Review of "Mapping JUICE’s Journey: PRIDE Observations from the Lunar–Earth Gravity Assist"

This manuscript presents PRIDE observations of the JUICE spacecraft during the August 2024 lunar–Earth gravity assist, using a network of radio telescopes in Australia and South Africa. The observations include VLBI experiments before and during the encounter, single-dish Doppler tracking, detection of the lunar occultation, and measurements during the subsequent Earth flyby. The authors also compare the measured Doppler frequencies with predictions generated using the Tudat framework and present analyses of phase fluctuations and terrestrial ionospheric contributions.

The observational campaign is interesting, and the lunar–Earth gravity assist provides a valuable test of PRIDE under an unusually rapidly varying tracking geometry. In particular, the successful tracking of the spacecraft through the lunar encounter, the detection of the occultation ingress and egress, and the multi-station Doppler observations during the Earth encounter demonstrate the capabilities of ground-based radio tracking during a challenging mission phase. The manuscript is generally clear and contains a useful observational data set.

However, several aspects of the analysis and interpretation require clarification before publication. In particular, the quantitative interpretation of the comparison between the measured Doppler and the Tudat prediction should be strengthened, and the manuscript should distinguish more clearly between successful VLBI detection/imaging and an actual astrometric determination of the spacecraft position. The interpretation of the phase fluctuations and TEC measurements also requires clarification, and the quality and readability of the figures should be substantially improved.

<u>Major comments</u>

Figure 13 presents one of the most important quantitative results of the manuscript: the comparison between the PRIDE Doppler measurements and frequencies predicted from the JUICE trajectory using Tudat. This is a useful independent validation of the PRIDE Doppler measurements, but the quantitative interpretation of the comparison is currently unclear. The manuscript states that the original observed-minus-computed residuals are at the Hz level and contain a systematic time-offset bias and errors in the a priori JUICE trajectory, whereas the quoted RMS of approximately 5 mHz is obtained only after linear detrending. The latter therefore characterizes the remaining short-timescale residuals rather than the absolute agreement between the measured and predicted Doppler. I suggest showing both the original and detrended residuals in Fig. 13 and quantifying the fitted offset and slope that have been removed. In particular, it would be useful to determine how much of the original discrepancy is attributable to the timing offset and how much to the assumed trajectory. The manuscript should also clarify whether similar results are obtained independently for the other stations. More generally, the authors should distinguish between the absolute agreement of the measurements with the trajectory-based prediction and the residual variability after detrending. The present 5 mHz result therefore characterizes the detrended observed-minus-computed residuals rather than the absolute Doppler accuracy or, without a corresponding error budget, the intrinsic measurement precision.

The manuscript should distinguish more clearly between successful VLBI detection and imaging of JUICE and an actual astrometric measurement of the spacecraft position. The Introduction emphasizes the ability of PRIDE to provide plane-of-sky spacecraft positions, and the Abstract states that phase-referencing observations were conducted to establish astrometric measurements. However, Section 4 states that the phase-referencing observations were not of sufficient quality for reliable astrometry, while Section 3.1 presents self-calibrated images and notes that applying the phase calibration to JUICE to determine its position offset from the a priori orbit remains ongoing. These are quite different results. Successful correlation and self-calibrated imaging demonstrate the interferometric detection of JUICE, but self-calibration does not provide the absolute phase information required for astrometry. The manuscript should therefore state explicitly what positional information, if any, was obtained independently from PRIDE during these experiments. If no reliable PRIDE astrometric position was obtained, this should be clear in the Abstract and Conclusions. A direct comparison between a PRIDE-derived spacecraft position and the operational JUICE/SPICE trajectory would ultimately provide the most direct validation of the astrometric capability, but from the present manuscript I understand that reliable astrometry could not be obtained from these observations. This distinction is important because it defines what has actually been demonstrated by the VLBI component of this campaign.

The interpretation of the phase fluctuations and TEC measurements in Section 3.5 should be clarified. The text states that the interplanetary plasma contribution is minimal and that the measured fluctuations are dominated by the terrestrial ionosphere. However, the caption of Fig. 15 states that the dominant spectral features are consistent with electronic noise originating at the receiving station, while the discussion associated with Fig. 16 refers to unmodelled tropospheric, spacecraft, and ground-station noise. It is therefore difficult to understand how confidently the measured phase variance can be attributed to the terrestrial ionosphere. The derivation of the quoted uplink and downlink TEC values should be explained more quantitatively, including how the ionospheric contributions are separated, how the uncertainties are obtained, and how instrumental phase fluctuations are treated. In particular, the quantity described as a "non-ionospheric contribution" should be clarified. Since instrumental, tropospheric, or spacecraft phase noise does not represent a physical electron content, if this value is an equivalent TEC obtained by converting residual phase fluctuations, it should be described accordingly. The very large uncertainty also suggests that the residual is consistent with zero. More generally, the manuscript should distinguish between what can be inferred robustly about the terrestrial ionosphere from these observations and what remains part of the developing PRIDE noise-budget analysis.

