EGU25-18662

Search for Low Altitude Polar Orbits for Future Enceladus Missions

Taruna Parihar[1,2], Hauke Hussmann[2], Alexander Stark[2], Kai Wickhusen[2], Jürgen Oberst[1], Roman Galas[1]

1. Technical University Berlin (TUB), Insitute of Geodesy and Geoinformation Science, Berlin, Germany
2. German Aerospace Centre (DLR), Institute of Planetary Research, Berlin, Germany

Abstract

Enceladus is one of the few objects in our Solar System that probably harbors a habitable environment. This makes it a highly interesting target for planetary exploration and the European Space Agency (ESA) has decided to send its large mission (L4) to Enceladus. With the active regions located at the South pole of the moon a polar orbit is most desirable for revealing the mechanism that powers the jets and to perform a chemical analysis of the material ejected from the deep interior of Enceladus. We carried out a comprehensive numerical integrations of spacecraft orbits, with the aim to find suitable candidate orbits for a future mission to Enceladus. All the relevant perturbations caused by mainly Saturn, as well as the Sun, Jupiter, and the other moons of the Saturn system, and also solar radiation pressure, are taken into account. We have considered the higher degree and order Stokes coefficients of Enceladus' and Saturn's gravity fields provided in Park et al. 2024. Furthermore, we performed a grid search to identify suitable orbits in inertial space by varying orbital parameters such as semi-major axis (340 to 420 km), inclination (40° to 120°) and longitude of ascending node. Moderately inclined orbits (inclination between 45° and 60°) covering the equatorial and mid-latitude regions of Enceladus were found to be stable from several months up to years. In contrast, the more useful polar mapping orbits were found to be extremely unstable due to the so-called "Kozai mechanism", which causes the spacecraft to impact the moon's surface within a few days. However, an example of a highly inclined orbit was found with inclination of approximately 76°, which had an orbital life time of 13 days. A longer mission duration in this orbit would require correction maneuvers every few days. This would provide coverage of the tiger stripes region and allow for a near-global characterization of the surface.

Methodology

To calculate the spacecraft trajectories around Enceladus and taking into account the relevant forces that are acting on the spacecraft, we have used a numerical integrator which solves the general equation of motion of the spacecraft as seen below:

$$\ddot{\vec{r}} = \underbrace{-\frac{GM}{r^3}\vec{r}}_{Enceladus\ GM} + \underbrace{\ddot{\vec{r}}_{HT}(\vec{r},t)}_{Higher\ Terms} + \underbrace{\sum_{SB}\ddot{\vec{r}}_{SB}(\vec{r},t)}_{Secondary\ Bodies} + \underbrace{\ddot{\vec{r}}_{SRP}(\vec{r},t)}_{Solar\ Radiation\ Pressure}$$

where $\vec{r}$, $\dot{\vec{r}}$ and $\ddot{\vec{r}}$ are the spacecraft's position, velocity and acceleration, respectively. The leading gravity term is given by the Enceladus' GM value representing its point-mass. The second term includes the higher-order terms which take into account deviations from the spherical gravity field of the Enceladus. The third term represents the perturbations by the other solar system bodies like the Sun, Jupiter, Saturn and its other moons. The last term considers the solar radiation pressure.

Perturbations Analysis

Fig.1. depicts all the relevant perturbations, caused by the Sun, Jupiter, Saturn and its other moons, the higher degrees and order of Enceladus' and Saturn's gravity field and solar radiation pressure, which are taken into consideration. Drag experienced due to the plumes is considered negligible (Benedikter et al., 2022).

