EGU24-17668

Numerical Analysis of Polar Orbits for Future Enceladus Missions

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Introduction

Saturn's moon Enceladus gained limelight with the discovery by the Cassini spacecraft of the plumes of ejected gas and ice particles from pronounced linear structures in its South Pole region called "Tiger Stripes". The small (504 km diameter) satellite is believed to have a porous rocky core and an ice shell, separated by a global subsurface saltwater ocean. The tidal heating potentially aids in driving chemical reactions in the moon's interior which makes it a very promising candidate where the right conditions for life formation may exist. This makes Enceladus a prime target for a future mission. Due to strong gravitational perturbations caused by Saturn, the higher gravitational moments of Enceladus and additional perturbations by the other moons of Saturn, the dynamic environment for artificial satellites around Enceladus is extremely complex. As a consequence, the search for natural stable orbits is far from trivial. A polar orbit is desirable to further investigate the Tiger Stripes region, and for mapping of the global subsurface ocean. We have used numerical integration methods to find suitable candidate orbits for such a mission.

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

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).

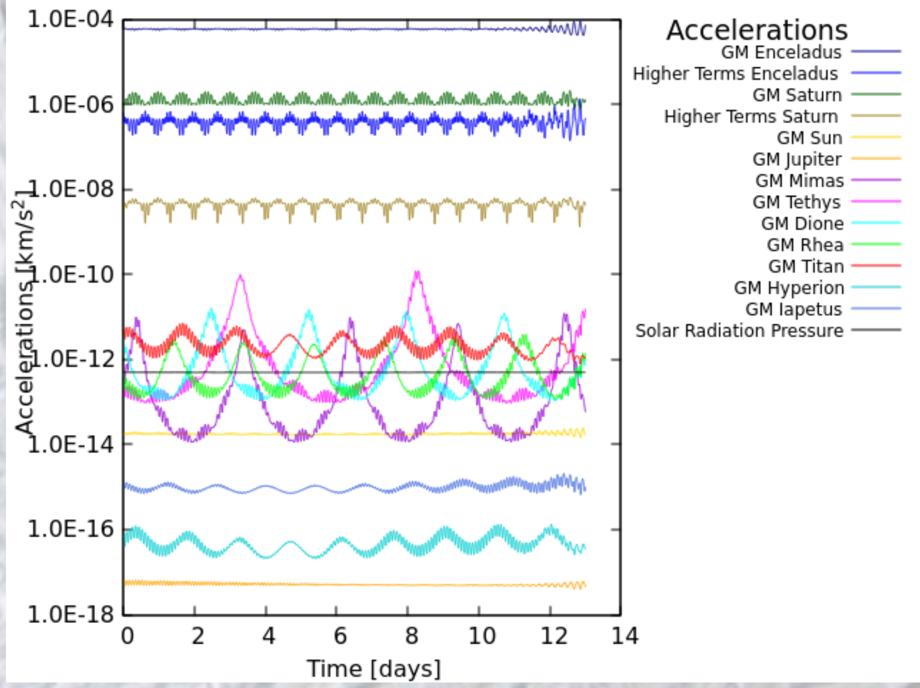

Fig.1. All the relevant accelerations experienced by the spacecraft in orbit around Enceladus at an altitude of 100 km from the surface.

Orbit Life Time Maps

We searched for suitable orbits in inertial space by varying orbital parameters such as semi-major axis (350 to 450 km), inclination (40° to 120°), argument of periapsis and longitude of ascending node. The Orbit life time maps in Fig.2. and Fig.3. 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 .

