



EnEx-RaTNOS: an enhanced orbit determination concept for planetary exploration spacecrafts involving radar transponders

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1. Introduction and State of the Art

Enceladus, Saturn's ice-covered moon, with its subglacial ocean, is a key focus for future planetary exploration missions in the search of habitable regions and extraterrestrial life forms. A variety of mission concepts for Enceladus include orbital radar systems as payloads, aimed at surface and subsurface imaging or geophysical exploration. Different radar techniques, such as repeated-pass interferometry and tomography enable the generation of high-resolution topographic models, deformation measurements, and volumetric imagery of the upper ice shell. For the generation of these products, accurate satellite position is needed. In the case of planetary exploration, localization cannot be achieved through GNSS, but is generally conducted via range and Doppler measurements between the spacecraft and the terrestrial Deep Space Network (DSN). Due to the relatively small distance between the DSN antennas compared to the distance to Saturn, there is significant uncertainty in the position of the orbiter. For a mission to Saturn and its moons, the expected accuracy is in the range of several hundred meters, which greatly limits the potential of the above-described and other geophysical measurement methods.

2. Objectives of the EnEx – RaTNOS (Radartransponder basierte Navigation und Orbitbestimmung von Satelliten) initiative

With the aim of achieving centimeter accuracy in the satellite positioning, EnEx – RaTNOS, a joint collaboration between DLR, FAU (Friedrich-Alexander-Universität) and TUB (Technische Universität Berlin) proposes utilizing an orbital radar system mounted on a satellite, augmented with a network of surface-based radar transponders and serving as local reference frame to improve the accuracy in the orbit determination. An illustration of the mission concept is provided in Figure 1. By measuring the transponder response in the radar product, it may be possible to determine the relative distance between the orbiter and the transponders with high accuracy. Moreover, by combining knowledge of the transponder distribution on the ground with such range measurements, enhanced orbit determination of the orbiter itself can be performed. This approach has the potential to significantly enhance the accuracy of satellite navigation by compared to the current state of the art, allowing

geophysical measurements, e.g., gravity field mapping, for Enceladus to be conducted with unprecedented accuracy.

The EnEx-RaTNOS mission concept presents an innovative approach to satellite positioning by high-resolution radar products. While aimed at Enceladus, the technique could be applied also to other planetary bodies enabling to overcome standard localization techniques and improve the accuracy in orbiter positioning.

Our preliminary objectives can be schematized as follows:

- the development of techniques for an improved range estimation between the transponder and the orbital radar system. Such techniques will exploit the properties of the transponder waveform in the measured data, e.g. range and phase signature, in either the range-compressed and SAR-focused data. Different acquisition geometries, including different transponder positions and design characteristics, are tested and evaluated by means of an advanced radar mission simulator, developed by DLR (refer to the next Section 3.);
- the development and characterization of a miniaturized transponder prototype at X-band. Particular attention is dedicated to the effect of delay and phase instabilities introduced by the transponder in the compressed waveform, finally affecting the range estimation. To achieve this objective, a comprehensive dataset from past and future airborne campaigns will be utilized (refer to Section 4.).