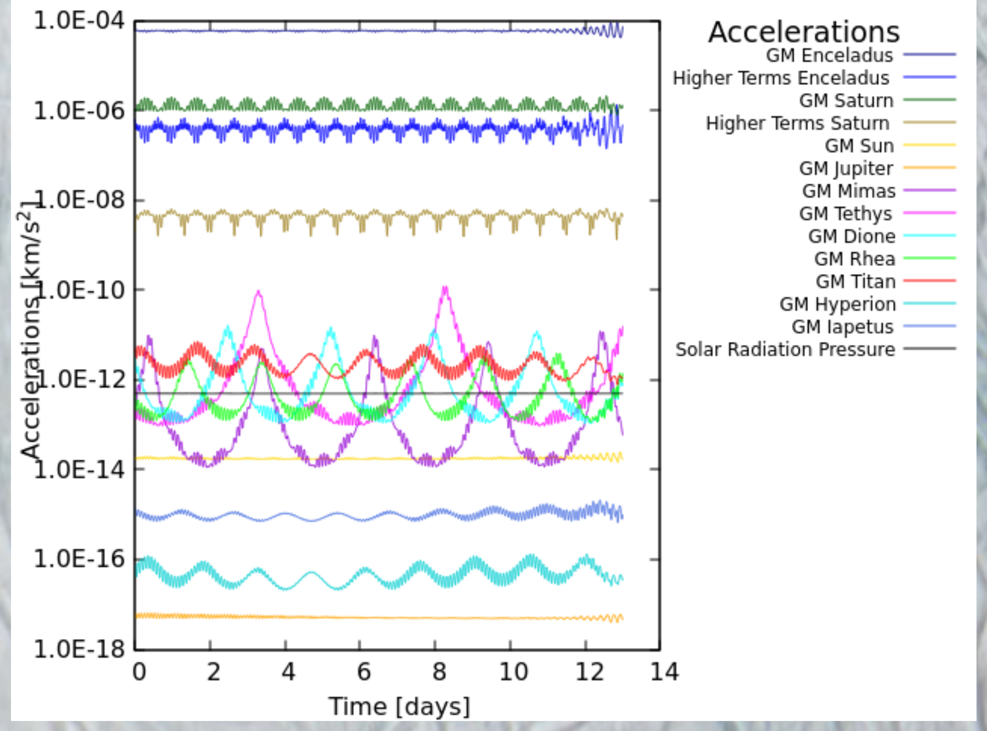

Fig.1. All the relevant accelerations experienced by the spacecraft in orbit around Enceladus at an altitude of 100 km from the surface.

Orbit Stability Maps

We searched for suitable orbits in inertial space by varying orbital parameters such as Semi-Major Axis (340 to 420 km) and Inclination (74° to 80°) in Fig.2., and Argument of Periapsis 0° to 360°) and Longitude of Ascending Node (320° to 360°) in Fig.3. The Orbit Life Time denotes the total time till the spacecraft impacts the surface. The orbit stability maps show that the orbit is very sensitive to these orbital parameters. There is a very small region, seen as green-yellow curves in Fig.2. and Fig.3., around Enceladus where the polar orbits have a life time of approximately 10-12 days.

