Global Trajectory Optimization for Solar-Sail Propelled Mercury Rendezvous and Impact Missions

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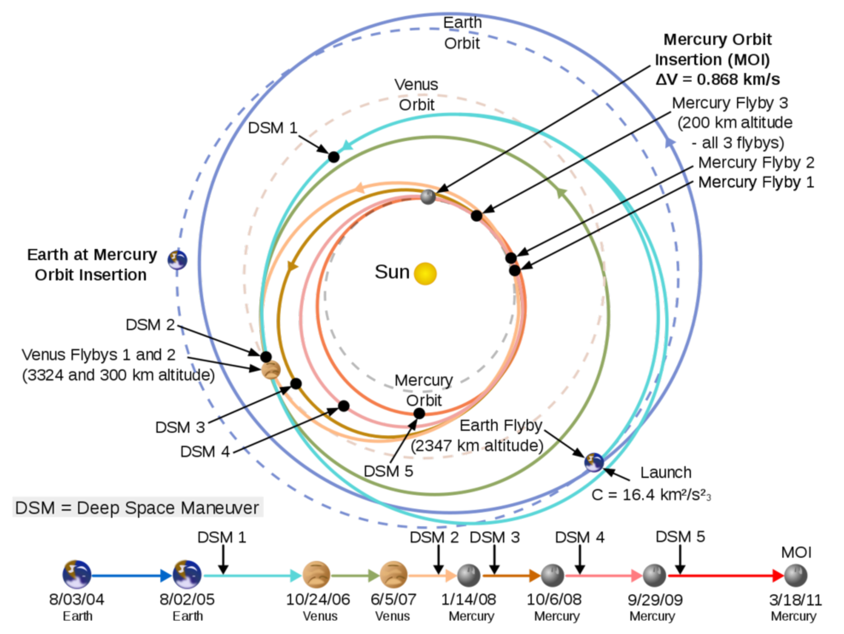
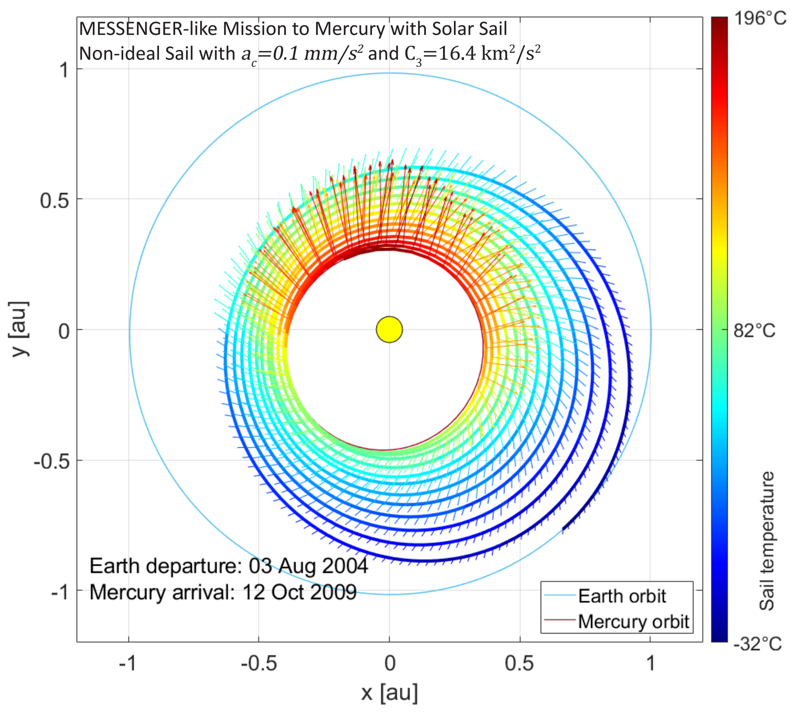
Abstract

