TRAJECTORY DESIGN FOR JOVIAN TROJAN ASTEROID EXPLORATION VIA SOLAR POWER SAIL

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Abstract: *This paper describes the trajectory design for the Jovian Trojan exploration mission JAXA has been preparing for a Jovian Trojan exploration mission via solar power sail. Jovian Trojan asteroids are a few remaining final frontiers of our solar system. Many of them are considered to be D-type or P-type asteroids and such bodies could give the clues of the solar system formation and revolution, and the origins of the life. However, exploring the Jovian Trojans is much more difficult than the exploration of the NEOs simply because the target body is far from the sun and the earth. Solar power sail is a way to realize such a challenging exploration. The solar power sail is the extended concept of the solar sail. The solar power sail spacecraft has large membranes with thin solar cells and it can generate sufficient electric power for outer solar system explorations. Ion thrusters are driven by the generated power and they can provide high thrust to accomplish the missions within admissible period. This paper introduces the outline of the solar power sail spacecraft and it also provides the target asteroid selection and trajectory design process and low-thrust trajectory design technique.*

Keywords: *Jovian Trojans, Solar Power Sail, Electric Propulsion, Low-Thrust Trajectory*

1. Introduction

The Japan Aerospace Exploration Agency launched a solar sail demonstration spacecraft "IKAROS" on May 21, 2010. IKAROS is the first interplanetary solar sail spacecraft and it is the precursor mission to demonstrate the key technologies for "Solar Power Sail" concept [1]. The solar power sail is a concept expanding the concept of a solar sail and it is proposed by JAXA for the future deep space explorations [2]. The solar sail is a spacecraft with a large membrane that acquires propulsive force by reflecting the sunlight. This solar photon propulsion is considered to be one of the most essential propulsion systems for future deep space because it does not required any consumable fuel. However, the pure solar photon propulsion is useless for rendezvous and orbiter missions and long mission duration is required because its propulsive force is quite small. The solar power sail can overcome the difficulties. The solar power sail combines a solar sail with electric power generation capability and high efficient ion engines. The ion engines can be driven by the large electric power supply from the flexible solar cells. The solar power sail is not fuel free, but it can realize flexible and efficient orbital control capability even at outer planetary regions of the solar systems.

JAXA has been preparing for a Jovian Trojan asteroids exploration mission via solar power sail. Jovian Trojan asteroids are a few remaining final frontiers of our solar system. Jovian Trojans could give the clues of the solar system formation and revolution, and the origins of the life. However, exploration of the Jovian Trojans is much more difficult than the exploration of NEOs simply because the target body is far from the sun and the earth. Large amount of fuel is required to reach and efficient power supply is difficult. We consider that the solar power sail is a best way to realize such a challenging mission.

We are now performing the conceptual study of the solar power sail spacecraft. We anticipate its launch in the early 2020's. This paper shows the outline of the spacecraft ant it also provides the trajectory design method and results for the Jupiter Trojan asteroid exploration mission.

2. Spacecraft Configuration

Fig. 1 shows the configuration of the solar power sail spacecraft. Our solar power sail spacecraft is a single spinner like IKAROS. The spacecraft has a cylindrical body. The lander is attached to the main body. The lander is the most important payload of the mission. After the arrival at the target body, the spacecraft observes the asteroid at several hundred km altitude (HP: home position). The size, gravity, rotational axis, rotational period, etc. are observed for the preparation of the landing. Then the spacecraft descends to a low altitude and the lander is separated. The lander reaches the surface of the asteroid and it collects samples and performs in-situ analysis. The lander tries to collect the fresh samples under the regolith. The spacecraft is equipped with some instruments for uch as IR astronomy, dust observation, high-energy astronomy. Although the time of flight (TOF) to the asteroid is quite long, it is useful for the cruising science.

The large membrane is deployed and maintained by the centrifugal force. A Deployment mechanism that holds and deploys the membrane is attached to the side panels of the main body. The membrane is folded around the deployment mechanism at the launch.