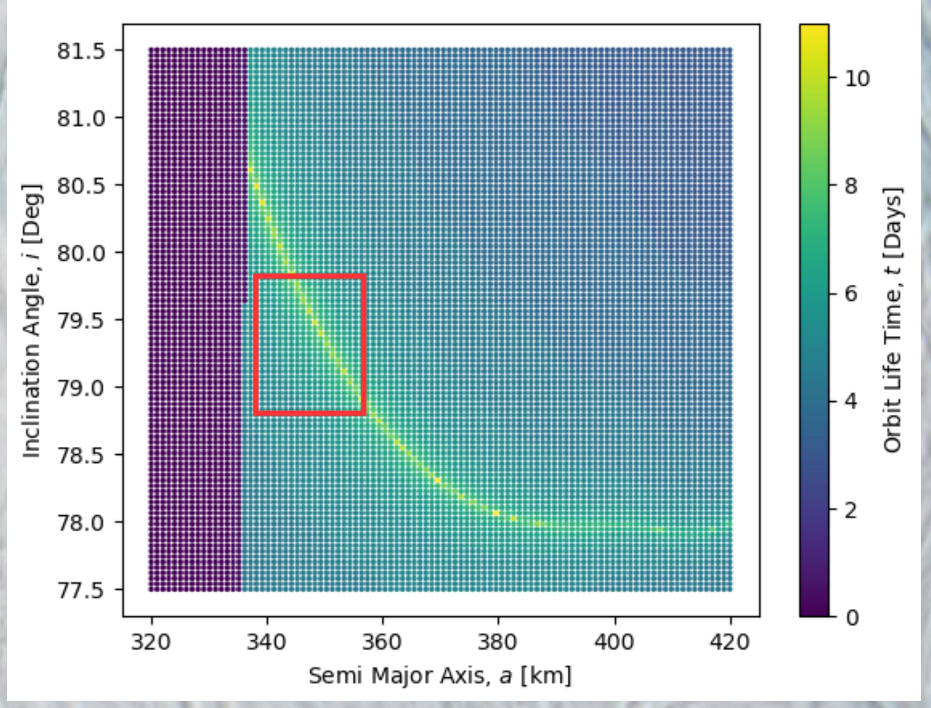

Fig.2. Orbit Life Time Map: The colour map shows the total life time of various orbits when Semi-Major Axis (320-420 km) and Inclination (77.5°-81.5°) are varied with respect to each other. The grid size of the map is 100 x 100.

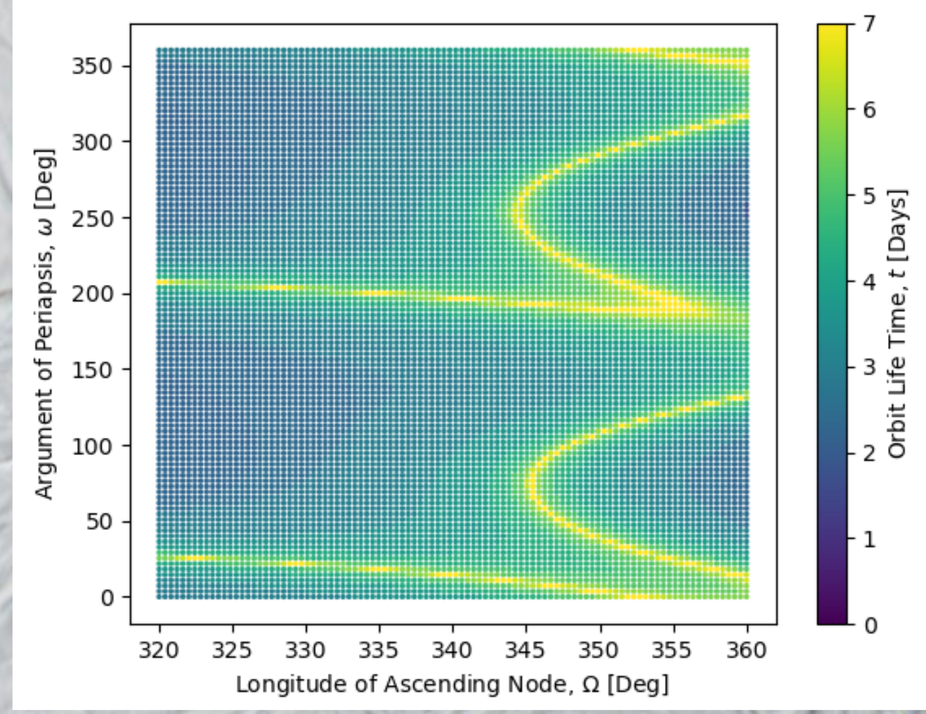

Fig.3. Orbit Life Time Map: The colour map shows the total life time of various orbits when Argument of Periapsis and Longitude of Ascending Node (320°-360°) are varied with respect to each other. The grid size of the map is 100 x 100.

Results

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 79°. This orbit has a total life time of approximately 12 days. The pericenter distance and eccentricity show a cyclic behaviour over time before the orbit gets destabilised due to high perturbations. The inclination oscillates between 79° and 81° providing the coverage of the Tiger Stripes region.