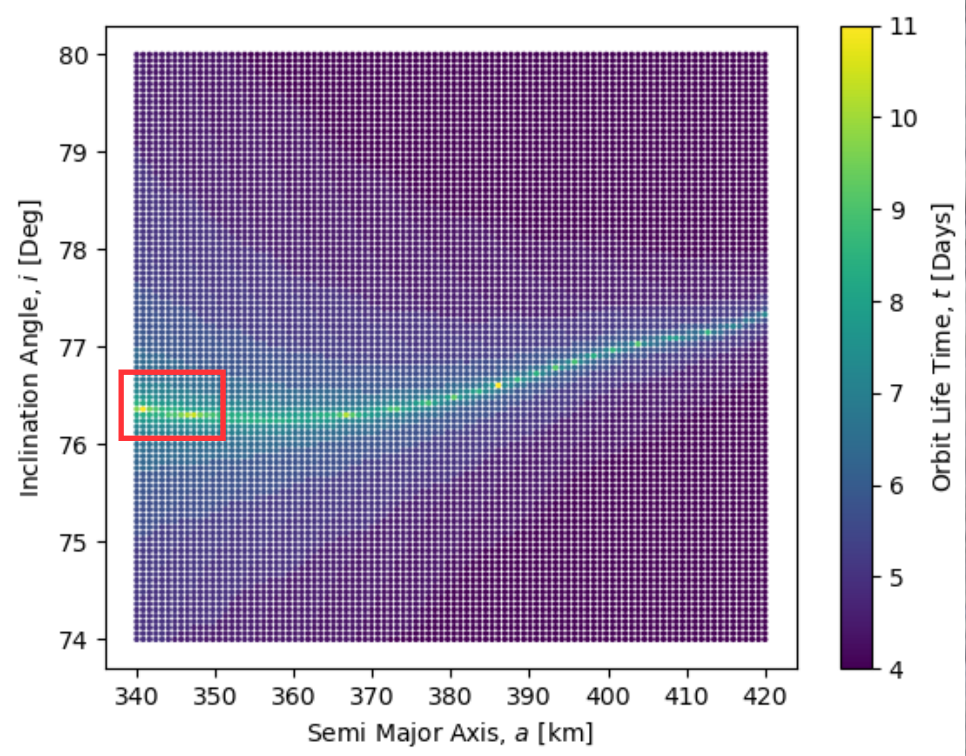

Fig.2. Orbit Life Time Map: The colour map shows the total life time of various orbits when Semi-Major Axis (340-420 km) and Inclination (74°-80°) are varied with respect to each other. The grid size of the map is 100 x 100.

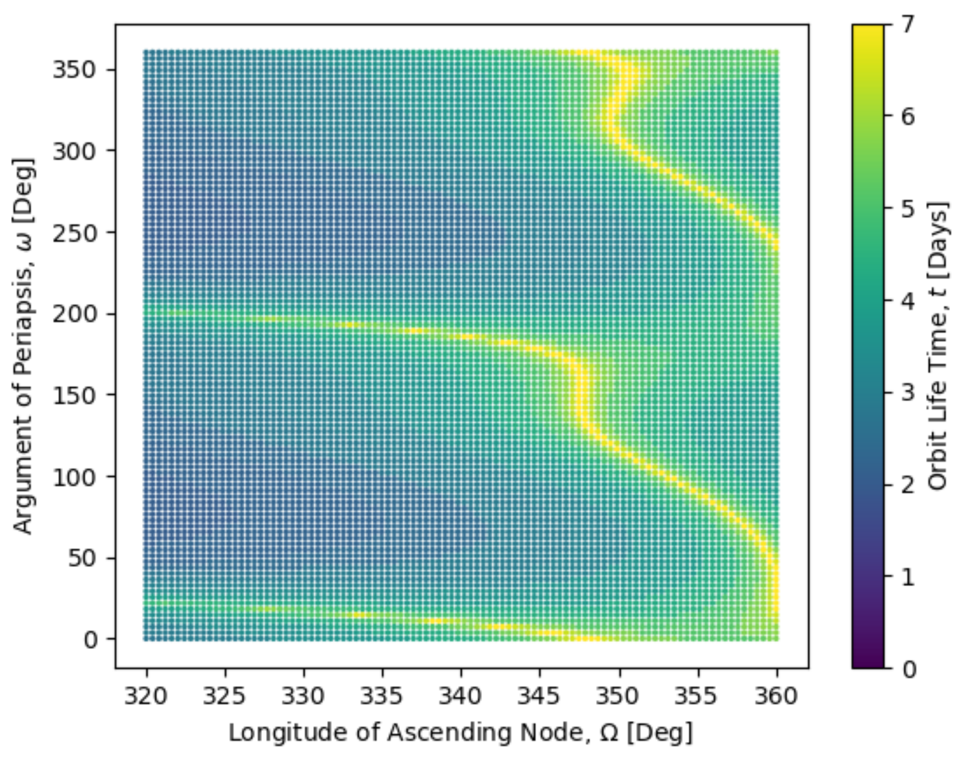

Fig.3. Orbit Life Time Map: The colour map shows the total life time of various orbits when Argument of Periapsis and Longitude of Ascending Node (320°-360°) are varied with respect to each other. The grid size of the map is 100 x 100.

Polar Orbit

Moderately inclined orbits (inclination between 45° and 60°) covering the equatorial and mid-latitude regions of Enceladus were found to be stable from several months up to years (Benedikter et al., 2022).

