Modelling the electron density distribution in the Io Plasma Torus using Juno radio occultations

Marco Zannoni[1*], Alessandro Moirano[1,2], Luis Gomez Casajus[1], Paolo Tortora[1], Daniele Durante[3], Luciano Iess[3]

1. The Juno mission

Juno is currently orbiting Jupiter following a low altitude and highly eccentric orbit, with a period of 53.5 days. During each Jupiter encounter, Doppler measurements between Juno and the Earth are acquired for about eight hours centered around Jupiter's closest approach. Due to the orbital geometry, the radio signal crosses the Io Plasma Torus (IPT), a toroidal cloud of plasma centered on the centrifugal equator of Jupiter at Io's orbital distance. The torus induces a path delay and a carrier frequency shift on radio frequency signals, yielding a non-dynamical Doppler shift, which in turn can be fitted with a density model [1] to infer the morphology of the IPT.

2. Radio signal through the IPT

The Juno gravity science instrument comprehends a Ka-band Translator System (KaTS), which provides a coherent two-way Ka/Ka link (34-32 GHz). In addition, Juno spacecraft telecommunications subsystem supports a standard two-way X/X (7.2-8.4 GHz) link. This equipment allows for the identification of the dispersive contribution to the path delay due to the plasma of the interplanetary medium (IPM) and the IPT [2]. Thanks to the relation between path delay and Total Electron Content (TEC), it is possible to exploit the many occultations Juno is performing to study azimuthal and temporal variability of the torus.

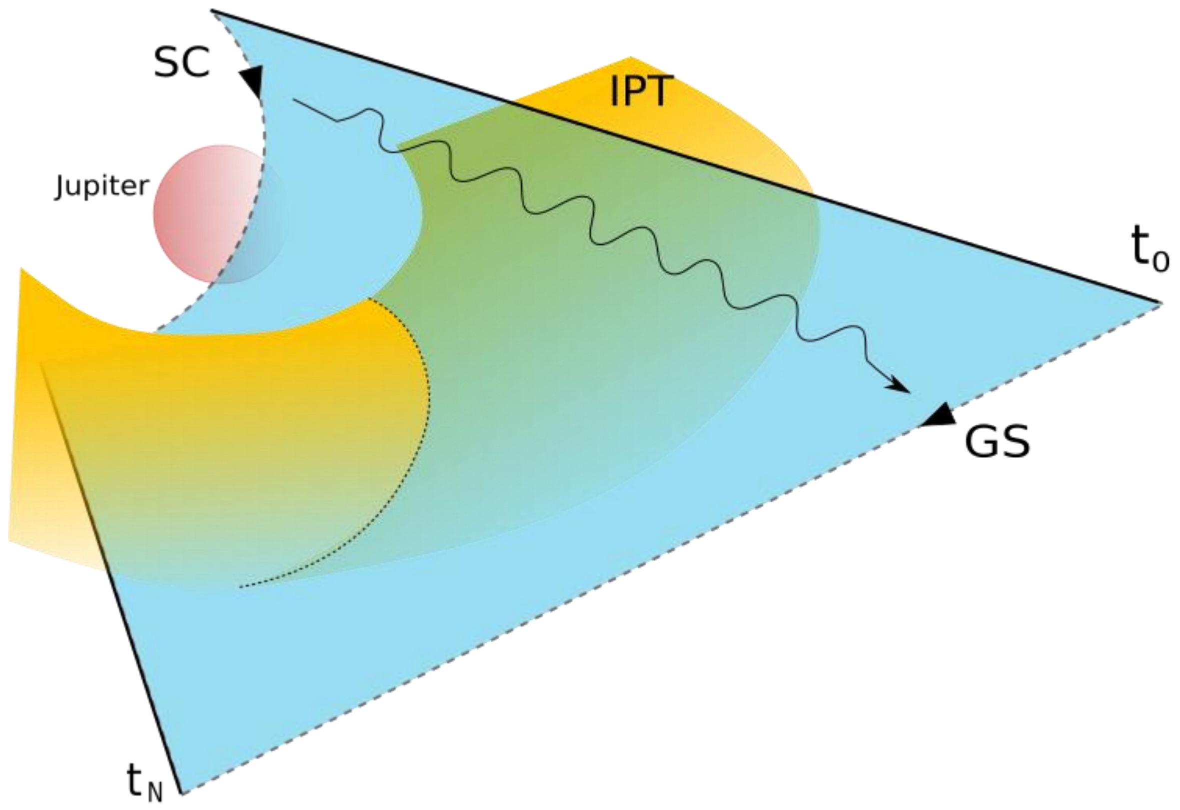


Figure 1: Schematic representation of the an occultation performed by Juno seen in an IPT-fixed frame (i.e: corotating with Jupiter, but around the centrifugal axis).

