Trajectory Design for a Solar Sail Mercury Impactor

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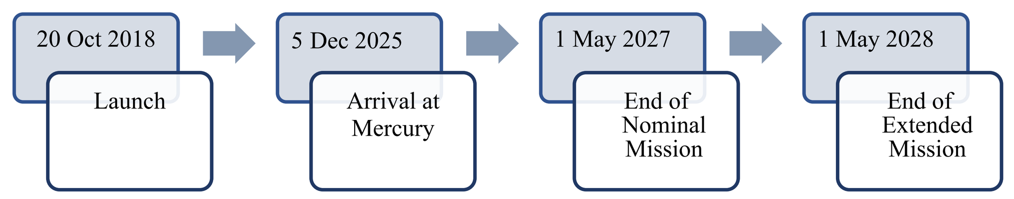
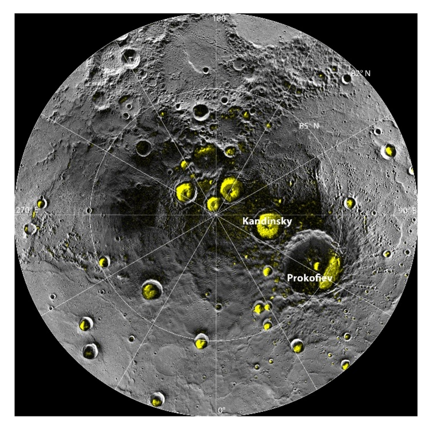
Our study analyzes the advantages of solar sailing for a Mercury impact mission. The mission goal is to create the largest and deepest crater possible in the polar regions of the planet, where there is evidence for the presence of ice [1,2]. A near-vertical impact in this region requires a high-inclination trajectory, which cannot be achieved with conventional chemical or electric propulsion systems due to the large ΔV required. The impact would produce an ejecta plume whose composition could be analyzed with the instruments onboard the BepiColombo spacecraft, a joint ESA/JAXA mission, if it could be achieved to reach Mercury while BepiColombo is still operational. Two mission design alternatives are analyzed for the interplanetary transfer to Mercury. In the first scenario, either the reusable or the expendable version of the Falcon Heavy launcher inserts the spacecraft on a ballistic trajectory that is aimed directly at the planet for impact. This scenario can be improved with an (almost) unpowered Venus flyby, which allows to reduce the escape energy for the Earth departure, thereby increasing the maximum launch (and thus impact) mass. Our analysis shows that such a mission is feasible, but its drawback is that a near-vertical impact can only be achieved at moderately low latitudes but not in the polar regions. In the second scenario, we investigate the feasibility of such a mission using a solar sail. Unfortunately, the solar-sail option is hardly feasible within the lifetime of BepiColombo, which has its Mercury insertion in December 2025 and its nominal end of mission in May 2027 with a probable 1-year extension. Given the still low technological maturity of high-performance solar sail hardware, we do not believe it is realistic to expect a suitable solar sail to be built and flown to Mercury in the short time available. However, the results of our study show that solar sails would significantly improve the performance of such a mission, i.e., create larger and deeper craters for the same impactor mass. Because solar sails are particularly effective close to the Sun, they allow the spacecraft's inclination to be changed very effectively at small heliocentric distances, achieving perpendicular or even retrograde impact trajectories with respect to the planet's orbital plane. Perpendicular impact trajectories allow near-vertical impacts at high latitudes, while retrograde impact trajectories allow near-vertical impacts at lower latitudes, but with impact velocities greater than 100 km/s. The low-thrust transfer of the solar sail is optimized using a combination of genetic algorithms and shooting methods. The results are validated against the results of InTrance ("Intelligent Trajectory optimization using neurocontroller evolution"), which uses evolutionary neurocontrol to find near-global time-optimal solar sail trajectories [3].

