6th International Symposium on Space Sailing

A Rendezvous Mission to Outer Solar System Bodies Using a 100-kg-Class Solar Power Sail

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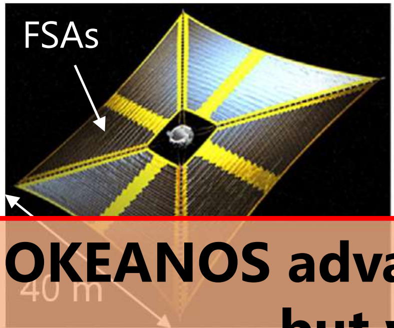
Background
What is solar power sail?

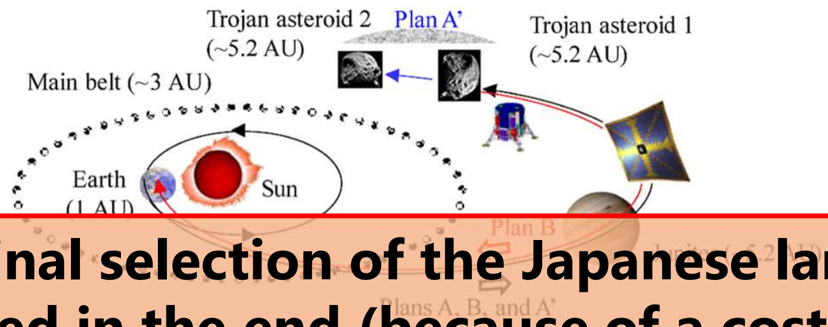
Solar Power Sail

- An extended concept of solar sail that is covered with flexible (thin-film) solar arrays (FSAs).
- A solar power sail can generate a large amount of power in a lightweight spacecraft system.

OKEANOS (Oversize Kite-craft for Exploration and AstroNautics in the Outer Solar system)

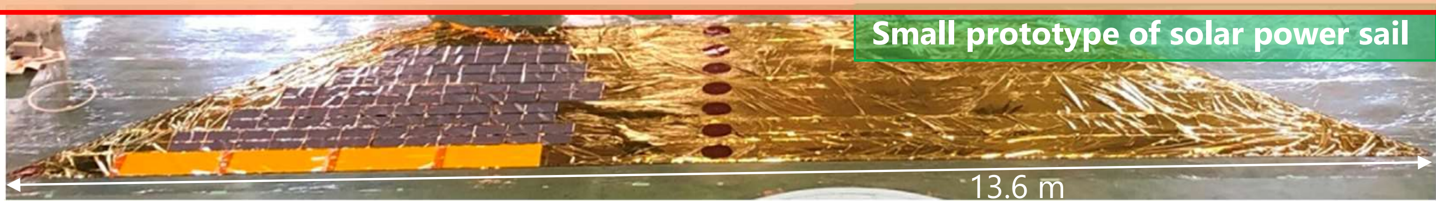
- A Jupiter Trojan exploration mission using a 40×40 m (1400 kg) solar power sail.
- Round trip to Jupiter Trojans is possible using high-Isp ion engines in the outer solar system.





Sampling lander

OKEANOS advanced to the final selection of the Japanese large-class mission, but was not selected in the end (because of a cost issue).



Background
Heritage of OKEANOS

DESTINY+ (JAXA)

- An asteroid flyby mission starting from a geocentric orbit with a 480 kg spacecraft.
- Thin-film lightweight solar array panels are used to drive ion engines.
- To be launched in 2024!

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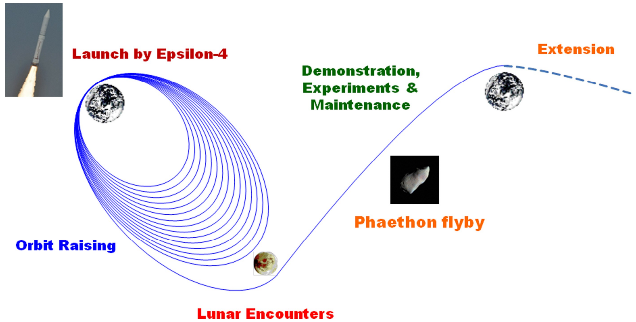
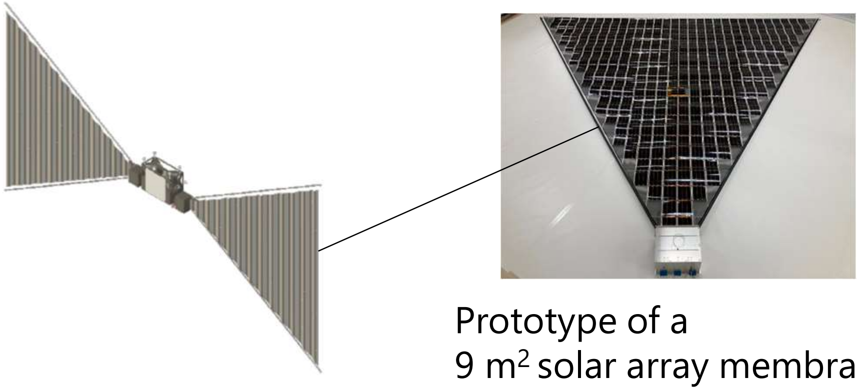
https://doi.org/10.1016/j.actaastro.2022.03.029



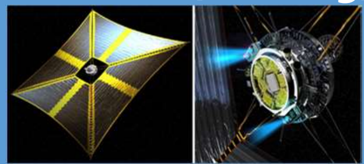
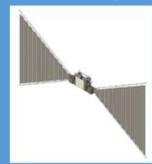
Saturn explorer OPENS (JAXA)

- A 140-kg-class small spacecraft mission to Saturn, which is under consideration in JAXA.
- Membrane structures covered with FSAs (solar array membranes) are deployed using deployable booms.
- The small spacecraft can survive in the outer solar system because of the ultralight power generation system.



Prototype of a
9 m^2 solar array membrane

Background
Future of solar sails in Japan

	OKEANOS (1400 kg)	DESTINY+ (480 kg)	OPENS (140 kg)
			
Power generation system	Centrifugal deployment of a solar power sail	Thin-film (rigid) solar array panels	Boom deployment of solar power sails
Attitude control	Spin-stabilized	Three-axis control	Three-axis control
Propulsion	High-Isp ion engines	Ion engines	Chemical engines
Mission	Rendezvous, multiple rendezvous, and sample return to the Jupiter Trojans	Near-Earth asteroid flybys	Saturn flyby
Status	Not selected	To be launched in 2024	Under study

- Although OKEANOS was not selected, the technologies of solar power sail developed so far is effective for future deep-space explorations.
- We have started a study of a new deep-space exploration mission that succeeds the heritage of the above three missions.