In order to determine the morphology of the IPT, we adopted the parametric density model given by:

$$n_e(r,z) = \sum_{i=1}^{2} N_i \, exp\left[-\left(\frac{r-R_i}{W_i^2}\right)^2 - \left(\frac{z-Z_i}{H_i^2}\right)^2\right]$$

Where N is the peak density, R and W the radial position and extension respectively, Z the offset from the centrifugal equator and H is the scale height.

3. Corrections

Exploiting the slight tilt of the radio signal with respect to the centrifugal equator and the multiple occultations make possible to constrain the radial position and extension of the IPT. Besides, as seen in a corotational frame, the radio signal between the ground station (G/S) and Juno has crossed the IPT in many different longitudinal sectors during the gravity passages: this allow us to inspect the longitudinal structure of the IPT.

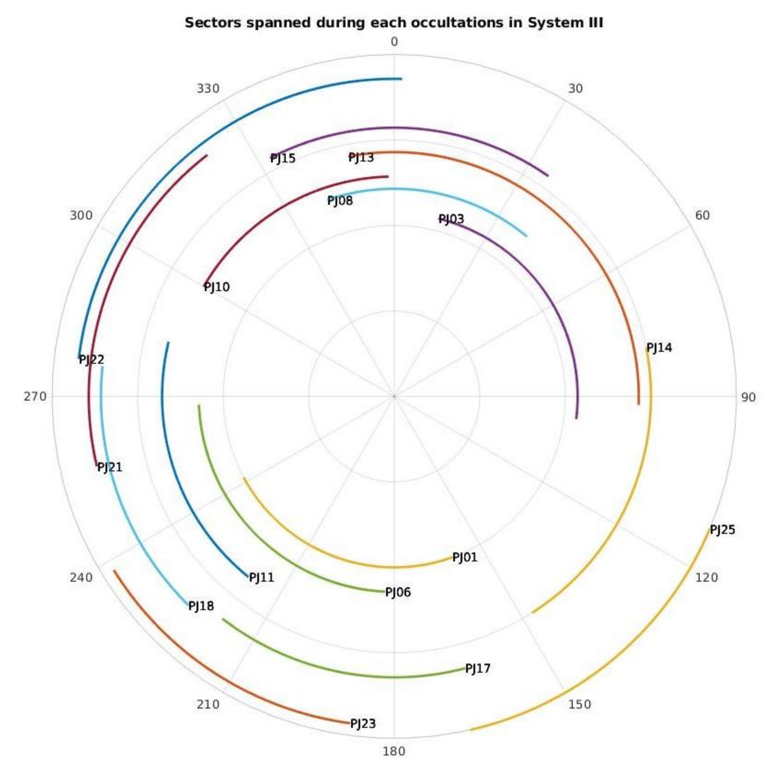


Figure 2: Longitudinal sectors spanned by Juno during the gravity experiment from PJ01 to PJ25.

Past observations of the IPT revealed that it has longitudinal modulation (e.g: [3]) as well as temporal variability (e.g: [4]). The typical time scales of the latter can range from hours to years. To investigate potential periodicities, we considered the Fourier expansion of the parameters of the density model n_e. We focused on the scale height H_2 and peak density N_2 of the outer region of the torus, which are the main responsible for the width and depth of the path delay signature. We modeled H_2 and N_2 as a 2-dimensional Fourier expansion up to the second order:

$$Q(\lambda,t) = \sum_{m=0}^{M_{max}} \sum_{n=0}^{N_{max}} A_{m,n} cos\left(\frac{360 m\lambda}{\Lambda}\right) cos\left(\frac{360 nt}{T}\right) + B_{m,n} sin\left(\frac{360 m\lambda}{\Lambda}\right) cos\left(\frac{360 nt}{T}\right) +$$

$$+ C_{m,n} cos\left(\frac{360 m\lambda}{\Lambda}\right) sin\left(\frac{360 nt}{T}\right) + D_{m,n} sin\left(\frac{360 m\lambda}{\Lambda}\right) sin\left(\frac{360 nt}{T}\right)$$

4. Results

Our results pointed out that a purely longitudinal or temporal correction didn't properly fit the data, while taking both into account improved the sum of the residuals by about 30%. Besides, the model with temporal and longitudinal corrections (i.e: M_{max}=1, N_{max}=1) predicts a density fluctuation of about 40%, half of which is due to the second order correction.

