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Search for Stable Orbits around Saturn's Moon Enceladus using Numerical Modeling

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Enceladus, a small icy moon orbiting Saturn, has become a key focus in the search for extraterrestrial life within our Solar System. Composed primarily of water ice, rock and other icy volatiles, Enceladus is part of a class of icy moons believed to harbor global oceans of liquid water underneath their crusts. With the presence of liquid water, the detection of life essential elements such as carbon, hydrogen, nitrogen, oxygen, phosphor and sulfur [1] (CHNOPS elements), and evidence of ongoing geothermal activity between the ocean and the rocky core of Enceladus [2], the moon meets the basic requirements for the existence of life and has therefore become a prime candidate for astrobiological research. To this end, the German Space Agency at DLR has launched the Enceladus Explorer (EnEx) initiative, a collaborative research project with the goal of studying Enceladus' geophysical characteristics and searching for biosignatures by sampling the moon's liquid subsurface water. As part of this initiative, the EnEx-RaTNOS (Radar Transponder based Navigation and Orbit Determination by Satellite) project aims to achieve precise orbit determination using radar transponders placed on Enceladus' surface [3].

The determination of stable orbits is a fundamental prerequisite for precise orbit determination and is also of high importance for topographic mapping and measuring surface deformationhrough synthetic aperture radar (SAR) imaging, as proposed in above mentioned EnEx [4] [5]. A satellite orbiting Enceladus should have a low altitude, low eccentricity and a high inclination to provide global coverage with a focus on the south polar region. However, orbits with such properties around planetary satellites are notoriously unstable, with the planet's gravitational perturbations causing the orbiting vehicle to impact the moon within short time periods [6]. The acquisition of SAR measurements imposes additional constraints on a satellite orbit [7]. For repeat-pass SAR, the SAR image acquisition is performed over two or more time instances by a single receiver, requiring a periodic orbit in which the ground track between an initial and a repeating orbit is parallel and repeats in a body-fixed reference frame. The distance between two consecutive ground tracks is constrained by the critical baseline B, which is in the range of several hundred meters for ka-band (26-40 GHz) and several kilometers for P-band (around 300 MHz) frequencies [8]. Short repeat periods are preferable due to the risk of decorrelation caused by surface changes occurring in the time interval between two image acquisitions.

This study focuses on determining stable and periodic orbits around Enceladus which fulfill the previously outlined requirements and includes a comparative evaluation of the orbit integration tools provided by the TU Delft Astrodynamics Toolbox (Tudat) and the DLR's Particle Integrator (pInt), in order to verify the similarity of propagation results produced by both integration tools. Building on prior research by Benedikter et al. (2022) [8], a grid-search method is implemented with the goal of identifying combinations of initial values within a defined parameter space for semi-major axis, inclination and eccentricity which lead to stable and long-term repeating orbits around Enceladus. In contrast to Benedikter et al. (2022), the orbit integration is achieved using the integration method of Tudat rather than pInt and uses the more recent non-spherical gravity terms of Enceladus published by Park et al. (2024) [9]. In addition to the higher gravity terms of Enceladus, Saturn's higher gravity terms are included as perturbing factors acting on the orbiting satellite.

In order to determine likely candidates for periodic orbits, the grid-search method looks for orbits that minimize the angle between the initial orbital state vector and the state vectors within a time window after an estimated repeat period. Results of the grid-search method show range of possible solutions for periodic orbits around Enceladus which are further analyzed for long-term stability and optimized towards higher inclinations. Three example orbits, K1′, K2′ and K3′, with short repeat periods of 1.2, 2.5 and 3.8 days and mean inclinations of 56.4, 52.5 and 57.8 degrees respectively are discussed in detail and compared to the orbits with similar repeat periods identified by Benedikter et al. (2022). The K3′ orbit shows the best long-term periodicity, with no visible differences between the orbit after 80 days and the orbit after 200 days. The identified orbits are promising candidates for stable and repeating satellite trajectories as required for the EnEx mission concept and can be used as a foundation for further analysis. Results from this study will be demonstrated and discussed at the conference.

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