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Mapping JUICE's Journey: PRIDE Observations from the Lunar–Earth Gravity Assist

Guifré Molera Calvés[1], Oliver James White[1], Jasper Edwards[1], Dominic Dirkx[2], Giuseppe Cimò[3,2], Tatiana M. Bocanegra-Bahamón[4], Sam Fayolle[5,2], Judit Fogasy[6], Sándor Frey[6], Luigi Gisolfi[2], Leonid I. Gurvits[2], Valery Lainey[7], Vidhya Pallichadath[2], Krisztina Perger[6], Sergey Pogrebenko[3], Jonathan Quick[8], Noor Masdiana Md Said[3], and Alfonso Sánchez Rodríguez[2]

[1]Physics discipline, School of Natural Sciences, University of Tasmania, Private Bag 37, Hobart, TAS 7000, Australia
[2]Delft University of Technology, Kluyverweg 1, 2629 HS, Delft, the Netherlands
[3]Joint Institute for VLBI ERIC, Oude Hoogeveensedijk 4, 7991 PD, Dwingeloo, the Netherlands
[4]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, 91109, CA, USA
[5]European Space Research and Technology Centre, ESA, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
[6]Konkoly Observatory, HUN-REN Research Centre for Astronomy and Earth Sciences, MTA Centre of Excellence, Konkoly Thege Miklós út 15-17, 1121 Budapest, Hungary
[7]IMCCE, Observatoire de Paris, Paris, 75014, France
[8]Hartebeesthoek Radio Astronomy Observatory, Krugersdorp, South Africa

Correspondence: Guifré Molera Calvés (guifre.moleracalves@utas.edu.au) and Dominic Dirkx (d.dirkx@tudelft.nl)

Abstract. This paper presents the results of Planetary Radio Interferometry and Doppler Experiment (PRIDE) observations of the JUICE spacecraft during its lunar and Earth gravity-assist manoeuvres on August 19 and 20, 2024, using a network of VLBI radio telescopes. Prior to the flyby sequence, VLBI phase-referencing observations were conducted to establish astrometric measurements and Doppler frequency calibration during the near-Earth approach. During the flyby events, the experiment successfully captured the signal ingress and egress during the lunar occultation, as well as the signal behaviour at closest approach to the lunar surface. Signal-diagnostic measurements were performed to characterise the received carrier signal and assess instrumental and propagation effects. The observed Doppler frequency measurements were subsequently compared with predicted values derived independently using the WebGeocalc service and the `Tudat` software framework. The close agreement between the measured Doppler observables and model predictions confirms that the tracking results are consistent with expectations for JUICE's cruise-phase configuration and the high-velocity dynamics of the Earth flyby. Finally, these measurements were also used to obtain complementary measurements of the terrestrial ionosphere and space weather conditions, and are being used for refining solar wind models using planetary spacecraft radio tracking.

1 Introduction

The Planetary Radio Interferometry and Doppler Experiment (PRIDE) employs ground-based radio techniques to perform precision tracking of interplanetary spacecraft. The PRIDE technique builds on more than two decades of experience in radio tracking of spacecraft using existing radio-astronomy infrastructure. Its development traces back to the very long baseline interferometry (VLBI) observations of the Huygens probe in 2004, which represented the first large-scale demonstration of

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global interferometric tracking of a planetary entry probe (Bird et al., 2005). Subsequent missions have allowed the PRIDE methodology to mature and expand in scope. The technique has been developed through campaigns with the European Space Agency (ESA) Venus Express and Mars Express missions, encompassing a wide range of radio science applications (Duev et al., 2012, 2016; Bocanegra-Bahamón et al., 2018, 2019; Sánchez Rodríguez, 2026). These include phase-referencing VLBI measurements for precise astrometric tracking and spacecraft radio occultations used to reconstruct vertical profiles of planetary atmospheres. In parallel, PRIDE has consistently incorporated single-dish Doppler and phase scintillation observations to probe the propagation medium between Earth and the spacecraft (Molera Calvés et al., 2014; Kummamuru et al., 2023). Measurements of interplanetary scintillation along the line of sight have provided valuable diagnostics of space weather conditions and solar wind turbulence (Molera Calvés et al., 2017). This body of work has established PRIDE as a flexible and robust framework for combining astrometric, radio science, and plasma-diagnostic measurements for deep-space missions.

The PRIDE experiment complements the core science of ESA's Jupiter Icy Moons Explorer (JUICE) mission by providing independent measurements of the spacecraft's radial velocity and plane-of-sky position in the celestial reference frame (Gurvits et al., 2023). PRIDE delivers differential lateral position measurements of the spacecraft relative to background extragalactic radio sources that define the International Celestial Reference Frame (ICRF, Charlot et al., 2020). These measurements achieve accuracies of tens to hundreds of microarcseconds over integration times ranging from minutes to tens of minutes. These observables enhance the determination of spacecraft state vectors and support a range of scientific and navigation-related applications. In particular, the inclusion of VLBI-based spacecraft tracking will improve ephemerides of Jupiter and the Galilean satellites (Dirkx et al., 2016; Fayolle et al., 2024), supporting investigations of the internal structure and long-term evolution of Ganymede, Europa, and Callisto, and improving the geophysical interpretation of other JUICE data.

The effectiveness of the PRIDE methodology has been demonstrated in previous planetary missions and is now being applied and extended within the JUICE mission. In addition to its role in precise orbit determination, PRIDE contributes to mission science through complementary experiments, including radio occultations, which provide constraints on planetary environments, and investigations of heliospheric effects. Together, these applications enhance the overall scientific return of JUICE by augmenting the mission's in situ and remote-sensing measurements with highly sensitive ground-based radio telescopes.

During the first two years of the cruise phase, the University of Tasmania (UTAS, Australia), in collaboration with the PRIDE team led by JIV-ERIC and TU Delft in the Netherlands, conducted more than 100 radio-tracking observations of the JUICE spacecraft (White et al., ASRC 24). Figure 1 summarises all observations conducted to date. The UTAS network comprises the 30-m Ceduna (Cd) radio observatory in South Australia, the 26-m (Ho) and the 12-m (Hb) radio telescopes located in Hobart, Tasmania, and the 12-m antennas at Katherine (Ke) and Yarragadee (Yg) geodetic stations in the Northern Territory and Western Australia, as shown in Figure 2. Together, these facilities form a continental-scale VLBI array spanning Australia. This infrastructure enabled both routine Doppler tracking and high-precision VLBI measurements for spacecraft navigation support and radio science investigations.

Two primary observational modes were employed throughout the JUICE cruise-phase observations, following the framework described in Gurvits et al. (2023): single-station Doppler tracking and VLBI phase-referencing experiments. Single-station

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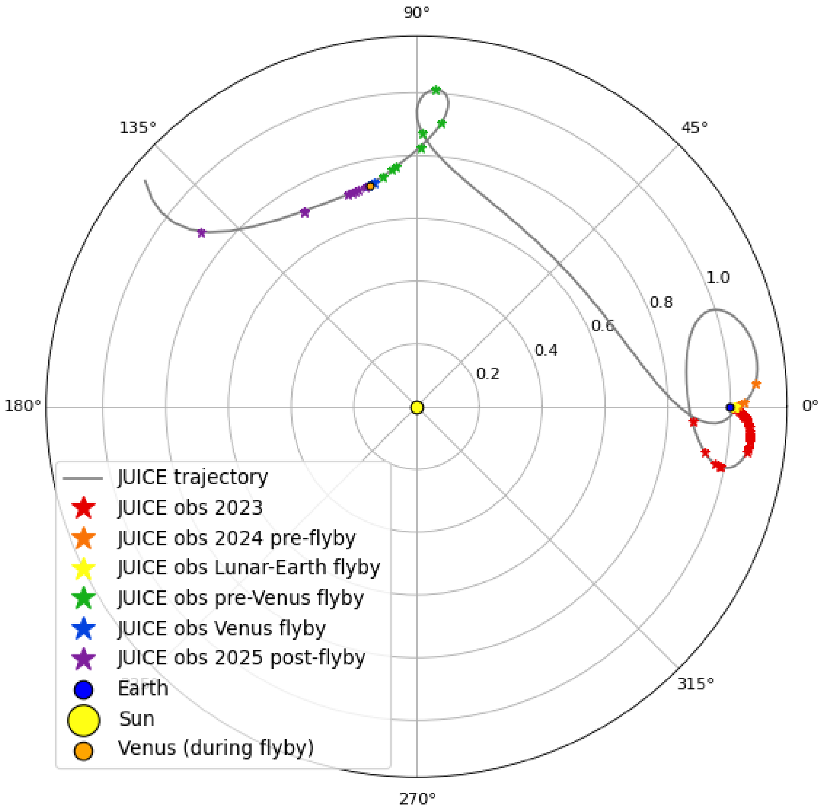

Figure 1. Summary of PRIDE observations of the JUICE mission during the first two years of the cruise phase. The projection is a top-down view of the Solar System with Earth fixed at 0° and 1 AU distance, and Venus located at its relative position during the 2025 JUICE flyby (White et al., ASRC 24).

