Stable, High-Inclination Orbits around Enceladus for South Polar Coverage

S. Auer Wilkins[1], W. Neumann[1,5], J. Oberst[1], L. Gambacorta[2,3], A. Benedikter[3], V. Marx[4], A. Stark[3], H. Hussmann[5], K. Wickhusen[5], M. Vossiek[4]

[1]Institute of Geodesy and Geoinformation Science, Technical University Berlin, Berlin, Germany ; [2]Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, Germany; [3]Microwaves and Radar Institute, German Aerospace Center (DLR), Weßling, Germany; [4]Institute of Microwaves and Photonics (LHFT), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, Germany; [5]Institute of Space Research, German Aerospace Center (DLR), Berlin, Germany

Introduction

Saturn's moon Enceladus harbors a global subsurface ocean, active south-polar cryovolcanic plumes and life-essential elements, making it a prime target for astrobiological research[1]. As part of the Enceladus Explorer (EnEx) Initiative of the German Space Agency at DLR, the EnEx-RaTNOS project (Radar Transponder based Navigation and Orbit Determination by Satellite) aims to enable geodetic mapping of Enceladus through precision orbit determination via a surface radar transponder network. The design of highly-inclined, stable science orbits is challenging due to the strong gravitational perturbations exerted by Saturn. This work analyzes two types of orbits in a full-fidelity ephemeris model: first, building on [2] and our previous work [3], periodic orbits are re-identified under an updated model to find long-term stable periodic orbits. Secondly, building on previous works [4, 5], halo orbits are translated into a full-fidelity ephemeris model and used as starting points for a grid-search targeting orbits with low altitude south polar flybys.

Model Setup

	Benedikter et al. (2022)[2]	Auer Wilkins et al. (2025)[3]	Boone et al. (2025)[4]	This study
Integration tool	pInt (DLR)	Tudat (TU Delft)	SEMPy	Tudat (TU Delft)
Enceladus gravity	Iess et al. (2014)[6]	Park et al. (2024)[8]	Point mass	Park et al. (2024)[8]
Saturn gravity	Iess et al. (2019)[7]	Jacobson (2022)[9]	Point mass	Jacobson (2022)[9]
Rotational model	-	-	-	Park et al. (2024)[8]
SH degree (Enc.)	3	3 (extended to deg. 85)	-	3 (extended to deg. 85)

Table 1: Model differences between previous works [2, 3, 4] and this study. The spherical harmonic (SH) gravity data from [8] was extended to degree 85 by collaborators at the DLR, under the assumption of Airy isostasy[10].