Mission Concept
Small spacecraft mission to outer solar system bodies

Advantages of solar power sail

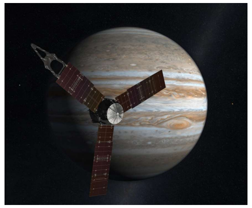
- Provides an ultralight large-power generation system.
- Capable of driving ion engines in the outer solar system.

Survivability & mobility in the outer solar system

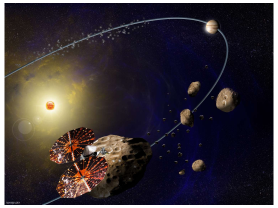
vs.

Past outer solar system exploration missions

- Access to outer solar system bodies, including rendezvous, is possible using conventional chemical propulsion if a powerful launch vehicle is available.



Juno (Jupiter orbiter)



Lucy (Multiple flybys of Jupiter Trojans)

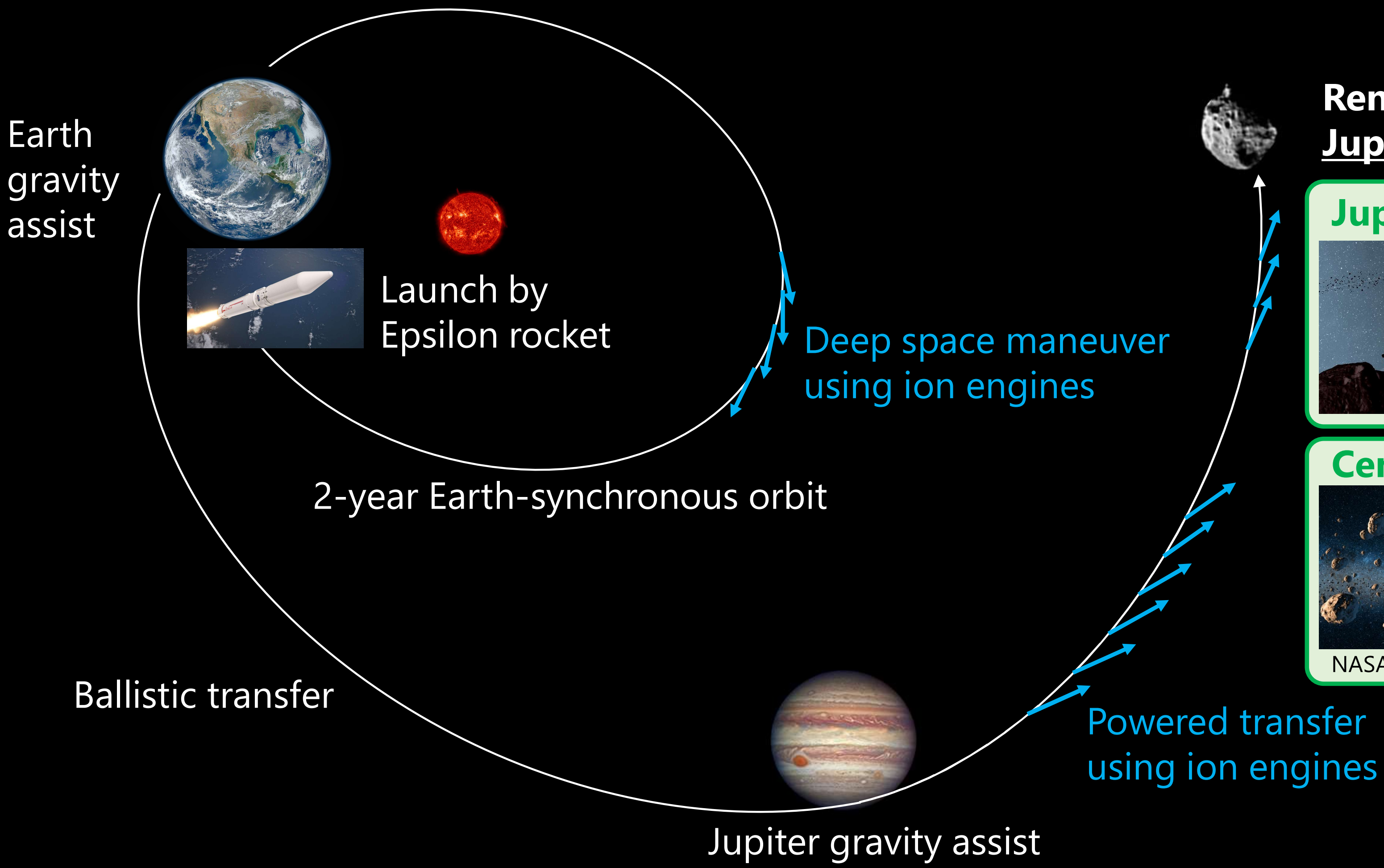
Extend the possibility of small spacecraft

- Small spacecraft are advantageous in terms of cost and development period.
- However, small spacecraft cannot often receive good launch conditions.
- This study demonstrates that small spacecraft can reach the outer solar system using a solar power sail.

Epsilon launch vehicle (solid rocket engine)

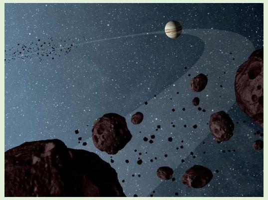
Toward frequent and timely exploration by small spacecraft

Mission Sequence



Rendezvous to
Jupiter Trojans or **Centaurs**

Jupiter Trojans



Asteroids located at Sun-Jupiter L4/L5 that contain essential information about solar system evolution.

