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Geophysical Research Letters

Supporting Information for

Radio Occultation Measurements of Europa's Ionosphere from Juno's close flyby

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Introduction

The following Supporting Information provides additional details on the processing and analysis of Juno's radio occultation data collected at Europa. The material will be particularly useful to the readers that wish to reproduce the results provided in the manuscript. Text 1 describes the data acquisition and calibration. Text 2 describes additional products of the data analysis.

Text S1. Dataset acquisition and calibration

The Europa occultation data collected by the Juno spacecraft was acquired in two-way, single-frequency coherent mode, using X-band only. The data was collected using the spacecraft's Medium Gain Antenna (MGA) and Goldstone's 70-m dish (DSS-14). The 1 kHz open loop recordings were processed using a fast Fourier transform (FFT) integrating 1000 samples, resulting in an integration time of 1 second.

During the ingress portion of the occultation the instrument configuration remained two-way coherent, with a data analysis Earth Receive cut-off time chosen at 10:06:16.5 UTC (see Figure S1, top plot of the signal-to-noise-ratio SNR). Loss of signal (defined in Buccino et al. 2022) occurred at least 1 second later, as clear from Figure S1. However, to avoid the effects of diffraction from Europa's surface, the samples after the cutoff epoch have been discarded, with a resulting minimum altitude of 7.5 km.

On egress, the Earth Receive cut-off epoch (10:09:31.5 UTC) corresponds to the re-acquisition of the coherent two-way signal, after the snap lock technique was executed. The non-coherent 1-way data points (red crosses in Figure S1) were discarded. As a result, there is no concern for diffraction effects on egress data, as the first available data point is already at an altitude of 52 km.

The entire ingress and egress datasets are shown in Fig. 2 of the manuscript. Panels a and b show the raw, uncalibrated data. In order to go from those to the residuals in panels c and d, two calibrations steps were performed:

- Calibration of the periodical effect due to the MGA offset with respect to the spin axis. The Juno spacecraft spins with an angular velocity of 2 RPM, therefore we expect periodical signatures on the frequency residuals characterized by this angular frequency. The calibration applied to the residuals was in the form of a sum of *k* sinusoidal functions:

$$\sum_{k=1}^{n} A_n \sin(\omega_n t + \emptyset_n), \qquad \text{(S1)}$$

  where A_n is the amplitude of the sinusoidal signal (mHz), ω_n is the angular frequency (rad s^{-1}), t is time (in seconds) and $\emptyset_n$ is the phase of the signal. For ingress, we obtained acceptable residuals by summing n=5 sinusoidal functions, with amplitudes between 3 and 1462 mHz and angular frequencies between 0.2014 and 0.2081 rad s^{-1} (corresponding to ~2 RPM). For egress, we obtained acceptable residuals by summing 5 sinusoidal functions, with amplitudes between 6 and 1463 mHz and angular frequencies between 0.2039 and 0.2084 rad s^{-1}.

- Linear fit of the baseline. This is a conventional step in radio occultation analyses. The baseline is defined as the batch of data available before ingress and after egress where the radio signal travels outside of the ionosphere. In the case of the Juno Europa occultations, this was determined to be between an altitude of 1,500 and 28,168 km for ingress and between 1,500 and 27,310 km for egress (see Figure 2, panels e and f, in the manuscript). Previous radio occultations of Europa (Kliore et al., 1997), suggest that the ionospheric densities above this altitude are negligible. We discovered a linear bias of amplitude 1.3 mHz on ingress and 0.3 mHz on egress (corresponding to linear trends of ~10^{-7}-10^{-6} Hz s^{-1}).

Text S2. Data analysis products

The Total Electron Content (TEC) profile is an integrated measurement that represents the column electron density along the ray path during an occultation. The TEC can be obtained directly from Doppler frequency residuals (Δf). First, phase residuals as a function of time are obtained from:

$$\Delta\varphi(t) = \int \Delta f(t)\, dt, \qquad \text{(S2)}$$

by solving the equation numerically (for instance with a simple trapezoidal rule). Then the TEC profile as a function of time (and consequently altitude *h*, the dependance of *h* on time is given in Figure 2e,f) is obtained from:

$$TEC(h) = \frac{\Delta\varphi(h)\cdot 8\pi^2 m_e \varepsilon_0 c f_x}{e^2}, \qquad \text{(S3)}$$

where m_e is the electron mass, ε_0 is the permittivity in vacuum, c is the speed of light, f_X is the received frequency in X-band and e is the elementary charge.