BepiColombo Timeline [4]

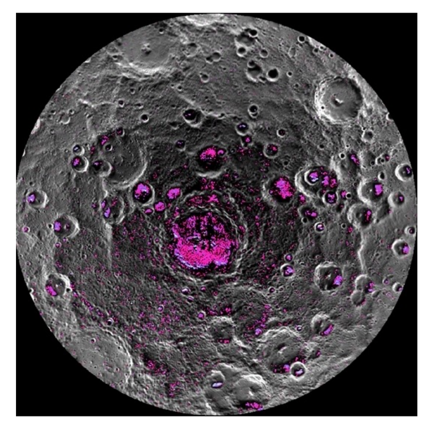


Ice Deposits

From 85° latitude North [1]

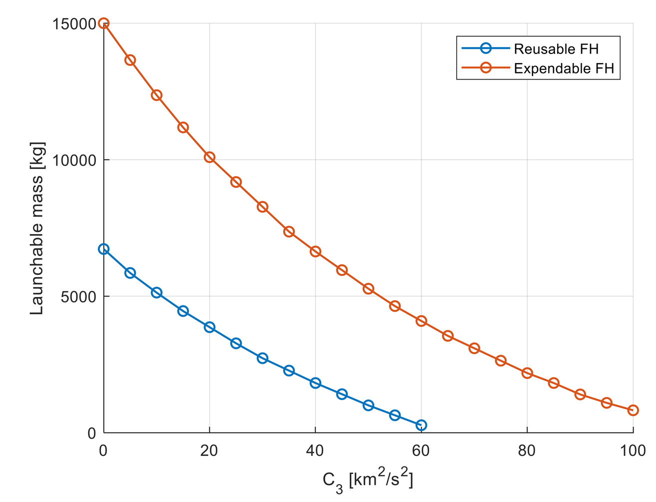


From 80° latitude South [2]

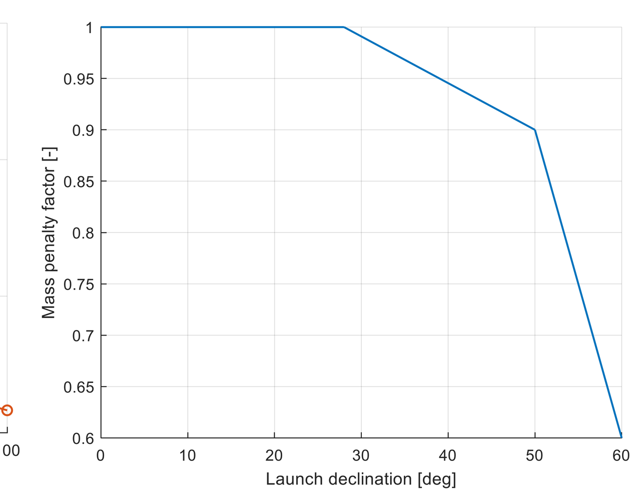


Launch

Falcon Heavy (FH) [5]

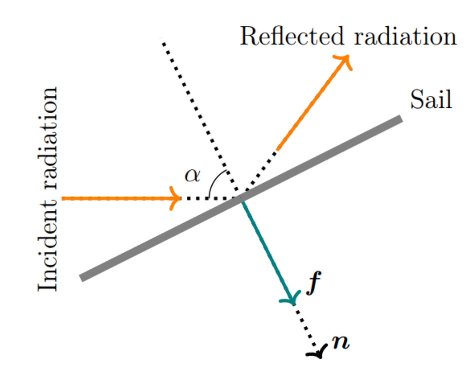


Cape Canaveral [6]