Centaurs

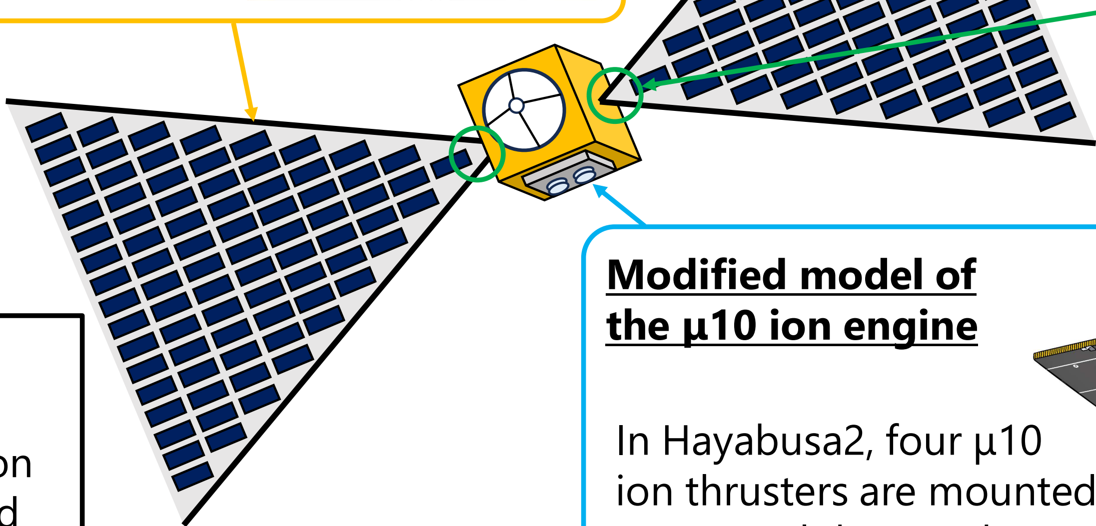
NASA/JPL-Caltech

Icy bodies beyond Jupiter that have both aspects of asteroids and comets.

Spacecraft System Overview

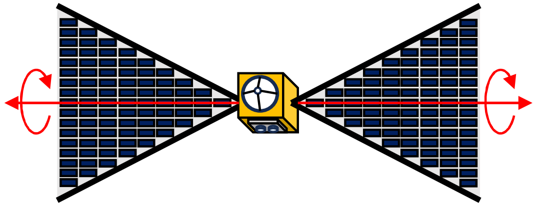
Solar array membrane

200 W/kg power generation capacity at maximum (world's highest performance).



One-axis gimbal

Each wing can be rotated to control disturbance torque due to solar radiation pressure.

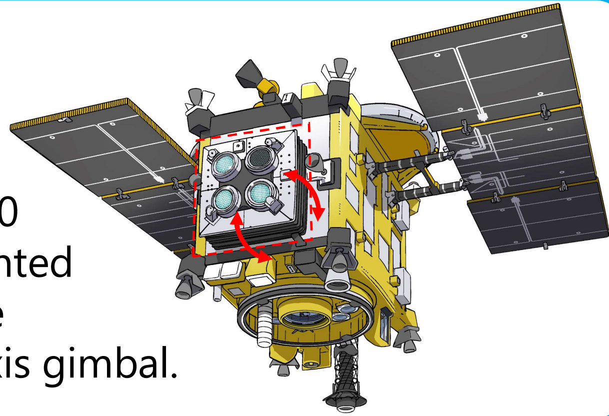


Total wet mass: 100~200 kg

Total mass depends on other instruments and payloads. System design is in progress.

Modified model of the µ10 ion engine

In Hayabusa2, four µ10 ion thrusters are mounted on a panel that can be actuated using two-axis gimbal.



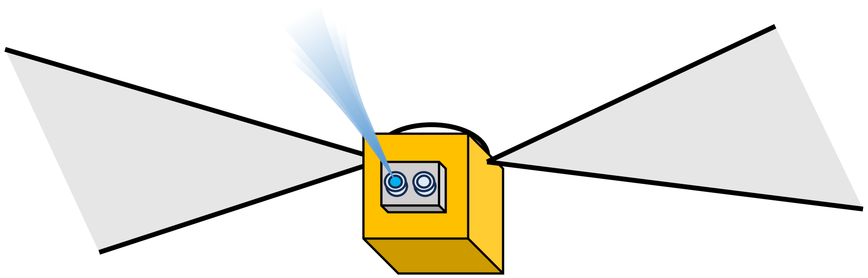
Spacecraft System
Details

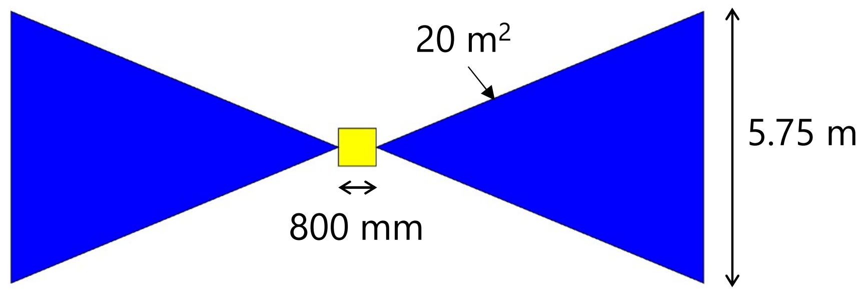
Ion Engine System (IES)

Parameter	New μ10	In Hayabusa2
Power/thruster	300 W	400 W
Thrust/thruster	5 mN	10 mN
Isp	3000 s	3000 s
Number of thrusters	2	4
Maximum number of simultaneous drive	1	3

Electric Power System

Parameter	Value
Bus power	50 W
IES power	300 W
Total power	350 W
Maximum Sun distance	6 au
Solar cell efficiency	30 %
Specific power	~38 W/m^2 @1 au
Total area	~40 m^2