The ion thrusters are mounted on the top panel in Fig. 1. But now we are considering another configuration where the ion thrusters are mounted on the bottom panel. Direction of the ion thrusters influences the trajectory design. Details are described below. The thrust direction of the ion thruster is tilted form the spin axis direction by several degrees to generate the spin up/down torque. And the ion thrusters also can control the direction of the spin axis by throttling their thrust forces.

The weight of the spacecraft is around 1300 kg including the lander weighting about 100 kg. 100 kg lander is similar to Philae lander of ESA's Rosetta mission. The weight of the Rosetta probe is about 2900kg and it is more than twice as heavy as the solar power sail. This means that the solar power sail spacecraft have the great carrying capability. The area of the sail membrane is assumed to be 3000 m2.

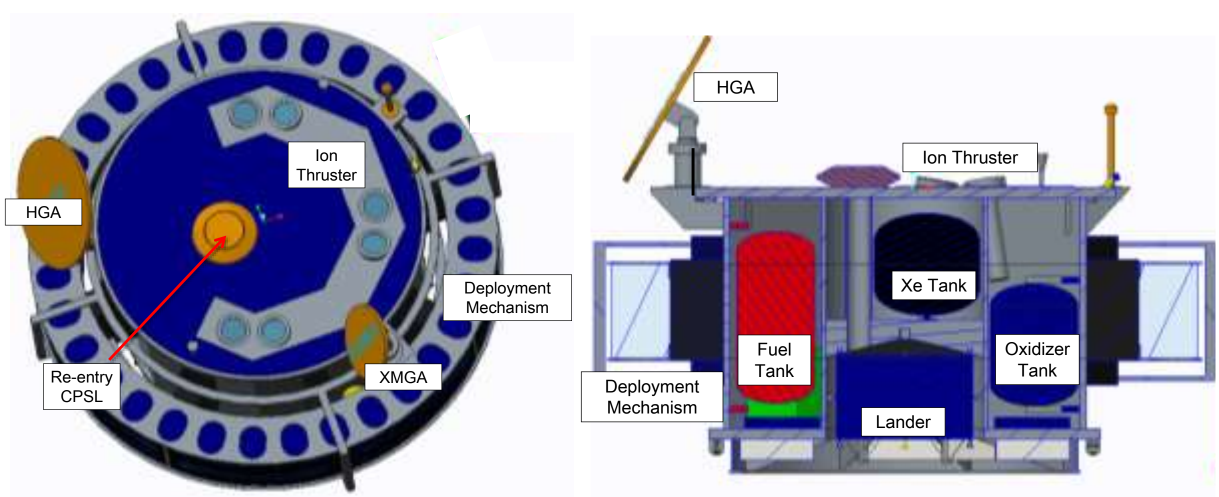

Figure 1. Configuration of solar power sail spacecraft

3. Mission Sequence

Our Jovian Trojan probe under consideration is supposed to be launched in early 2020s. Jupiter swing-by is used to reduce the fuel consumption and Earth swing-by is also applied before transfer to Jupiter. Two scenarios are considered in this paper. One is sample return scenario and another is one-way scenario. The sequence for the sample return mission consists of six phases; 1) an EDVEGA phase to increase the departure velocity relative to the Earth, 2) a transfer phase from the Earth to Jupiter, 3) a rendezvous phase from Jupiter to the asteroid, 4) a proximity operation phase, 5) a return phase from the asteroid to Jupiter and 6) a transfer phase from Jupiter to the Earth. 1), 3) and 5) are the powered flight phases. In the one-way mission, phase 5) and 6) are not unnecessary. The total mission duration of the sample return case is longer than 30 years because the timing of the Jupiter swing-by strongly influences the mission duration. The opportunities of Jupiter swing-by occur every 6 years. 6 years is the half of the period of the revolutions of the target asteroid. In one-way mission, TOF to the target body can be reduced by selecting the "good target bodies".