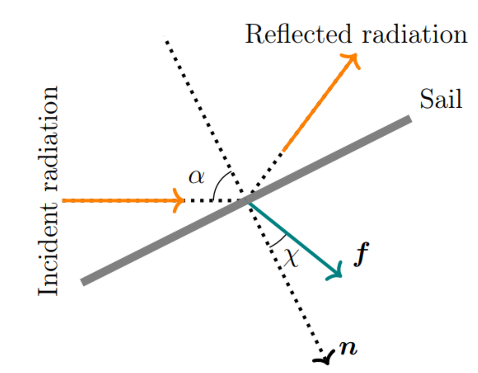


Sail Force Models

Ideal sail

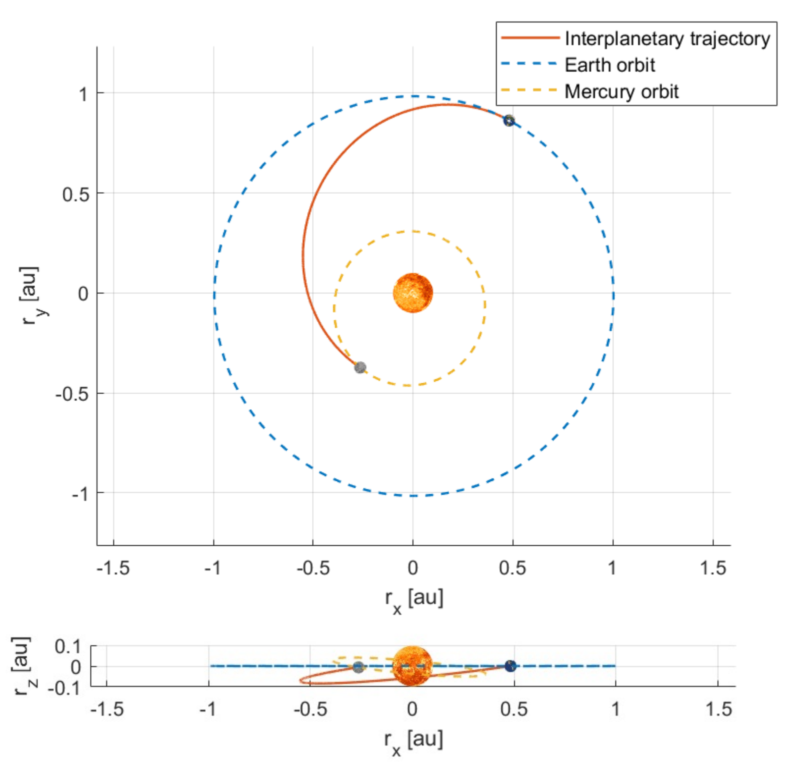


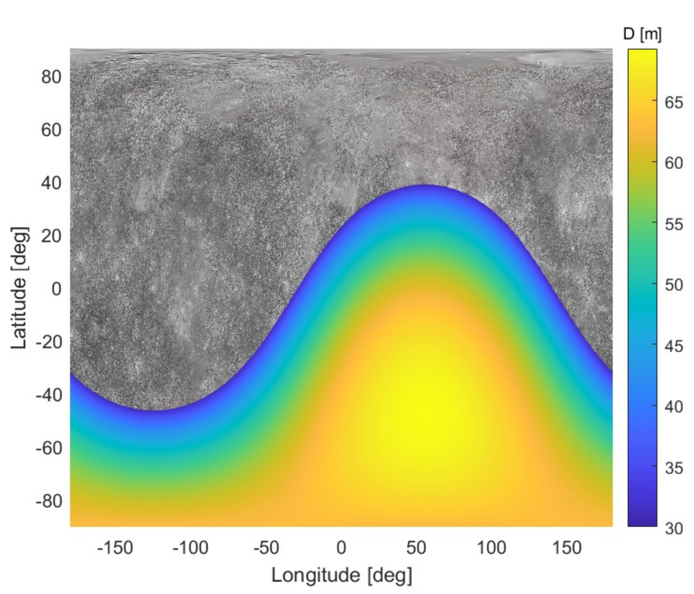
Optical model



Characteristic acceleration (a_c)	0.593 mm/s²
Launch escape energy (C_3)	0 km²/s²