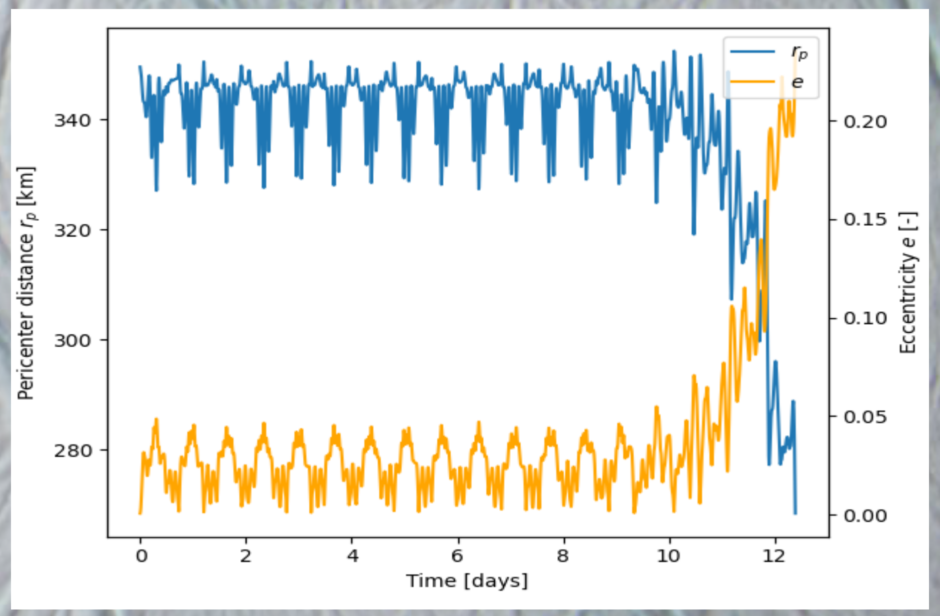

Fig.4. Pericenter distance, r_p in km (Altitude of 100 km from the surface) and Eccentricity, e of the polar orbit with perturbations from the higher degrees of Enceladus and Saturn and its moons, Sun and Jupiter.

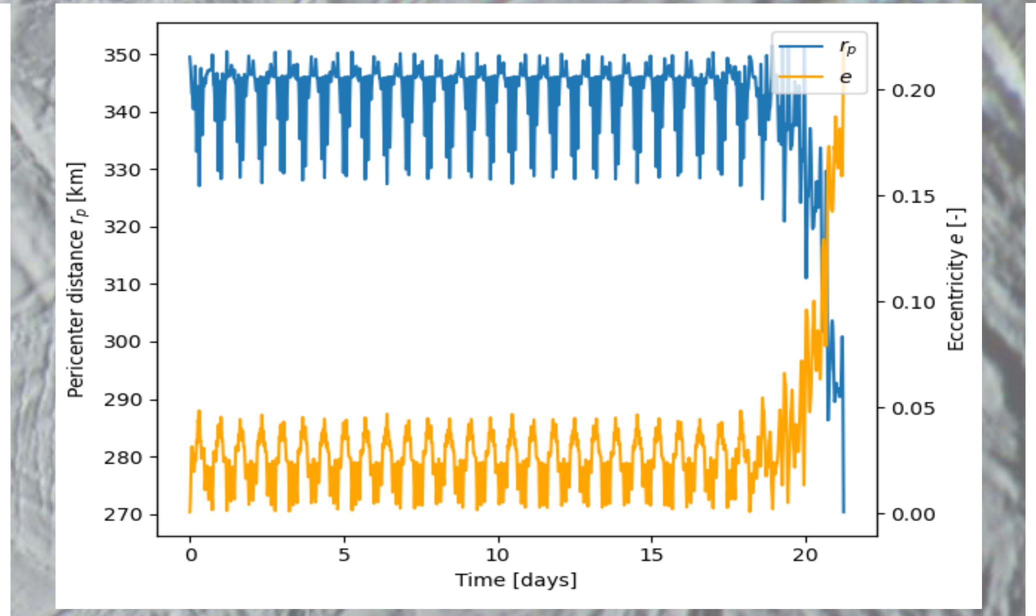

Fig.5. Pericenter distance, r_p in km (Altitude of 100 km from the surface) and Eccentricity, e of the polar orbit with perturbations only from the higher degrees of Enceladus and Saturn.

The stability of a near-polar orbit is significantly reduced due to perturbations from Saturn's moon, Jupiter and the Sun, resulting in a reduction of the orbital life time. The orbit life time period is reduced from potentially 20 days in Fig.5. to around 12 days in Fig.4.

Orbit Control Strategy

The delta-v values necessary to maintain such a highly inclined orbit over a mission of several months were determined. This is a preliminary strategy which uses along-track manoeuvres only, i.e., accelerating or decelerating the spacecraft, to maximise the life time of the orbit. The budgets are assessed for an example reference semi-stable orbit solution with the parameters as per the initial condition in Table 1 and various correction manoeuvre frequencies, e.g., every 1, 2, and 4 days. Fig.6. shows the evolution of orbit over a period of 60 days when we apply delta-v manoeuvre every day.