The innermost planet in the solar system, with its enigmatic craters, and its hostile environment, defined by an atypical magnetic field, dynamic gravitational forces, and rapid thermal cycling, has long captivated the attention of planetary scientists. But the exploration of Mercury is particularly challenging. Because of its close proximity to the Sun, the high eccentricity and inclination of its orbit, and the resulting high delta-V-requirements, it requires complex and sophisticated trajectory designs with multiple flybys. Although we have previous successful missions such as MESSENGER and BepiColombo, these missions required intricate trajectory designs with multiple flybys to satisfy the demanding delta-V-requirements and resulting in longer flight times and high propellant consumptions. As a propellantless alternative propulsion system, driven only by the free and inexhaustible solar radiation pressure, a solar sail with a moderate performance can deliver similar or even larger payloads to Mercury than MESSENGER and BepiColombo, while also potentially achieving the same or even lower flight times. Another advantage that is gained by using solar sails is the provision of more flexible trajectories that do not rely on the exact timing of flybys and an always perfectly functioning propulsion system. Therefore, solar sails prevail to be a better and more cost-effective means for the exploration of the inner solar system. This study highlights their potential to provide a better performance for Mercury missions compared to conventional propulsion systems, such as the chemical system used by MESSENGER and the electric ion thrusters used by BepiColombo. However, designing an optimal solar-sail trajectory for a minimum flight time is a complex optimization problem due to the continuous and relatively low thrust of the spacecraft. Traditional direct and indirect optimization methods require a fairly good initial guess for the solution, leading to a high computational effort to obtain good solutions. To overcome this problem, we have optimized the trajectories using a smart, nature-inspired trajectory optimization method to determine the optimal spacecraft steering angles, evolutionary neurocontrol. This approach combines an evolutionary algorithm and an artificial neural network, allowing for a more extensive search within the vast search space, which typically leads to not only good but near-global optimal solutions. In this study, trajectories are proposed for two types of Mercury mission scenarios, rendezvous missions and Mercury impactor mission. In the rendezvous mission scenario, the sailcraft is steered from Earth to Mercury with the lowest characteristic acceleration to achieve the same flight time as MESSENGER / BepiColombo. In the Mercury impactor scenario, we analyze the required performance of a solar sail for this type of mission as a function of impact velocity and flight time. This analysis allows for a better understanding of the benefits and limitations of using a solar-sail propulsion for future Mercury missions