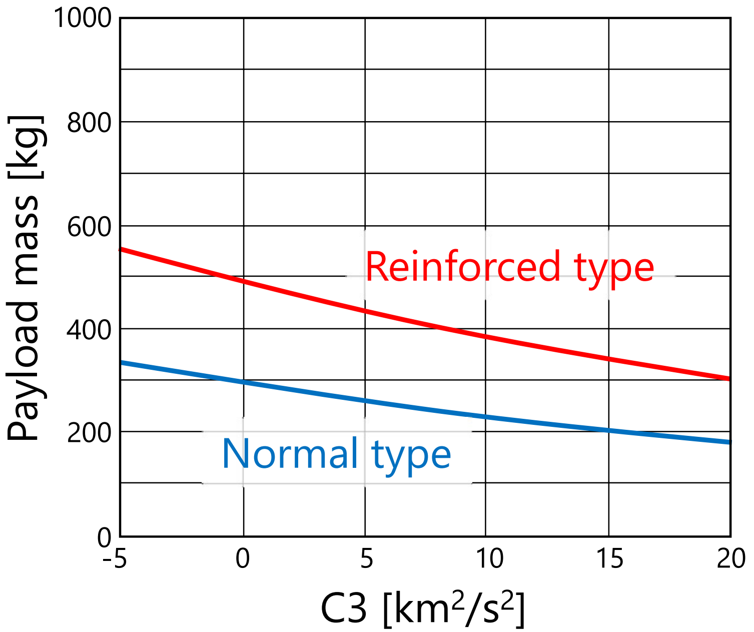


Solar power sail of the actual size

Conditions and requirements

Launch vehicle

Approximate performance of the Epsilon launch vehicle



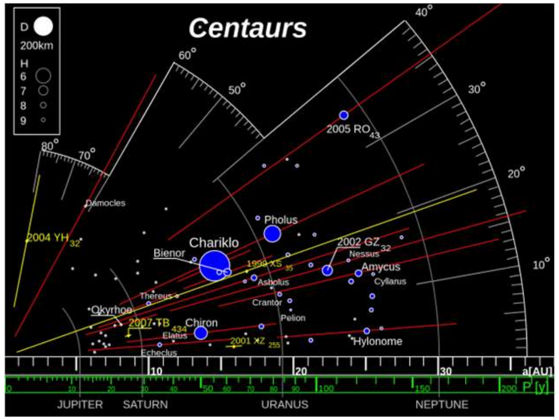
The normal-type Epsilon rocket can deliver **a 150 kg spacecraft** into an orbit of C3 = 26 m^2.

Equivalent to 2-year Earth-synchronous orbit

Target bodies

Most of the Jupiter Trojans and Centaurs fly beyond the Jupiter orbit with large inclination.

Jupiter/Saturn gravity assist is used to raise the orbital inclination.



Requirements

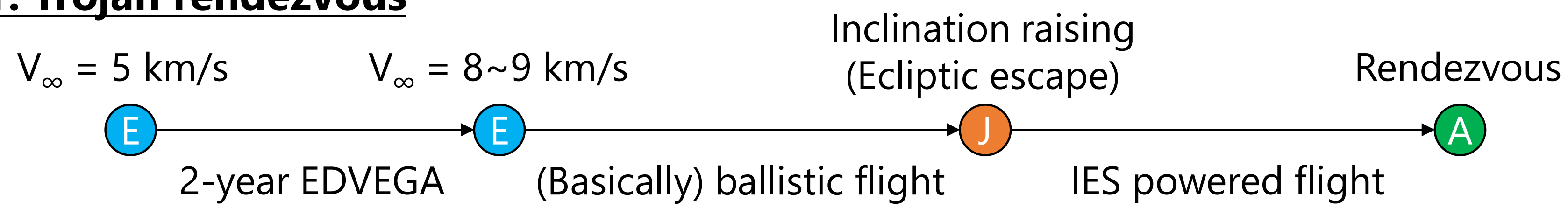
In OKEANOS, the very long mission duration was problem.

Scenario	ΔV	ToF
One-way trip	3452 m/s	13 years
Round trip	5661 m/s	32 years

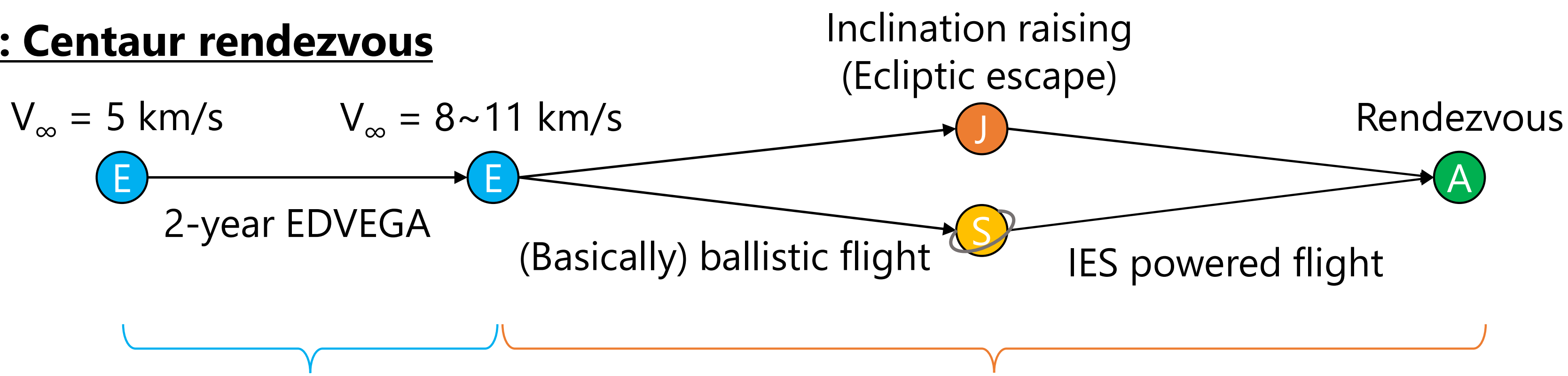
In this study, we aim to design a trajectory with as small ΔV and ToF as possible.

Approach to trajectory design

Plan 1: Trojan rendezvous



Plan 2: Centaur rendezvous

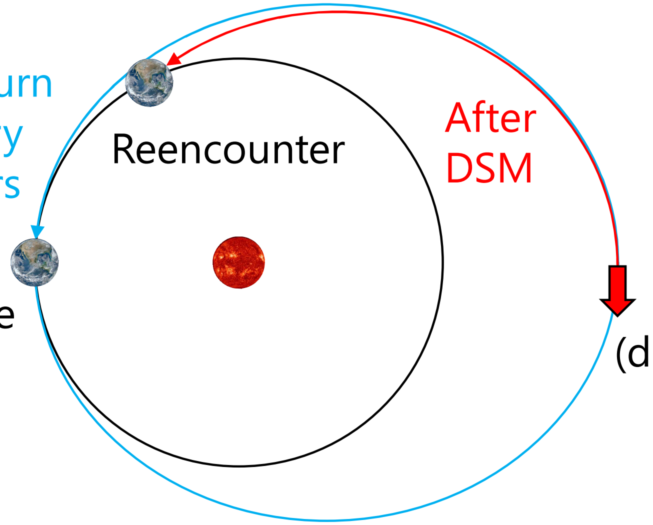


Electric Delta-V Earth-Gravity-Assist (EDVEGA) trajectories can be solved independently.

Low-thrust gravity-assist (LTGA) trajectories are designed using a global optimization method.