Doppler observations are performed with individual antennas; although multiple stations may observe simultaneously, each does so independently. In contrast, phase-referencing observations require rapid switching between the spacecraft and a nearby compact calibrator source, enabling high-precision astrometric measurements; this mode requires all participating observatories to follow a common observation schedule. Doppler tracking is primarily used for space weather investigations (Molera Calvés et al., 2021; Edwards et al., 2025a), planetary radio occultations (Bocanegra-Bahamón et al., 2018, 2019), and validation of signal quality (Kummamuru et al., 2025). Recent work has shown that Doppler measurements can be processed using the TU Delft Astrodynamics Toolbox (Tudat) software package (Gisolfi et al., 2025; Sánchez Rodríguez, 2026) to perform spacecraft orbit determination solutions using PRIDE Doppler data (at an accuracy comparable to state-of-the-art analyses from regular Doppler data). Phase-referencing observations have been shown to provide two-dimensional position estimates of the

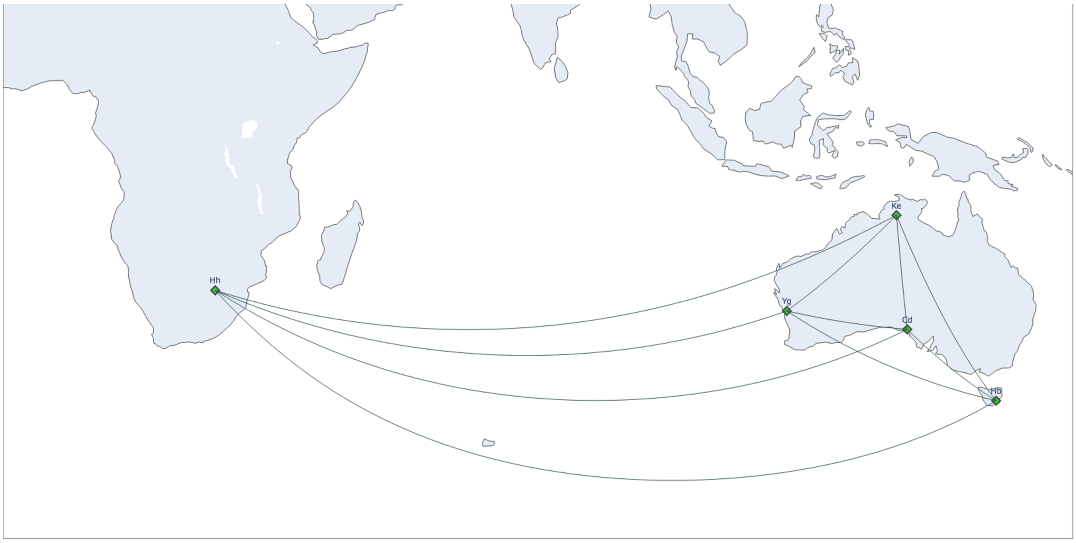

Figure 2. University of Tasmania (UTAS) array of radio telescopes including Hobart, Katherine, Yarragadee (12-m), Hobart-26, and Ceduna (30-m). This configuration was complemented during the Lunar–Earth gravity assist with the Hartebeesthoek radio telescope (26-m) in South Africa.

spacecraft in the plane of the sky. While Doppler observations were conducted regularly over the two-year observation period, phase-referencing experiments were reserved for key mission events, including the lunar–Earth gravity assist and Venus flyby.

2 Data and Methods

PRIDE was developed as a mission-enhancement activity to maximise the scientific return of space missions by utilising existing spaceborne and ground-based infrastructure. However, neither component was originally developed specifically for PRIDE; both were instead designed to fulfil their respective primary objectives. During flight operations, the JUICE onboard instrumentation functions in accordance with the mission's core scientific goals, while the global network of VLBI radio telescopes operates within the framework of its own independent astrophysical and geodetic research programmes. The effectiveness of PRIDE therefore relies on the careful definition and optimisation of the operational interface between these two fundamentally different systems, ensuring that spacecraft tracking procedures are adapted to the operational constraints of astronomical facilities (Pallichadath et al., 2025).

2.1 Station Configuration

All UTAS radio telescopes are equipped with standard VLBI back-end systems, hydrogen-maser frequency standards, and narrowband (hundreds of MHz) or broadband receivers (12 GHz) both suitable for spacecraft tracking. The smaller antennas employ dual-linear polarisation receivers, while the larger antennas are equipped with right- and left-hand circular polarisation receivers. For these observations, two parallel data-acquisition chains were operated at the four sites:

- Conventional Digital Baseband Converter 2 (DBBC2) VLBI backends for the Ceduna, Hobart 26-m, and Hartebeesthoek antennas, and the DBBC3 VLBI backend for the broadband 12-m antennas (Molera Calvés et al., 2021).
- Software-defined radio (SDR) units using Ettus Research Universal Software Radio Peripheral (USRP) hardware. A set of USRP X310 and X410 units deployed across all participating UTAS sites.

This dual-device configuration allowed us to record both standard VLBI narrowband data and high-bit-depth complex samples simultaneously, providing redundancy and flexibility during the rapidly evolving gravity assist event.

The DBBC3 units initially operated with 32-MHz channels and 2-bit sampling, while the newest firmware updates allowed narrower bandwidths and up to 8-bit sampling for improved dynamic range. In parallel, the SDR systems produced real or complex data streams at 32-bit depth with 1-MHz bandwidth, offering an independent, high-precision dataset optimised for planetary spacecraft tracking. The DBBC2 units recorded across 4 channels with frequency bandwidths of 8 or 16 MHz. All recorded data were stored locally and transferred via network links for subsequent correlation and Doppler analysis.

All receiving systems are referenced to on-site hydrogen maser frequency standards, which provide a stable 10 MHz reference for radio-frequency down-conversion and signal digitisation. The hydrogen masers exhibit fractional frequency stability characterised by an Allan deviation of approximately 10^{-13} at 1 s reaching a few times 10^{-15} over integration times of 10^{2}–10^{4} s. Phase coherence across all stations is maintained through the hydrogen maser references. In addition, a one-pulse-per-second (1 PPS) signal is distributed to ensure synchronous start and stop times across the recording systems. Data acquisition is further synchronised to GPS-derived time stamps recorded locally at each station for time alignment during VLBI correlation and analysis.

2.2 Data Processing and Logistics

The single-dish Doppler data were processed using the Multi-Tone spacecraft tracking software developed for use with VLBI radio telescopes (Molera Calvés et al., 2021). The raw data were processed with the `SWspec` to obtain an initial spectral overview the broadband spectra of the full recorded bandwidth containing the spacecraft signal. The integration time varied from 1 to 10 seconds with 2 to 10 Hz frequency resolution, depending on the spacecraft's radial velocity and downlink transmission power.

The carrier signal was first tracked in frequency and used to derive phase-polynomial representations over 20-minute scans. These phase polynomials were subsequently applied within the `SCtracker` program, which phase-stopped the carrier tone and produced a binary spectral file with a bandwidth of 2 kHz, centred on the expected signal frequency. Finally, a digital phase-locked loop (dPLL) was applied to generate high-precision frequency and phase estimates on shorter timescales, typically using an integration time of 10 s. Figure 3 presents a summary of this dPLL output.

The extracted carrier phases can be used to compute a phase power spectral density of the residual fluctuations. A frequency threshold is then applied to this spectrum based on the scan length and contributions from system noise, separating the signal of

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interest from instrumental contributions. A Kolmogorov spectrum can subsequently be fitted to the remaining signal to estimate the contribution of the interplanetary plasma to the observed phase fluctuations.

For the VLBI phase-referencing sessions, we used the Distributed FX (`DiFX`) software correlator (Deller et al., 2007) to correlate the raw data, with `DiFXcalc` (Gordon et al., 2016) providing the delay models. The correlated outputs were first analysed in `fourfit` to confirm successful correlation and measure residual single-band delays (SBD). For JUICE, we employed the Duev near-field delay model (Duev et al., 2012; Duev et al., 2015), with ephemerides derived from the operational JUICE (OPS) SPICE kernels. `DiFXcalc` also implements the Sekido–Fukushima and spacecraft ranging delay models; however, differences in single-band delays between models were negligible, and we therefore adopted the Duev model, as it was designed specifically for PRIDE VLBI experiments. In parallel, the results were validated with the European VLBI Network (EVN) software correlator (`SFXC`) (Keimpema et al., 2015), which uses a different implementation of the Duev model.

The correlated data were then compiled into a FITS-IDI file for analysis with the Astronomical Image Processing System (`AIPS`). We have implemented pipelines for fringe-finding and for producing self-calibrated images of both the spacecraft and phase-reference sources. Ongoing work aims to refine the phase solutions and apply them to produce phase-calibrated images of JUICE, which will enable measurement of the spacecraft's offset from phase centre and refinement of the spacecraft's ephemeris.

2.3 Observations

We conducted seven VLBI sessions spanning the period before, during, and after the gravity assist event, as summarised in Table 1. The first session took place on August 3, 2024, and consisted of a phase-referencing experiment (`jc0803`) designed to obtain an initial VLBI-based position estimate of the spacecraft. This early observation served as the reference point for the subsequent tracking sessions leading up to the lunar and Earth gravity assists events.

Table 1. Summary of the VLBI and Doppler observations supporting the 2024 JUICE lunar–Earth gravity assist conducted by the PRIDE team.

Date	Time (UTC)	Antennas	Distance (AU)
03.08.24	19:00–21:30	Hb Ke Yg	0.029
13.08.24	19:00–21:45	Hb Ke Yg	0.013
14.08.24	19:00–21:45	Hb Ke Yg	0.011
19.08.24	10:00–22:00	Hb Ke Yg Cd Hh	0.002
20.08.24	17:30–21:15	Hb Ke Yg Cd Hh	0.001
21.08.24	04:06–10:00	Cd	0.002
22.08.24	04:06–11:00	Cd	0.004

To support the VLBI tracking of JUICE, we selected three extragalactic radio sources to serve complementary calibration and referencing roles. The bright, compact source J2258-2758 was used as a fringe finder to verify antenna performance, calibrate station clocks, and ensure the stability of the array. Given the spacecraft's high apparent sky motion and the limited number of suitably close calibrators, we identified two additional reference sources, J2229-0832 and J2240-0836, all located within 5° of the spacecraft's trajectory during the session. These nearby calibrators were selected to enable rapid phase referencing and to minimise differential atmospheric effects.

The observation was carried out using the Hobart, Katherine, and Yarragadee antennas of the Australian VLBI network, providing long north–south and east–west baselines well suited for precise plane-of-sky tracking. The session ran from 19:00 to 21:30 UTC, during which we alternated between the spacecraft and the selected reference sources on a one-minute cycle. This fast switching cadence ensured frequent calibration updates while maintaining sufficient on-source time for high-quality VLBI delay measurements.

