 4. This simulation includes such possible error factors as initial estimation error, LIDAR measurement error, thrust magnitude error, and thrust direction error. These errors are added as Gaussian noise with standard deviation shown in Table 5.

Figure 15(a) shows the result of the simulations from phase (1) to phase (2), and its terminal error after phase (2) is shown in Table 6(a). There is a bias between the centroid calculated from the discretized image and the actual center of gravity, leading to the bias between the estimated position and the true position. Figure 15(a) shows this bias, as the mean value of lateral position control error is not zero. Note that this difference depends on the shape of the asteroid. If the density distribution is not uniform, the estimation error would be large. However, since the diameter of the target asteroid is 20–30 km, it is expected that the asteroid shape is close to a sphere. At the end of phase (2), each error is growing through large ΔV input, caused by thrust error.

Figure 15(b) shows the result of simulations of phase (3) and the terminal error after phase (3) is shown in Table 6(b). Comparing lateral velocity errors in Tables 6(a) and 6(b), standard deviation σ is reduced to some extent. The errors' order, however, leaves a few decimeters per second. Therefore, lateral position errors grow.

Figure 15(c) shows the result of simulations from

Table 4 Simulation condition

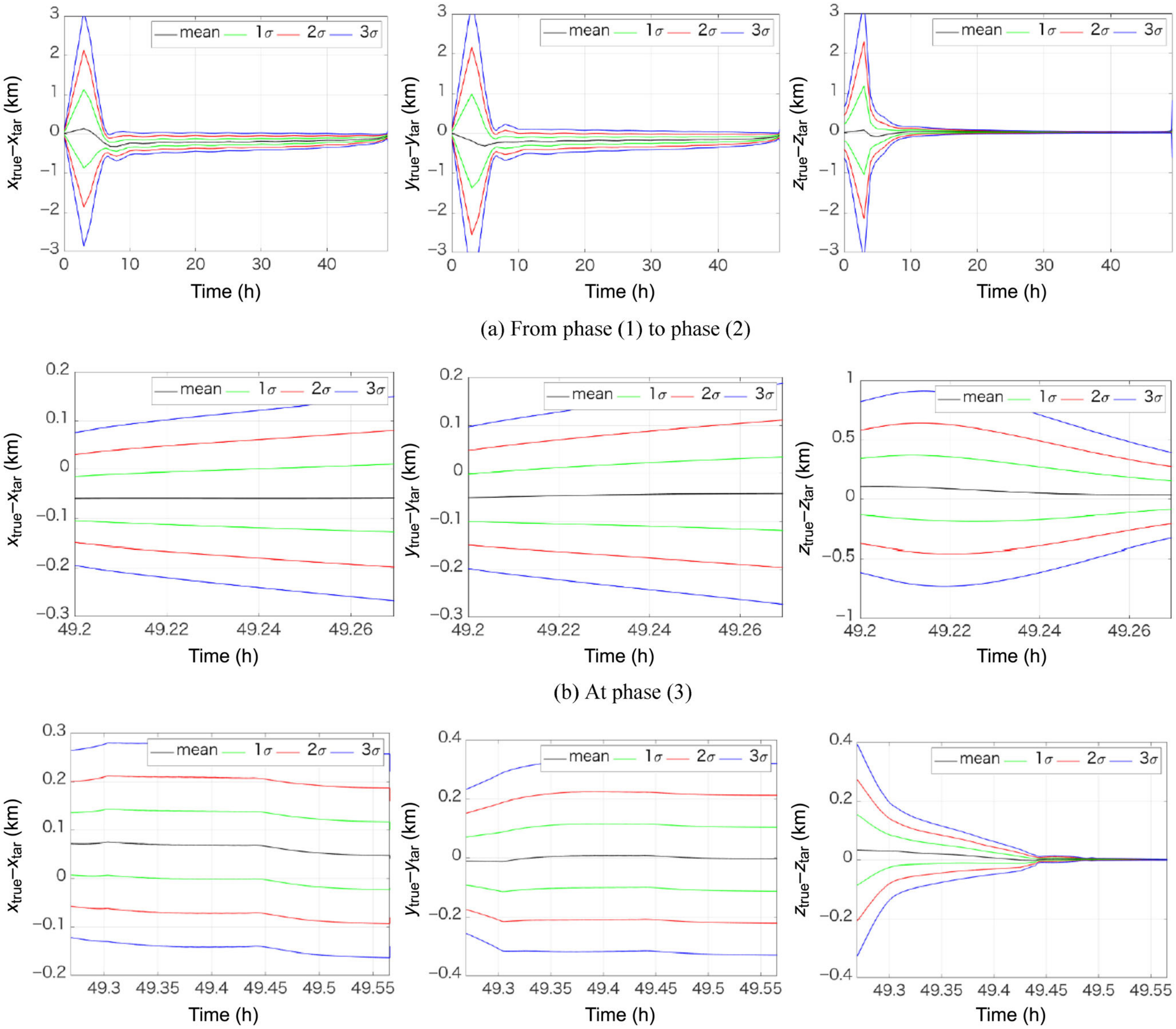
Radius	30 km
Rotation period	5 h
Density	2 g/cm^3
Rotation axis	(1,1,1)
Focal length	10.4 mm
Image pixel size	26 micron (512×512 pxls)