2-year EDVEGA trajectory

Overview of 2-year EDVEGA trajectories

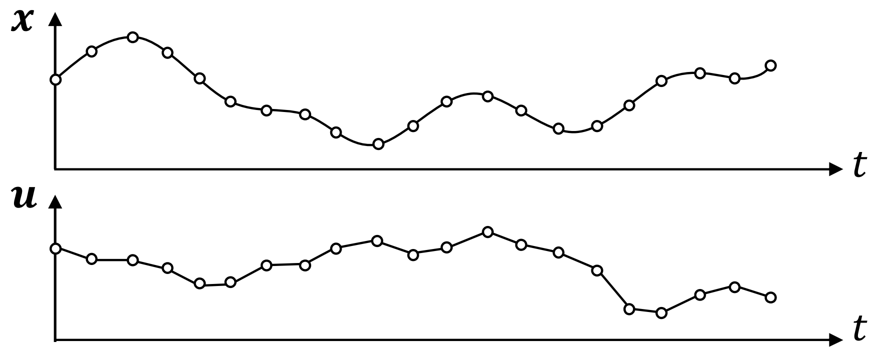


EDVEGA trajectories exploit free-return trajectories in which the spacecraft unconditionally reencounters Earth in a specific period.

A deep space maneuver (DSM) ΔV is applied at the aphelion to lower the perihelion distance, so as to change (amplify) the infinity velocity at reencounter.

Design method

Direct collocation with nonlinear programming (DCNLP)



State vector: $\boldsymbol{x} = [x, y, z, \dot{x}, \dot{y}, \dot{z}, m]^T$

Control vector: $\boldsymbol{u} = [F_x, F_y, F_z]^T$

1. Discretize the state vector and control vector.
2. Interpolate the nodes using 3rd-order polynomials (for $\boldsymbol{x}$) and a linear function (for $\boldsymbol{u}$).
3. Solve the nonlinear programming problem:

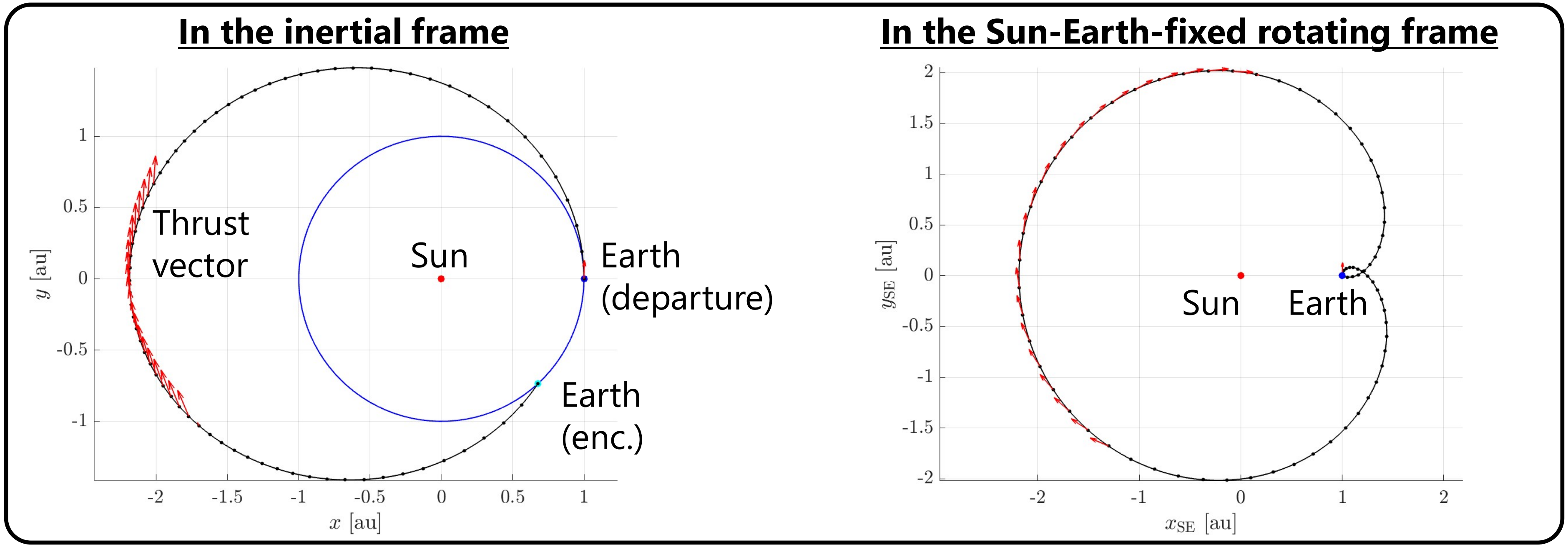
$$\min_{\boldsymbol{x}} \Delta V \quad \text{s.t.} \quad \hat{\dot{x}} = f(\hat{t}, \hat{\boldsymbol{x}}, \hat{\boldsymbol{u}})$$

and other constraints (B.C., etc)

Trajectory Design
Example of 2-year EDVEGA trajectory

B.C.	Value
Initial state	V_∞ = 5099 m/s (C3 = 26)
Terminal state	V_∞ = 9023 m/s (from E-J-A transfer, as explained later)

Result	Value
Total ΔV	590.46 m/s
Propellant	2.98 kg
V_∞ amplification efficiency	6.65



Trajectory Design
Candidate body search

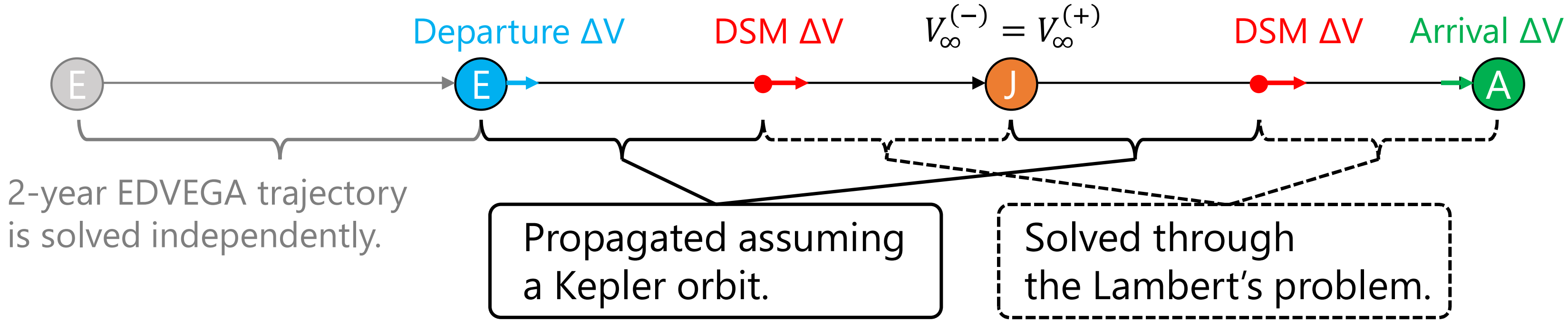
- Orbital elements of the Jupiter Trojans and Centaurs are retrieved from the JPL's Small Body Database.
  - Jupiter Trojans: 11,346 candidates (condition code ≤ 2)
  - Centaurs: 690 candidates (no constraint)

→ **It is impossible, in practice, to perform LTGA trajectory optimization for all candidates.**

- Candidate bodies that can possibly be reached with realistic ΔV and ToF are investigated assuming ballistic transfers.

