Interstellar Interceptors

Mission design for rendezvous with objects in hyperbolic orbits

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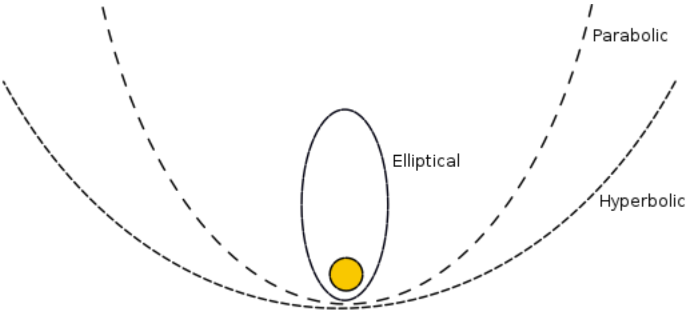
What are interstellar objects?

Definition

Interstellar objects (ISOs) are asteroids, comets or planetary bodies moving through interstellar medium (ISM) without being gravitationally bound to a star.



ISOs follow hyperbolic orbits

Why are interstellar objects important?

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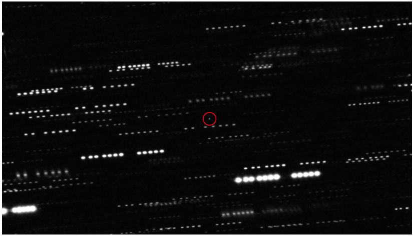
Motivation of this work

Design orbits for rendezvous with ISOs to study their physical properties.

Discovered interstellar objects

There are two confirmed ISOs to this day:



1I/'Oumuamua

ESO's VLT and GST Telescopes

2I/Borisov

NASA Hubble Space Telescope

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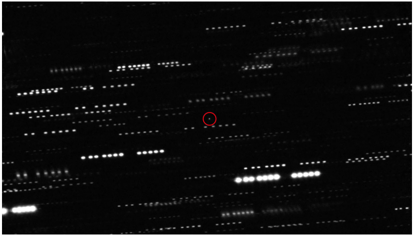

1I/'Oumuamua

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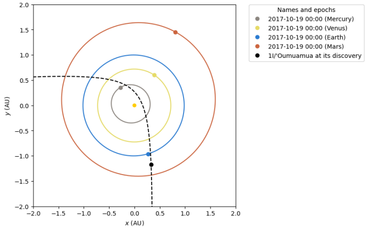
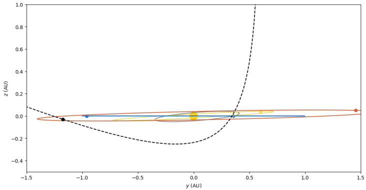
These interlopers present the following orbit attributes:

- Hyperbolic orbits
- High relative velocity w.r.t. the Sun
- Random inclination
- Discovered close to the direction of the Solar Apex

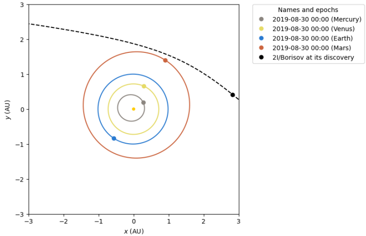
Orbits of 1I/'Oumuamua and 2I/Borisov



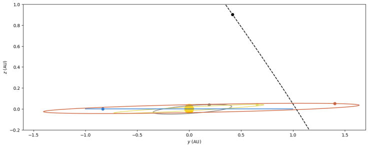
1I/'Oumuamua orbit top view



1I/'Oumuamua orbit side view



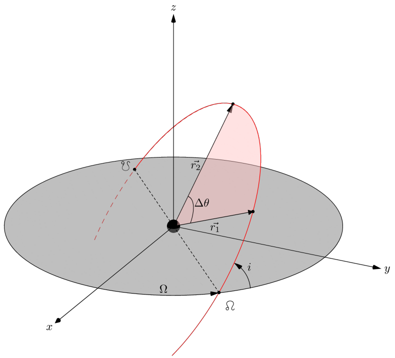
2I/Borisov orbit top view



2I/Borisov orbit side view

Navigating through space: the Lambert's problem

Lambert's problem is the Boundary Value Problem (BVP) in the context of the restricted two-body problem dynamics.