Table 5 Simulation condition

Error factor	Error value
Initial estimation	**Position** Lateral 50 m (1σ random) Height 200 m (1σ random) **Velocity** 0.1 m/s (1σ random)
LIDAR	20 m (1σ random)
Thrust magnitude	5% (1σ random)
Thrust direction	1% (1σ random)

Table 6 Terminal control error

(a) After phase (2)						
	x (m)	y (m)	z (m)	$\dot{x}$ (m/s)	$\dot{y}$ (m/s)	$\dot{z}$ (m/s)
Mean	−60	−51	105	0.013	0.055	0.099
1σ	45	49	239	0.164	0.165	0.862
(b) After phase (3)						
	x (m)	y (m)	z (m)	$\dot{x}$ (m/s)	$\dot{y}$ (m/s)	$\dot{z}$ (m/s)
Mean	−59	−42	34	0.013	0.006	−0.040
1σ	70	77	120	0.117	0.111	0.776
(c) After phase (5)						
	x (m)	y (m)	z (m)	$\dot{x}$ (m/s)	$\dot{y}$ (m/s)	$\dot{z}$ (m/s)
Mean	47	−4	−3	0.008	−0.003	−0.001
1σ	70	108	2	0.007	0.003	0.015



(a) From phase (1) to phase (2)

(b) At phase (3)

(c) From phase (4) to phase (5)

Fig. 15 Operational policy at the Trojan asteroid.

phase (4) to phase (5) and the terminal error after phase (5) is shown in Table 6(c). Figure 16 shows the terminal landing points. Radius of red circle in Fig. 16 is 100 m, which contains about half of the landing points. Notice that in this phase, the coordinate system is asteroid-fixed, which is different from the previous two analyses that use inertial frames. Since the OF algorithm aims to kill the relative motion against the asteroid surface features, the lateral velocity errors in the asteroid-fixed frame are much smaller than the errors at previous phases, e.g., Table 6(b).

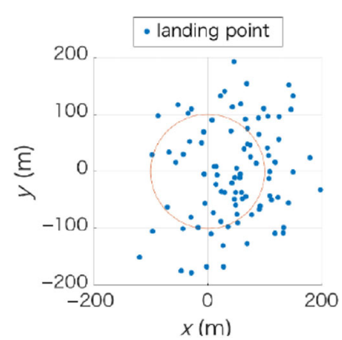


Fig. 16 Simulated landing points of lander.

This study shows the terminal error of proposed descent method is about a hundred meters (1σ). There are two main causes of this error. One is the difference between the centroid of discretized image and the actual center of gravity, which injects errors in the AIT process. The second is the thrust error causing estimation errors in every process.

The image-based on-board GNC method using AIT and OF is completely autonomous. Unlike the Hayabusa missions, this will allow for a much more responsive and punctual landing sequence, and will ultimately save propellant. This is highly important for OKEANOS, as target gravity is not negligible, thus prolonged hovering is undesirable. Although the performance will be different for each asteroid, the method has various applicability to the exploration of distant celestial bodies in which the target mass is heavy, or the propagation delay is large.