MGA-1DSM (Multiple Gravity Assist, 1 Deep Space Maneuver) problem

An impulsive ΔV is allowed only once in each leg, and the legs are connected assuming Kepler orbits.



Candidate body search

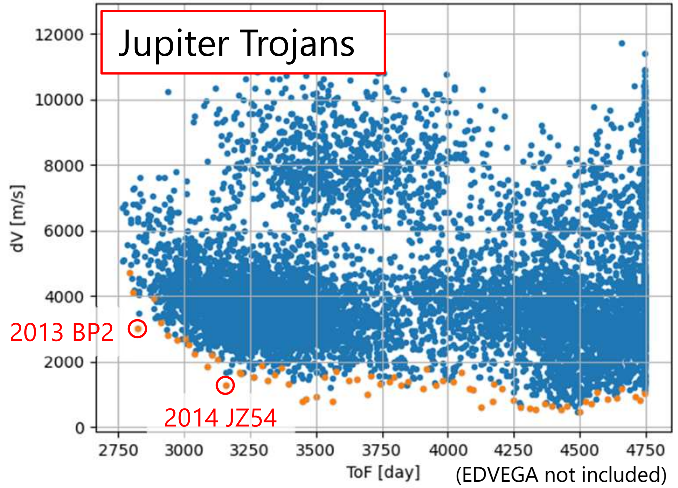
Decision variables: $[\underbrace{t_E, t_J, t_A}_{\text{Epochs at each body}}, \underbrace{t_{EJ}, t_{JA}}_{\text{Epochs of DSMs}}, \underbrace{\boldsymbol{V}_{\infty E}, \boldsymbol{V}_{\infty J}}_{V_\infty \text{ at each body}}]$ → Minimize total ΔV

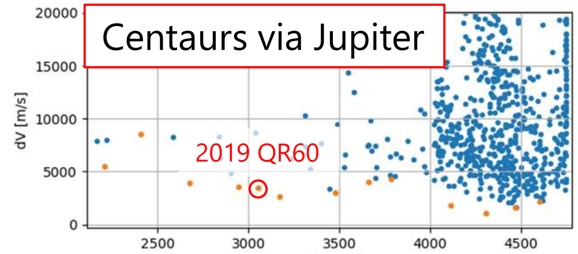
Unconstrained single-objective optimization problem

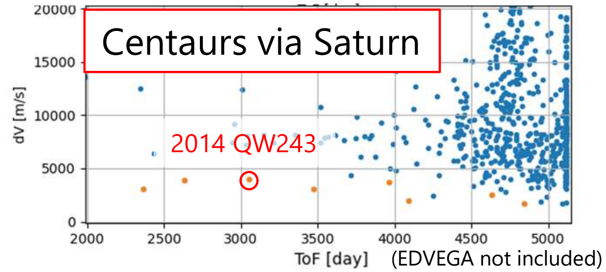
- Population-based optimization is performed using the self-adaptive differential evolution algorithm.
  - Global optimum can be searched rapidly.
  - No initial guess is needed.

Result

- The launch window was set to Jan. 1 - Dec. 31, 2030.
- Good solutions with ToF shorter than 10 years and ΔV smaller than 3000 m/s are found in the pareto front.