Grid-Search Methods

Periodic Orbits

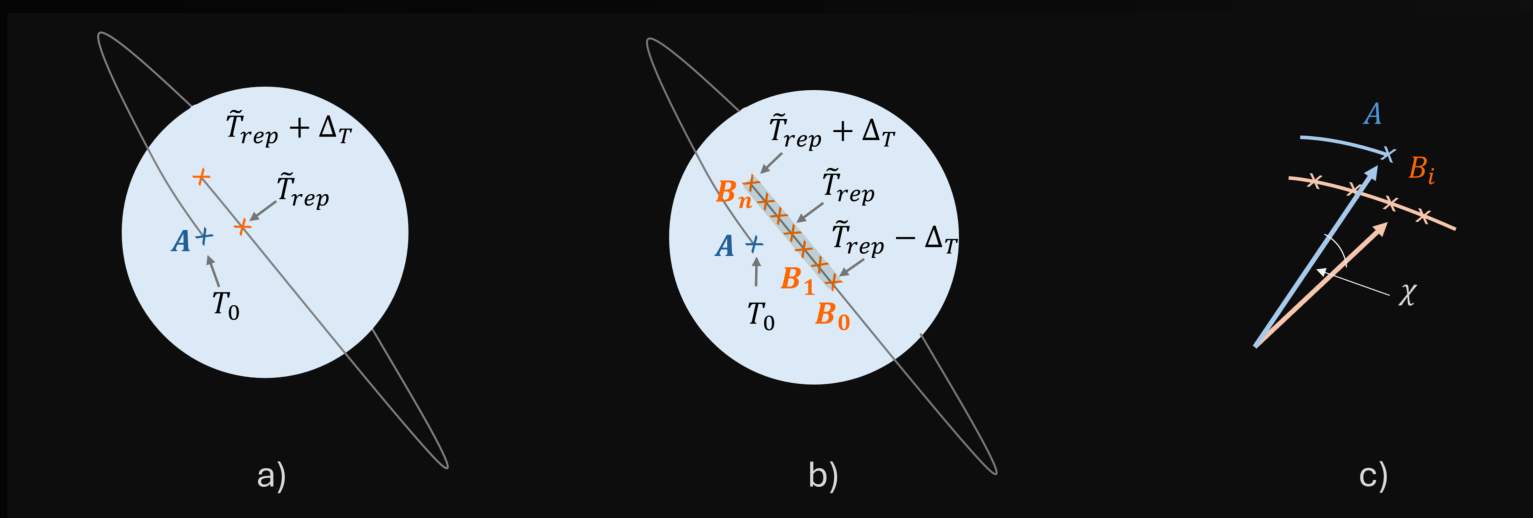


Figure 1: Sketch of the grid-search method for N=1. a) Propagation for one repeat period $\tilde{T}_{rep} \approx N \times \sqrt{(4\pi^2 a^3)/\mu_E}$. b) Interpolation of state vectors within time window B. c) Determination of the cosine difference between initial and end-state.

Based on [2], a grid-search method identifies candidate periodic orbits. Each combination of initial semi-major axis a, inclination i and eccentricity e is propagated for N revolutions and assigned a metric $m = \min(|\chi| + |\nu|)$, representing the minimum angular difference between initial and final position and velocity vectors. Candidate orbits with $m < 0.02$ are propagated for a time period of $20 \cdot T_{rep}$ in an additional grid-search pass to verify long-term stability. K'_1, K'_2, K'_3 with N=5, 9, 14, respectively, are the three orbits with best long-term stability.

Halo Orbits

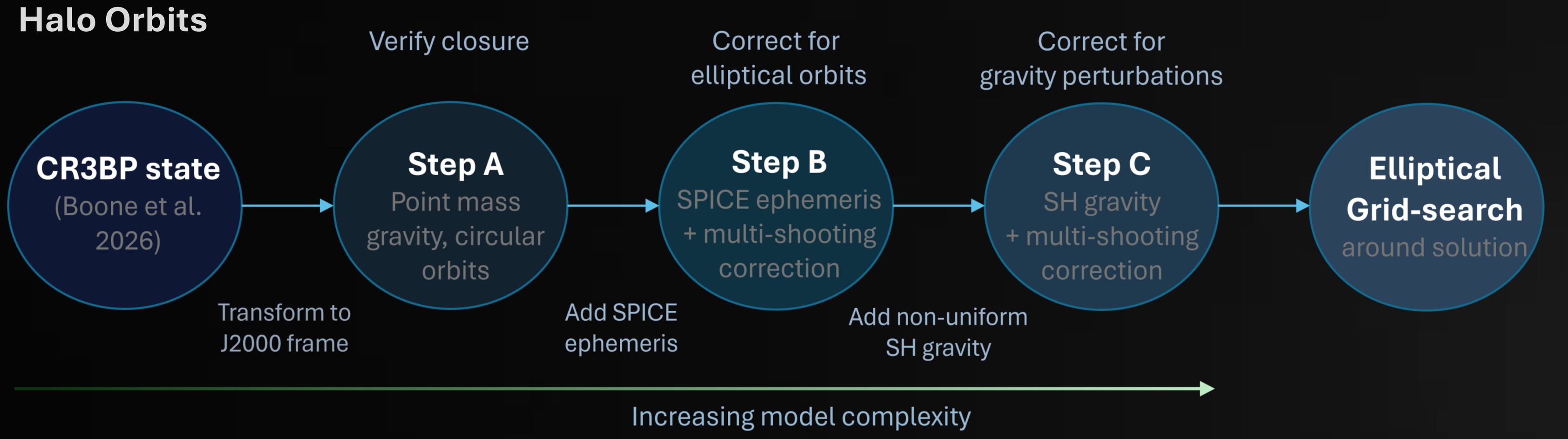


Figure 2: Multi-step correction from CR3BP to full ephemeris model, followed by an elliptical grid-search around the corrected state.