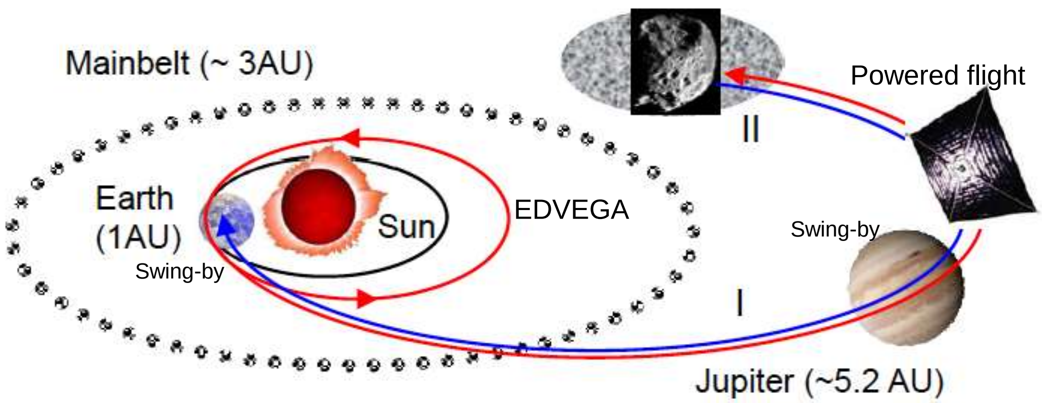

Figure 2. Mission sequence of Jovian Trojans exploration

4. Selection of Target Asteroid

The target asteroids are selected by the ballistic analysis based on the two body dynamics. In this paper, Jupiter swing-by is used to reduce the fuel consumption. Fig. 3 shows the outline of the ballistic analysis.

T_1 is departure time from the Earth, T_2 is the Jupiter swing-by time and T_3 is the arrival time to the target body. These are the variables. V_1, V_2 and V_3 are the relative velocities to Earth, Jupiter and the asteroid, respectively. We can search the target body as follows;

1. Give T_1, T_2 and T_3.
2. The position and velocity of Earth, Jupiter and the asteroid are calculated.
3. V_1^{out}, V_2^{in}, V_2^{out} and V_3^{in} are calculated by solving Lambert's problem.
4. If $|V_2^{in}|=|V_2^{out}|$, T_1, T_2 and T_3.are the feasible solutions.
5. Do 1-3 by changing , T_1, T_2 and T_3.
6. Pick up the asteroids that have small $|V_1^{out}|$, $|V_3^{in}|$ and TOF($T_3 - T_1$).

Three-dimensional search is required. However, the timing of the Jovian swing-by (T_2) is restricted and opportunities occur every 6 years.
The size of the asteroids is important factor. In the case of very large target body, the proximity operation becomes difficult due to the large gravity force. On the other hand, very small asteroid have possibility that it is neither D-type nor P-type. In this paper, asteroids whose diameter is about 20-30km are selected as the target body.
The long-term stability of the asteroid's orbit is also important. If the life time of the orbit is small, the asteroid is judged to be "intruder". On the other hand, the asteroid whose orbital life time is long is considered as "survivor". After the ballistic analysis, the dynamical stability investigation is performed and only survivors are picked up.
Table 1 lists part of the candidate asteroids. In the table 1, both L4 and L5 asteroids are listed. From the view point of the science, L4 and L5 asteroids have little difference. However, there is a large difference between L4 and L5 in the trajectory design. Generally, the flight time from Jupiter to L4 target is shorter than L5 target due to the geometrical reasons. Of course, the flight time from L4 to Jupiter is longer than the flight time from L5 to Jupiter. It means that the L4 is better than L5 about the flight time in one-way mission although they have little differences in the sample return mission.
Additionally, L4 is better in the one-way mission about the power generation. Fig. 4 shows the flight path from Jupiter to Jovian Trojan asteroids. As the figure shows, the sun distance of the flight path from Jupiter to L4 targets is smaller than the path from Jupiter to L5 targets. As a result, the power generation and thrust force of the ion engine become large and it becomes possible to reduce the flight time to the asteroid. It is a great advantage for the trajectory design. Of course the sun distance of the return path from L4 asteroid to Jupiter is large. However, in one-way mission, we should choose L4 target.