Figure S2 shows the TEC profiles for ingress and egress as a function of altitude (up to 1,000 km). The profiles are consistent with electron density profiles shown in Figure 3 of the manuscript. Electron density is a measure of volume density, and the conversion to TEC profiles involves an integration step. The 3σ uncertainties shown in the plot were calculated by taking the RMS of the TEC profile outside of the ionosphere (between ~1,500-30,000 km altitude) and multiplying it by 3.

Text S3. Assumption of local spherical symmetry

In order to justify the use of the assumption of local spherical symmetry, we show the geometry of the Juno radio occultation of Europa in Fig. S3, in terms of spacecraft visibility with respect to the magnetospheric wake. During the ingress portion of the radio occultation, the rays traverse a region of Europa's ionosphere which is entirely outside of the magnetospheric wake. According to models of the ionosphere by Harris et al. (2022), most combinations of surface density, scale height and magnetospheric plasma densities result in ionospheric profiles that can be considered spherically symmetric along the ingress ray paths, for the purposes of this analysis. The only exception would be for models with high magnetospheric plasma densities and large scale height (330 km). However, these conditions also predict electron densities of ~10,000 cm^{-3} at low altitudes, which were not observed on either Juno occultations.

During the egress portion of the radio occultation, the rays traversing the lower layers of Europa's ionosphere are partially located inside the magnetospheric wake (Fig. S3). However, the ionosphere can still be considered, to first order, spherically symmetric in that region for most models by Harris et al. (2022). Again, the only exception would be for high magnetospheric plasma densities and large scale heights, which once again predict electron densities that are too high to be consistent with Juno observations.