Halo orbits around the Saturn-Enceladus L_1 and L_2 Lagrange points are described by [4,5] using the Circular Restricted Three Body Problem (CR3BP) model. Initial states in the CR3BP model are translated into a full-fidelity model and adjusted through a multi-step process during which model fidelity is progressively increased, with a multi-shooting differential corrector applied at each step. A grid-search over the parameters a, e, i, and argument of periapsis ω is centered around this corrected state. Each orbit is propagated for 5 days and a combined score s (equations below) is computed. The highest-scoring orbit per family is selected as a science orbit candidate.

Survival score:

$$s_{surv} = \frac{1}{N}\sum_{i=1}^{N} b_i , \qquad with\ b_i = \begin{cases} 1, if\ (a_i > 0\ and\ e_i < 1) \\ 0, \qquad otherwise \end{cases}$$

South polar coverage score:

$$s_{cov} = \frac{1}{N}\sum_{i=1}^{N} l_i , \qquad with\ l_i = \begin{cases} 1, if\ \varphi_i < \varphi_{thr} \\ 0, \qquad otherwise \end{cases}$$

Favorable altitude score:

$$s_{alt} = exp\left(-\frac{h_{min}}{h_{thr}}\right)$$

Good-pass score:

$$s_{gp} = \frac{1}{N}\sum_{i=1}^{N} g_i , \qquad with\ g_i = \begin{cases} 1, if\ (\varphi_i < \varphi_{thr}\ and\ h_i < h_{thr}) \\ 0, \qquad otherwise \end{cases}$$

Final score:

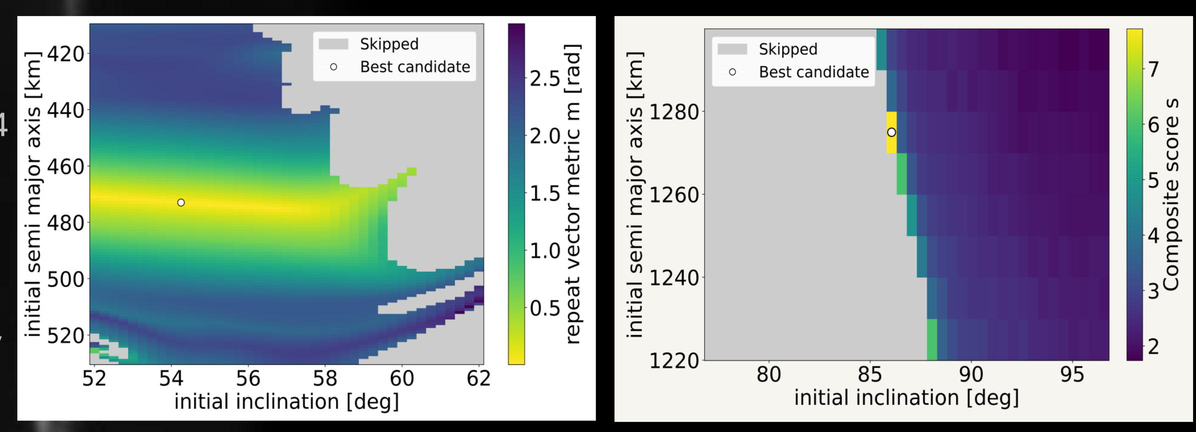
$$s_i = 4 \cdot s^i_{surv} + 3 \cdot s^i_{cov} + 2.5 \cdot s^i_{alt} + 5 \cdot s^i_{gp}$$

N: time steps; thr: threshold; φ_i: sub-spacecraft latitude, φ_{thr} = −60°; h_i: altitude, h_{min}: south polar minimum altitude, h_{thr} = 50 km; a_i, e_i: semi-major axis and eccentricity at step i

Results

Grid-Search Parameter Space

Figure 3: Slice through the grid-search space. *Left*: Repeat metric m at N=14 and fixed e=0.08. *Right*: Composite score s at fixed e=0.77 and ω = 270.39 deg. Grey areas represent orbits skipped due to an early crash or escape trajectory.