MESSENGER-like Rendezvous Mission



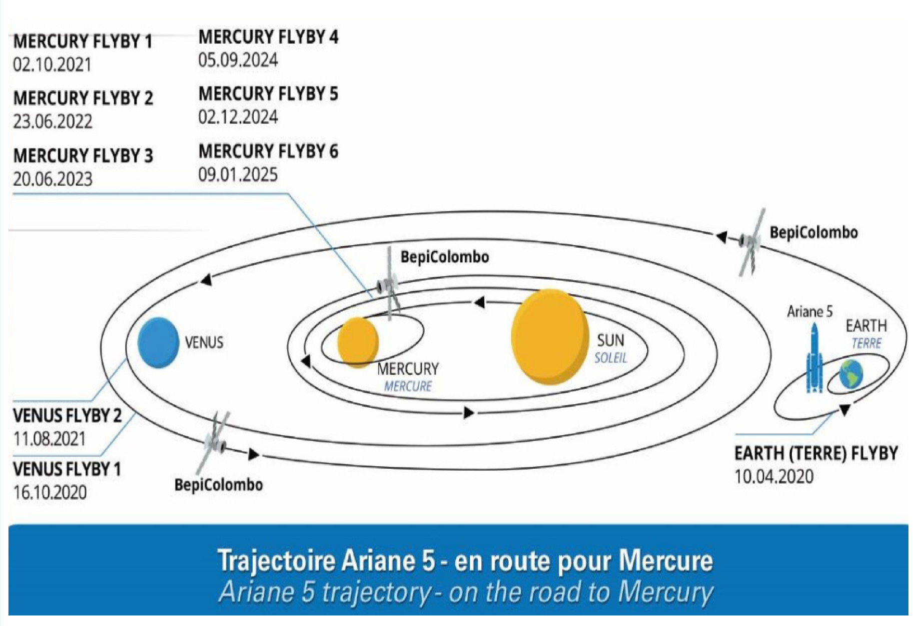


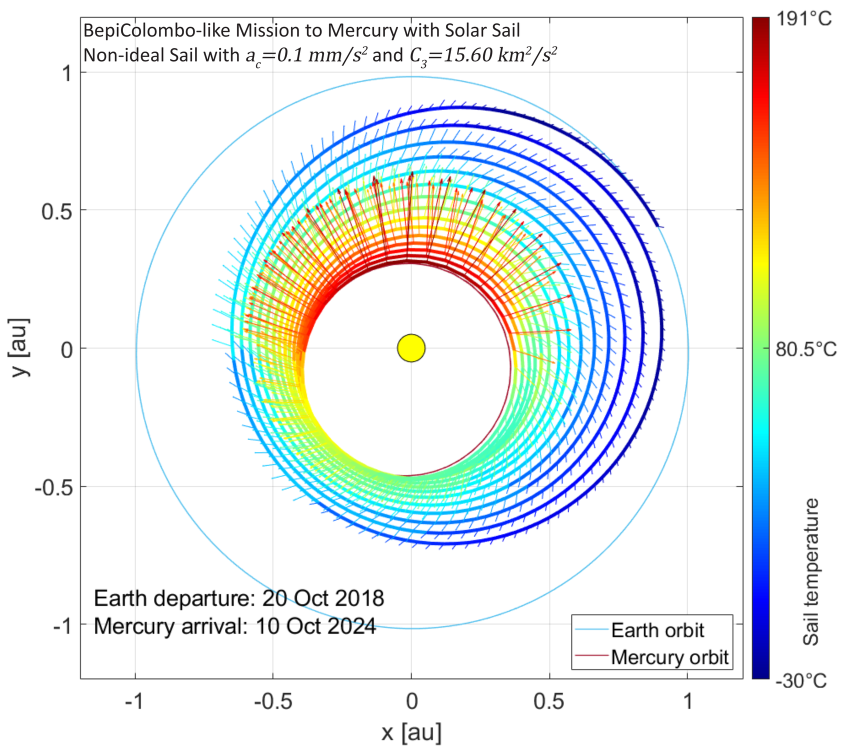
Launch mass	: *1 107.9 kg*
Dry mass	: *482.5 kg*
Duration	: *6.6 years*
Propulsion	: Liquid chemical propulsion system (hydrazine fuel & nitrogen tetroxide oxidizer)
I_{SP}	: *317 s*

Solar sail performance:

Flight time	: *1896 d (5.19 yrs)*
Final distance to Mercury	: *92 354.03 km*
Final velocity w.r.t. Mercury	: *92.10 m/s*