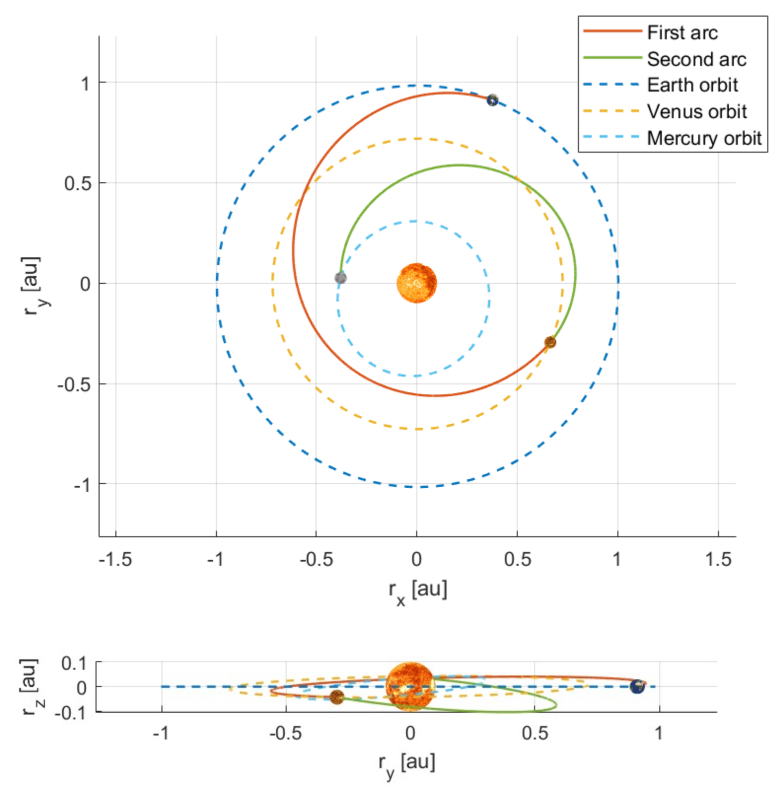
Ballistic Transfer

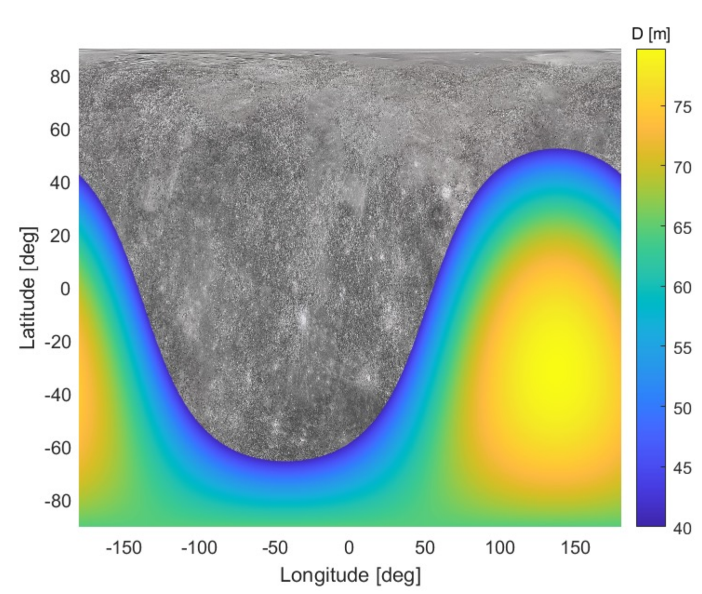




	Reusable FH	Expendable FH
Launch escape energy (C_3)	43.4 km²/s²	56.1 km²/s²
Impactor mass	1542.3 kg	5068.2 kg
Impact velocity	16.3 km/s	17.7 km/s
Time of flight	109.0 days	110.7 days
Polar crater diameter	44.5 m	65.5 m