Finally, the quality and readability of most figures should be improved. First, the figures do not appear to be provided in vector format, resulting in poor resolution and making several of them difficult to inspect in detail. More importantly, the legends, axis labels, tick labels, and annotations are very small in many figures, particularly Figs. 5–7 and 10–15. These figures contain much of the quantitative information discussed in the manuscript, and all text should remain clearly readable at the final publication size. The authors should therefore regenerate the figures at publication quality, preferably in vector format, and increase the font sizes throughout. In addition, Fig. 2 provides a map of the participating stations but does not include latitude–longitude information or another geographic coordinate reference. I suggest that the authors systematically revise all figures to ensure consistent formatting, readable labels and legends, and sufficient resolution.

Minor comments

Introduction: The manuscript states that PRIDE VLBI measurements achieve accuracies of tens to hundreds of microarcseconds. It would be useful to distinguish the expected/general PRIDE performance from the accuracy actually achieved in the present JUICE observations, particularly since reliable astrometry was not obtained here.

Section 2.1: The statement that "phase coherence across all stations is maintained through the hydrogen maser references" is somewhat misleading since the stations use independent masers. I suggest referring instead to the local frequency stability and phase coherence required for subsequent VLBI correlation.

Section 2.1: "broadband receivers (12 GHz)" is ambiguous. Please clarify whether 12 GHz refers to the receiver bandwidth, observing-frequency coverage, or another quantity.

Section 2.2: Please define more precisely what is meant throughout the manuscript by "Doppler noise." Table 3 gives standard deviations of approximately 87–744 mHz, whereas residual levels of 3–5 mHz are quoted elsewhere. These presumably correspond to different processing steps and/or integration times, but the terminology currently makes direct comparison difficult.

Section 2.2: The processing description would benefit from stating clearly which integration time is associated with the final Doppler measurements used in the principal figures. Values ranging from 1 to 10 s are mentioned earlier, while 10 s appears to be typical for the dPLL output.

Section 3.1: Residual single-band delays of several hundred nanoseconds are attributed to the precision of the JUICE SPICE kernels. Other contributions could presumably include station clocks, atmospheric propagation, instrumental delays, station-coordinate errors, and details of the near-field delay model. Unless these contributions have been quantified, the attribution to the spacecraft ephemeris should be softened.

Figure 5: Six JUICE scans are overlaid in different colours. Since these are self-calibrated images, please explain explicitly what information should be inferred from the apparent source locations and whether the offsets between scans retain any astrometric meaning.

Section 3.2: The coordinate offsets that affected the August 13 phase-referencing observation should be quantified. This would help the reader understand whether the failure was primarily due to pointing, calibrator geometry, switching cadence, or other factors.

Figure 6: The approximately tenfold increase in Doppler noise associated with the transition from two-way to one-way tracking is interesting. A short physical explanation of why this increase is expected would be useful.

Table 2/Section 3.3: The observing intervals reported for August 19 do not appear fully consistent. For example, the Ceduna observing blocks and the Hartebeesthoek start/end times differ between Table 1, Table 2, and the text. Please check all reported times and use a consistent definition of recording time versus actual spacecraft tracking time.

Table 3: The SNR values for Hartebeesthoek are several orders of magnitude larger than those of the Australian stations. Please define the SNR estimator and state whether the values are linear or logarithmic and whether the bandwidth and integration time are identical between stations.

Figure 3: "60 dBs" should be "60 dB."

Figure 10: Please clarify what is meant by "closest approach to the Moon." Since this occurs after occultation egress in the figure, it would be useful to specify whether this refers to the minimum physical JUICE–Moon distance rather than the apparent geometry as viewed from Hartebeesthoek.

Figure 15: The statement that the spectrum resembles a Kolmogorov spectrum should be treated cautiously given that the caption attributes the dominant spectral features to electronic noise. Please clarify which part of the spectrum, if any, is interpreted as propagation-induced.

Figure 16: Please state clearly what TEC quantity is plotted, provide the units explicitly, and explain the physical parameters defining the nominal, slow, and fast solar-wind model curves.

Section 4: The statement that the high radial velocity of JUICE caused the spacecraft to separate rapidly from the calibrator in the plane of the sky should be corrected. Plane-of-sky separation is controlled by the apparent transverse/angular motion, not the radial velocity.

Section 4: Since the target–calibrator angular separation is identified as one of the principal limitations of the phase-referencing experiment, it would be useful to give the actual angular separation during the relevant observations.

Conclusions: The statement that "all experiments presented here were conducted in a continuous-tracking mode" appears inconsistent with the phase-referencing observations, for which the antennas switched between JUICE and calibrator sources. Please clarify what is meant by continuous tracking in this context.

Conclusions: The statement that nine VLBI phase-referencing experiments were successfully conducted should be clarified. Table 1 lists seven sessions around the gravity assist, some of which were Doppler-only, and at least one phase-referencing session did not achieve its original objective. If the nine experiments refer to the full two-year JUICE campaign, this should be stated explicitly.

Code and data availability: It would be useful to provide software versions, reference the principal processing tools and Tudat configuration, and, if available, include a permanent archive identifier for the observational data underlying the main figures.