BepiColombo-like Rendezvous Mission



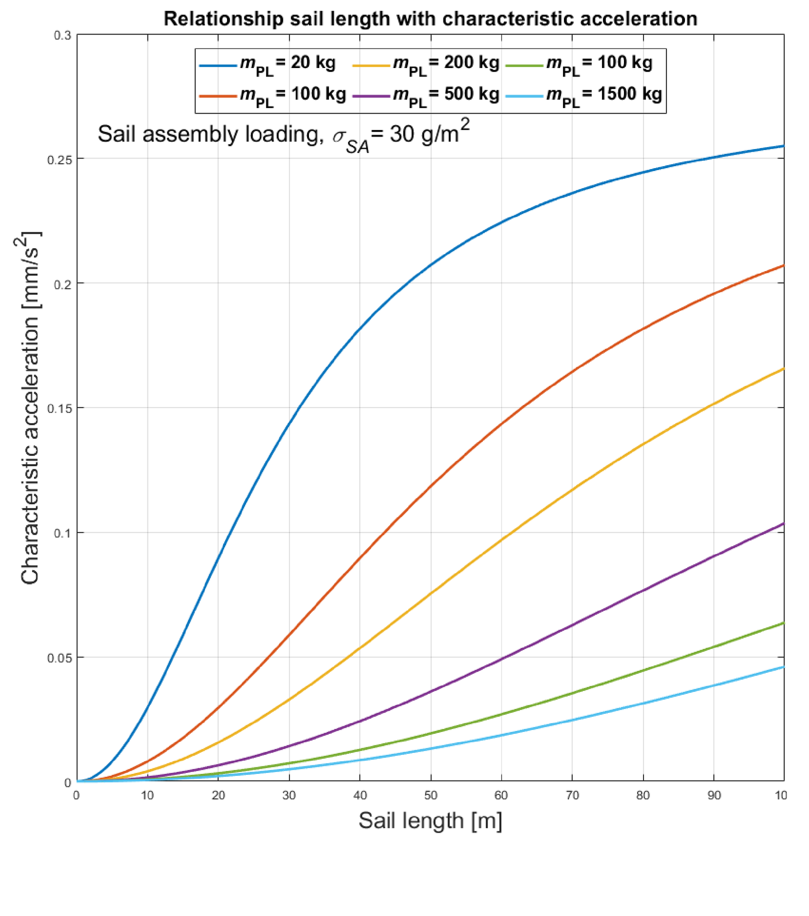


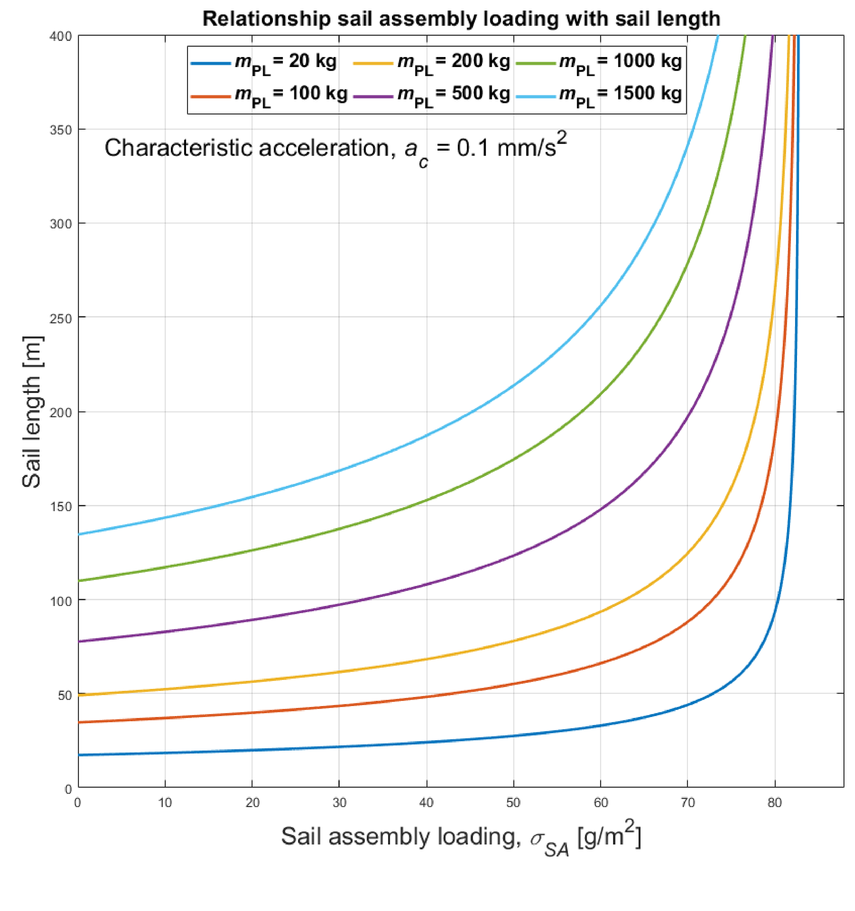
Launch mass	: *4 100 kg*
Dry mass	: *2 700 kg*
Duration	: *7.1 years*
Propulsion	: Solar electric propulsion system
I_{SP}	: *4 300 s*