In contrast, the more useful polar mapping orbits were found to be extremely unstable due to the so-called "Kozai mechanism", resulting a spacecraft to impact the moon's surface within a few days.

However, an example of a highly inclined orbit shown in Fig.4. was found with inclination of approximately 76°. This orbit has a total life time of approximately 13 days.

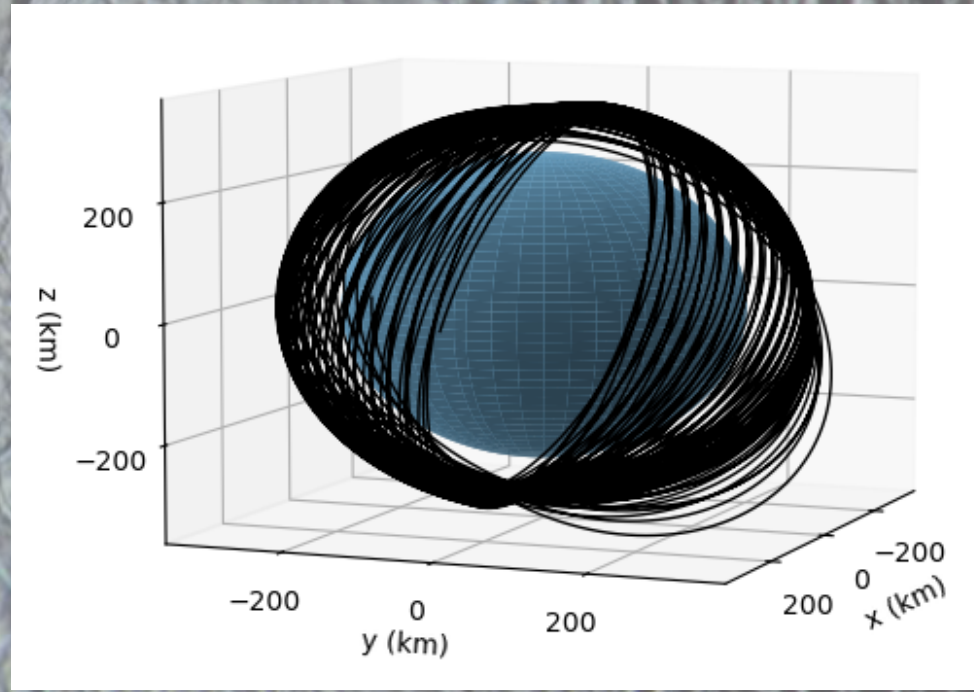

Fig.4. Orbit trajectory of the polar orbit at inclination angle i = 76.36°. Semi-major axis a = 341 km.

The pericenter distance and eccentricity depicted in Fig.5. show a cyclic behaviour over time before the orbit gets destabilised due to high perturbations. The inclination, shown in Fig.6., oscillates between 76° and 82° providing the coverage of the "Tiger-Stripes" region. The orbital parameters for the initial condition are specified in Table 1.

Orbital Parameters	Value
Semi-Major Axis, a	341 km
Inclination, i	76.37°
Eccentricity, e	0.001
Longitude of Ascending Node, Ω	0°
Argument of Periapsis, ω	0°
Mean Anomaly, ma	0°