6 Conclusions

For the proposed OKEANOS mission, this article has described the following points:

- A trade-off analysis is performed between various available power subsystems and propulsion subsystems for the proposed outer solar system exploration satellite. This study found that up to Saturn (10 AU), the combination of solar power sail and high-Isp ion propulsion leads to overall lightest spacecraft. It also explored in detail a sample return scenario to Jupiter Trojan asteroids, and the result shows that this can be achieved with satellite mass under 1500 kg. Beyond Saturn, it is found that the combination of nuclear power generator and high-Isp ion propulsion is the lightest option. These results underscore the importance of developing high-Isp ion thrusters.
- Three mission sequences are proposed for Jovian Trojan exploration and suitable trajectories for these mission sequences are designed. Plan A deploys the lander for in-situ analysis, Plan B lands and returns samples to Earth, and Plan A' performs multiple Trojan rendezvous after deploying the lander on the target asteroid. Mutual compatibility of the three mission sequences with the Lucy multi-flyby mission is studied. The benefits of conducting cruising-phase science also are outlined.
- The system design is proposed for the MSC and the lander. Various instruments are described and proposed for obtaining, handling, and analyzing the asteroid samples.
- The proposed HP and descent/ascent operations are described. With the maximum thruster of the selected ion, 200–350 km has been selected as the ideal HP holding altitude.
- In order to conduct automated descent, an image-based on-board GNC is presented, using AIT and the OF. The purpose of these two techniques during the five descent phases proposed for OKEANOS is described. The descent performance of this method has been simulated by conducting 100 simulations with extended Kalman filters, including sensor and thruster errors. The simulations show that the terminal error of the proposed descent method is about a hundred meters, and probable causes for this error are found and discussed.

We conclude that OKEANOS can lead the exploration of outer solar system, as well as provide a breakthrough in space astronomy as a new scientific field.

References

[1] Kawaguchi, J. A solar power sail mission for a Jovian orbiter and Trojan asteroid flybys. In: Proceedings of the 35th Scientific Assembly of the Committee on Space Research, **2004**: COSPAR04-A-01655.

[2] Mori, O., Saiki, T., Kato, H., Tsuda, Y., Mimasu, Y., Shirasawa, Y., Boden, R., Matsumoto, J., Chujo, T., Kikuchi, S., *et al.* Jovian Trojan asteroid exploration by solar power sail-craft. *Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan*, **2016**, 14(ists30): Pk_1–Pk_7.

[3] Mori, O., Sawada, H., Funase, R., Endo, T., Morimoto, M., Yamamoto, T., Tsuda, Y., Kawakatsu, Y., Kawaguchi, J. Development of first solar power sail demonstrator–IKAROS. In: Proceedings of the 21st International Symposium on Space Flight Dynamics, **2009**.

[4] Yokota, R., Miyauchi, M., Suzuki, M., Andoh, A., Kazama, K., Iwata, M., Ishida, Y., Shimamura, H., Ishizawa, J. Heat sealable, novel asymmetric aromatic polyimide having excellent space environmental stability and application for solar sail, IKAROS membrane. In: Proceedings of the 28th International Symposium on Space Technology and Science, **2011**: 2011-o-4-02v.

[5] Tanaka, K., Soma, E., Yokota, R., Shimazaki, K., Tsuda, Y., Kawaguchi, J., IKAROS Demonstration Team. Development of thin film solar array for small solar power demonstrator "IKAROS". In: Proceedings

of the 61st International Astronautical Congress, **2010**: IAC-10.C3.4.3.

[6] Sawada, H., Mori, O., Okuizumi, N., Shirasawa, Y., Miyazaki, Y., Natori, M., Matunaga, S., Furuya, H., Sakamoto, H. Mission report on the solar power sail deployment demonstration of IKAROS. In: Proceedings of the 12th AIAA Gossamer Systems Forum, **2011**: AIAA-2011-1887.

[7] Matunaga, S., Inagawa, S., Nishihara, T., Kimura, S., Sawada, H., Mori, O., Kitamura, K., Structure Team IKAROS. On-orbit demonstration of deployable camera system for solar sail IKAROS. In: Proceedings of the 28th International Symposium on Space Technology and Science, **2011**: 2011-o-4-07v.

[8] Tsuda, Y., Saiki, T., Mimasu, Y., Funase, R. Modeling of attitude dynamics for ikaros solar sail demonstrator. In: Proceedings of the AAS/AIAA Space Flight Mechanics Meeting, **2011**: AAS11-112.

