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## Contribution of simultaneous PRIDE observations of JUICE and Clipper spacecraft to the Galilean satellites' ephemerides

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### JUICE's and Europa Clipper's synergistic contribution to the Galilean moons' ephemerides

An accurate determination of the ephemerides of natural satellites is critical to our understanding of planetary systems' evolution, and of tidal dissipation mechanisms in particular. Diverse interior or dissipation-related parameters can be retrieved when reconstructing the moons' dynamics from space missions' radiometric data [1,2,3]. For the Galilean moons of Jupiter, unique challenges complicate the estimation of the satellites' dynamics, as the Laplace resonances between Io, Europa and Ganymede result in a strongly coupled dynamical problem. Efficiently improving the current ephemerides solution would thus ideally require a balanced data distribution between these moons. In this context, the synergy between the upcoming JUICE and Europa Clipper missions is of primary importance. In particular, the ~ 50 flybys at Europa to be performed by the Clipper spacecraft will efficiently supplement JUICE's trajectory (2 flybys at Europa, 7 at Ganymede, 21 at Callisto, followed by a long orbital phase around Ganymede), leading to complementary radiometric data sets. Most importantly, in-system concurrent observations will be possible according to current missions' schedules. Preliminary analyses show that a joint solution from JUICE and Europa Clipper range and Doppler measurements can improve the estimation solution for the Galilean satellites' ephemerides and related dynamical properties (e.g. tidal dissipation parameters) [4].

### Contribution of PRIDE multi-spacecraft observations

The Planetary Radio Interferometry and Doppler Experiment (PRIDE) has been selected as one of the eleven experiments of the JUICE (JUper ICy moons Explorer) mission [5]. It relies on Very Long Baseline Interferometry (VLBI) techniques to process radiometric signals used for tracking, communications and/or radioscience. The main PRIDE observables are measurements of the spacecraft's lateral position with respect to a phase calibrator (VLBI), expressed in the ICRF (International Celestial Reference Frame) [6], but by-product Doppler observables are also generated [7]. Compared to range and Doppler measurements, which are collected in the line-of-sight direction, PRIDE VLBI data are sensitive to the spacecraft's position in the two other directions.

They thus provide very complementary information, which could help achieving an improved solution for the spacecraft's and moons' states in particular. A previous analysis has quantified the contribution of PRIDE VLBI observations to the Galilean moons' ephemerides for the JUICE test case [2], using a simplified non-coupled model [8]. A noticeable improvement was indeed obtained in the out-of-plane direction when including VLBI data, especially for Ganymede and Callisto (more data collected at these two moons).

In addition to these single-spacecraft VLBI measurements, the concurrent in-system tracking of the JUICE and Europa Clipper spacecraft will offer PRIDE a unique opportunity to fully exploit the synergy between the two missions' trajectories. If the two spacecraft are both visible from a telescope (*i.e.* in-beam or within the same telescope beam) and simultaneously transmitting a radio signal, it is possible to realise multi-spacecraft VLBI observations, which will directly provide accurate measurements of the relative lateral position of the two spacecraft (right ascension and declination difference in the ICRF). Such observations were already successfully collected between several Martian orbiters (MRO, MEX, TGO) in 2019 [9], as shown in Figure 1.

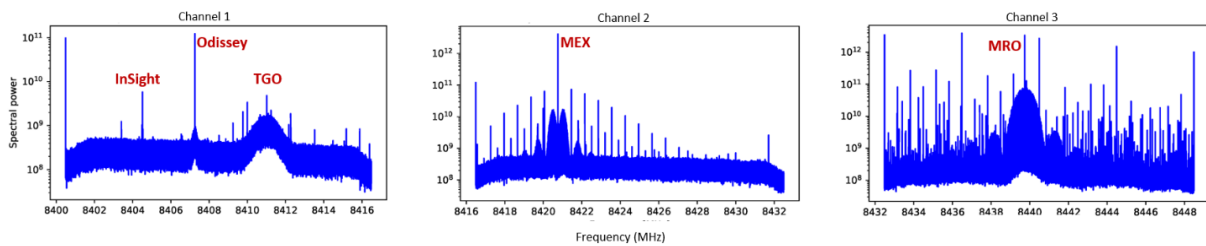


Figure 1: Simultaneous detection of the signals transmitted by several Martian orbiters and landers, from [9].

Given the synergistic nature of the JUICE and Clipper trajectories, the signals of the two spacecraft are expected to be visible in the same beam of ground-based telescopes during a significant fraction of their Jovian tours. Looking in detail at JUICE and Clipper flybys' sequences displayed in Figure 2, the two spacecraft will occasionally perform near-simultaneous flybys around different moons, with typically only a couple of days between JUICE's and Clipper's flybys. The relative angular measurements derived from PRIDE VLBI observations might then translate into direct constraints of the moons' relative states, expected to be extremely valuable for the ephemerides solutions.