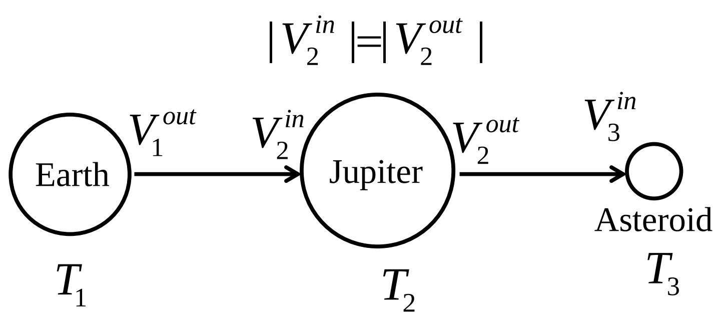

Figure 3. Ballistic analysis for Jovian Trojans exploration

Table 1. Part of candidate asteroids

ID	L4/L5
2005 EL140	L5
2007 RQ278	L4
2001 DY103	L4
2000 ST347	L5
2002 CM208	L4

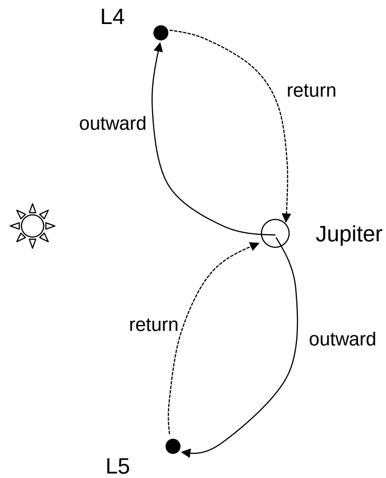

Figure 4. Flight path to L4/L5 target

5. Low-Thrust Trajectory Design
5.1 Conditions

The low-thrust trajectory is designed after the selection of the target asteroid. Table 1 lists the conditions for the low-thrust trajectory design. The mass of the spacecraft at launch is 1300kg. The spacecraft is equipped with high Isp Ion engine system (IES). The thrust force of the ion thruster is 26.1mN and its power consumption is 1.6kW. The operation rate is 0.7. The power generation for IES is 2600W at 5.2AU. As the spacecraft is a single spinner, the direction of the thrust force is controlled by changing the attitude of the spacecraft. The sun angle should be less than 45deg.

Table 2. Conditions for the low-thrust trajectory design

Spacecraft Mass @ launch	1300kg
Spacecraft Mass @ asteroid departure	1100kg
Launch	2021 or 2022
IES thrust	26.1mN/unit
IES power	1600W/unit
IES Isp	7000sec
IES throttling	100%, 80%
IES operation rate	0.7
Power generation for IES	2600W@5.2AU (Sun angle=0deg)
Attitude	Sun angle < 45 deg
Ion thruster direction	+Z or -Z

The direction of thrust force influences the trajectory. Fig. 5 shows the conceptual diagram of the trajectory from Jupiter to an L4 asteroid in Sun-Jupiter fix coordinate. When an L4 asteroid is the target body, the spacecraft flies the sun-side area as the figure shows. If the spacecraft has the ion thrusters mounted on -Z (shadow side) panel, the direction of the thrust force looks toward the sun side. Thus the approaching the asteroid is smooth because the thrust force can cancel the approaching velocity. On the other hand, the spacecraft with +Z (sun side) thrusters approaches the asteroid after it flies the far side area form the sun. It means that the flight time of the spacecraft with +Z thrusters becomes longer than the spacecraft with –Z thrusters. Of course, the spacecraft with +Z thruster is better in the return way (from L4 asteroids to Jupiter). However, the direction of the thrust force is a very important factor for the trajectory design, especially in the one-way mission.