These observations were followed by two additional sessions on August 13 and 14. The August 13 session (`jc0813`) was conducted in phase-referencing mode, with the aim of providing an updated VLBI position estimate as the spacecraft approached the lunar flyby. The subsequent session on August 14 (`jc0814`) was carried out in single-dish Doppler mode, enabling high-precision line-of-sight velocity measurements to complement the interferometric data. Together, these observing sessions strengthened the pre-flyby trajectory reconstruction, ensured continuity of the tracking campaign leading up to the gravity assist event, and improved the robustness of the tracking campaign. Figure 3 presents an example of the signal recorded at the Katherine antenna. The upper panel shows the spacecraft carrier signal within a 2 kHz bandwidth after two iterations of phase stopping. The second panel displays the carrier signal-to-noise ratio, which is above 60 dBs. The third panel presents the topocentric frequency measurements following the two phase-stopping steps, where the residual frequency fluctuations are confined to within 5 mHz, as further illustrated by the residuals shown in the fourth panel. For more information on the data types, see Molera Calvés et al. (2021).

The lunar–Earth gravity assist event was monitored through two dedicated observing sessions conducted on August 19 and 20. On August 19, VLBI tracking was performed between 10:00 and 15:00 UTC using the Ceduna, Hobart 12-m, Katherine, and Yarragadee antennas, providing continuous coverage of the inbound segment of the lunar flyby. This was followed by a second observing block with Ceduna from 17:30 to 21:15 UTC, which extended the tracking beyond the first observing window. The August 19 observations concluded with a final block using the 26-m Hartebeesthoek (Hh) antenna in South Africa between 19:00 and 22:00 UTC. The inclusion of the South African station enabled extended longitudinal coverage and allowed the lunar radio-occultation phase, including signal egress, to be observed under favourable elevation conditions that were not achievable with the Australian antennas. For the lunar flyby, we combined phase-referencing scans with single-dish Doppler measurements to maximise the PRIDE's observational capabilities while accommodating the spacecraft's transmission schedule and the cycling of the target and calibrator sequence.

The Earth flyby PRIDE observations on August 20 tracked the signal of JUICE continuously for the entire session, again using the same set of antennas where station visibility permitted. Tracking was performed between 17:30 and 21:15 UTC, constrained both by station elevation limits and the spacecraft's transmission windows with the European Space Tracking (ESTRACK) ground station of New Norcia. These measurements provided high-precision line of sight velocity data during closest approach. Over the two days following the Earth flyby, Doppler observations were conducted with the Ceduna radio telescope.

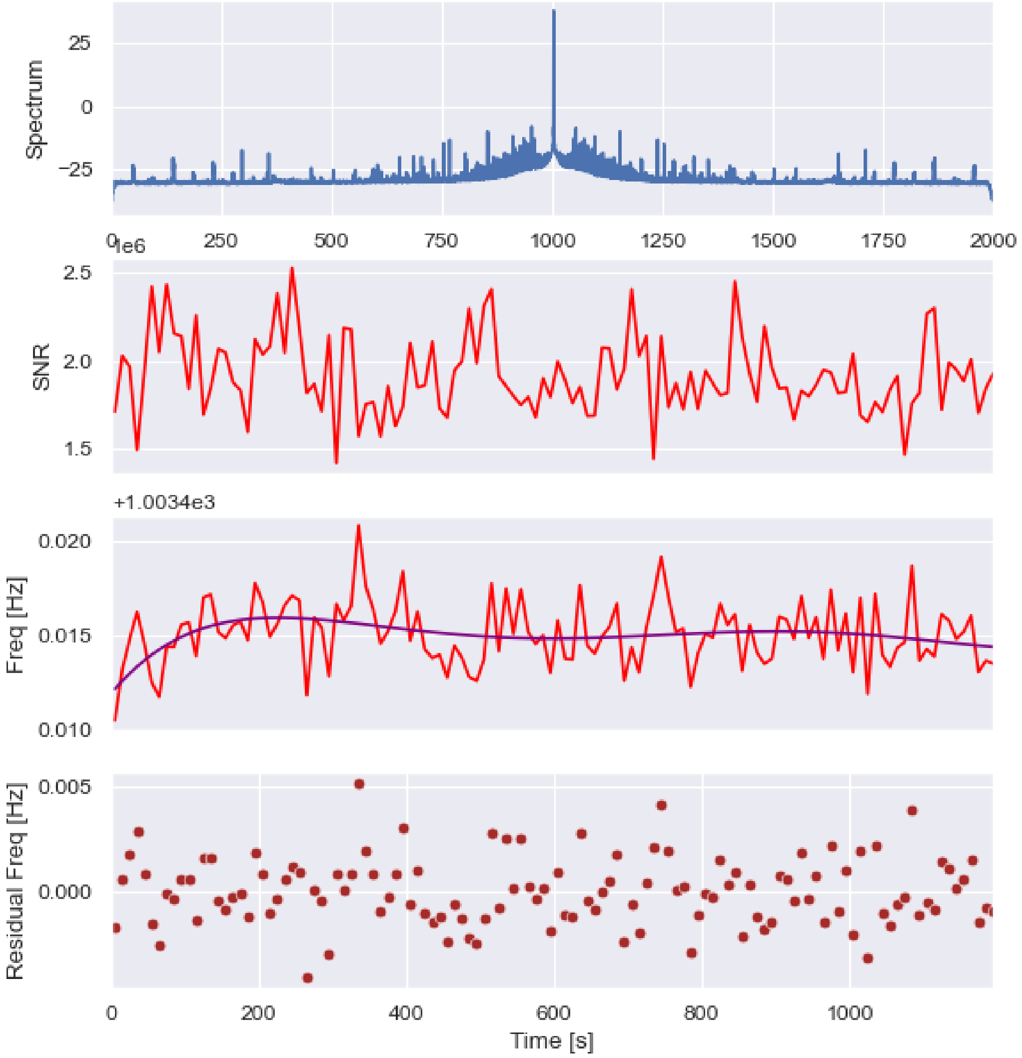

Figure 3. Summary of the frequency detections for the `jc0814` session observed at Katherine. The upper panel displays the carrier signal after a complete phase stop over a 20-minute window. The second and third panels show the signal-to-noise ratio and baseband frequencies as a function of time after Doppler compensation. The bottom panel displays the second set of frequency residuals, i.e., Doppler noise.

3 Results

This section is divided into selected observations before, during, and after the lunar–Earth gravity assist event, highlighting the key results obtained and the lessons learned at each stage.

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3.1 August 3, 2024: VLBI Experiment

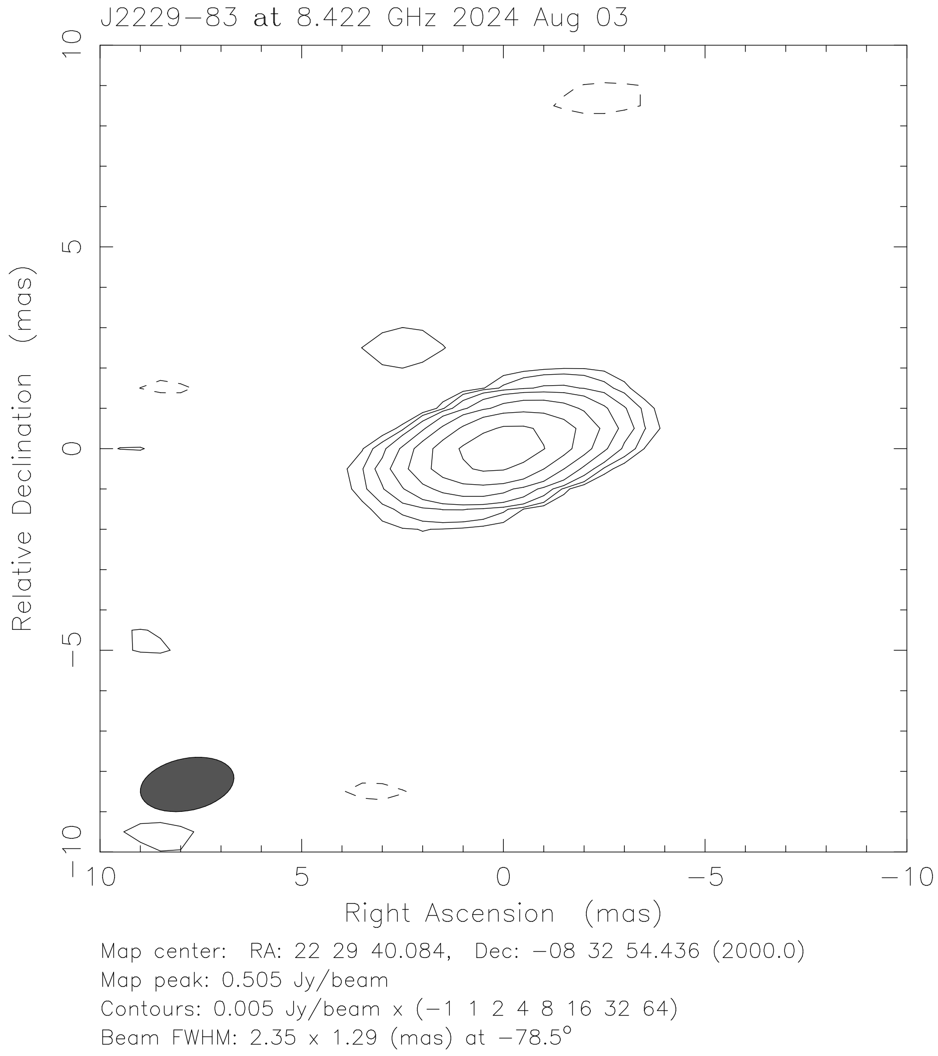

Figure 4. Self-calibration image of phase-calibrator quasar J2229-0832 during the August 3 VLBI experiment (White et al., 2025a).

The August 3 PRIDE phase-referencing VLBI experiment represented the first successful imaging of JUICE during the cruise phase. The 12-m antennas at Hobart, Katherine, and Yarragadee were used, with J2258-2758 as the fringe-finder source, and J2229-0832 and J2240-0836 as phase-reference sources.

The phase calibrator scans were successfully correlated along every baseline for all J2229-0832 scans, and this source was therefore used as the calibrator in further processing. The Duev near-field model was used in the successful correlation of the JUICE scans. Significant, though not unexpected, residual single-band delays (SBD) were present in the JUICE scans, of the order of a few hundred nanoseconds. Single-band delays measure the residual group delay within a single frequency band after correlation; large values indicate a mismatch between the delay model and the actual spacecraft position. We attribute these residuals to the precision of the JUICE SPICE kernels, and the accuracy of the orbital model will be assessed once phase-calibrated images of JUICE have been produced in future analysis.