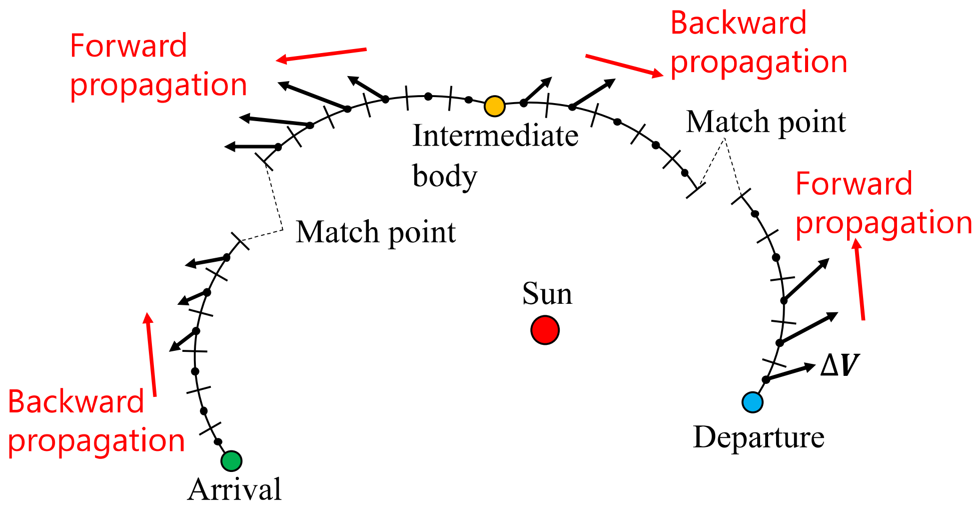






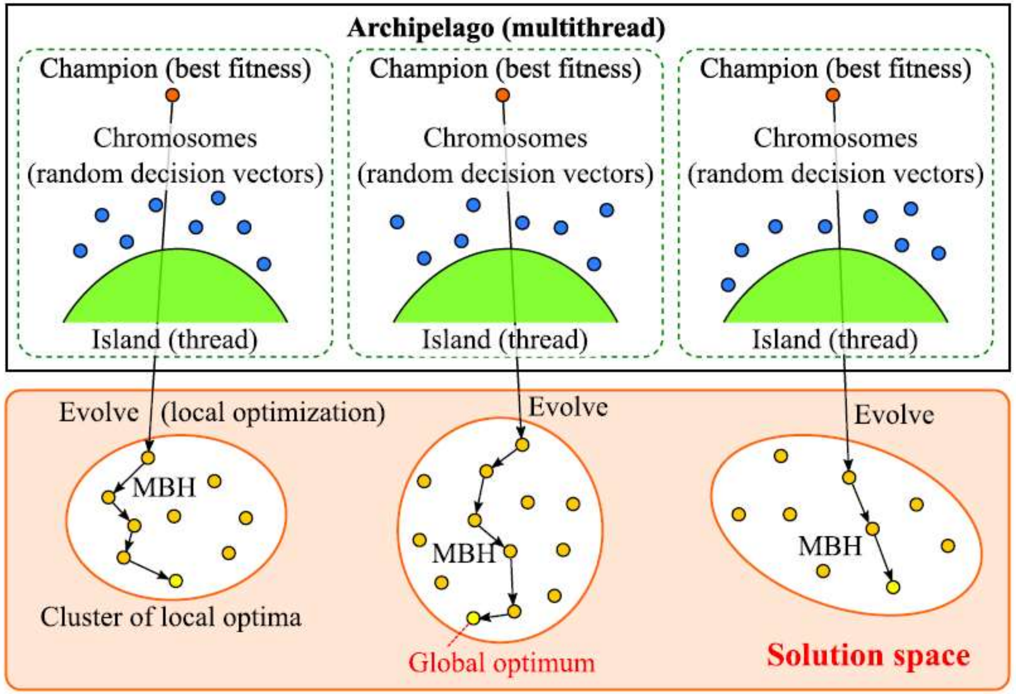
Trajectory Design
Global optimization of LTGA trajectories

Sims-Flanagan transcription



- Trajectory legs are discretized into multiple nodes, and are propagated forward/backward from the departure/arrival bodies.
- Trajectories between two nodes are propagated rapidly assuming a Kepler orbit.
- A constraint is given such that each leg is continuous at the match point.

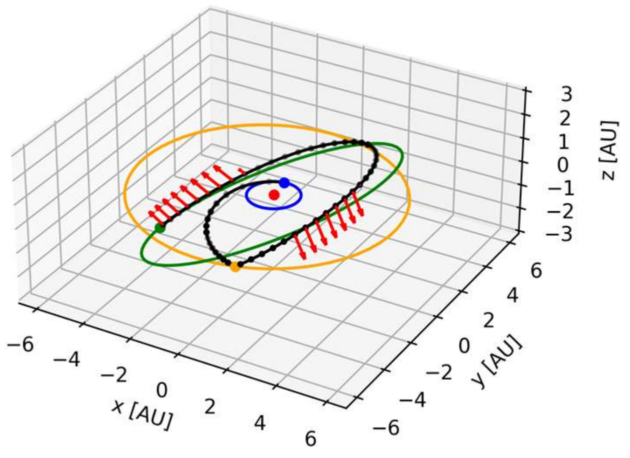
Meta-heuristic global optimization

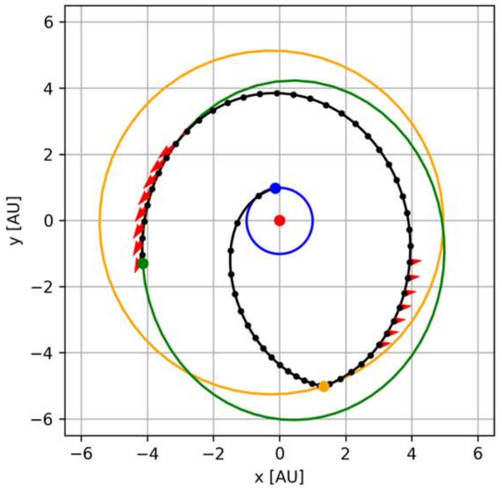


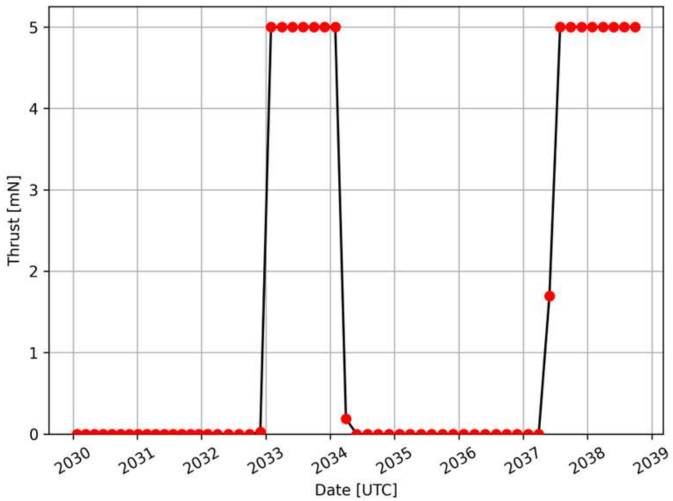
- Among randomly generated decision vectors, a champion individual is selected, which is evolved through local optimization algorithm such as SQP.
- This process is run in parallel in a multiple threads.

Trajectory Design
Rendezvous trajectory to 2013 BP2 (Jupiter Trojan)

Phase	Start	End	IES ΔV, m/s	Propellant, kg	ToF, day
2-year EDVEGA	2028-Feb-19	2030-Jan-02	590.46	2.98	682.4
Earth – Jupiter	2030-Jan-02	2032-Mar-01	0	0	789.2
Jupiter – Asteroid	2032-Mar-01	2038-Oct-31	2831.33	13.76	2435.0
Total	2028-Feb-19	2038-Oct-31	3421.79	16.74	3906.6 (10.7 year)





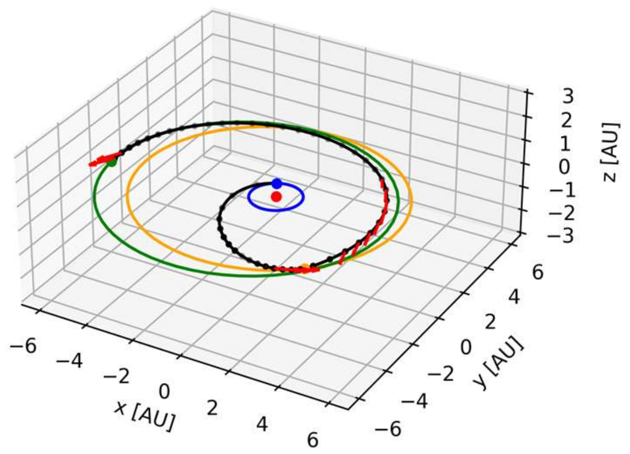


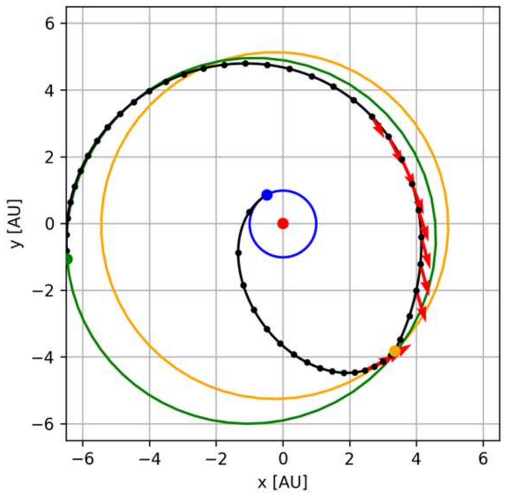
* The 2-year EDVEGA trajectory is omitted in the figures.