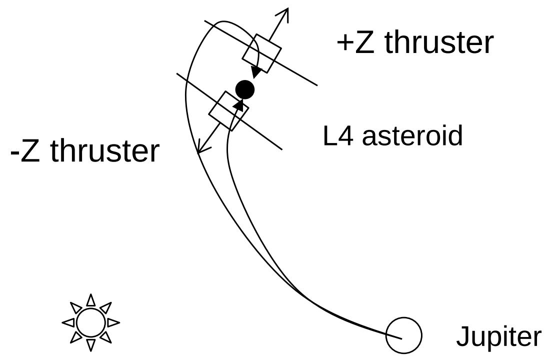

Figure 5. Conceptual diagram of Jupiter to L4 asteroid (Sun-Jupiter fix coordinate)

5.2 Trajectory Optimization

The low-thrust trajectory is designed as follows.

1. Jupiter swing-by time (T_2) can be fixed.
2. Give the Earth departure time (T_1)
3. Earth departure velocity (Earth swing-by velocity) V_1^{out} can be calculated by solving Lambert's problem of Earth to Jupiter transfer.
4. EDVEGA trajectory is calculated. Boundary conditions are T_1 and V_1^{out}.
5. The Earth swing-by condition is checked by using the result of step 4. If it is NG, go back to step 2.
6. Low-thrust trajectory from Jupiter to the target asteroid is calculated. The arrival time T_3 is free or given.

The return trajectory can be obtained in a similar way.

Equations of motion are as follows;

$$\begin{aligned}
\ddot{x} &= -\frac{\mu}{r^3}x + \frac{T}{m}\cos(\gamma + u_1)\cos(\phi + u_2) \\
\ddot{y} &= -\frac{\mu}{r^3}y + \frac{T}{m}\sin(\gamma + u_1)\cos(\phi + u_2) \\
\ddot{z} &= -\frac{\mu}{r^3}z + \frac{T}{m}\sin(\phi + u_2) \\
\dot{m} &= -T / I_{sp}g
\end{aligned} , \qquad (1)$$

where

$$T = \Gamma T_{\max} \quad (0 \le \Gamma \le 1)$$
$$\gamma = \tan^{-1}(y/x)$$
$$\phi = \tan^{-1}\left(z/\sqrt{x^2+y^2}\right) . \tag{2}$$

Γ is throttling parameter. The trajectory design is based on the following optimization problem

$$\min f(x) \text{such that} \begin{cases} c(x) \le 0 \\ ceq(x) = 0 \end{cases}, \tag{3}$$

where $f(x)$ is an objective function and $c(x)$ is the state inequality constraints and $ceq(x)$ is the state equality constraints.

Two types of objective function are used in this study. The Nonlinear Sequential Quadratic Programming (NLSQP) is applied to solve the problem. Two types of objective function are used in this paper. One is

$$f(x) = \int_{t_0}^{t_f} a dt . \tag{4}$$

Eq. 4 means minimizing delta-V. It is used in EDVEGA phase and sample return case. In the sample return mission, the fuel should be saved for the return phase. Therefore, the objective function Eq. 4 is considered. On the other hand, in the one-way mission, it is important to reduce the TOF. In this case, the following objective function is used.

$$f(x) = t_f . \tag{5}$$

5.3 Sample Return Trajectory

Here we show the trajectory for the exploration of 2007 RQ278. 2007 RQ278 is an L4 asteroids and it is considered the survivor. Table 3 shows the summary of the sample return for 2007 RQ278 with +Z ion thruster configuration. Table 4 shows the summary with –Z ion thruster configuration. Both configurations have difference in required delta-V and asteroid arrival/departure time. However, Earth return date are same because the Jupiter swing-by timing is restricted. Fig. 6 shows the sample return trajectory.