Solar sail performance

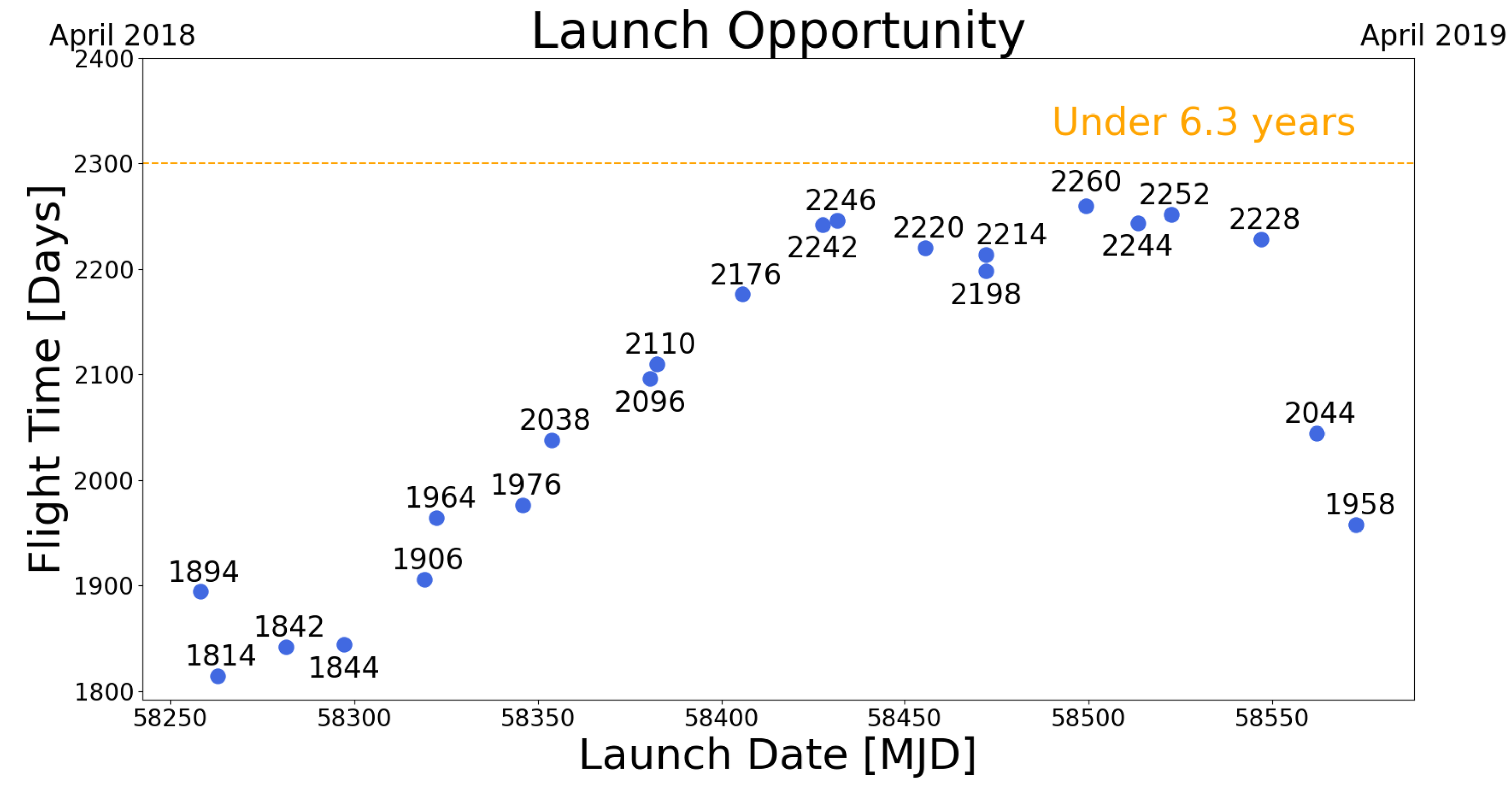
Flight time	: *2182 d (5.97 years)*
Final distance to Mercury	: *137 423.81km*
Final velocity w.r.t. Mercury	: *37.49 m/s*

