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Orbit determination and error quantification of planetary missions using PRIDE open-loop Doppler data: Application to the Mars Express flyby of Phobos

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Doppler tracking of planetary missions is crucial for science objectives related to understanding, among others, solar system interiors and evolution. These analyses conventionally rely on closed-loop Doppler data from networks such as ESTRACK and the DSN. The Planetary Radio Interferometry and Doppler Experiment (PRIDE) can provide complementary data by extracting open-loop Doppler and VLBI observables from spacecraft radio signals recorded by radio-astronomical telescopes [1,2,3]. These (three-way) observables are generated using the existing downlink from the spacecraft and therefore generated concurrently with the typical (usually two-way) closed-loop tracking data. While PRIDE data of planetary missions have been used for various applications, their direct use in a full orbit-estimation problem had not yet been demonstrated. Here, we report on the first end-to-end PRIDE-based orbit estimation of a planetary mission, using PRIDE Doppler data.

We use the 2013 Mars Express flyby of Phobos, for which both conventional closed-loop Doppler data and PRIDE open-loop Doppler (EVN experiment GR035, PI: Pascal Rosenblatt) data are available [4]. Using the open-source TU Delft Astrodynamics Toolbox (Tudat) [5,6], we independently estimate the Mars Express trajectory and the gravitational parameter of Phobos from the closed-loop and open-loop datasets. The solutions are cross-validated against the Mars Express orbit computed by the Royal Observatory of Belgium (ROB) team from closed-loop Doppler data using the GINS software.

The closed-loop solution gives RMS position differences with respect to the ROB Mars Express ephemerides of approximately 0.27 m radial, 17 m along-track, and 130 m cross-track, consistent with the expected uncertainty of the reference solution. For the PRIDE open-loop Doppler data, we form 27 different three-station combinations of PRIDE datasets, with one station on each of three continents, such that each combination spans the full tracking interval. From each combination, we estimate an independent orbit of Mars Express, leading to separate orbit estimates, each of comparable quality to those derived from closed-loop data, as quantified by the difference with respect to the ROB reference. The estimated gravitational parameter of Phobos is likewise consistent between the open-loop and closed-loop analyses and with reference values from the literature.

To further quantify the uncertainty of the PRIDE-based orbit estimates, we compute the RMS dispersion of the 27 station-combination solutions at each point along the estimated trajectory. This

dispersion peaks at approximately 0.4 m radial, 15 m along-track, and 100 m cross-track. Its temporal behaviour closely matches the difference between our closed-loop solution and the ROB reference ephemeris, indicating that the spread between PRIDE station-combination solutions provides a measure of the true orbit-estimation error that is comparable to the difference with respect to an external reference solution. This is a key advantage of PRIDE's multi-station redundancy: it enables an internal assessment of solution uncertainty, without relying exclusively on formal covariance estimates, which are often too optimistic, or on comparison with an external reference solution, which is not always available.

Assessing the true uncertainty of radio-tracking-based estimation is crucial for robustly using estimated parameters (for instance the gravitational parameter of Phobos) to improve our understanding of planetary interiors and Solar System evolution. PRIDE observations are particularly valuable for selected tracking intervals of high scientific interest, where the multi-station redundancy can provide validation and error quantification beyond what is available from conventional tracking alone. For events such as flybys of the Galilean moons [3], PRIDE Doppler data can therefore provide a complementary source of information for assessing the reliability of orbit and parameter estimates. Future work will include the processing of PRIDE Doppler data during the JUICE flyby of Venus, and spacecraft orbit estimation using a combination of open- and closed-loop tracking data.

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