As mentioned, the sequence for the sample return consists of six phases; 1) an EDVEGA phase to increase the departure velocity relative to the Earth, 2) a transfer phase from the Earth to Jupiter, 3) a rendezvous phase from Jupiter to the asteroid, 4) a proximity operation phase, 5) a return phase from the asteroid to Jupiter and 6) a transfer phase from Jupiter to the Earth.

Fig. 7 shows the EDVEGA trajectory. It is difficult to launch the spacecraft direct into the transfer orbit. The conventional delta-VEGA strategy has been frequently used for the missions chemically propelled to increase the departure velocity relative to Earth. This technique can be applied to our solar power sail spacecraft. In this study, two-year EDVEGA (Electric Delta-V

Earth Gravity Assist) is used. The spacecraft is accelerated by the ion engines around the aphelion.
Fig. 8 shows the trajectory from Jupiter to 2007 RQ278 and thrust force history and Fig. 9 shows the trajectory from 2007RQ278 to Jupiter. Both trajectories are calculated by using the Eq. 4 to reduce the fuel consumption. In one-way mission, it is important to reduce the TOF. However, in the sample return mission, reducing the TOF of J2A/A2J phase does not contribute to shorten the total mission duration, because the timing of Jovian swing-by is restricted.

Table 3. Summary of sample return for 2007 RQ278 (+Z ion thruster configuration)

Phase	Start	End	dV[m/s]
2yr EDVEGA	2021/8/7	2023/6/22	1355(C3=25)
Earth to Jupiter	2023/6/22	2025/12/10	-
Jupiter to Asteroid	2025/12/10	2036/7/1	1757
Proximity Ope.	2036/7/1	2037/7/1	-
Asteroid to Jupiter	2037/7/1	2049/9/1	1685
Jupiter to Earth	2049/9/1	2052/7/5	-

Table 4. Summary of sample return for 2007 RQ278 (-Z ion thruster configuration)

Phase	Start	End	dV[m/s]
2yr EDVEGA	2021/8/9	2023/6/29	983(C3=28)
Earth to Jupiter	2023/6/22	2025/12/10	-
Jupiter to Asteroid	2025/12/10	2034/7/1	1852
Proximity Ope.	2034/7/1	2035/7/1	-
Asteroid to Jupiter	2035/7/1	2049/9/1	2745
Jupiter to Earth	2049/9/1	2052/7/5	-