Sail Size Relationship

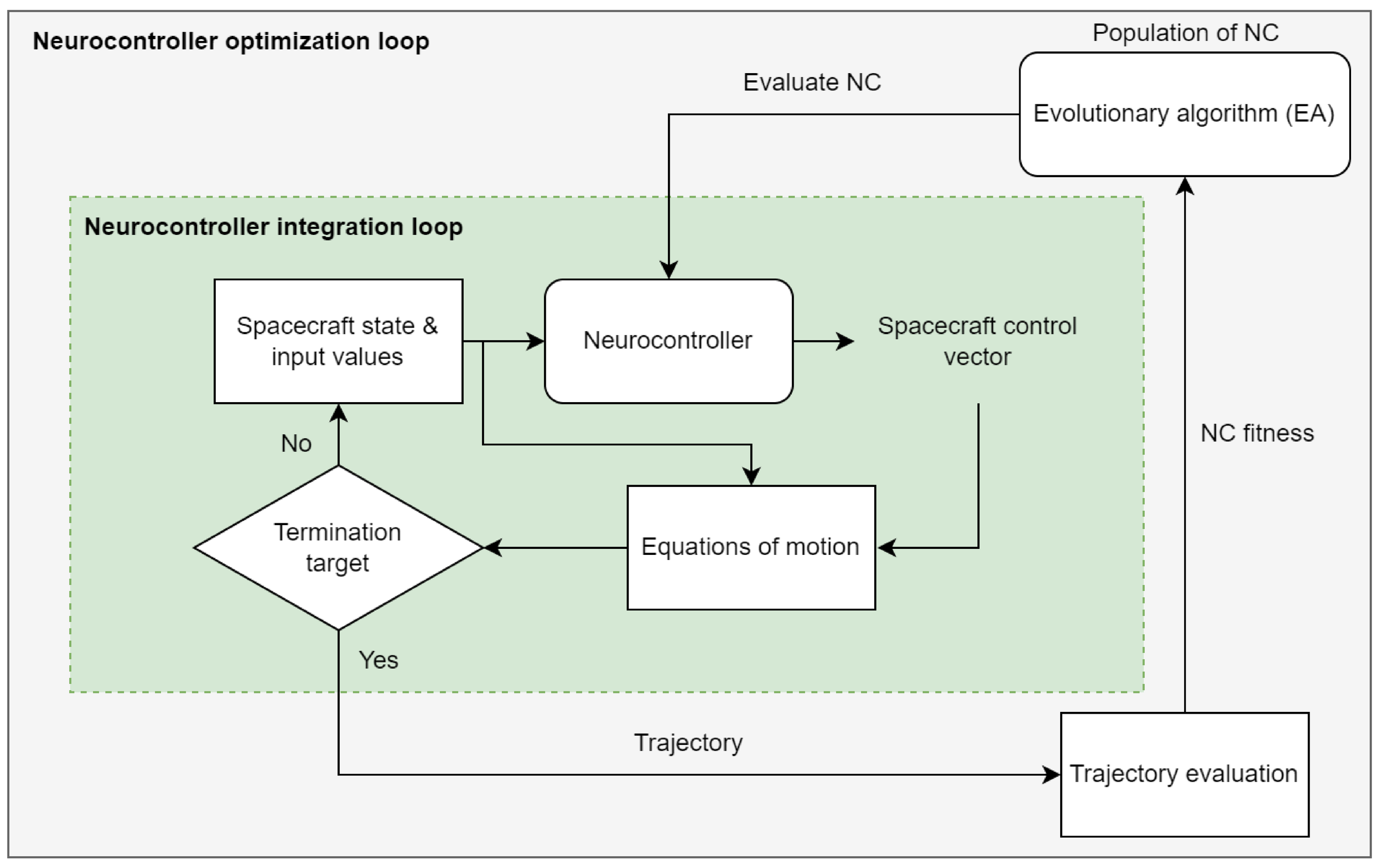




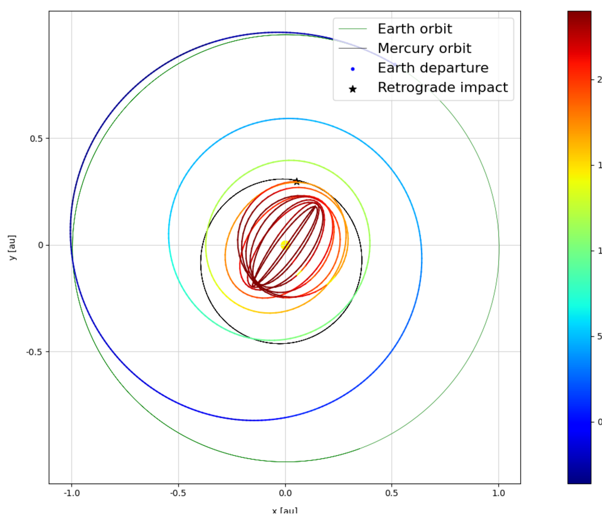
Solar Sail Flexible Launch Window

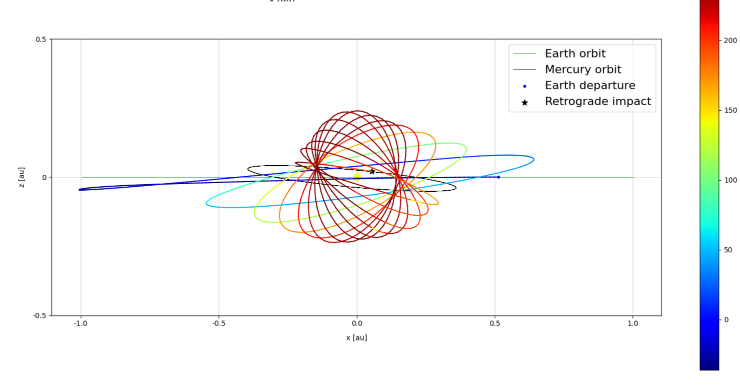


Evolutionary Neurocontroller Loop



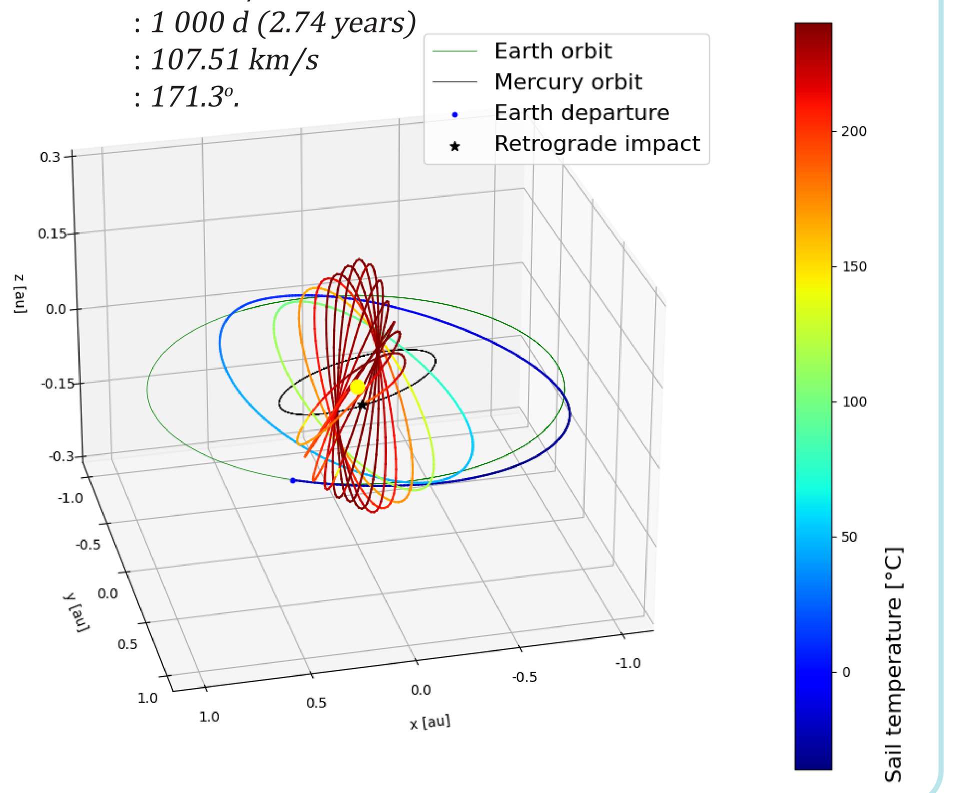
Mercury High Velocity Impact Mission





Solar sail impactor performance

Target body	: Mercury
Characteristic acceleration	: *1.0 mm/s²*
Flight time	: *1 000 d (2.74 years)*
Impact Velocity	: *107.51 km/s*
Inclination	: *171.3°.*



Summary

Our study proposes the use of solar sails as an alternative propulsion system for missions to Mercury, highlighting their advantages over existing multi-gravity-assist missions with chemical and electric propulsion systems, namely MESSENGER and BepiColombo. Using the "real solar radiation pressure force model", the analysis of our near-globally optimized trajectories shows that a solar sailcraft with a modest performance (characteristic acceleration of *1.0 mm/s²*) can reach Mercury under 6 years. With the same C_3 as MESSENGER (*16.4 km²/s²*) and BepiColombo (*15.6 km²/s²*), the solar sail outperforms both missions, which take *6.6 years* and *7.1 years* respectively. Our trajectories are calculated using an evolutionary neurocontroller program as a smart solver to optimize the complex trajectory of a solar sail. This solver is not only capable of generating a near-global optimal results for interplanetary rendezvous missions but is also capable of generating scientifically interesting high-velocity impact missions. We have demonstrated the capability of a solar sail to crank its orbit to achieve a retrograde orbit relative to Mercury, generating a very high momentum to impact the planet and produce an impact plume that can be studied by an orbiter. In this demonstration, the solar sail achieves an impressive impact velocity of *107.51 km/s* in just *2.74 years* of flight time. These results highlight the significant advantages of solar sails for missions to Mercury such as shorter transfer times and flexible mission scenarios that does not depend on gravity assists. Our team is committed in promoting solar sail technology as a modern alternative in space exploration and we will continue to work on the analysis of novel solar sail missions.

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