Periodic Orbits

Parameter	unit	K'_1	K'_2	K'_3
N	-	5	9	14
a_0	km	450.0	486.0	473.0
e_0	-	0.07	0.08	0.08
i_0	deg	54.5	55.0	55.0
T_{rep}	days	1.27	2.55	3.82
mean i	deg	55.68	56.33	56.26

Table 2: Initial values for orbits K'_1, K'_2, K'_3 in the ephemeris model body fixed frame. Fixed values from [11]: Arg. of periapsis = 268.14 deg; long. of ascending node = 235.39 deg; true anomaly = 91.85 deg.

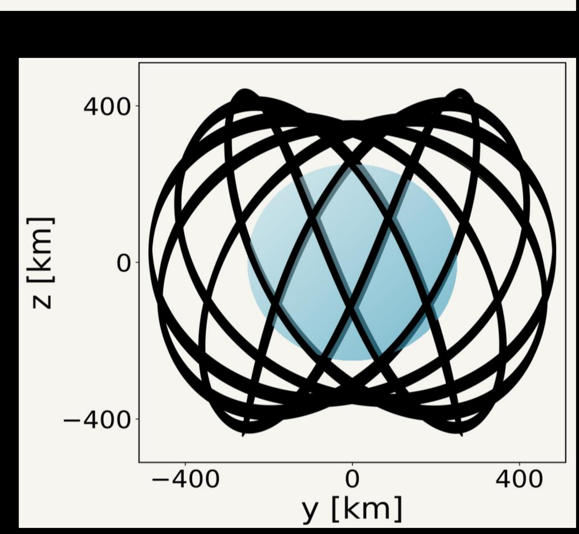


Figure 4: Example orbit K'_3. Orbit trajectory in body fixed frame over a period of 200 days.

Halo Orbits

Parameter	unit	NRHO L_1	NRHO L_2	L_1 period 3
a_0	km	1274.94421	737.61252	1193.97708
e_0	-	0.77	0.75	0.76
i_0	deg	86.05	117.84	89.64
ω_0	deg	270.39	268.82	266.44
Ω_0	deg	85.36	264.82	90.61
ν_0	deg	359.60	179.96	3.57
min alt.	km	2.94	0.6744	1.39
passes < 100 km	-	6	21	9
bound period	days	4.54	11.14	5.75

Table 3: Candidate orbits with the highest composite score s per analyzed halo family group: The L_1 and L_2 near rectilinear halo orbits (NRHO) and the L_1 period 3 orbit. During the grid-search, parameters Ω_0 and ν_0 remained fixed to the value of the initial CR3BP to Ephemeris translation.