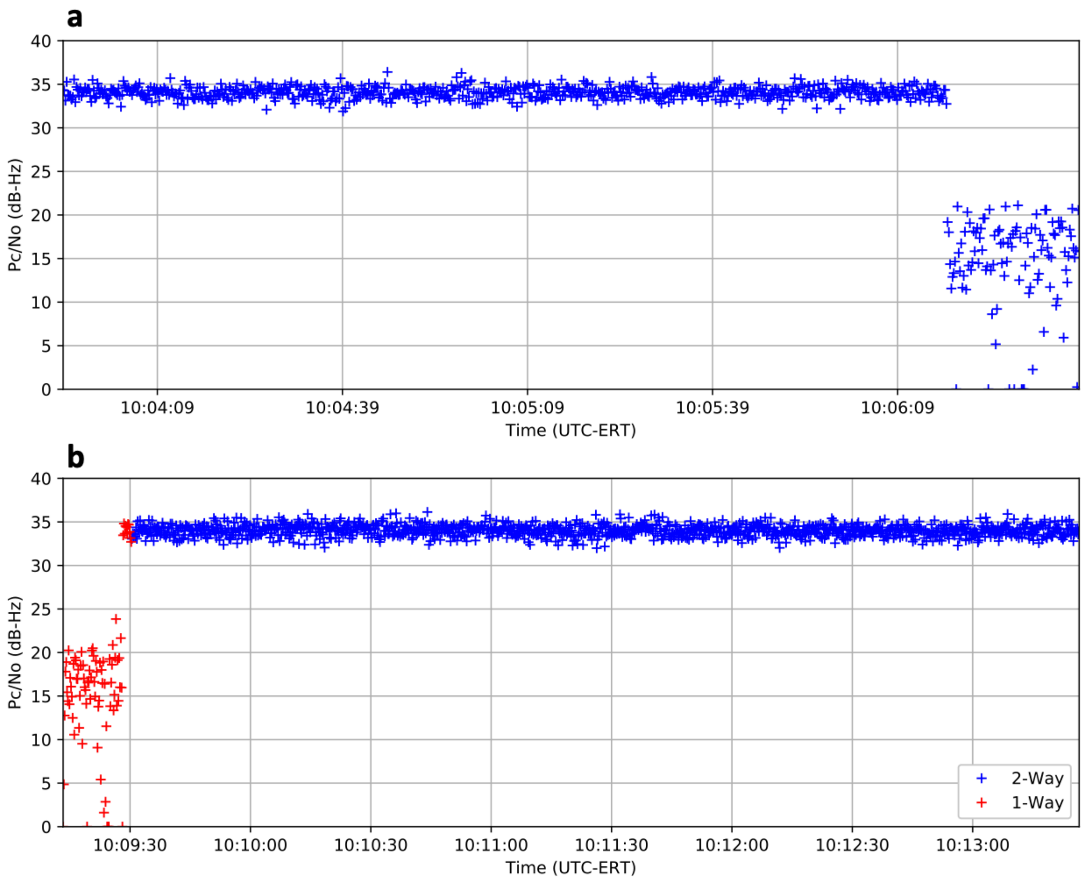

Figure S1. SNR for the X-band signal for ingress (a) and egress (b), as a function of time. The loss of signal during ingress occurred at 10:06:17.5 UTC. On egress, the transponder reacquired the uplink signal at 10:09:31.5 UTC.

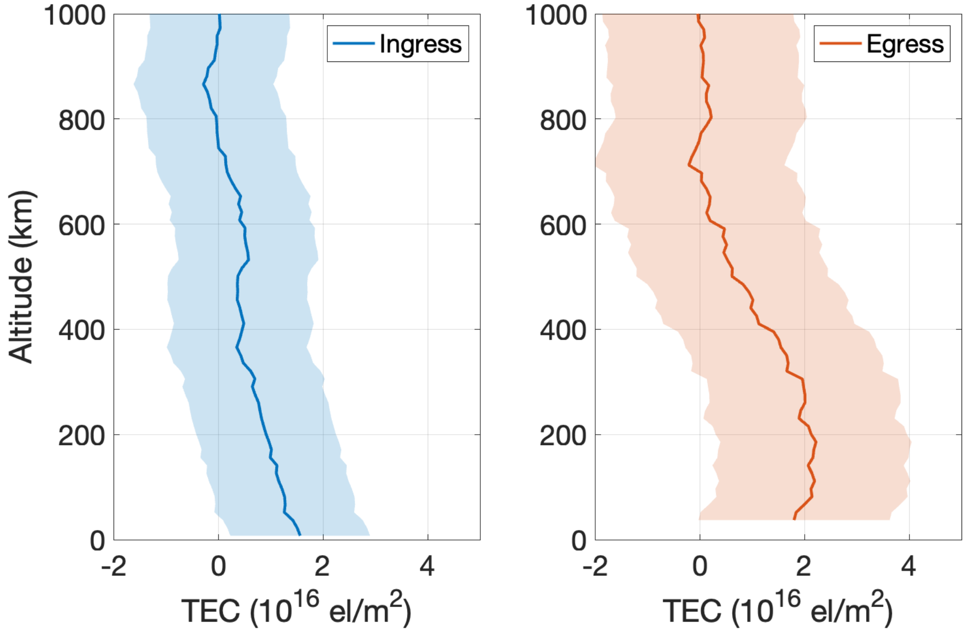

Figure S2. Total electron content (TEC) for ingress (left) and egress (right) occultations, as a function of ray path altitude over the surface of Europa. The shaded areas represent the 3σ uncertainties.