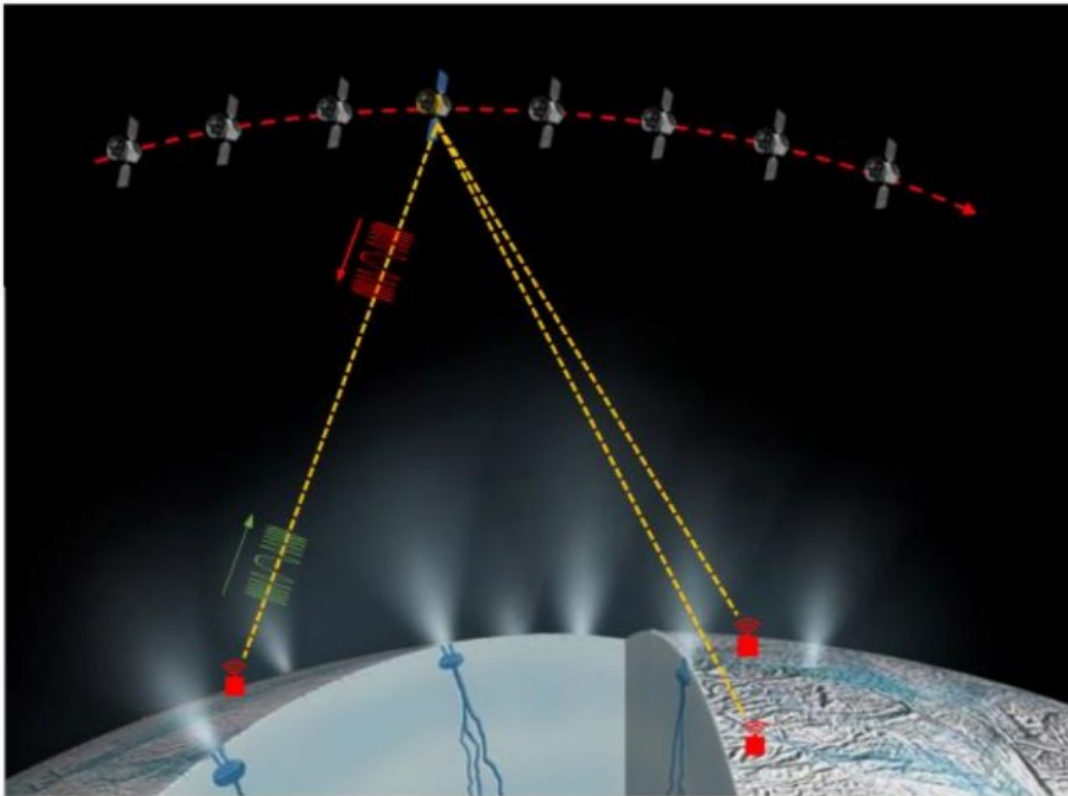


Figure 1. Schematic illustration of the EnEx-RaTNOS mission concept

3. Performance Evaluation via end-to-end radar simulation

The performance of this mission concept and the employed methodology will be evaluated by conducting high-fidelity simulations of radar imagery. At the heart of this validation approach is a comprehensive simulation framework that enables the end-to-end modeling of raw radar data [1]. This simulator is utilized to evaluate the expected performance, which considers various aspects of the radar system and its associated error sources, including transponder-

intrinsic errors. The simulation scenario includes the use of a high-resolution digital elevation models for Enceladus, a suitable backscattering model of the planet's surface, and other geophysical properties such as deformation, decorrelation models, and atmospheric delays (e.g., by the plume). Furthermore, the simulation includes the effect of the transponder signature and eventual instabilities in terms of point-target-like behavior, signal delay, phase instabilities and additional error sources. Incorporating the specific orbit geometries around Enceladus, range compressed and SAR-focused radar data are generated and the transponder signature is analyzed to evaluate the effect of these components on the final performances in the range estimation. As an illustrative example, Figure 2 displays the results from the simulation employing Enceladus topography, providing a basis for comparison with the SAR image acquired by the Cassini RADAR instrument (NASA). The output highlights the elongated structures characteristic of Enceladus' terrain, demonstrating the effectiveness of the simulation in replicating real-world features.