Geometry of the Lambert's problem

$$\ddot{\vec{r}} = -\frac{\mu}{r^3}\vec{r} \qquad \begin{cases} \vec{r}\,(t_1) = \vec{r_1} \\ \vec{r}\,(t_2) = \vec{r_2} \end{cases}$$

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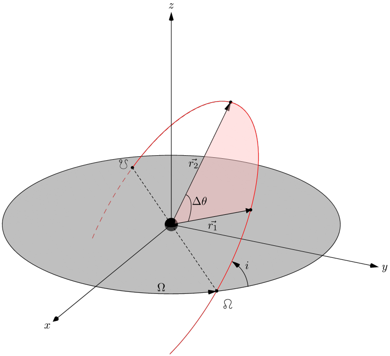

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Solve for the orbit which passes through $\vec{r_1}$ and $\vec{r_2}$ over a finite amount of time $\Delta t = t_2 - t_1$.

Estimating the cost of the maneuver using the C_3 energy

Lambert's problem computes the initial velocity $\vec{v_1}$ and final velocity $\vec{v_2}$ of the orbit.

- First impulse: $\Delta v_1 = \|v_1 - v_{\text{origin}}\|$
- Last impulse: $\Delta v_2 = \|v_2 - v_{\text{iso}}\|$

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The total cost of the maneuver is $\Delta v = \Delta v_1 + \Delta v_2$. This relates with the fuel mass via the Tsiolkovsky rocket equation:

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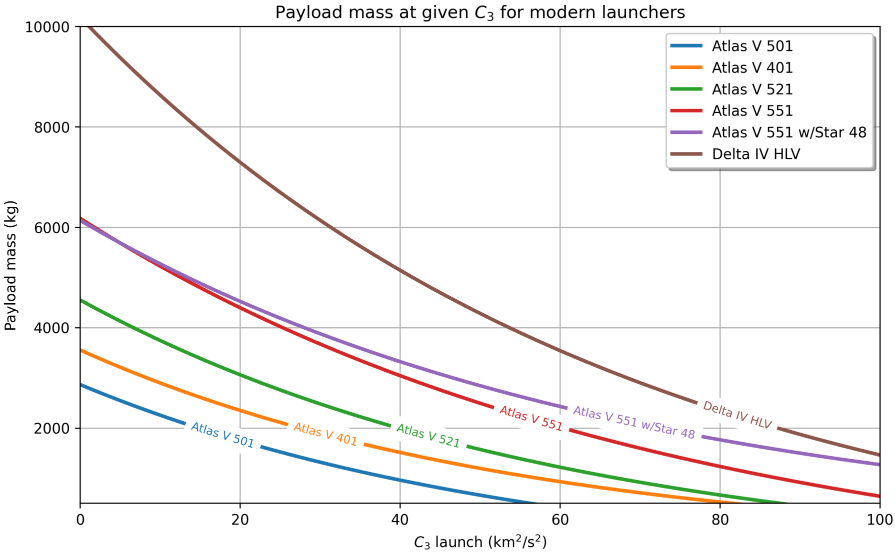
The characteristic energy for hyperbolic orbits C_3 is defined as:

$$C_3 = v_\infty^2$$

Modern launching technologies



Maximum payload mass vs. C_3 energy for different launchers

Minimizing the cost of the maneuver

Porkchop plots are used to find the optimal launch and arrival dates by solving Lambert's problem for a variety of trajectories.

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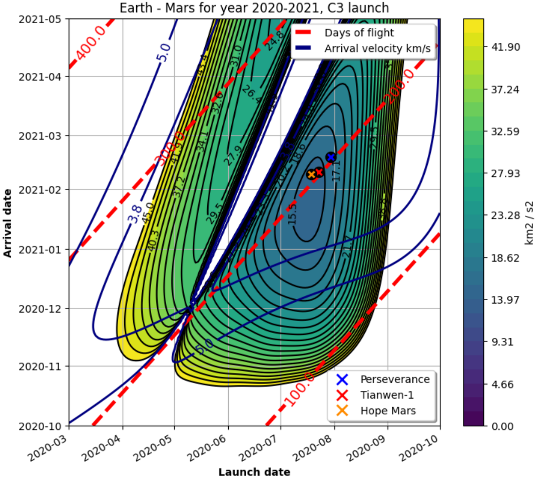

Porkchop plot between Earth and Mars

Analyzed scenarios

The analyzed scenarios in this work for each discovered ISO include:

- Direct transfer between the Earth and the ISO
- Direct transfer between the L2 point and the ISO

