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Jupiter spin-pole precession rate and moment of inertia from Juno radio-science observations

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ABSTRACT

Through detailed and realistic numerical simulations, the present paper assesses the precision with which the Juno spacecraft can measure the normalized polar moment of inertia (MOI) of Jupiter. Based on Ka-band Earth-based Doppler data, created with realistic 10 μm/s of white noise at 60 s of integration, this analysis shows that the determination of the precession rate of Jupiter is by far more efficient than the Lense–Thirring effect previously proposed to determine the moment of inertia and therefore to constrain the internal structure of the giant planet with Juno.

We show that the Juno mission will allow the estimation of the precession rate of Jupiter's pole with an accuracy better than 0.1%. We provide an equation relating the pole precession rate and the normalized polar moment of inertia of Jupiter. Accounting for the uncertainty in the parameters affecting precession, we show that the accuracy of the MOI inferred from the precession rate is also better than 0.1%, and at least 50 times better than inferred from the Lense–Thirring acceleration undergone by Juno. This accuracy of the MOI determination should provide tight constraints on the interior structure of Jupiter, especially the core size and mass, helping to distinguish among competing scenarios of formation and evolution of the giant planet.

In addition, though the Juno mission operations are already defined, the exact duration of the tracking and its occurrence with respect to the spacecraft pericenter pass are not definitely scheduled. The simulations performed here quantify the impact of this aspect of the mission on the Juno sensitivity to (in particular) the spin-pole precession rate of Jupiter.

Finally, additional simulations have been performed to test the usefulness of combining Doppler data with VLBI data, showing the latter measurements to be 10^4–10^5 times less sensitive than the former to our parameters of interest and therefore, obviously, totally needless.

1. Introduction

The Juno New Frontiers NASA mission was launched on August 5, 2011 and is now en route to Jupiter. After a five-year trip, the spacecraft will be injected on July 5, 2016 into an highly elliptical 53-day polar orbit around the giant planet. After two revolutions, Juno's orbital period will be reduced to 14 days for science operation. The spacecraft will orbit Jupiter 36 times over 595 days before deorbit into its atmosphere. The mission aims to study the planet's composition and interior structure, gravity field, magnetic field, and polar magnetosphere in order to investigate the origin and evolution of the giant planet (Matousek, 2007; Bolton, 2010).

Among nine scientific instruments, the payload of Juno includes radio-science instruments that will be used to accurately map the gravity field of Jupiter through classical Precise Orbit Determination (POD) techniques (e.g. Iess et al., 2013; Tommei et al., 2015). In addition to the gravity field, the very accurate reconstruction of the orbit of Juno enabled by the high precision Ka-band Doppler data will permit, among others, the determination of the main moments of inertia (MOI) of the giant planet. MOI characterize the internal mass distribution inside the planet. Such information about the interior structure is key for the understanding of the planet's formation and evolution (Guillot and Gautier, 2007).

The MOI of Jupiter can be inferred (1) from the degree-two gravity coefficient assuming the planet to be at the hydrostatic equilibrium, (2) from the planet orientation changing (precession) and (3) from the Lense–Thirring relativistic acceleration experienced by the spacecraft (Iorio, 2010; Helled et al., 2011). Expected to be very small, the acceleration experienced by Juno due to Jupiter pole precession rate has not been analyzed in detail before. So far, only Helled et al. (2011) considered Jupiter's polar

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precession to return to the normalized polar moment of inertia, C/MR^2 (M the mass of Jupiter and R its mean radius). Other studies about the estimation of Jupiter's moment of inertia with Juno were mainly focused on the measurement of the Lense–Thirring acceleration (Iorio, 2010; Finocchiaro et al., 2011; Iess et al., 2013; Tommei et al., 2015). This relativistic acceleration of the spacecraft appeared first to be a promising way to constrain Jupiter internal structure and has been predicted by some of these authors to allow estimating C with a relative accuracy of about 2%. However, this precision is one order of magnitude too large to bring significant constraint on Jupiter's core properties as pointed out by Helled et al. (2011).

It is worthwhile to mention that the previous simulations published on Juno's gravity experiment have all been performed assuming an 11-day orbit tracked during one Earth-year. Our simulations are the first ones based on the very recently adopted 14-day orbit over the extended 1.6 Earth-year nominal mission duration.

A brief review of the model-predicted moment of inertia of Jupiter is presented in Section 2. A discussion on the precessional equations of the spin-pole of Jupiter leading to our recommended formula is done in Section 3. Section 4 describes the simulations set up and Section 5 provides and discusses the simulations results. The interest of the VLBI data is assessed in Section 6 and Section 7 summarizes the main results of the paper.