180 Self-calibrated images of both J2229-0832 and JUICE were produced in `Difmap` and `AIPS`, respectively, as shown in Figures 4 and 5. Self-calibration is an iterative technique in which an initial source model is used to correct antenna-based phase and amplitude errors in the visibilities, progressively improving image fidelity without relying on an external calibrator. Work is underway to apply the resulting phase calibration solutions to JUICE in order to determine its position offset from the a priori orbital model.

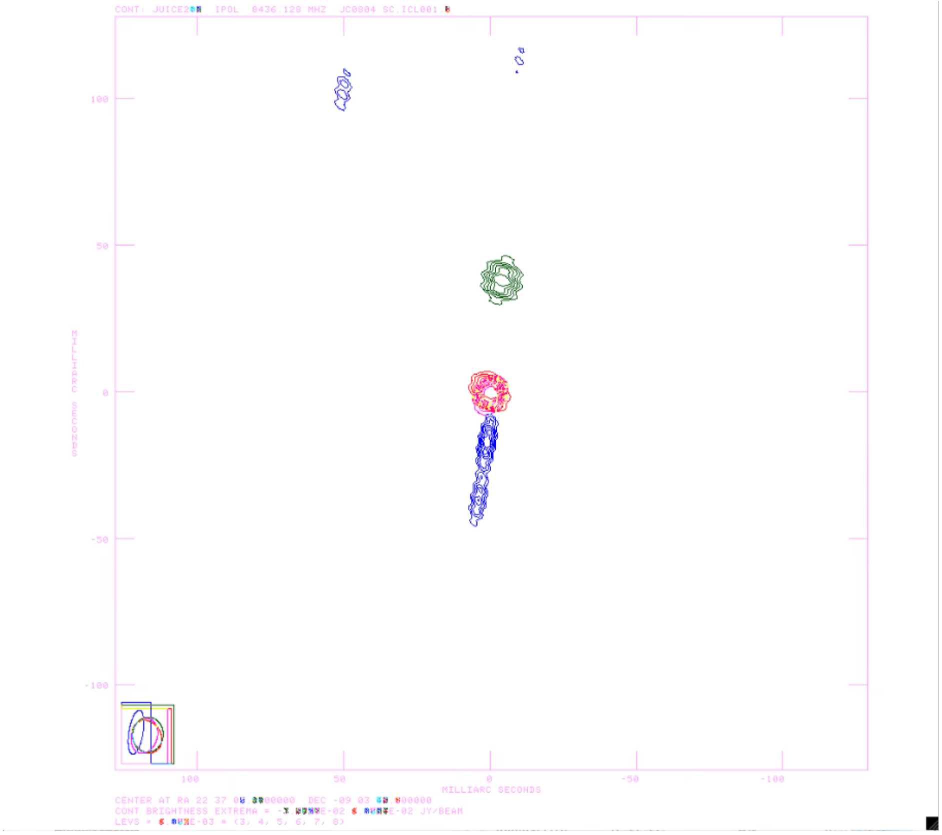

Figure 5. Self-calibration images of JUICE during the August 3 VLBI experiment. Six scans from 20:03 to 21:24 UTC have been overlaid in different colours.

3.2 August 13 and 14, 2024: VLBI Experiment and Doppler

An additional phase-referencing VLBI observation was conducted on August 13, 2024; however, this session encountered several technical and operational challenges. First, small offsets in the planned coordinates of both the spacecraft and the phase-reference calibrator arose due to an error during the scheduling and setup phase, resulting in sub-optimal source pointing. Second, the frequent switching between the target and calibrator required the antennas to re-slew and recalibrate at each cycle very frequently, substantially reducing the effective on-source integration time. Approximately half of the session was devoted to calibration rather than data acquisition. Although these limitations prevented the observation from achieving its original objectives, the experience proved valuable in refining future planning procedures, verifying antenna coordinates, and improving calibration strategies for later experiments.

On August 14, 2024, a dedicated set of Doppler-tracking observations was carried out using Hb, Ke, and Yg antennas. For this session, we employed a continuous-tracking approach with repointing every second, rather than the standard VLBI nodding approach. This eliminated the pointing offsets introduced during the previous day's phase-referencing experiment and enabled stable tracking throughout the session. All three radio telescopes successfully delivered continuous Doppler measurements throughout the session.

Figure 6 shows the topocentric frequency detections from the three stations throughout the experiment. The spacecraft's transition between two-way and one-way tracking modes was clearly identified in the Doppler time series. These data provide a valuable test case for upcoming analyses and will be used with the newly implemented `Tudat`-based orbit determination framework processing both PRIDE open-loop and closed-loop Doppler data, to refine the JUICE orbital solution.

3.3 August 19, 2024: Lunar Gravity Assist

On August 19, 2024, the JUICE lunar gravity assist was supported by a coordinated ground-based radio-tracking experiment using a global network of radio telescopes. Observations were conducted at the Ceduna, Yarragadee, Katherine, Hartebeesthoek, and Hobart-12m station, providing extensive temporal and geometric coverage of the flyby. The combined dataset enabled continuous monitoring of the spacecraft signal before, during, and after the lunar encounter, supporting radio science investigations of the lunar flyby, as summarised in Table 2.

Table 2. Observing times for the JUICE lunar gravity assist experiment on August 19, 2024. Start and end times are expressed in UTC.

Station	Antenna Location	Start Time	End Time
Cd	Ceduna, Aus	10:54:15	15:01:15
Cd	„	15:45:00	20:45:00
Hb	Hobart, Aus	10:54:15	15:01:15
Ke	Katherine, Aus	10:54:15	15:01:15
Yg	Yarragadee, Aus	10:54:15	15:01:15
Hh	Hartebeesthoek, SA	19:11:00	22:10:00

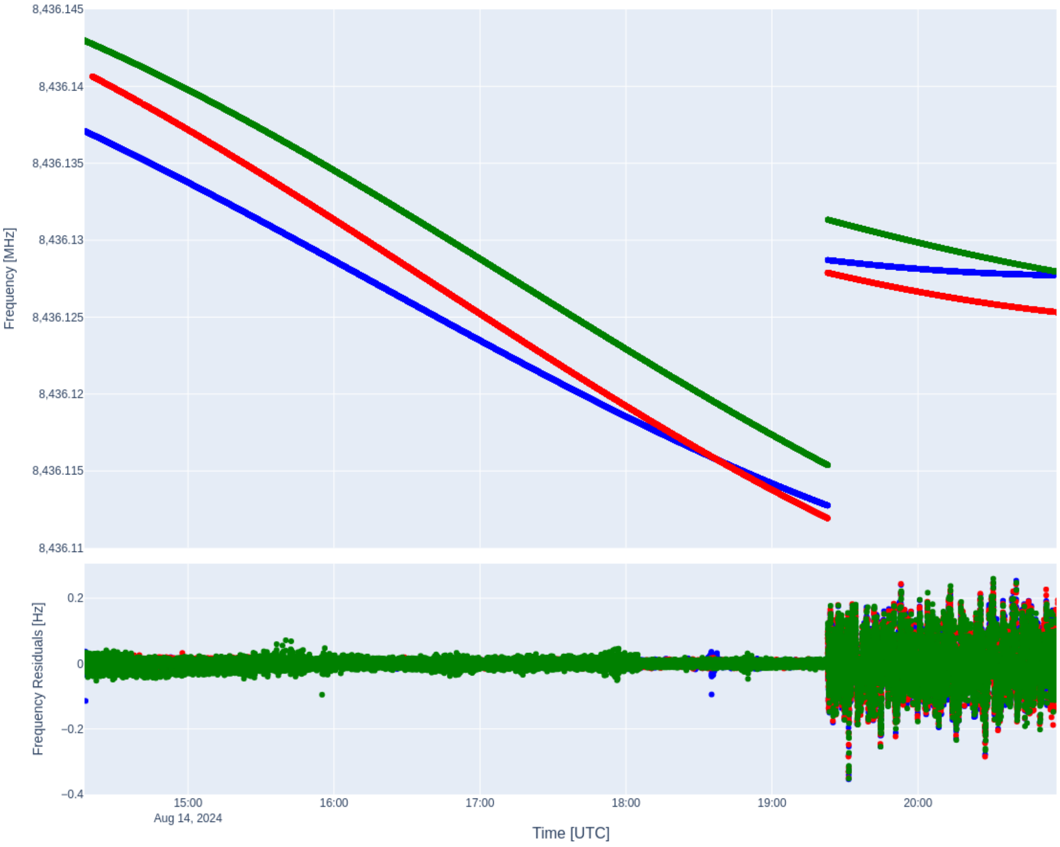

Figure 6. Topocentric frequency detections of JUICE on August 14. The communication mode switched from two-way to one-way at 19:30, when the Doppler noise increased tenfold. Hb (blue), Ke (red), and Yg (green).

The European Space Tracking (ESTRACK) network antenna at New Norcia (NNO) provided an uplink transmission to support continuous two-way tracking of the JUICE spacecraft. The uplink commenced at 10:58:36 UTC at a transmitted frequency of 7180.142419 MHz, selected to maintain the received signal within the capture and tracking bandwidth of the spacecraft transponder throughout the pass. The downlink signal was coherently generated onboard by the spacecraft transponder, enabling stable two-way frequency tracking. At the end of the tracking interval, the residual receiver loop offset from the nominal carrier frequency was approximately +37 Hz, confirming stable closed-loop operation throughout. The uplink transmission was terminated at 22:10:22 UTC.

Figure 7 shows the azimuth and elevation angles of the JUICE spacecraft as observed by each of the five participating antennas. The Ceduna station reached its minimum elevation during the lunar radio occultation, and, as a result, was unable to continue tracking the spacecraft through the egress phase. Consequently, only the Hartebeesthoek antenna was able to observe the egress of the signal. While the minimum elevation varies between stations, it typically lies in the range of 5–9° for the UTAS antennas.