In the end, we left the characteristic period T as a free parameter. Indeed, the orbital period of Juno allowed us to investigate periodic features of the IPT which ranges from a few months to yearly variations. We found approximately T=400 days. These value is about 10% less than the main period of orbital changes of Io, which may be related to volcanic activity on this moon [5] and thus on mass loading in the IPT. Nevertheless, this result should be taken very carefully because more investigation are needed about the response of the IPT to different types of volcanism that took place on Io, such as eruptions, lava flows and plumes.

5. Data fit

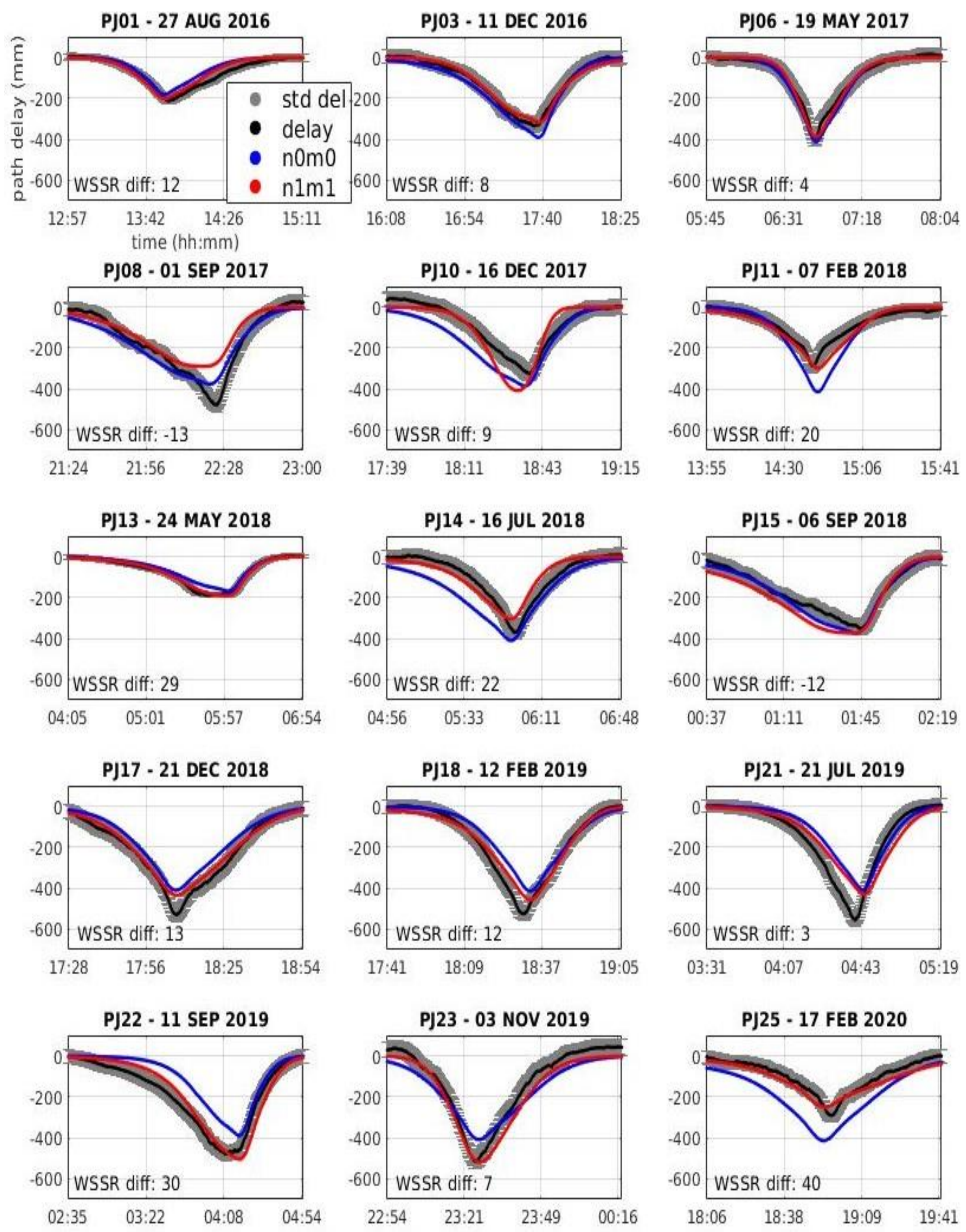


Figure 3: Fit to the path delay signature. *Black*: data with uncertainty (*grey area*). *Blue*: fit with an axisymmetric model (i.e: zero-order Fourier expansion). *Red*: fit including longitudinal and temporal variability (second-order Fourier expansion).

6. Future Work

The IPT shows a substantial variability of its electron content in both time and longitude, but its origin is still unknown. Nevertheless, our work showed they are both relevant on the morphology of the IPT. The intense volcanic activity of Io and the strong interaction between the moon, the IPT and Jupiter's magnetosphere may be responsible for such variability, but further modelling is required to better understand the underlying physical processes at play.