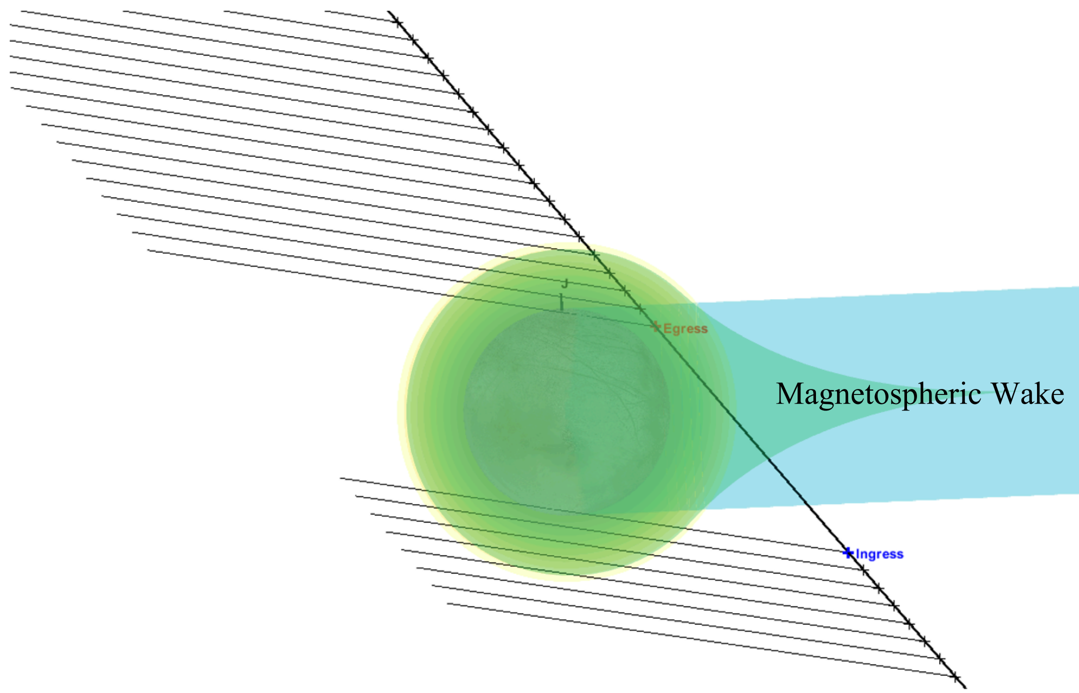

Figure S3. Geometry of the Juno Europa occultation that highlights the portion of the moon's ionosphere traversed by the radio signals. Trajectory ticks are generated every 15 seconds. The blue shaded area represents the magnetospheric wake. The yellow shaded area represents the spherical ionospheric shells (same as Fig. 1). The green shaded area shows a cartoon illustration of Europa's global non-spherical ionosphere, using models from Bagenal & Dols (2020) and Harris et al. (2022) as reference.

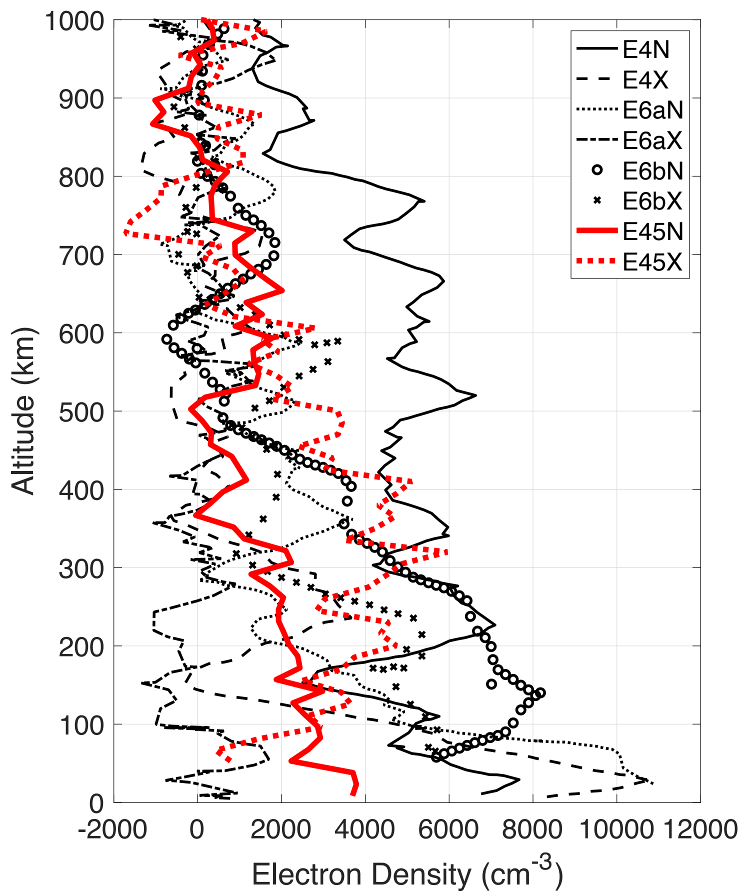

Figure S4. Comparison between the six Galileo electron density profiles (black curves) from Kliore.et al. (1997) and the two Juno profiles of Europa's electron density (red curves), as a function of altitude over Europa.