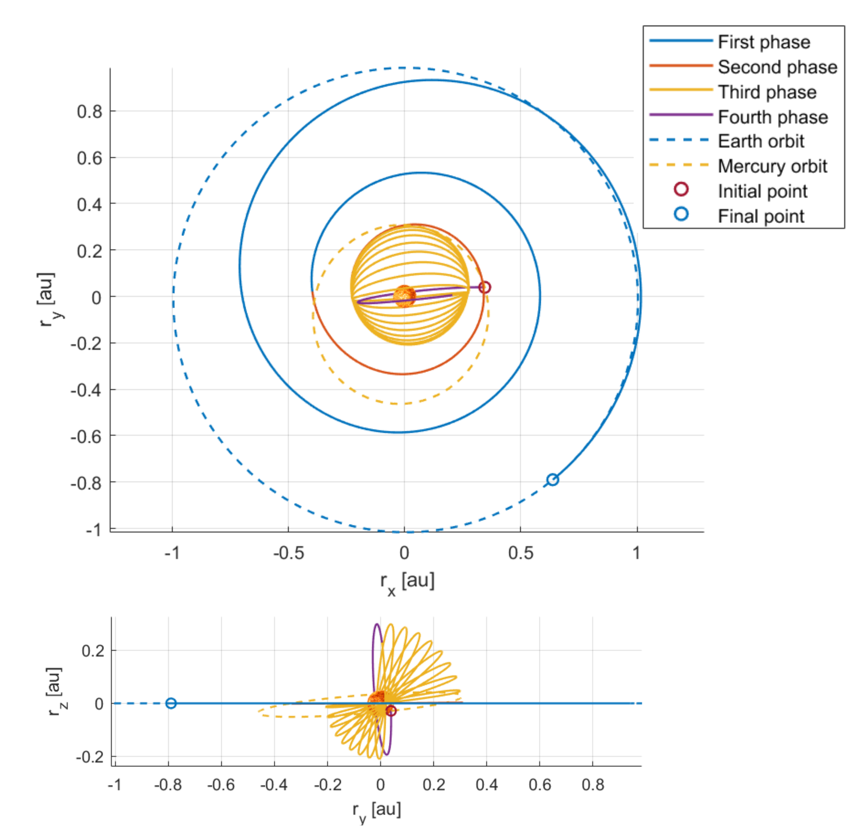
Venus Flyby

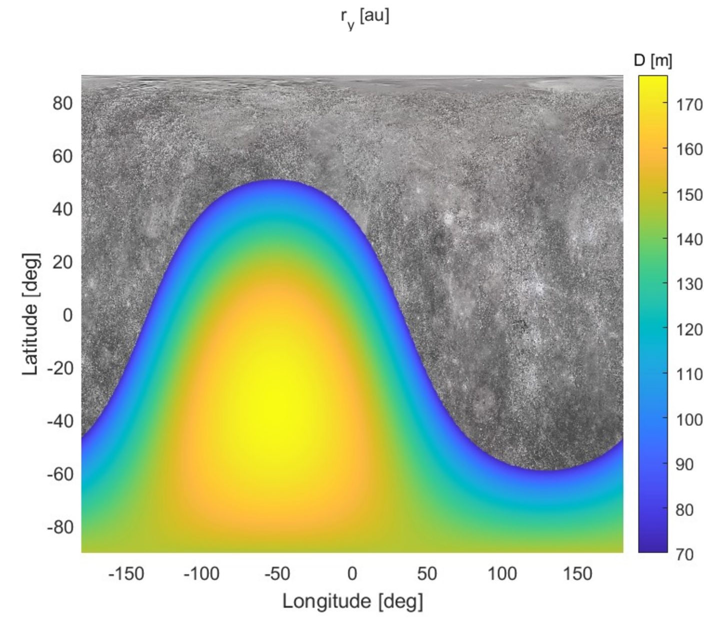




	Reusable FH	Expendable FH
Launch escape energy (C_3)	29.9 km²/s²	29.9 km²/s²
Impactor mass	2736.7 kg	8288.4 kg
Impact velocity	18.7 km/s	18.7 km/s
Time of flight	242.4 days	242.4 days
Polar crater diameter	52.8 m	70.5 m

