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Radar Transponder Based Orbit Determination Around Enceladus

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Saturn's icy moon Enceladus is one of the most compelling targets for future planetary exploration due to strong evidence for a global subsurface ocean, ongoing cryovolcanic activity, and the potential for habitable environments beneath its ice shell [1-3]. Future missions to Enceladus will require highly accurate spacecraft navigation to enable geophysical investigations, radar sounding, gravity-field recovery, and precise measurements of tidal deformation. Within the German Space Agency's Enceladus Explorer Initiative project RaTNOS (Radar Transponder based Navigation and Orbit determination for Satellites), we investigate advanced orbit determination strategies for spacecraft operating in Enceladus orbit using combinations of Earth-based radio tracking and local radar transponder measurements.

An orbit determination framework was developed using open-source orbit estimation software Tudat(Py) (TU Delft Astrodynamics Toolbox in Python) [e.g., 4]. The framework estimates the spacecraft initial state vector together with additional dynamic and observational parameters. Simulations consider realistic dynamical perturbations, including higher-order gravity harmonics of Enceladus, perturbations from Saturn, and tracking noise from radar observations. Three tracking architectures are analysed: (1) classical communication between the spacecraft and Earth-based Deep Space Network (DSN) stations, (2) communication between the spacecraft and radar transponders deployed on the surface of Enceladus, and (3) a hybrid configuration combining DSN and transponder-based tracking. Our results demonstrate that local radar transponders improve orbit determination accuracy compared with DSN-only tracking. While a single transponder provides limited improvement because of short communication windows during orbital flyovers, configurations with multiple transponders yield significant gains. The analysis further shows that the number and spatial distribution of transponders exert a stronger influence on navigation performance than moderate variations in signal quality.

Precise orbit determination contributes to constraining geophysical properties of Enceladus. In particular, accurate measurement of tidal deformation through repeated orbital observations may provide critical insight into the internal structure and habitability of the moon. Our findings demonstrate that radar-assisted orbit determination architectures offer a promising pathway toward high-precision navigation for future Enceladus missions. Our methodology supports both mission design optimisation and the scientific interpretation of future geodetic and geophysical measurements around icy ocean worlds.

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