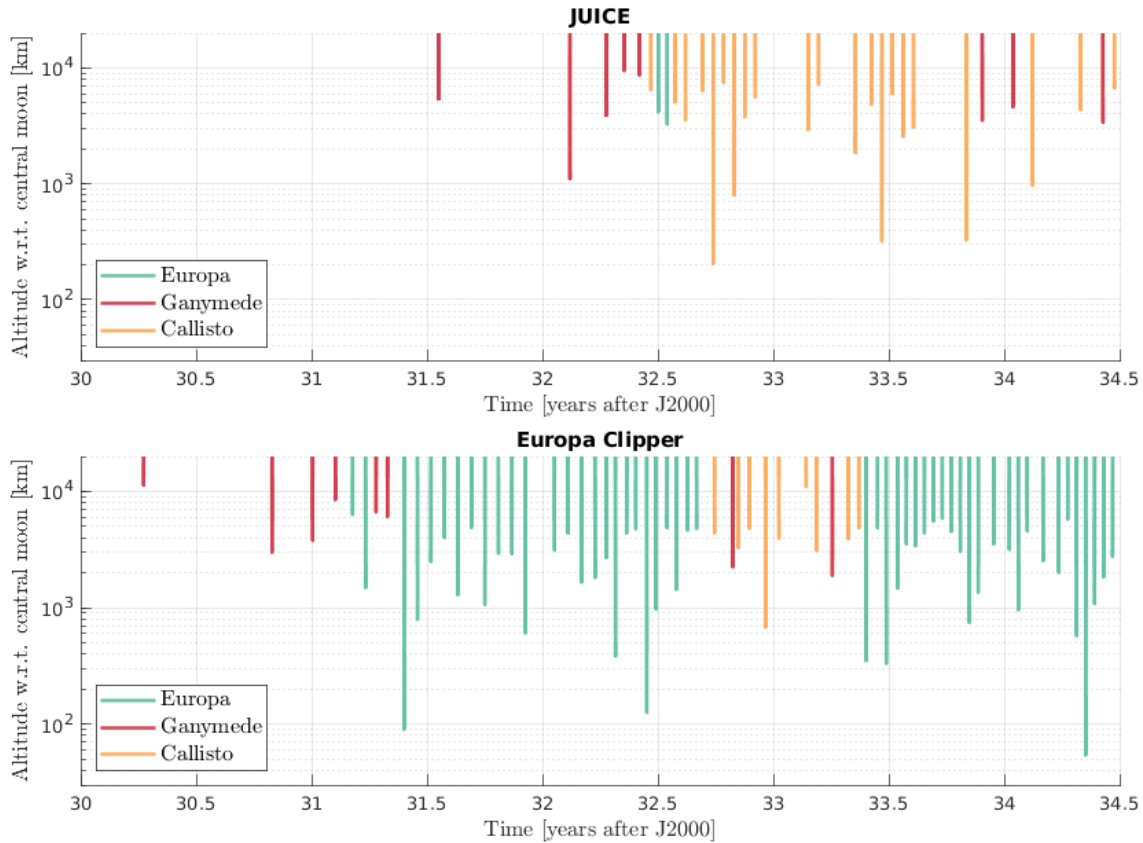


Figure 2: JUICE and Europa Clipper trajectories (altitude with respect to the moons)

### Contribution of these observations to the Galilean satellites' ephemerides

Our open-source estimation tool (Tudat(py)<sup>1</sup>) is now able to concurrently simulate several missions with different trajectories and observation schedules in a single estimation [10]. It is also linked with a VLBI prediction tool allowing to search for suitable phase calibrators close to the spacecraft at any potential observation epoch. Using these functionalities, we perform a simulation study to quantify the potential contribution of multi-spacecraft (in-beam) VLBI observations, also analysing its sensitivity to the observations' cadence and accuracy.

To this end, we will investigate when multi-spacecraft VLBI observations could be obtained from the JUICE and Clipper spacecraft. This involves searching for suitable phase calibrators and ensuring that both spacecraft are visible from ground telescopes at a given epoch. We will also further investigate promising observation geometries (*e.g.* near-simultaneous flybys, see Figure 2). The simulated multi-spacecraft observables will then be added to a joint JUICE – Clipper estimation, which also includes *nominal* (single-spacecraft) PRIDE VLBI observations for JUICE.

We will then precisely quantify the contribution of these simulated multi-spacecraft VLBI observations to the estimation solution, focusing on the moons' ephemerides and related dynamical parameters in particular. If proven beneficial, this will motivate the acquisition of such observations during the JUICE and Clipper missions. Additionally, our sensitivity analysis will provide direct recommendations regarding observation scheduling. If need be (*i.e.* particularly interesting multi-spacecraft VLBI observation but no phase calibrator in the angular vicinity of the spacecraft), this could also highlight the need to search for yet unknown calibrators in a certain region of the sky.

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<sup>1</sup> <https://docs.tudat.space>