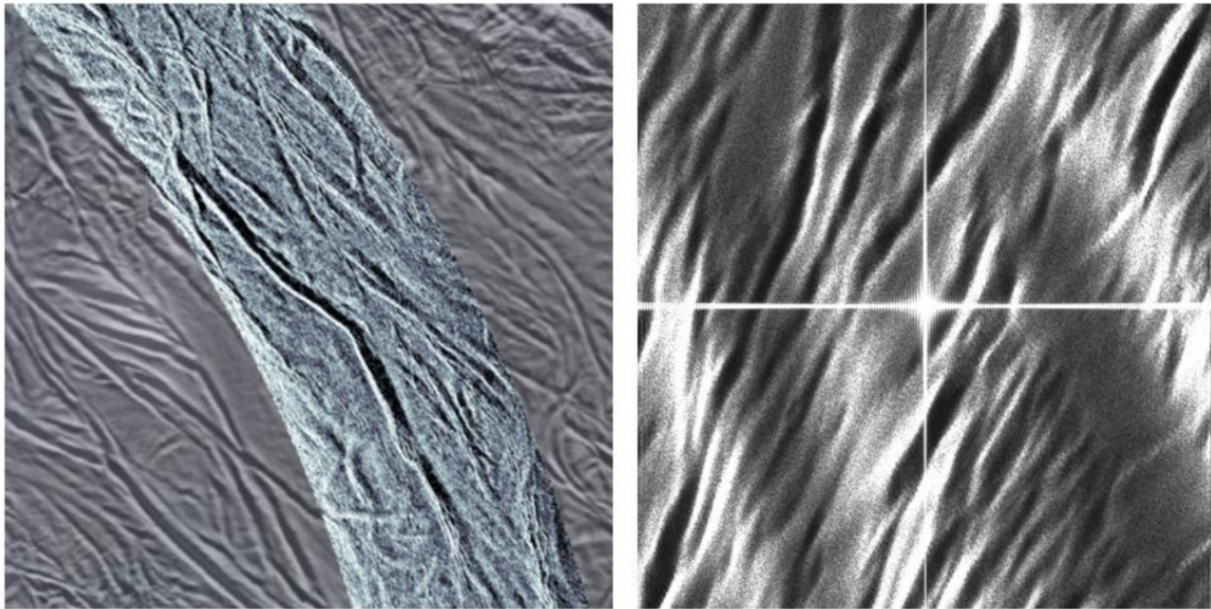


Figure 2. (left panel) SAR image acquired by the Cassini RADAR in a close fly-by of Enceladus (credits to NASA/JPL/Space Science Institute). (right panel) Our end-to-en simulated product using interpolated Enceladus DEM at 25m. The central signature shows a point target signature (representative for the transponder signature) for performance evaluation.

4. Evaluation of the Transponder instabilities and performance validation via experimental data

To validate the results from simulations, we exploited F-SAR airborne data from a 2022 campaign over the Aletsch glacier [2,3], acquiring radar data at L-, C-, and X-band, where a first development of the transponder along with corner reflectors was employed. By means of a joint analysis of the

signatures from corner reflectors and the radar transponder at the different frequencies, we aim to evaluate the transponder instabilities and their effect in terms of phase

and range, to be considered into the transponder modelling for the simulation scenario.

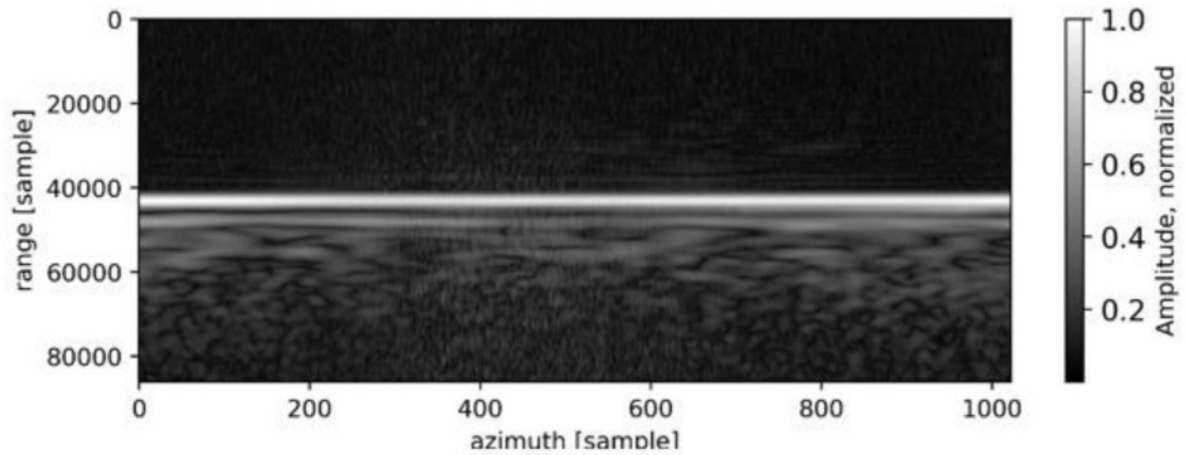


Figure 3. Transponder signature after range compression acquired during the 2022 Aletsch Campaign.

Currently, a new, miniaturized and lightweight transponder design is being developed and tested. To further validate its performance, controlled experimental measurements are planned and will be carried out using the F-SAR system. The aim is to conduct the final set of measurements by the end of July, thereby enabling a comprehensive characterization of the transponder's properties, including waveform modifications and their impact on range accuracy.

5. References

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- [3] Stelzig, Michael, et al. (2021) IEEE Microwave and Wireless Components Letters 32.3: 249-252.