References

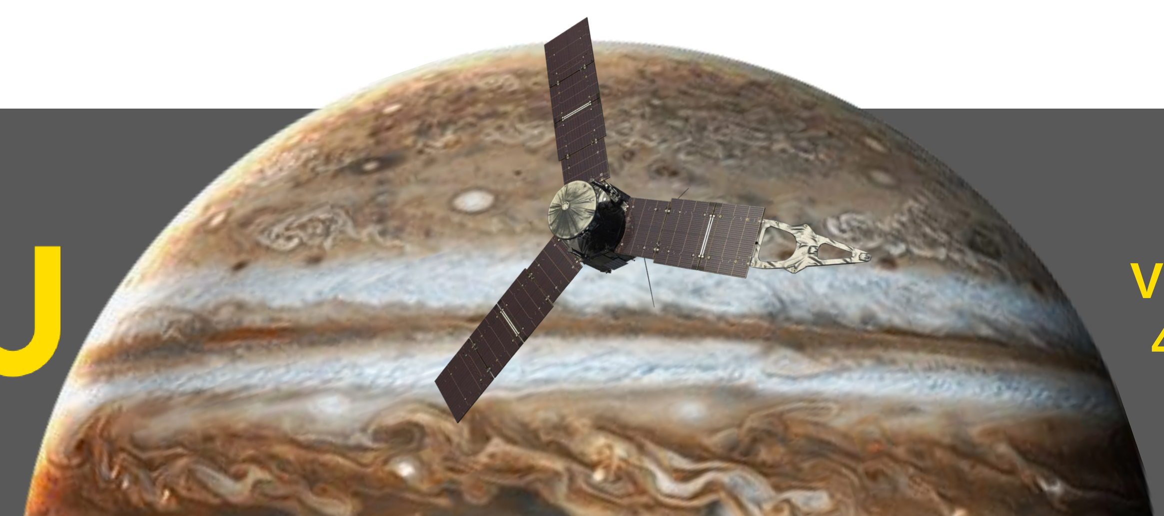
[1] Phipps, P.H., Whiters, P., Buccino D. R., Yang Y.M., (2018), *Distribution of plasma in the Io plasma torus as seen by radio occultation during Juno Perijove 1*, J. Geophys. Res. Space Physics, 123, 6207-6222

[2] Mariotti, G., and P. Tortora (2013). *Experimental validation of dual uplink multifrequency dispersive noise calibration scheme for Deep Space tracking*. Radio Science 48, 111-117

[3] Steffl, A.J., Delamere, P.A., Bagenal, F., *Cassini UVIS observations of the Io Plasma Torus. III. Observations of temporal and azimuthal variability*, arXiv: astro-ph/0508055

[4] Thomas, N. (1993), *The variability the Io plasma torus*, J. Geophys. Res., 98(E10), 18,737– 18,750

[5] de Kleer, K., Nimmo, F., Kite, E., *Variability in Io's volcanism on timescales of periodic orbital changes*, Geophys. Res. Let., 46, 12, 6327– 6332



Vienna, Austria
4–8 May 2020

(*) m.zannoni@unibo.it

1) University of Bologna, Dipartimento di Ingegneria Industriale, Forlì, Italy.
2) INAF, IAPS, Rome, Italy
3) Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Italy.

Radio Science and Planetary Exploration - Laboratory -

SCAN ME