[9] Funase, R., Shirasawa, Y., Mimasu, Y., Mori, O., Tsuda, Y., Saiki, T., Kawaguchi, J. On-orbit verification of fuel-free attitude control system for spinning solar sail utilizing solar radiation pressure. *Advances in Space Research*, **2011**, 48(11): 1740–1746.

[10] Kawaguchi, J. Performance evaluation for the Electric Delta-V Earth Gravity Assist (EDVEGA) scheme. In: Proceedings of the AIAA/AAS Astrodynamics Specialist Conference and Exhibit, **2002**: AIAA 2002-4899.

[11] Okada, T., Iwata, T., Matsumoto, J., Chujo, T., Kebukawa, Y., Aoki, J., Kawai, Y., Yokota, S., Saito, Y., Terada, K., *et al.* Science and exploration in the solar power sail OKEANOS mission to a Jupiter Trojan asteroid. In: Proceedings of the 49th Lunar and Planetary Science Conference, **2018**: 1406.

[12] Saiki, T., Mori, O., Kawaguchi, J. Trajectory design for Jovian Trojan asteroid exploration via solar power sail. In: Proceedings of the 4th International Symposium on Solar Sailing, **2017**: 17086.

[13] Saiki, T., Matsumoto, J., Mori, O., Kawaguchi, J. Solar power sail trajectory design for Jovian Trojan exploration. *Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan*, **2018**, 16(5): 353–359.

[14] Ishida, H., Chujo, T., Mori, O., Kawaguchi, J. Optimal design of advanced reflectivity control device for solar sails considering polarization properties of liquid crystal. In: Proceedings of the 26th International Symposium on Space Flight Dynamics, **2017**: ISSFD-2017-061.

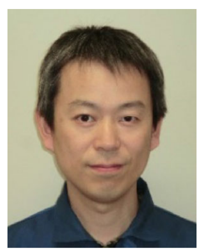
[15] Chujo, T., Ishida, H., Mori, O., Kawaguchi, J. Liquid crystal device with reflective microstructure for attitude control. *Journal of Spacecraft and Rockets*, **2018**, 55(6): 1509–1518.

[16] Okada, T., Iwata, T., Yano, H., Kebukawa, Y., Ito, M., Aoki, J., Kawai, Y., Yokota, S., Matsuoka, A., Matsuura, S., *et al.* OKEANOS—Jupiter Trojan asteroid rendezvous and landing mission using the solar power sail. In: Proceedings of the 42nd Scientific Assembly of the Committee on Space Research, **2018**: B1.1-0045-18.

[17] Okada, T., Kebukawa, Y., Aoki, J., Matsumoto, J., Yano, H., Iwata, T., Mori, O., Bibring, J. P., Ulamec, S., Jaumann, R. Science exploration and instrumentation of the OKEANOS mission to a Jupiter Trojan asteroid using the solar power sail. *Planetary and Space Science*, **2018**, 161: 99–106.

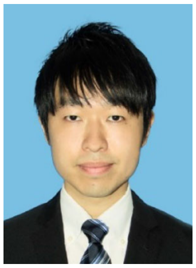
[18] Matsumoto, J., Okamoto, C., Oki, Y., Nakamura, T., Aoki, J. Sampling system and its operation scenario for the Jupiter Trojan asteroid explorer. *Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan*, **2018**, 16(7): 698–705.

[19] Sakamoto, K., Takao, Y., Mori, O., Ono, G., Terui, F., Chujo, T., Terui, F., Mimasu, Y., Tsuda, Y., Kawaguchi, J. Image-based autonomous guidance navigation and control of spacecraft. In: Proceedings of the 69th International Astronautical Congress, **2018**: IAC-18-C1.6.8.x44645.



Osamu Mori received his Ph.D. degree in engineering from Tokyo Institute of Technology, Japan, in 2002. He is currently an assistant professor at Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA). His research includes spacecraft systems, multibody dynamics, guidance, navigation and control. He is a project manager of the IKAROS mission and a core member of the OKEANOS mission. E-mail: mori.osamu@jaxa.jp.

Jun Matsumoto received his Ph.D. degree in engineering from the University of Tokyo in 2016. He is an engineer at Japan Aerospace Exploration Agency (JAXA). His research includes mission design of deep space explorations, astrodynamics, and small-body exploration technology. E-mail: matsumoto.jun2@jaxa.jp.