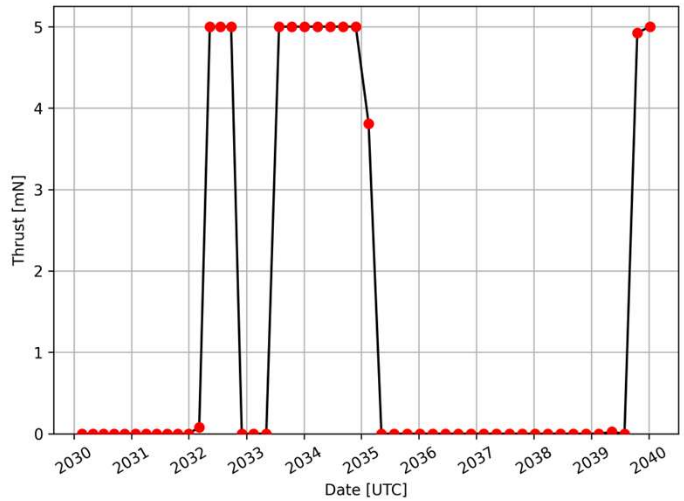
A 150 kg small spacecraft can rendezvous with a Trojan asteroid in 11 years!

Trajectory Design
Rendezvous trajectory to 2019 QR60 (Centaur via Jupiter)

Phase	Start	End	IES ΔV, m/s	Propellant, kg	ToF, day
2-year EDVEGA	2028-Mar-07	2030-Jan-19	590.46	2.98	682.4
Earth – Jupiter	2030-Jan-19	2033-Jan-04	594.91	3.00	1081.2
Jupiter – Asteroid	2033-Jan-04	2040-Feb-17	2419.65	11.61	2599.8
Total	2028-Mar-07	2040-Feb-17	3605.2	17.59	4363.4 (11.9 year)





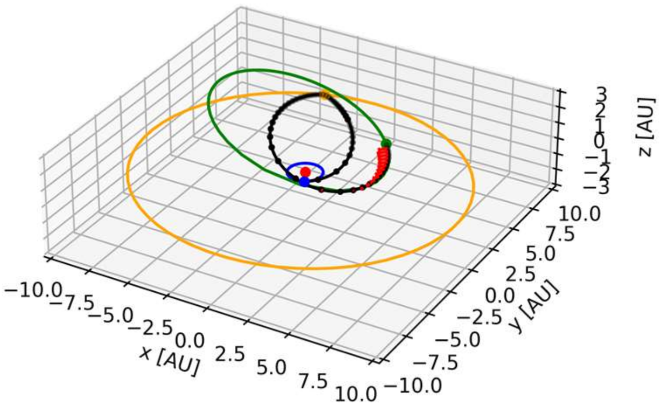


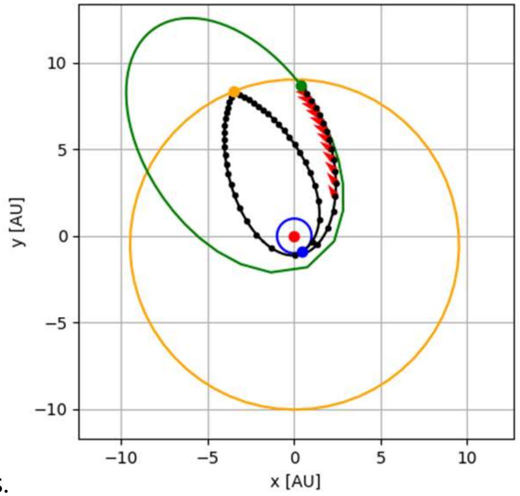
* The 2-year EDVEGA trajectory is omitted in the figures.

Centaurs can be accessed in a similar trajectory to Jupiter Trojans

Trajectory Design
Rendezvous trajectory to 2014 QW243 (Centaur via Saturn)

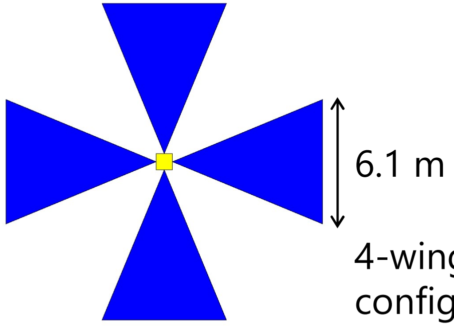
Phase	Start	End	IES ΔV, m/s	Propellant, kg	ToF, day
2-year EDVEGA	2028-Oct-10	2030-Aug-10	1126.15	5.82	668.7
Earth – Saturn	2030-Aug-10	2034-Jun-06	0	0	1395.2
Saturn – Asteroid	2034-Jun-06	2042-Aug-18	2854.85	13.87	2995.6
Total	2028-Oct-10	2042-Aug-18	3981.00	19.69	5059.5 (13.9 year)





* The 2-year EDVEGA trajectory is omitted in the figures.

Note: Solar array membranes of 90 m^2 are needed to operate ion engines near the Saturn orbit.



4-wing configuration

The Centaur in a long-elliptic orbit can be accessed via Saturn.

Summary

- A rendezvous mission to outer solar system bodies, namely the Jupiter Trojans and Centaurs, using a 100-kg-class small solar power sail was proposed.
  - The 150 kg small spacecraft can generate 350 W solar power at the 6 au sun distance.
  - Despite the low capacity of the launch vehicle for small spacecraft, rendezvous with the outer solar system bodies is possible because of propellant-efficient ion engines.
- The preliminary design of the spacecraft system was presented.
  - The spacecraft deploys two solar array membranes with the total area of 40 m^2.
  - The modified model of the μ10 ion engines, which were used in the Hayabusa2 mission, are used.
- Trajectories to both the Jupiter Trojans and Centaurs were designed using a global optimization method.
  - In the case of OKEANOS, the long mission duration over 13 years was considered problem.
  - This study successfully obtained better trajectories with the ToF of 11~12 years and ΔV of about 3500 m/s.