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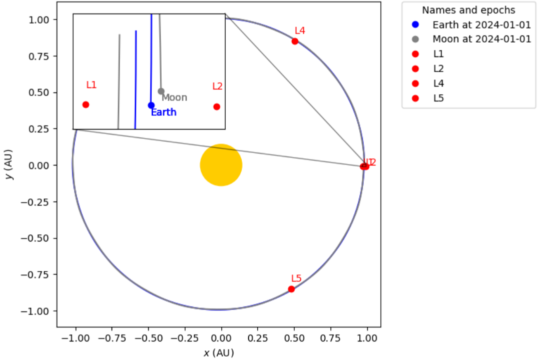
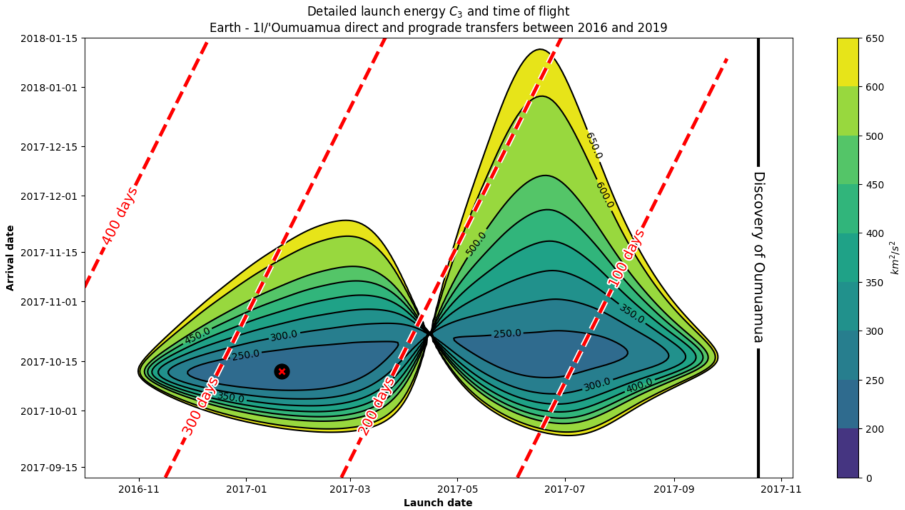


Lagrange points for the Sun Earth-Moon system

1I/'Oumuamua: direct prograde transfer from Earth



Direct transfer from Earth

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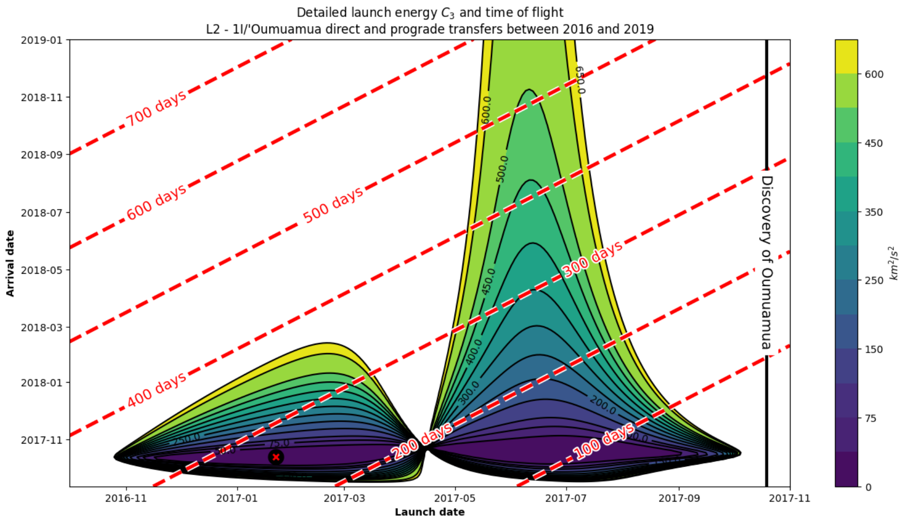