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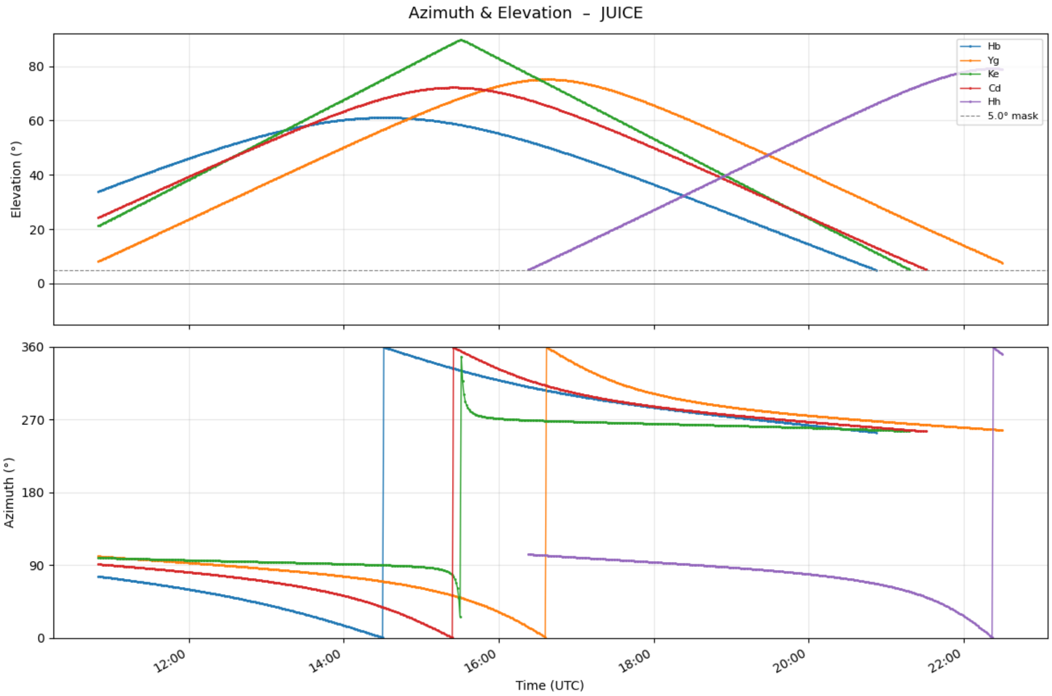

Figure 7. Azimuth and elevation of JUICE as observed by the participating antennas during the August 19 lunar gravity assist. Ceduna reached its minimum elevation during the lunar radio occultation, limiting egress detection to the Hartebeesthoek antenna.

For the lunar gravity assist tracking campaign, we conducted a phase-referencing experiment starting well in advance of the nominal tracking window and continuing until JUICE set below the horizon as seen from the Australian stations. The bright calibrator source $J1924$-2914 was observed for initial system calibration and fringe-finding. Subsequently, the nearby compact source $J2211$-1328 was used as the phase-reference calibrator throughout the experiment. The key parameter indicators of the detections are summarised in Table 3. 225

Table 3. Summary of signal-to-noise ratio (SNR) and Doppler statistics for the JUICE lunar gravity assist tracking experiment on August 19, 2024. Cd, Yg, Ke, and Hb are from the VLBI tracking experiment, whilst Hh is the Doppler session during the flyby itself.

Antenna	Total Doppler Shift (Hz)	SNR (min)	SNR (max)	SNR (mean)	Doppler Noise Std. Dev. (mHz)
Ceduna (Cd)	13734	87	1367	791	266
Yarragadee (Yg)	11198	15	3775	1176	183
Katherine (Ke)	14783	21	186	61	538
Hobart (Hb)	13689	13	1268	174	744
Hartebeesthoek (Hh)	33821	272632	564088	314268	87

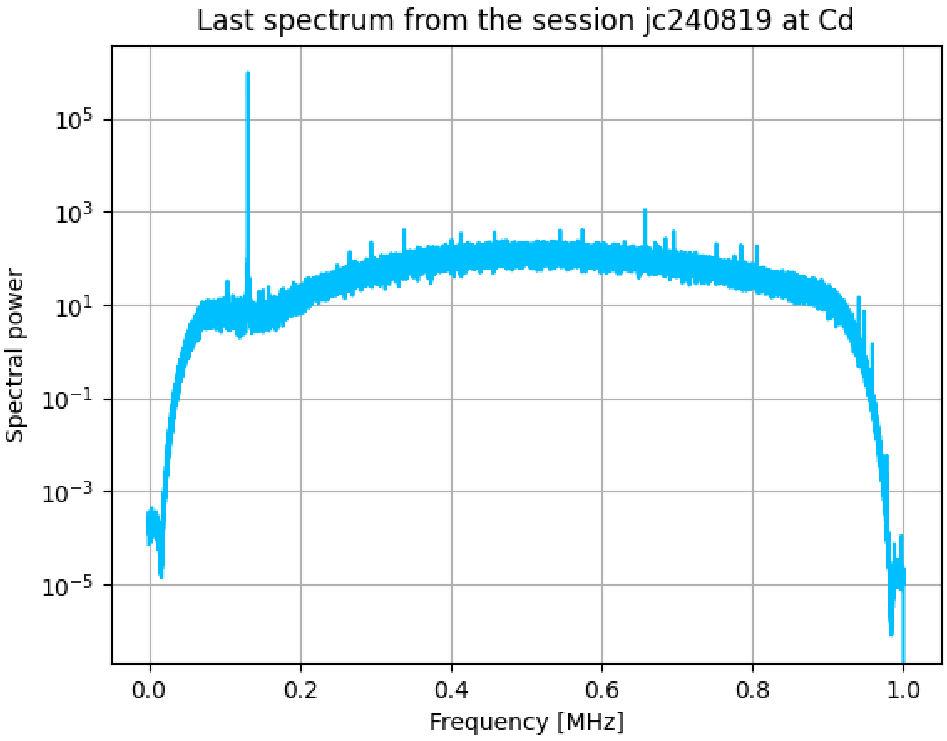

Figure 8. Full spectrum of the JUICE carrier signal recorded with the software-defined radio during the lunar flyby. The initial baseband channel was set to 8436.00 MHz.

Figure 8 presents full narrowband spectral representations of the received signal, showing the JUICE carrier tone at an offset of approximately 0.1 MHz within the recorded bandpass. The spectra were generated after frequency down-conversion and channelisation, allowing the spacecraft signal to be isolated from the surrounding noise floor. For these observations, the lower edge of the recorded bandpass was set to 8436.00 MHz.

Following the VLBI observations, only the Ceduna radio telescope continued tracking the Doppler signal from JUICE. This stand-alone Doppler session extended from 15:30 to 20:45 UTC, by which time the spacecraft had become occulted by the Moon. As a result, the observations captured the ingress of the spacecraft signal behind the lunar limb. Figure 9 shows the Doppler time series as recorded by Ceduna during this interval.

The Hartebeesthoek radio telescope commenced observations at 19:11 UTC and continued tracking the JUICE spacecraft until 22:00, providing extended longitudinal coverage during the flyby. This interval encompassed the ingress, egress, and closest approach of the spacecraft relative to the Moon, allowing the full geometry of the lunar radio occultation to be observed from the South African station. The corresponding Doppler frequency measurements, shown in Figure 10, capture the signal's disappearance and re-emergence associated with the occultation, as well as the rapid dynamical evolution near closest approach.

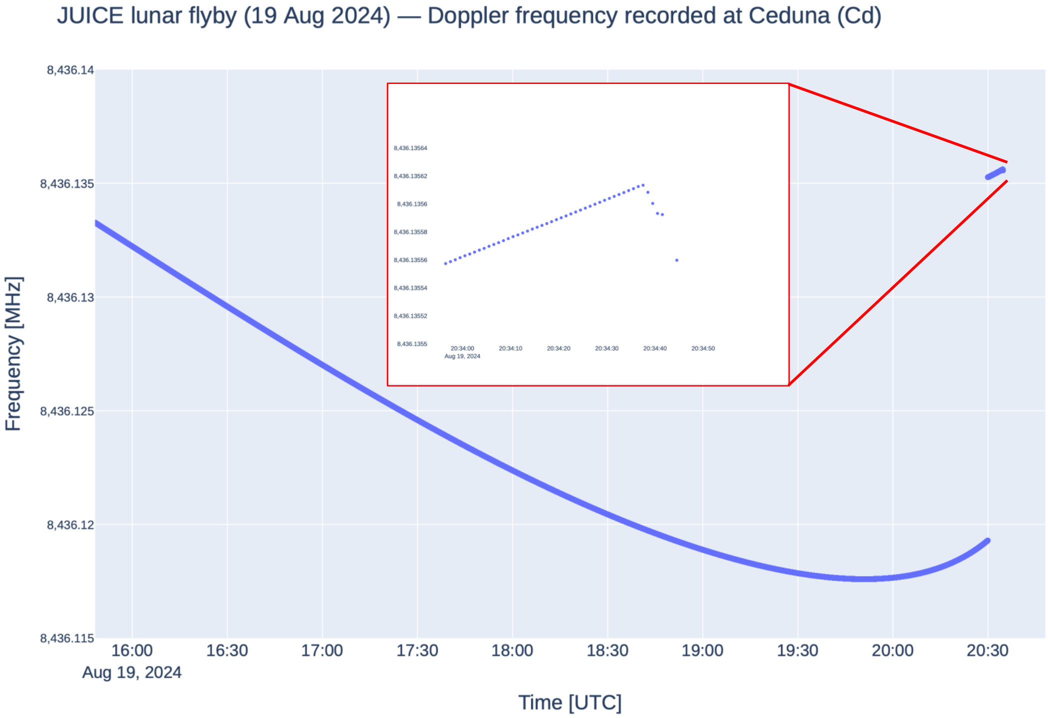

Figure 9. Doppler frequency detections of the JUICE spacecraft during its lunar gravity assist manoeuvre on August 19, 2024, as observed by the Ceduna radio telescope. The frequency evolution reflects the spacecraft's changing line-of-sight velocity relative to the ground station. A frequency jump is visible at approximately 20:30, corresponding to the transition from two-way to one-way tracking mode. The inset shows a zoom into the signal ingress during the lunar occultation.