Toshihiro Chujo received his Ph.D. degree in engineering from the University of Tokyo, Japan, in 2017. He is currently an assistant professor at Tokyo Institute of Technology. He was previously a postdoctoral researcher at Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), working on the Solar Power Sail OKEANOS mission and the Transformable Spacecraft mission. His main field of study is spacecraft system, mission analysis, and astrodynamics. E-mail: chujo.t.aa@m.titech.ac.jp.

Masanori Matsushita is a research and development staff member in the ISAS/JAXA. He works on the OKEANOS solar power sail and is mainly in charge of the sail membrane structure. He received his M.S. and Ph.D. degrees of engineering from Tokyo Institute of Technology, in 2014 and 2018, respectively. He joined the TSUBAME micro-satellite mission (launched in 2014), and contributed to the research and development of electrical power system from 2009 to 2014. His research interests are space membrane structures, electrical power systems, CubeSats, and micro-satellites. E-mail: matsushita.masanori@jaxa.jp.

Hideki Kato received his master degree of engineering from Tokyo Metropolitan Institute of Technology, Japan, in 1996. He is currently an associate senior administrator at Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA). His research includes spacecraft systems, systems engineering, propulsion and combustion. He is an SS-520-5 project sub-manager. E-mail: kato.hideki@jaxa.jp

Takanao Saiki received his Ph.D. degree in engineering from the University of Tokyo, Japan, in 2005. He is currently an assistant professor at Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA). He is now involved in Hayabusa2 project. He was the chief developer of the impact system and currently he is the project engineer of Hayabusa2 project. He is also a member of the OKEANOS team. E-mail: saiki.takanao@jaxa.jp.

Yuichi Tsuda received his Ph.D. degree in aeronautics and astronautics from the University of Tokyo in 2003, and joined JAXA in 2003 as a research associate. He was a visiting scholar of Dept. of Aerospace Engineering, University of Michigan and Dept. of Aerospace Engineering Sciences, University of Colorado Boulder in 2008–2009. He was a deputy lead of the IKAROS project, the world's first interplanetary solar sail mission. He is currently an associate professor of ISAS/JAXA and is also the project manager of the Hayabusa2—an asteroid sample return mission. His research interests are astrodynamics, spacecraft system, and deep space exploration. E-mail: tsuda.yuichi@jaxa.jp.

Jun'ichiro Kawaguchi graduated from the Department of Mechanical Engineering, Kyoto University in 1978, and obtained his doctor degree of engineering in aerospace engineering from the Graduate School of Tokyo University in 1983. He has been serving as an assistant professor at the Institute of Space and Astronautical Science (ISAS) since 1988. He was promoted to a full professor at ISAS in 2000. He participated in a variety of projects including Japan's first planetary probes to comet Halley, Lunar Orbiter missions Hiten and GEOTAIL, Nozomi, a Mars mission, and Hayabusa, the world's first sample-and-return mission from a solar body outside Earth's gravity sphere. He was the project manager of the Hayabusa mission since 1996 till 2011, during which time the mission successfully touched down to the surface of near-Earth asteroid Itokawa and returned samples to Australia in 2010 for the first time. He is currently the official advisor for the Hayabusa2 mission. He is also the founder of IKAROS, the world's first solar sail demonstrator project, which was launched in 2010. He is also a senior fellow at Japan Aerospace Exploration Agency (JAXA). Along with his JAXA agency activities, he is a professor in the Aerospace Engineering Department at the University of Tokyo and has been engaged in the education of post-graduate students for more than 20 years. He was the president of the Japan Society for Space and Astronautical Science. He also served as the secretary-general at the Strategic Headquarters for Space Policies, Cabinet Secretariat, Government of Japan. E-mail: kawaguchi.junichiro@jaxa.jp.

Fuyuto Terui is a staff member of Japan Aerospace Exploration Agency (JAXA) and is now a function manager of Hayabusa2 project as well as a representative of attitude and orbit control system of Hayabusa-spacecraft. His main research field is robust control and image-based guidance, navigation and control of a spacecraft such as debris removal space robot and the asteroid exploration probe. E-mail: terui.fuyuto@jaxa.jp.