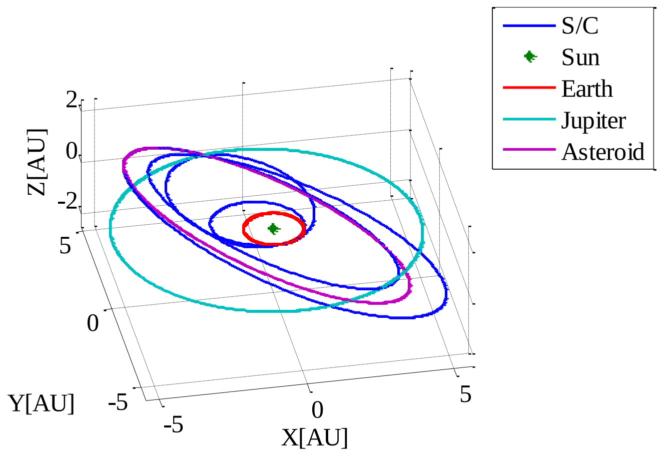

Figure 6. Sample return trajectory for 2007 RQ278

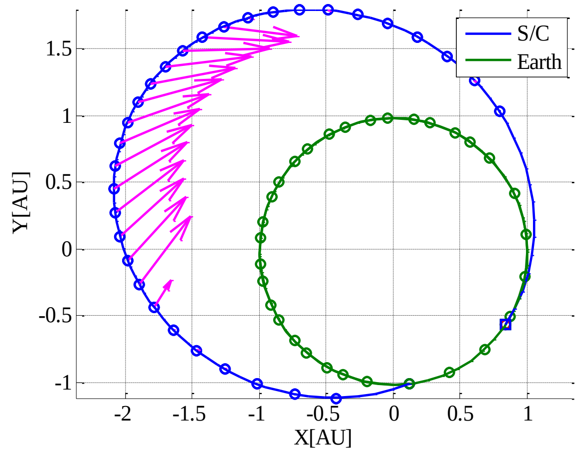

Figure 7. EDVEGA trajectory (-Z ion thruster configuration)

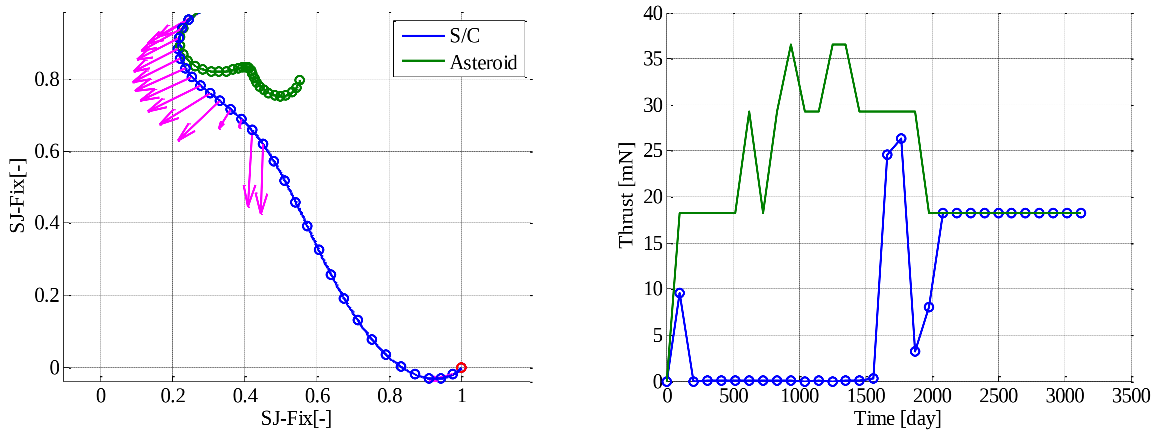

Figure 8. Jupiter to Asteroid trajectory and thrust force history (-Z ion thruster configuration)

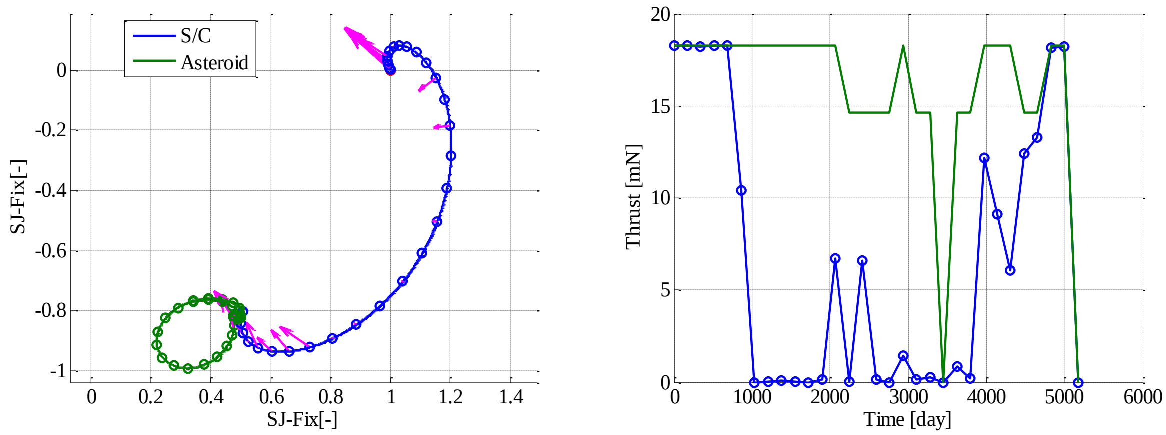

Figure 9. Asteroid to Jupiter trajectory and thrust force history (-Z ion thruster configuration)