Annotations included in the figure indicate changes in the spacecraft communication mode, aiding interpretation of the observed Doppler features in the context of mission operations.

Figure 11 summarises the Doppler residuals of the topocentric frequency detections with respect to the polynomial fit over the full observing session. The observations were segmented into continuous 20-minute intervals, ensuring continuity between scans during processing and enabling a consistent evaluation of Doppler stability throughout the session. The resulting residual Doppler measurements were maintained at a stable level of approximately 3 mHz.

3.4 August 20, 2024: Earth Gravity Assist

As during the lunar gravity assist, the New Norcia antenna again provided an uplink transmission over an extended tracking session during the Earth gravity assist. The uplink commenced at 11:32:17 UTC, transmitting a Doppler-compensated uplink frequency of 7180.127320 MHz. By the end of the frequency sweep, the onboard residual receiver loop offset from the nominal

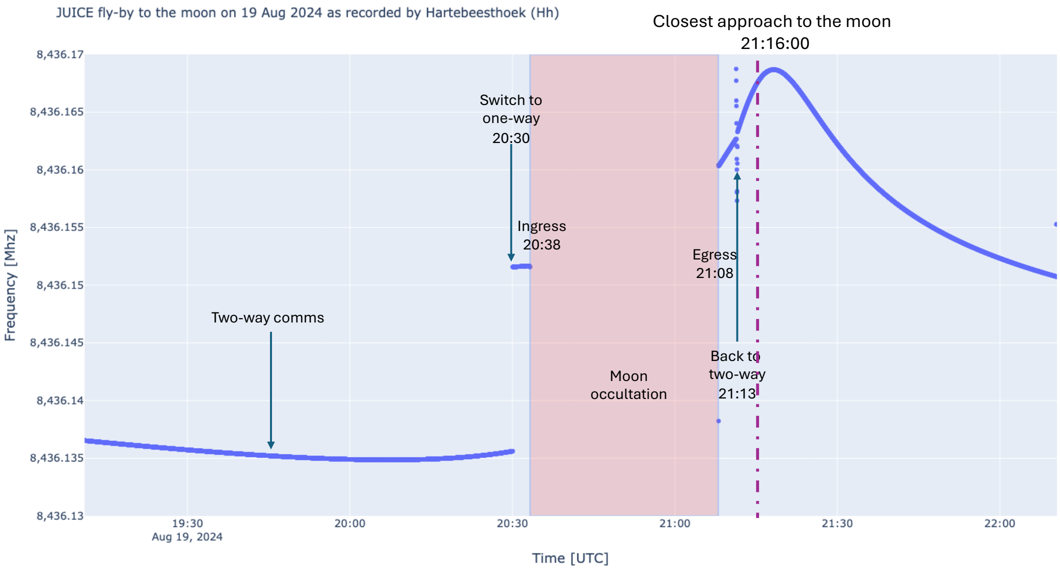

Figure 10. Revised Doppler frequency measurements obtained with the Hartebeesthoek antenna during the lunar flyby observation. The time series shows the lunar radio-occultation event, including the ingress and egress of the spacecraft signal, with the occultation interval highlighted in red. Annotations indicating the spacecraft communication mode transitions are included to assist the interpretation of the different operational phases of the mission.

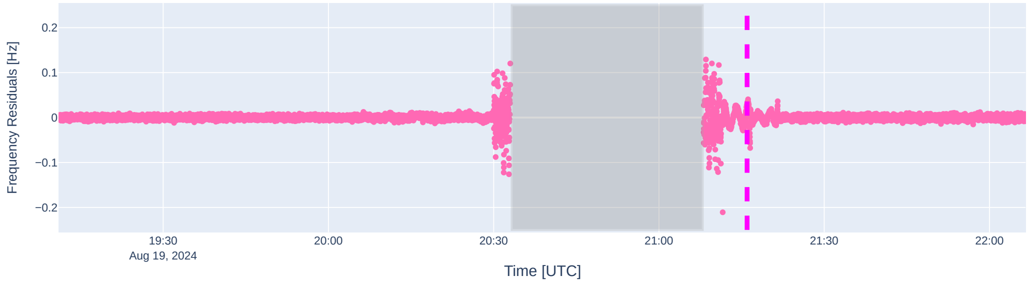

Figure 11. Residual Doppler frequency fluctuations measured over the full tracking session. The data are primarily segmented into continuous 20-minute intervals to avoid discontinuities in the frequency time series. However, shorter intervals were utilised around the occultation period to prevent large residuals due to frequency jumps or loss of signal. The residuals are consistently at the 3 mHz level. The radio occultation is highlighted in grey.

carrier frequency was approximately -31 Hz, indicating stable closed-loop tracking conditions throughout the pass. The uplink
250 transmission was terminated at 19:28:09 UTC, completing the planned Doppler-compensated support interval.

Tracking and data acquisition with the Australian radio telescopes commenced at 12:00 UTC. The Ceduna antenna was the first station to acquire the JUICE signal. Due to prior scheduling commitments, the 12-m antennas were unable to begin

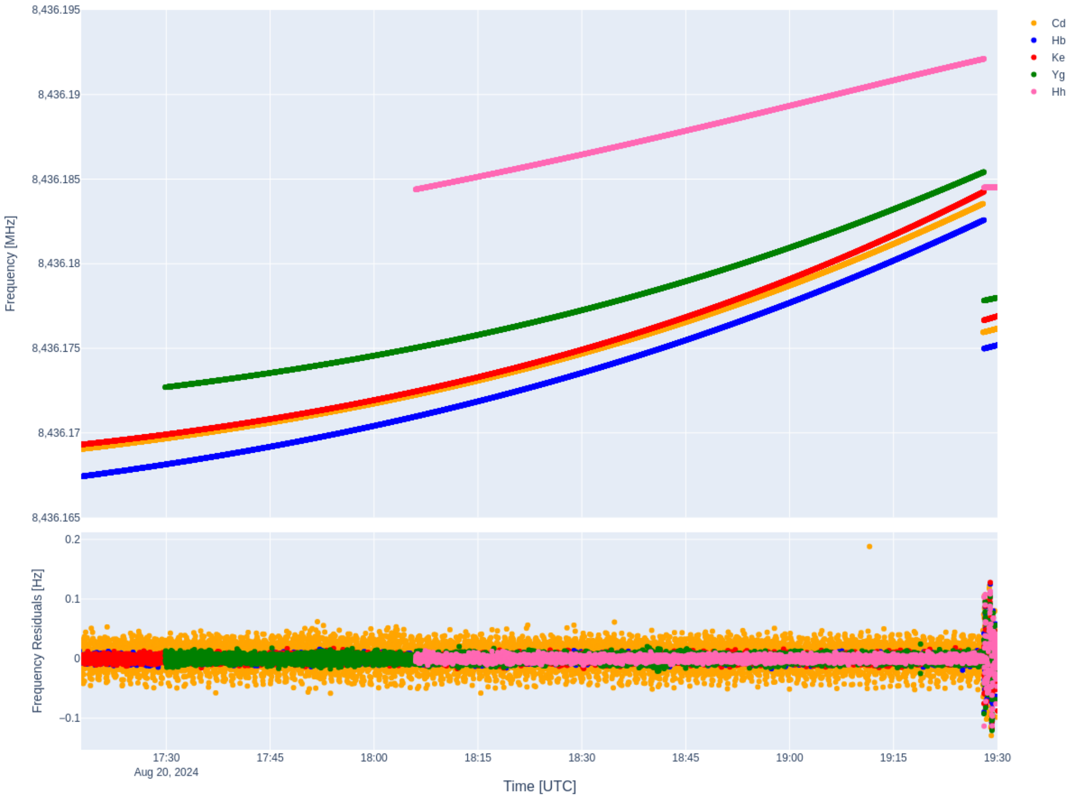

Figure 12. Revised Doppler frequency detections of the JUICE spacecraft acquired by the Hartebeesthoek, Katherine, Yarragadee, Hobart, and Ceduna radio telescopes on August 20, 2024, during the Earth flyby. All participating stations are included from 17:15 UTC.

observations until approximately 17:30 UTC, at which time the spacecraft signal was immediately detected. The 12-m stations successfully tracked the signal from shortly after 17:30 UTC until loss-of-signal at approximately 19:30 UTC. Figure 12 upper panel presents the Doppler measurements obtained from the five UTAS antennas and the Hartebeesthoek radio telescope, while the lower panel shows the corresponding residual frequency time series for all participating stations.

The residual frequency noise was found to be comparable across all participating radio telescopes, at the level of 5 mHz, with the exception of the Ceduna antenna, which exhibited elevated noise levels of 20 mHz. This increased frequency noise is attributed to limitations in the local reference-frequency distribution, which affected the stability of the locking signal provided to the software-defined radio unit during the observation.

Figure 13 presents a comparison between the Doppler frequency detections measured at the Hartebeesthoek antenna and the predicted values computed using the `Tudat` software framework. Overall, the measurements and predictions show good agreement across the observed arc. As the single-dish observations were not conducted as part of a standard VLBI session, the RMS of the frequency residuals is on the Hz level and residuals present an uncorrected systematic time-offset bias in the data across all stations and errors in the a priori trajectory of JUICE. Following linear detrending to account for such bias, the RMS is within 5 mHz. Similar results are also found for other stations. These results demonstrate the reliability of the `Tudat`-based predictions for the JUICE cruise-phase dynamics and highlight the importance of maintaining GPS timing records across all participating stations, including those operating outside standard VLBI mode.