Yuya Mimasu is a researcher at Japan Aerospace Exploration Agency (JAXA). He graduated with his Ph.D. degree in aerospace engineering from the Kyushu University in 2011. He joined JAXA in 2011, and has been working on guidance, navigation, and control subsystem of Hayabusa2 mission, which is JAXA's sample return mission from the asteroid. His research interests are astrodynamics and mission analysis around the small body, such as an asteroid. E-mail: mimasu.yuya@jaxa.jp.

Go Ono is a researcher at Japan Aerospace Exploration Agency (JAXA). He graduated with his master degree of engineering from the University of Bath in 2011, and with his Ph.D. degree in aerospace engineering from the University of Tokyo in 2014. He joined JAXA in 2015, and has been working on guidance, navigation, and control systems of JAXA's deep space missions such as Hayabusa2 and MMX. His current research interests are astrodynamics and deep space exploration. E-mail: ono.go@jaxa.jp.

Naoko Ogawa received her B.E., M.E., and Ph.D. degrees in mathematical engineering and information physics in 2000, 2002, and 2005, respectively, from the University of Tokyo, Japan. From 2004 to 2008 she was a research fellow of the Japan Society for the Promotion of Science. Since 2008 she has been an engineer at Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA). Her current research interests include astrodynamics, mission design, robotics, spacecraft systems and operation. E-mail: naoko.ogawa@isas.jaxa.jp.

Yuki Takao received his bachelor and master degrees in aerospace engineering from the University of Tokyo, Japan, in 2015 and 2017, respectively. He is now pursuing his Ph.D. degree at the University of Tokyo under the direction of Prof. Kawaguchi. His research specialties are astrodynamics, spacecraft navigation, and structural dynamics, especially of solar sails. His master's thesis focused on active shape control of solar sail membranes. He received the JAXA President Award at the 31st International Symposium on Space Technology and Science for his work on the topic. He has been working on the Solar Power Sail OKEANOS mission and the Asteroid Explorer Hayabusa2 mission at Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA). E-mail: takao.yuki@ac.jaxa.jp.

Yuki Kubo is a Ph.D. candidate of engineering at the University of Tokyo. His research includes orbital mechanics, attitude mechanics, multibody dynamics, and propulsion system. He is engaged in the OKEANOS mission as a mission analyst. E-mail: kubo.yuki@ac.jaxa.jp.

Kaoru Ohashi received his master degree in engineering from the University of Tokyo, Japan, in 2019. After graduation, he joined Patchedconics, LLC, and has been working on developing thrusters for small satellites. E-mail: ohashi.kaoru@ac.jaxa.jp.

Ahmed Kiyoshi Sugihara obtained his Ph.D. degree at the University of Southampton, UK, in 2019, on a geostationary atmospheric sounding mission concept using precision satellite formation flight. He is currently a postdoctoral project researcher at the Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), developing an advanced reflectivity control device for solar sail membrane control and precision satellite formation control. E-mail: sugihara.ahmedkiyoshi@jaxa.jp.

Tatsuaki Okada received his Ph.D. degree in science from the University of Tokyo, Japan, in 1996. He is currently an associate professor at Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA). His research includes planetary science and instrumentation. He has been involved in the series of ISAS planetary missions such as Hayabusa, Kaguya, and Hayabusa2, and he is a member of the OKEANOS mission. E-mail: okada@planeta.sci.isas.jaxa.jp.

Takahiro Iwata received his Ph.D. degree from Nagoya University, Japan, in 1989. He is currently an associate professor at Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA). His research includes planetary science, radio astronomy, and space geodesy. He is in charge of Hayabusa2 mission and future planetary explorations. E-mail: iwata.takahiro@jaxa.jp.

Hajime Yano is an assistant professor at ISAS/JAXA, and a guest associate professor at both Keio University and Hosei University, as well as a visiting scientist of MIT. He obtained his Ph.D. degree in space science at University of Kent at Canterbury in 1995. His research extends to cosmic dust, solar system small bodies and astrobiology through sample return missions like Stardust, Hayabusa, and Hayabusa2, and dust collection and detection in space including IKAROS, Tanpopo, Mio, and OKEANOS. The asteroid (8906) Yano was named after him by IAU in 2003, and IAA elected him as an Academician in 2017. E-mail: yano.hajime@jaxa.jp.