5.4 One-way Trajectory

In the one-way mission, it is meaningful to reduce the transfer time to the target body because it can shorten the total mission duration. TOF can be reduced by increasing the delta-V As described, the combination of L4 targets and -Z thrusters is required for the significant reduction of the TOF. Fig. 10 shows the Jupiter to 2007 RQ278 fastest trajectory. The left hand figure shows the +Z ion thruster case and the right hand figure shows the –Z ion thruster case, respectively. TOF of +Z thruster case is 9.6 years and –Z thruster case is 7.32 years. As mentioned, the flight path becomes longer if the +Z thruster is used in the L4 target exploration. Table 5 shows the summary of the one-way mission for 2007 RQ278. The total TOF to asteroid is less than 12 years.

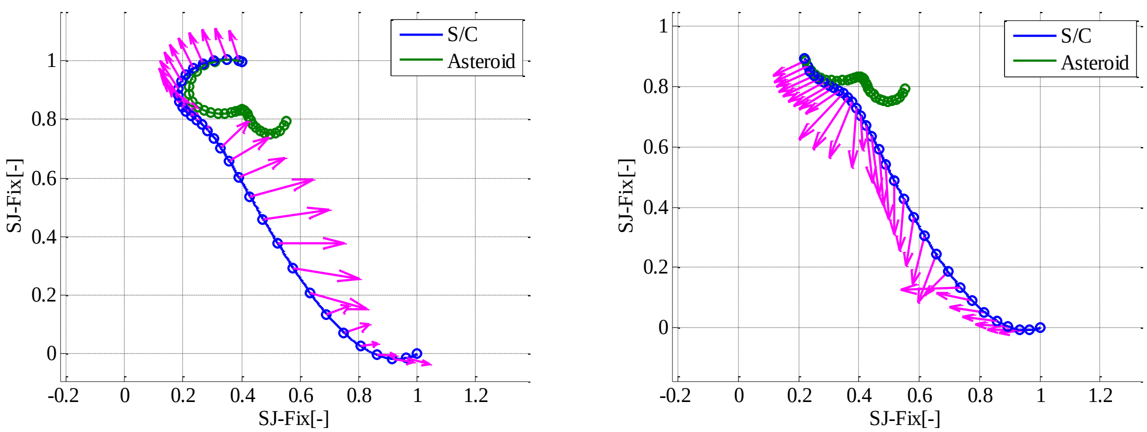

Figure 10. Jupiter to 2007 RQ278 fastest trajectory
Left: +Z ion thruster, Right: -Z ion thruster

Table 5. Summary of one-way mission for 2007 RQ278 (-Z ion thruster configuration)

Event	Date	Note
Launch	2021/8/9	C3=28.1
Earth SWB	2023/6/29	dV(2yr EDVEGA): 983m/s S/B Alt: 1606km
Jupiter SWB	2025/12/10	Vinf: 5720m/s
Arrival	2033/4/5	dV(Jupiter to Asteroid): 4300m/s
Total TOF	4257d (11.66yr)	

6 Conclusions

This paper described Jovian Trojan exploration mission via solar power sail. The solar power sail is JAXA’s original concept that combines the solar sail with the high Isp ion engine system. The trajectory design method and results are shown in this paper. The total mission duration of the sample return mission is longer than 30 years. However, in the one-way mission, the TOF to the asteroid can be reduced significantly by selecting an L4 target and using -Z ion thrusters.

7. References

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