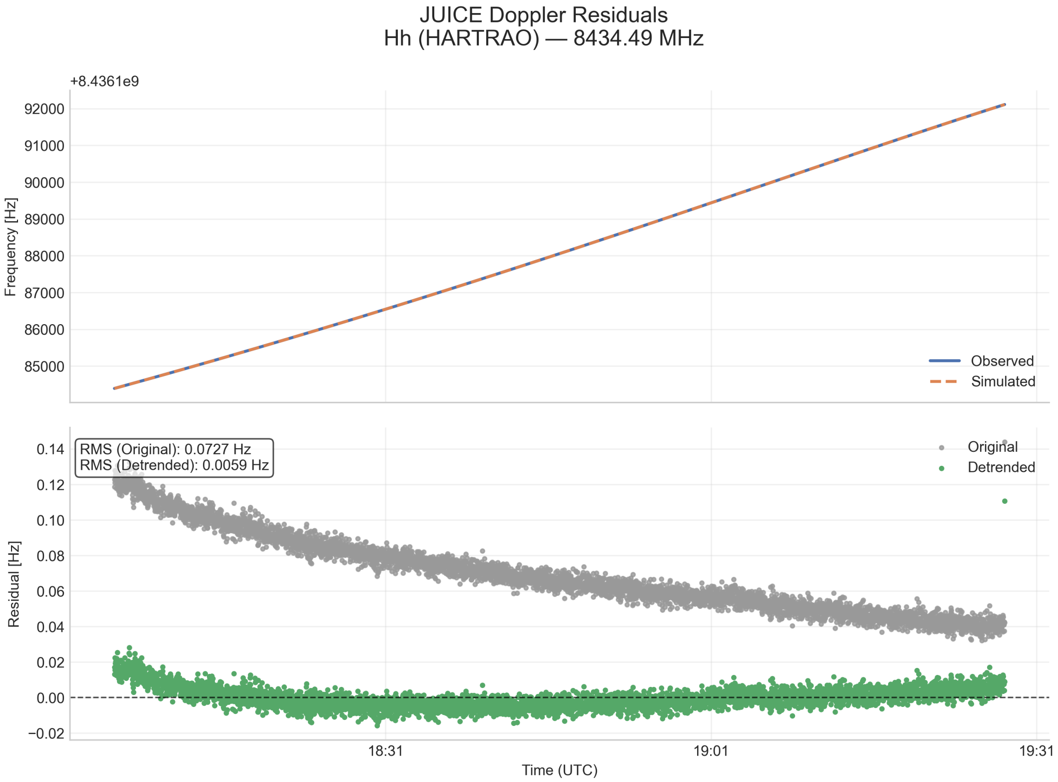

Figure 13. Comparison between the predicted Doppler frequency detections computed using the `Tudat` software framework and the measurements obtained at the Hartebeesthoek (Hh). The upper panel show the measured and predicted frequencies and the bottom panel panels the linearly detrended residuals. The detrended RMS of the frequency residuals is within 5 mHz.

3.5 August 21 and 22, 2024: Doppler Follow-up

Over the two days following the flyby, Ceduna conducted single-dish observations of JUICE during the post-flyby phase. All data were recorded with the Ettus system. As shown in Figure 14, the spacecraft transmitted in one-way mode until until 04:19 UTC, when it switched to two-way mode for the remainder of the observation.

We extracted the carrier phase from the scans acquired on August 21 to analyse the phase fluctuations present in the received signal. The phase extraction was performed using the PRIDE processing pipeline, as described in Molera Calvés et al. (2021), applying a narrow bandwidth of 20 Hz. From the resulting phase time series, we estimated the phase power spectral density of the fluctuations and separated the contributions at low and high frequencies. As expected given the observing geometry,

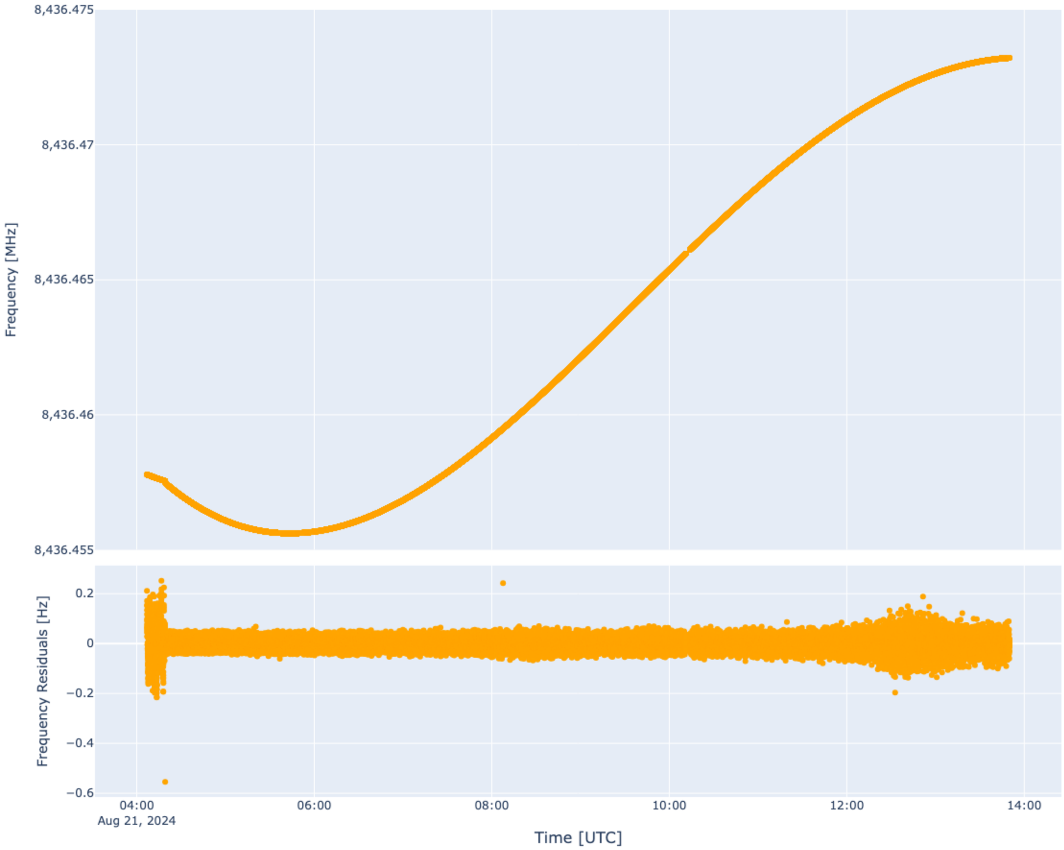

Figure 14. Revised Doppler frequency detections and residuals of JUICE from Ceduna following the lunar Earth gravity assist on August 21, 2024. Note the transition from one-way to two-way transmission modes at 04:19 UTC.

the contribution from the interplanetary plasma was minimal, with the fluctuations dominated by the terrestrial ionosphere, as illustrated in Figure 15.

Following the methodology outlined in Duev et al. (2012), we estimated the uplink and downlink ionospheric total electron content (TEC) contributions. The derived TEC values were found to be 48.5 ± 11.2 TECU (total electron content unit) for the uplink ionospheric contribution and 80.5 ± 12.1 TECU for the downlink. The mean phase fluctuation recorded on the session was 0.103 ± 0.022 radians. Based on the conversion factor between TEC and phase scintillation determined in Kummamuru et al. (2023), this would indicate a line of sight TEC of 150 ± 31.5 TECU. The non-ionospheric contribution of 21.0 ± 36.3 TECU is likely dominated by other sources of noise due to the minimal contribution of the solar wind at such proximity to Earth.

Using the full data set accumulated over the past two years of observations, we analysed the Doppler noise characteristics of the JUICE mission as measured by ground-based radio telescopes. The aim was to isolate the individual contributions from

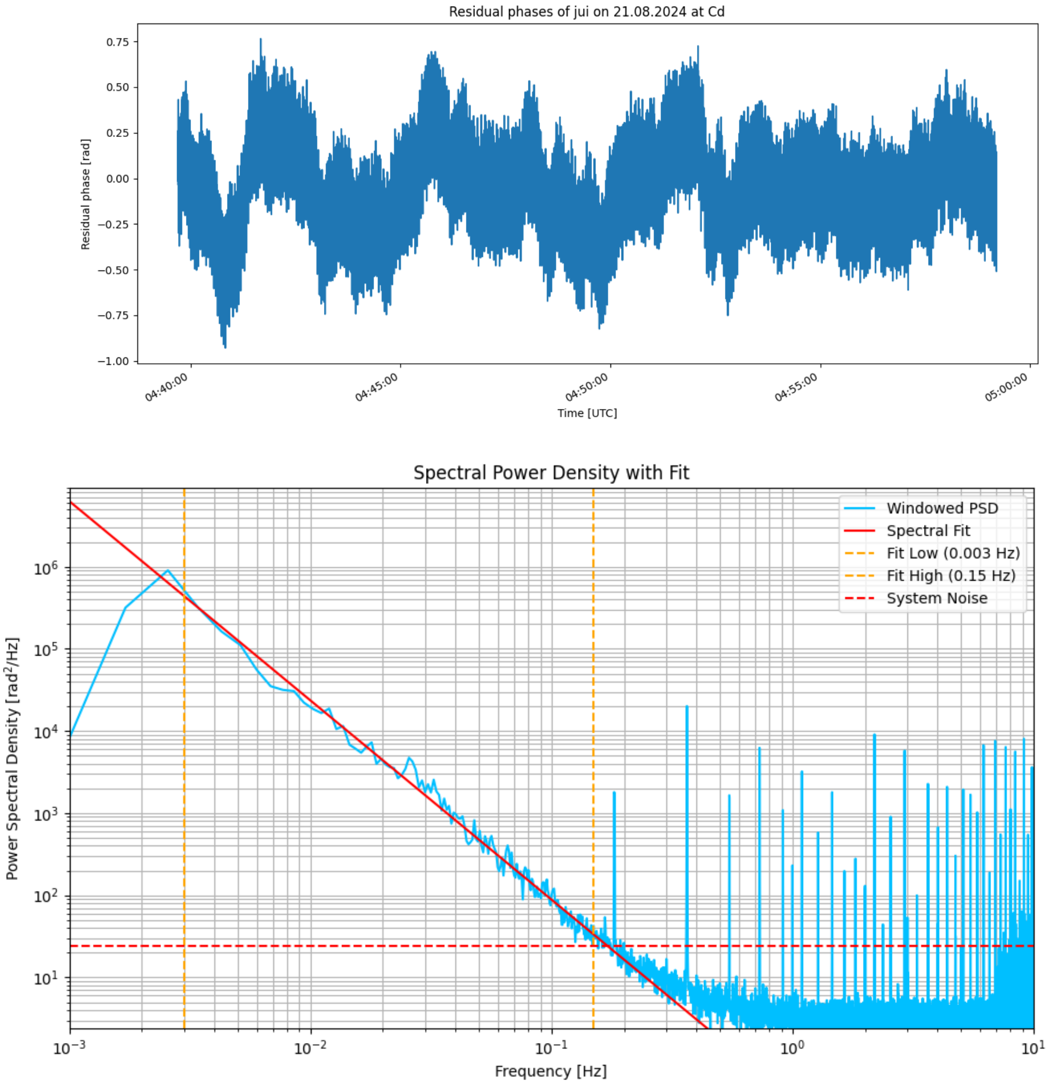

Figure 15. The residual phase was extracted from Ceduna recordings on August 21, 2024, corresponding to scan 3 recorded at 04:39:27 for a duration of 20 minutes. The lower panel presents the power spectrum of the phase residuals. The dominant peaks above the noise floor are consistent with electronic noise originating at the receiving station, as indicated by the broadband increase in phase noise. The spectra still resembles a Kolmogorov spectrum as expected.