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 ocean. The simulation results summarised in Table 2 show that short manoeuvre intervals are more efficient in saving delta-v and consequently propellant. Next, we will consider uncertainty errors in the position and velocity knowledge of the orbit.

Frequency of Delta-v Maneuvers	Total Delta-v (m/s)	Total number of Maneuvers Events
Every 4 days	0.3	15
Every 2 days	0.2	30
Every 1 day	0.04	60

Table 2: Summary of Delta-v requirements

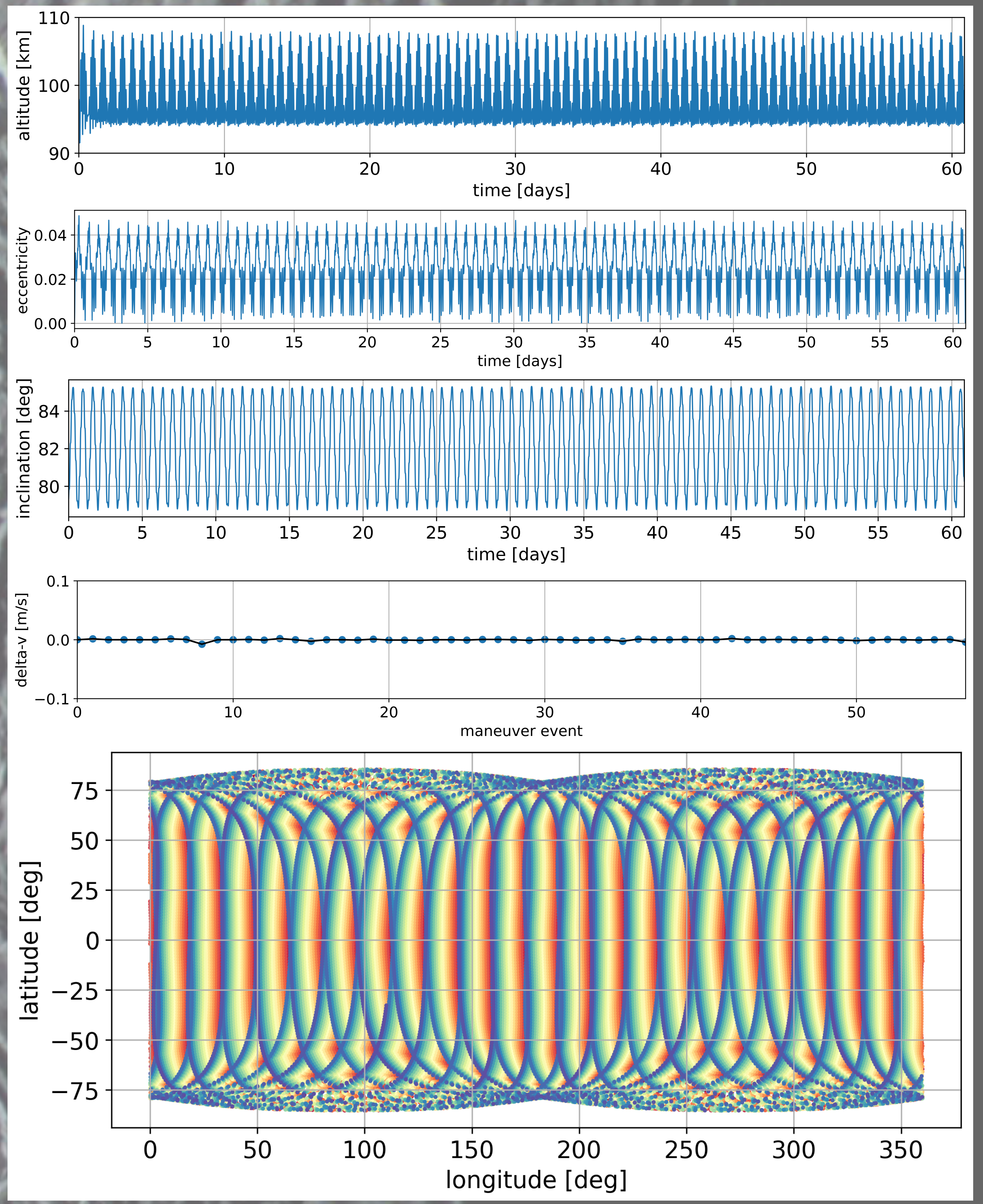

Fig. 6. From top to bottom: Altitude, Eccentricity, Inclination, Delta-v manoeuvres applied every 1 day, Ground track of the orbit (with colours indicating temporal evolution) over a period of 60 days.

Orbital Parameters	Value
Semi-Major Axis, a	350 km
Inclination, i	79.35°
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

References

- Benedikter, A., et al. (2022) *Acta Astronautica.*
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