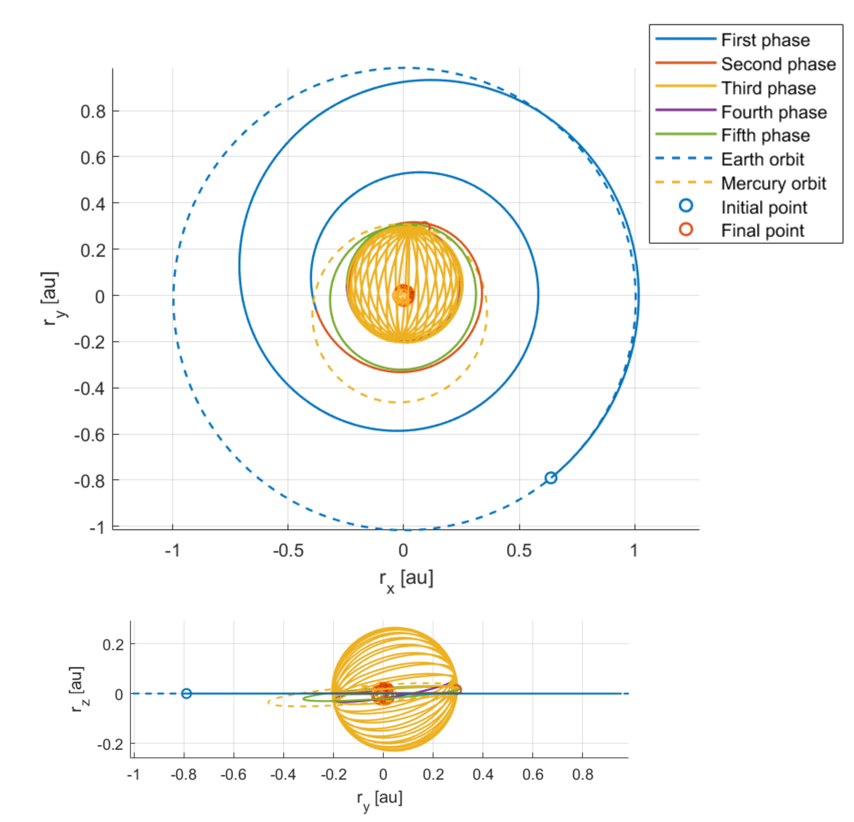
Ideal Sail Orbit-normal Impact

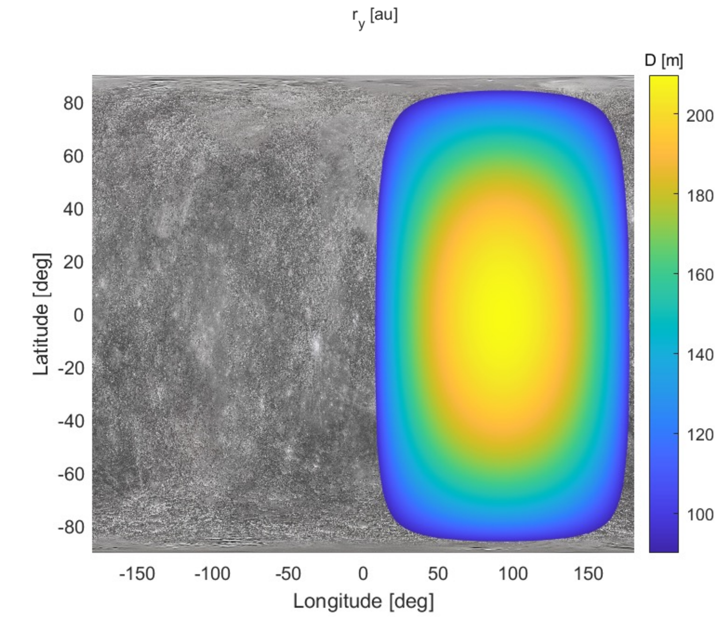




	Reusable FH	Expendable FH
Impactor mass	6727.3 kg	15000.0 kg
Impact velocity	77.7 km/s	77.7 km/s
Time of flight	2.48 yr	2.48 yr
Polar crater diameter	127.5 m	157.1 m