Direct transfer from L2

1I/'Oumuamua: summary of results

Δv launch Earth [km/s]	Δv launch L2 [km/s]	Reduction [%]
13.85	3.80	72.56

Launch energy comparison

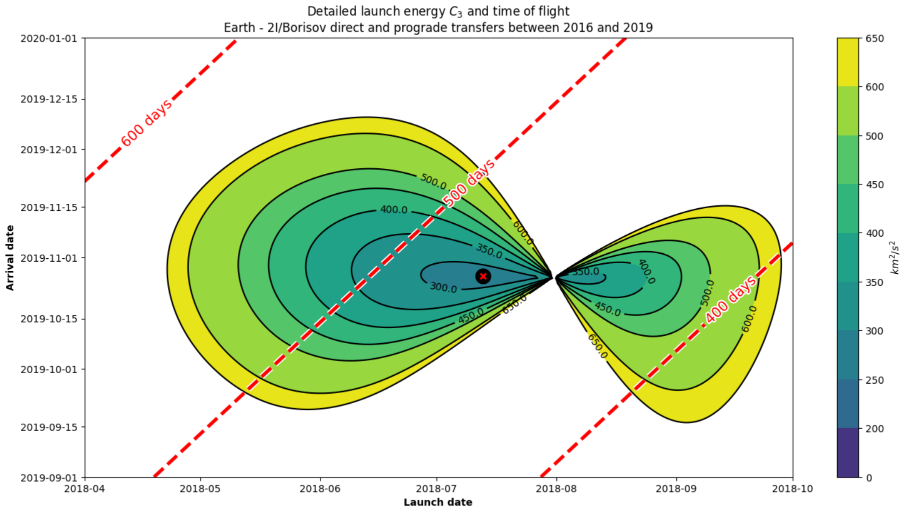
ΔV arrival Earth [km/s]	ΔV arrival L2 [km/s]	Reduction [%]
62.33	61.46	1.40

Arrival velocity comparison

C_3 launch Earth [km^2/s^2]	C_3 launch L2 [km^2/s^2]	Reduction [%]
192.00	14.41	92.51

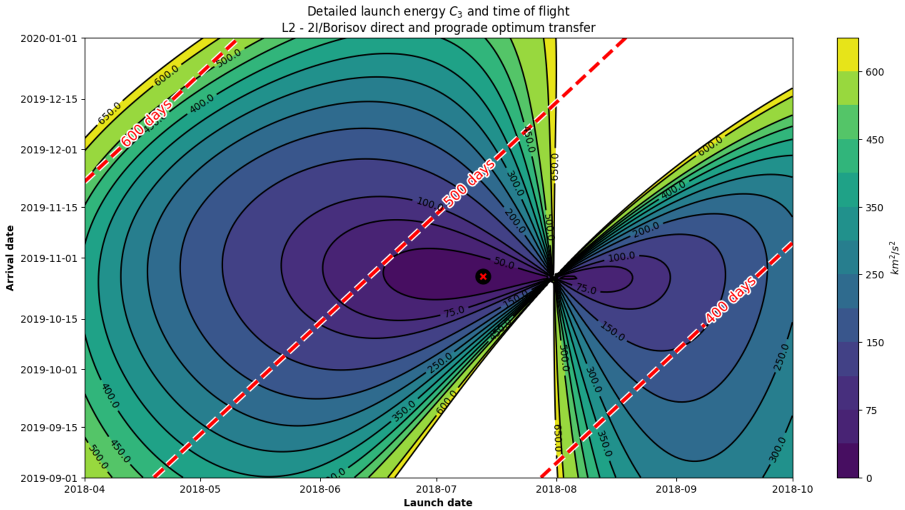
Characteristic energy comparison

2I/Borisov: direct prograde transfer from Earth



Direct transfer from Earth

2I/Borisov: direct prograde transfer from L2



Direct transfer from Earth

2I/Borisov: summary of results

Δv launch Earth [km/s]	Δv launch L2 [km/s]	Reduction [%]
16.90	5.85	65.38

Launch energy comparison

ΔV arrival Earth [km/s]	ΔV arrival L2 [km/s]	Reduction [%]
33.00	33.02	-0.06

Arrival velocity comparison

C_3 launch Earth [km^2/s^2]	C_3 launch L2 [km^2/s^2]	Reduction [%]
286.00	34.30	88.08

Characteristic energy comparison

Conclusions

L2 as the optimal launching point

Launching an intercepting spacecraft from L2 is more fuel efficient. These results agree with the ones presented by the Comet Interceptor mission.

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Need of increased vigilance in the search for ISOs

Both optimum transfer dates take place prior the discovery of 1I/'Oumuamua and 2I/Borisov. Surveillance of the sky is crucial to detect future ISOs.

Future work

Generating a synthetic population of ISOs

Synthetic orbits of ISOs can be generated by using Monte-Carlo simulations. This could allow to predict future ISO encounters.

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Drafting optimum transfers

Optimum transfers can be solved for previous synthetic data. Solutions would be used by future missions parked at L2.