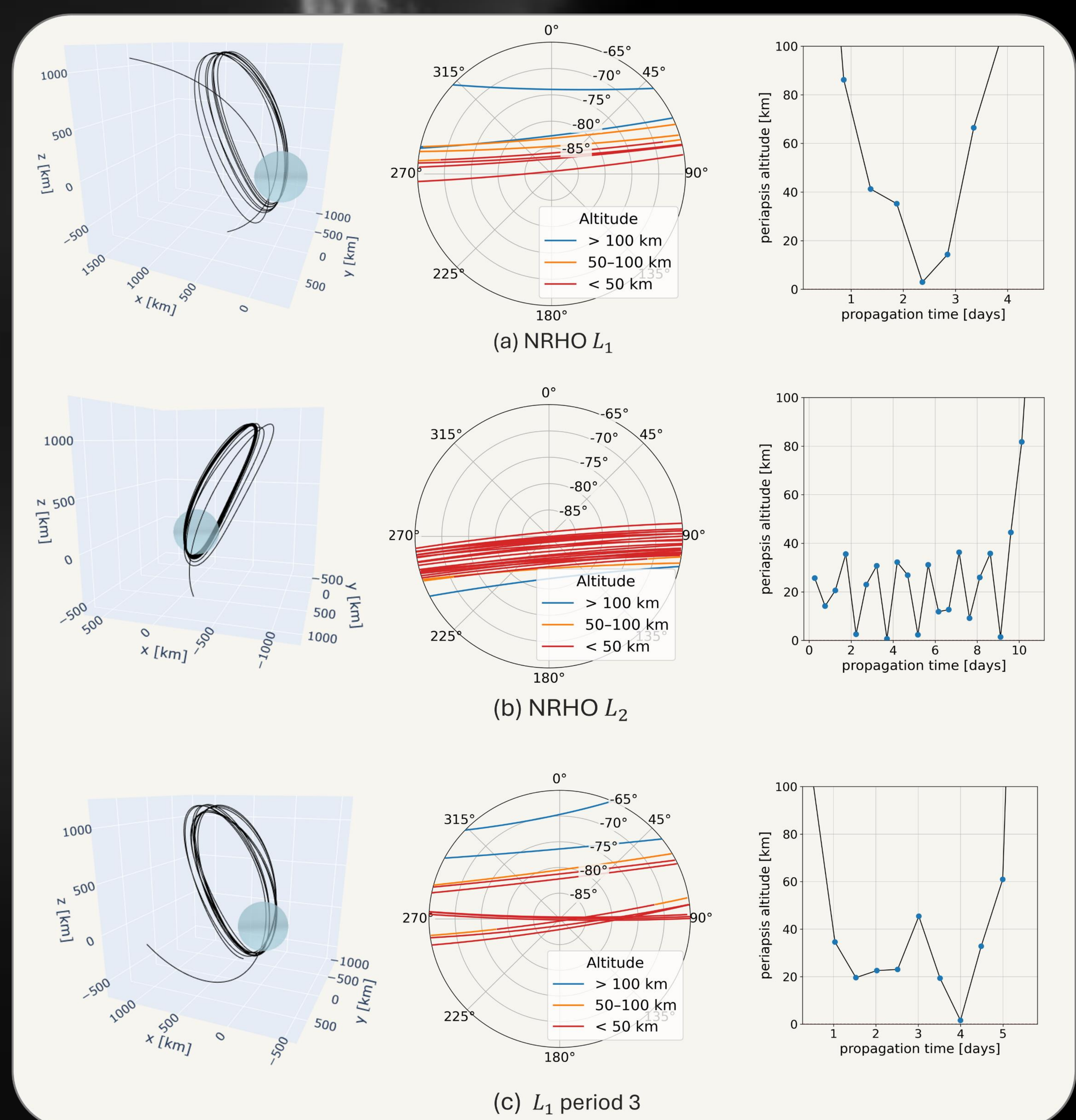


Figure 5: Orbit trajectory (left), south polar ground-track (center) and periapsis altitude (right) per analyzed halo orbit group.

Summary and Conclusion

Periodic Orbits

- Compared with [2], the extended gravity model [8] shifts solutions to slightly lower mean inclination.
- The addition of Enceladus' rotational model deteriorates the long-term stability of our previous solutions [3]. The updated K'_1, K'_2, K'_3 show similar characteristics: K'_2 and K'_3 remain the most stable while K'_1 shows a pronounced drift over time.

Halo Orbits

- In contrast to their CR3BP counterparts, the halo orbits in the full ephemeris model remain bound for shorter time periods of 4-12 days.
- The NRHO L_2 orbit remains bound for the longest period during which it performs 21 low passes over the south polar terrain.
- NRHO L_1 and L_1 period 3 are shorter-lived with fewer south-polar passes.
- All halo orbits perform low passes over the latitudes between −70° and −90°, covering the geologically active "tiger stripe" region of the south polar terrain.

References:
Background image: PIA11688, NASA/JPL/Space Science Institute
[1] Weiming Xu et al. (2025). *The Astrophysical Journal Letters*, 980(1):L10
[2] Benedikter et al. (2022). *Acta Astronautica*, 191, 326–345
[3] Auer Wilkins et al. (2025). *Copernicus GmbH*
[4] Boone et al. (2025). *arXiv e-prints*, page arXiv:2510.12421
[5] Boone et al. (2026). *Acta Astronautica*, 240:198–207
[6] Iess et al. (2014). *Science*, 344(6179):78–80
[7] Iess et al. (2019). *Science*, 364(6445)
[8] Park et al. (2024). *Journal of Geophysical Research Planets*, *129*(1)
[9] Jacobson (2022). *The Astronomical Journal*, 164(5):199
[10] Airy (1855). *Philosophical Transactions of the Royal Society of London* (145):101–104
[11] Russell and Lara (2009). *Acta Astronautica*, 65(1–2):27–39