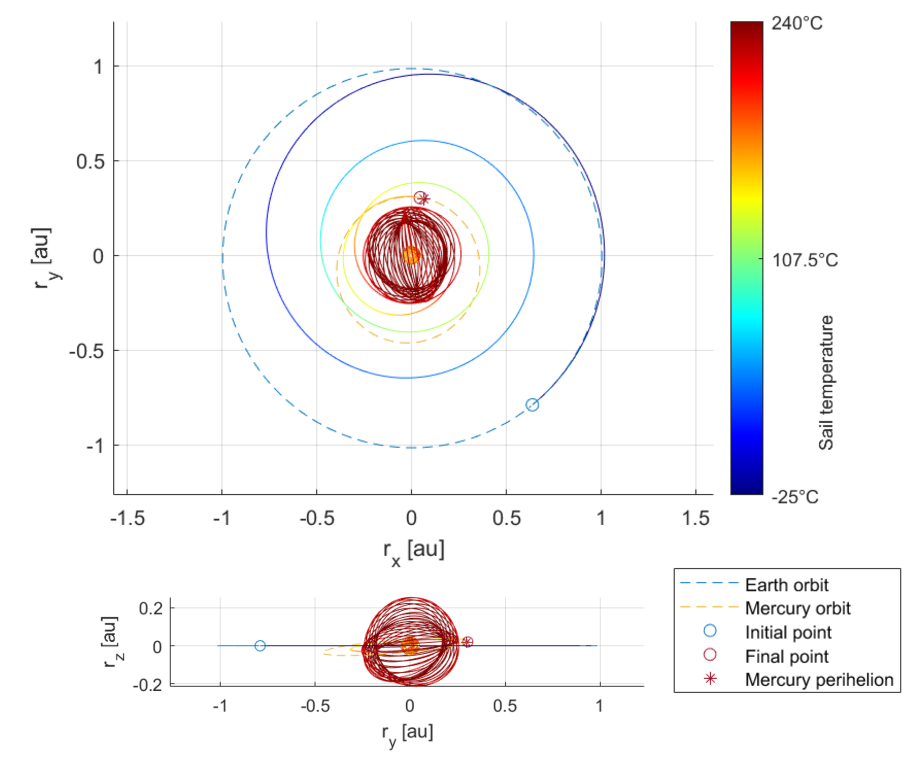
Ideal Sail Retrograde Impact





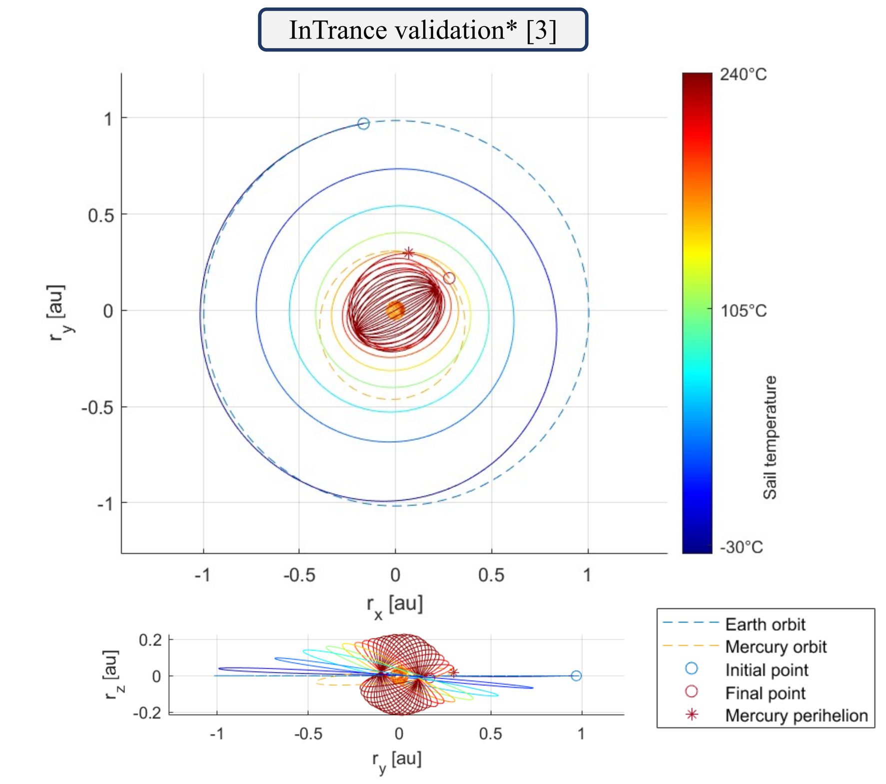
	Reusable FH	Expendable FH
Impactor mass	6727.3 kg	15000.0 kg
Impact velocity	115.5 km/s	115.5 km/s
Time of flight	3.72 yr	3.72 yr
Polar crater diameter	97.4 m	120.0 m

Non-ideal Sail Retrograde Impact



Impact velocity	115.2 km/s
Time of flight	4.45 yr

InTrance validation* [3]



Impact velocity	100.1 km/s
Time of flight	4.43 yr

* feasible but not fully optimized solution

[1] N. L. Chabot, C. M. Ernst, J. K. Harmon, et al, Craters hosting radar-bright deposits in Mercury's north polar region: Areas of persistent shadow determined from MESSENGER images, Journal of Geophysical Research: Planets, **118** (1) 26–36, 2013.
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[3] B. Dachwald, Optimization of interplanetary solar sailcraft trajectories using evolutionary neurocontrol, Journal of Guidance, Control, and Dynamics, **27** (1) 66–72, 2004.
[4] ESA. BepiColombo Journey Timeline, 2017. URL: https://sci.esa.int/web/bepicolombo/-/60082-bepicolombo-timeline.
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[6] E. J. Sturm, M.-J. Deutsch, C. Harmon, et al. Mission options scoping tool for Mars orbiters: mass cost calculator (MC2). In 58th International Astronautical Congress, Hyderabad, India, September 2007.