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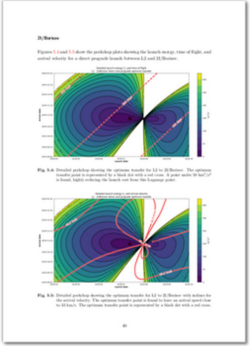
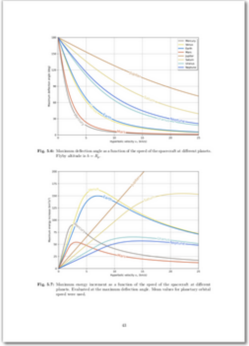
Trajectory optimization

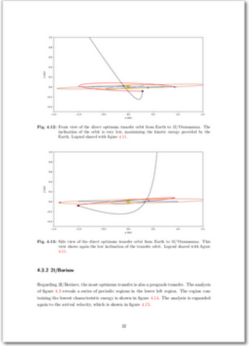
A combination of multiple gravity assists and deep space maneuvers may allow for a more efficient transfer to an ISO, depending on the scenario.

References

All this work is reproducible, including figures and results.







Document and figures generated via LaTeX and Python

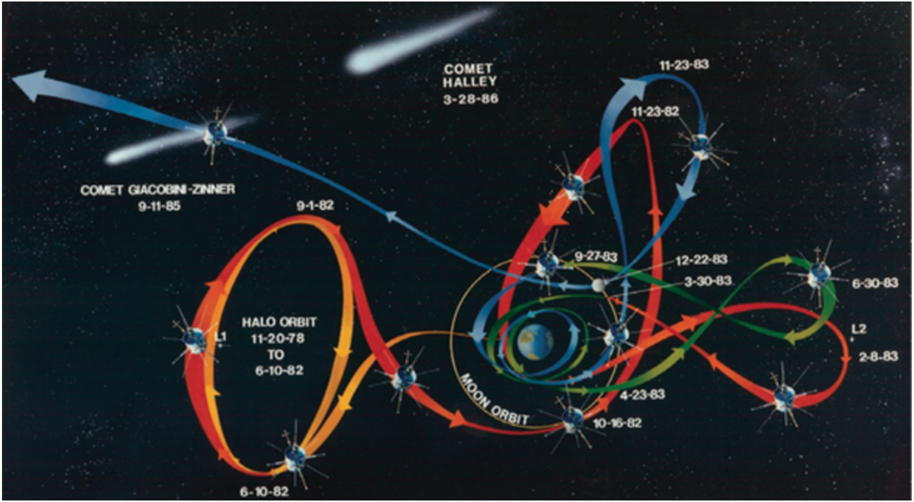
Official repository

All source code is hosted in **https://github.com/jorgepiloto/tfm**

Additional materials: 1I/'Oumuamua shape

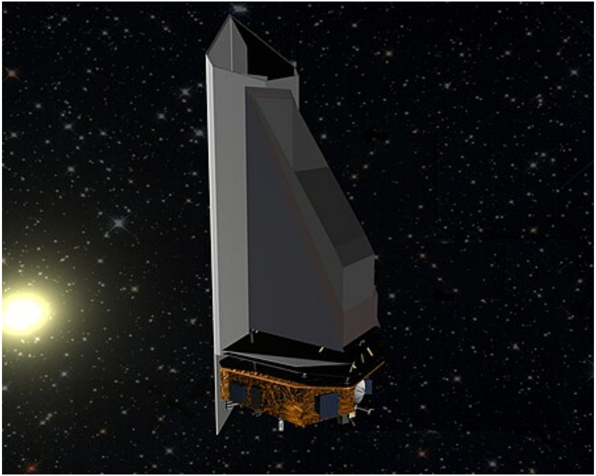
1I/'Oumuamua shape
Illustration by William Hartmann/Michael Belton/AP

Additional materials: ISEE-3 mission



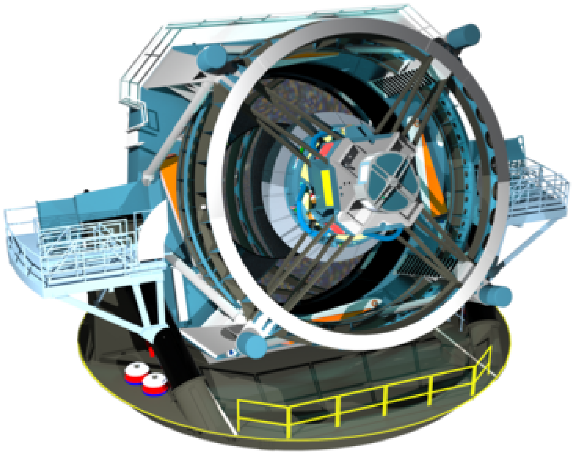
ISEE-3 mission
Illustration by NASA

Additional materials: NEO surveyor



NEO surveyor
Illustration by NASA

Additional materials: Large Synoptic Survey Telescope



LSST
Illustration by LSST Project Office