the terrestrial ionosphere, troposphere, solar wind, spacecraft system noise, and ground-station instrumentation. As a first step, we computed a theoretical model of the solar-wind contribution under nominal, slow, and fast wind conditions as a function of mission phase, employing the Young solar-wind scintillation framework (Molera Calvés et al., 2014; Kummamuru et al., 2023). The model was adapted to the JUICE cruise phase using the operational JUICE (OPS) kernel release.

Comparison between the model predictions and the observed Doppler noise shows generally good agreement. As expected, the solar-wind contribution is significantly weaker than that observed in missions operating at smaller heliocentric distances. As shown in Figure 16, the observed signal is largely dominated by unmodelled noise sources, such as tropospheric effects, and ground-station and spacecraft noise. Work is underway to model and characterise these noise sources to enable improved characterisation of the Solar System plasma environment at greater heliocentric distances and larger solar elongations, particularly for the Jovian segment of the mission. The measurements taken during the lunar–Earth gravity assist, and other periods of the cruise phase, will be particularly useful for this calibration due to the minimal contribution of the solar wind to phase noise.

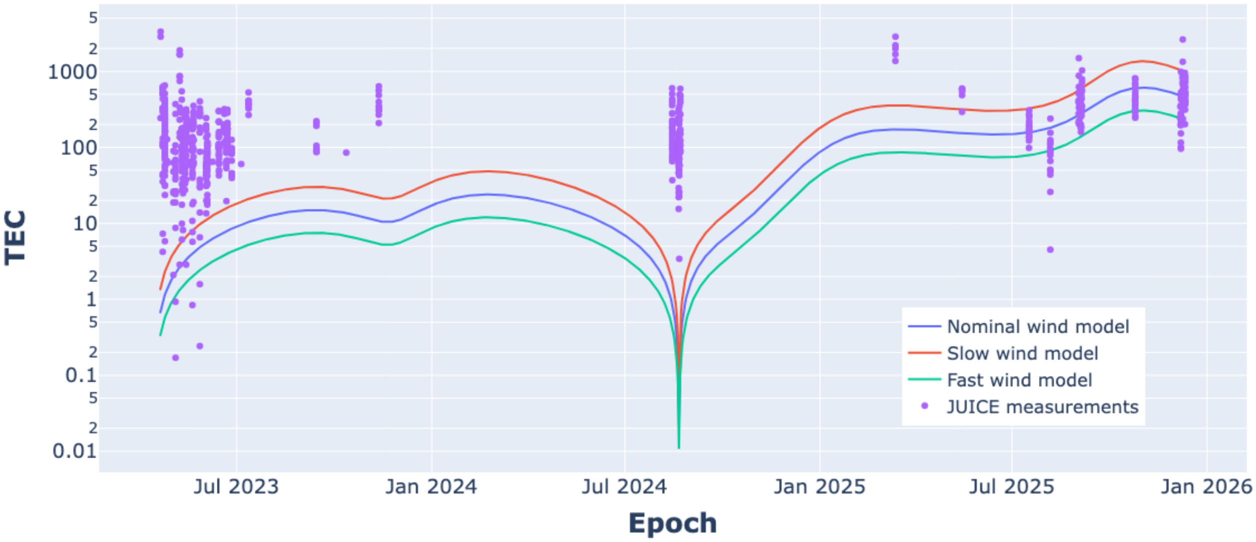

Figure 16. Modelled and predicted Total Electron Content based on interplanetary phase scintillation measurements from the past two years of JUICE operations. Downlink and uplink ionospheric corrections have been applied.

4 Discussion

The PRIDE initiative has focused on spacecraft radio observations to investigate space-weather phenomena, including solar activity, coronal mass ejections, and the large-scale properties of the interplanetary plasma (Molera Calvés et al., 2017). This work has evolved over successive missions, from Venus Express and Mars Express to more recent work with BepiColombo. Two years of JUICE observations have provided a valuable opportunity to refine and validate observing strategies and analysis techniques. Although the influence of the solar wind on phase fluctuations during the cruse phase has been relatively small due to JUICE's current heliocentric distance, this period has nevertheless been valuable in preparing for future mission phases. Beyond traditional phase-scintillation studies, we have expanded the analysis to include spectral broadening, frequency fluctuations, and amplitude scintillation, allowing a more comprehensive characterisation of turbulent plasma regimes. Looking ahead, future observations offer promising opportunities to study corotating interaction regions, multi-spacecraft configurations sampling different heliospheric locations, and near-in-beam observations involving JUICE and the Europa Clipper mission (M Said et al., 2025; Edwards et al., 2025b).

Phase-referencing observations were also attempted using the UTAS VLBI array with the aim of deriving astrometric measurements of JUICE, but the results were not of sufficient quality for reliable astrometry. Several factors contributed to this. The angular separation between the spacecraft and the available calibrator sources was too large to ensure effective phase transfer, as larger separations introduce differential atmospheric and ionospheric path delays that cannot be adequately corrected. Compounding this, the integration times at the target and calibrator were not optimally selected, and the reference sources used were insufficiently bright to yield proper phase calibration. The absence of at least one large-aperture antenna further reduced the overall sensitivity, which is critical for the detection of the spacecraft signal and for obtaining high signal-to-noise solutions on weak calibrators. Finally, the high radial velocity of JUICE caused the spacecraft to separate rapidly from the calibrator in the plane of the sky, complicating the post-processing analysis. These lessons will improve the design of future phase-referencing campaigns, with attention to calibrator selection, antenna inclusion, and scheduling strategies adapted to the spacecraft trajectory for the short UTAS array.

The PRIDE team recently implemented the open-loop Doppler observable in the `Tudat` orbit propagation and estimation software. The validation of the model was presented by Gisolfi et al. (2025) and the first application to orbit estimation was performed by Sánchez Rodríguez (2026) using Mars Express data. These analyses showed post-fit residuals and orbit estimates that are consistent with those obtained using classical closed-loop Doppler data. The Mars Express orbit estimation results indicated that the use of multiple stations for Doppler data provides valuable opportunities for orbit validation. Specifically, there were strong indications that the variability in converged orbit solutions when using one combination of stations instead of another could provide a good indication of the level of orbit estimation error (rather than the formal error, which is typically overly optimistic). In the near future, PRIDE Doppler data collected during the cruise phase, the lunar–Earth gravity assist, and the Venus flyby will be used for orbit estimation experiments, and compared to results that could be obtained from JUICE navigation data. Moreover, the combination of Doppler data from multiple stations and VLBI observations will be used to investigate and quantify the impact on orbit estimation results. The tests during these various phases of the JUICE mission will provide a more robust understanding of how the PRIDE tracking data will contribute to achieving the JUICE mission's science objectives (Gurvits et al., 2023), building on the VLBI-focused simulation study of Fayolle et al. (2024).

5 Conclusions

The University of Tasmania (UTAS) VLBI network has provided sustained support for PRIDE tracking of JUICE over two years, with more than 100 observations conducted since launch. These activities included validation of observing modes and system configurations during the near-Earth commissioning phase, comparison of one-way and two-way tracking modes, and evaluation of data quality across both signal polarisations. Nine VLBI phase-referencing experiments were successfully conducted, yielding reliable correlation and resolved images of the spacecraft (White et al., 2025a). Measurements of interplanetary phase scintillation along the Earth–JUICE line of sight were consistent with total electron content models used in earlier experiments with Mars Express and Venus Express. Finally, coordinated multi-station observations during the lunar–Earth gravity assist and Venus flyby were carried out with both the UTAS and EVN networks.

Radio telescopes have traditionally been designed to track distant extragalactic sources at fixed sidereal coordinates. Recent developments, however, have demonstrated the potential of these instruments for a broader range of applications, including space-domain awareness, planetary-defence monitoring, and spacecraft tracking (White et al., 2025b). These advances have driven the development of new observing and control strategies capable of tracking non-sidereal targets, such as interplanetary spacecraft. All experiments presented here were conducted in a continuous-tracking mode, enabling seamless monitoring of the spacecraft signal and reducing operational complexity. More broadly, an increasing number of radio telescopes worldwide are adopting this capability, enabling the global VLBI infrastructure to support future planetary missions and space science objectives.

Code availability. All the PRIDE software used to prepare this article is published open-source repositories. The Multi-tone spacecraft tracking software (`SCTracker`) is available at https://gitlab.com/gofrito/sctracker. The data post-processing is available at https://gitlab.com/gofrito/pysctrack/. `Tudat` was used for Doppler predicitions and is available at: https://docs.tudat.space/en/latest/.

Data availability. Data will be published in the European Space Agency Planetary Science Archive (PSA).

Author contributions. Conceptualization and experiment design were carried out by all authors. Observations were planned and executed by the UTAS and PRIDE teams. Data processing, analysis, and interpretation were performed by the authors, with contributions to software development, correlation, and validation. The manuscript was written by the lead author with input, review, and approval from all co-authors.

Competing interests. No competing interests are present

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