Table 1: Initial Condition for Orbital Parameters

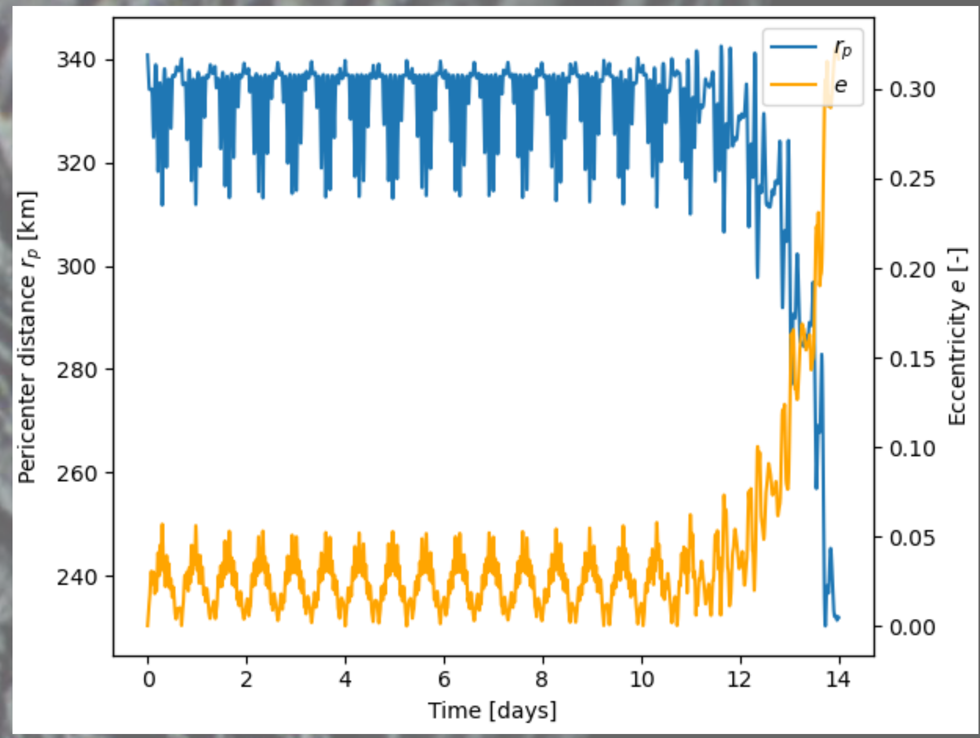

Fig.5. Pericenter distance, r_p in km (Altitude of 80 km from the surface) and Eccentricity, e of the polar orbit with perturbations from the higher degrees of Enceladus and Saturn and its moons, Sun and Jupiter.

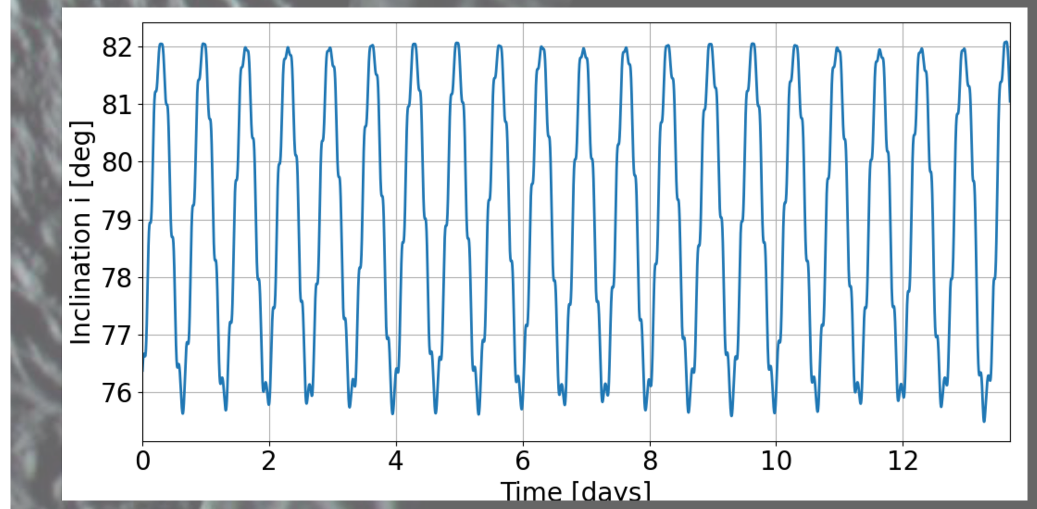

Fig.6. Inclination angle of the polar orbit

Conclusion & Outlook

A longer mission in a highly inclined orbit would require correction manoeuvres every few days. This would provide coverage of the tiger stripes region and allow for a global characterisation of the surface. Furthermore, the delta-v budget necessary to maintain such a highly inclined orbit over a mission of several months needs be investigated.

References

- Park, R. S., et al. (2024) Journal of Geophysical Research: Planets
- Benedikter, A., et al. (2022) *Acta Astronautica*
- Hussmann, H., et al. (2012) *Planetary and Space Science*

DLR