2. Jupiter's polar moment of inertia

We know only a little about the interior of the largest planet of our solar system. Is there a core inside Jupiter? What can be its size and its mass? These are remaining secrets that could be revealed by the Juno orbiter through the determination of the moment of inertia of the whole planet, providing thereby key information on the origin and evolution of Jupiter. Although the interior structure and composition of the giant planet remain very uncertain, we know from its mass–radius relation that Jupiter is not made of pure hydrogen and helium but also contains an additional fraction of heavy elements (Guillot and Gautier, 2007). The mass spectrometer aboard the Galileo probe measured the abundance of heavy elements in the troposphere of Jupiter (Wong et al., 2004). However, it is currently impossible to claim if most of the heavy elements have collapsed in the center to form a dense core or if they are still distributed in the envelope. Measuring the MOI related to the density profile inside the planet will help to answer this critical question about Jupiter's interior.

Different methods have been used to predict the MOI of Jupiter. Jeffreys (1924) used the Radau–Darwin approximation to infer the MOI from the second degree gravity coefficient, J_2. The large MOI value they obtained (see Table 1) indicates a small or even non-existent core. However this first order approximation is not unequivocal and the MOI could actually be shifted considering higher order terms of the Radau–Darwin equation. Helled et al. (2011) provided a range of MOI based on a simple core/enveloppe interior model of Jupiter exactly fitting the measured zonals J_2 and J_4 and matching J_6 within its error bar. They found a range of possible MOI centered on 0.2637 and varying by $\pm 0.3\%$ allowing for either a core as large as one third of the planet size, with a mass up to 40 Earth mass, or no core at all. These authors nevertheless acknowledge that the range provided is interior-model-dependent and could be biased. Finally, a more peculiar method has been used by Ward and Canup (2006) to deduce the MOI of Jupiter from its obliquity. These authors assumed that a portion of the obliquity of Jupiter results from a spin-orbit secular resonance with Uranus whose orbital plane precession rate was observed to be close to the Jupiter polar precession rate. The several-percent-smaller value they obtained (see Table 1) would be in favor of a massive core, but is maybe more speculative.

In conclusion, the MOI predicted by the theories (geophysical and dynamical) are model-dependent and not in accordance with each other, currently providing only a poor constraint on the interior structure and composition of Jupiter. Therefore trying to determine the actual MOI of Jupiter with Juno is of great interest. If obtained with enough precision (tenth of percent, Helled et al., 2011), such a measurement could definitely prove the existence of a heavy-element core and bring strong constrain on its mass and size taking a huge leap forward in our comprehension of Jupiter, the solar system and beyond (Guillot and Gautier, 2007; Bolton, 2010).

Table 1
Non-exhaustive published values for Jupiter normalized polar moment of inertia.

Reference	C/MR^2	Core properties	Technics
Jeffreys (1924)	0.265	Small or inexistent	Radau–Darwin approximation
Hubbard and Marley (1989)	0.264	Not constraining[a]	Most plausible interior model
Ward and Canup (2006)	0.236	Massive	Dynamical considerations
Helled et al. (2011)	0.2629–0.2645	$M_{core} < 40 M_{Earth}$ $R_{core} < 0.3 R_{Jupiter}$	Core/enveloppe interior model

[a] Helled et al. (2011) hinge value.

3. Jupiter's pole precession

Due to the gravitational torque from the Sun on the Jovian system, the orientation of the spin-axis of Jupiter changes in inertial space, sliding the equatorial plane of the planet along the invariable plane of the Sun-Jupiter system (slightly inclined from Jupiter orbital plane) by an angle equal to $\dot{\psi}(t-t_0)$ with respect to the pole direction at epoch t_0. This very slow motion of the tilted rotation axis around the invariable plane pole is called precession and is characterized by the rate $\dot{\psi}$ at which the pole orientation evolves. $\dot{\psi}$ is inversely proportional to the planet normalized polar moment of inertia, C/MR^2, giving the precession rate a real geophysical interest. However, returning to the MOI from a precise measurement of $\dot{\psi}$ is not straightforward since the precessional equations are not obvious, especially in the case of a planet with a batch of accompanying satellites as for Jupiter. Indeed, as pointed out by Ward (1975), the presence of its numerous moons (especially the four Galilean satellites) plays a major role in the precessional motion of Jupiter spin pole.

3.1. Proposed precession model

In this section we provide a new precession model for Jupiter. Starting from the equation of rotational motion of the planet's pole torqued by the Sun and k satellites, the basic equations for the long term motion of the right ascension, α, and declination, δ, of Jupiter's pole are Jacobson (2014)

$$\dot{\alpha}\cos\delta = -\frac{3}{2}\left(\frac{MR^2 J_2}{C\dot{\omega}}\right)\left[\frac{\mu_\odot}{r_0^3}\left(\hat{\mathbf{h}}_0\cdot\hat{\mathbf{s}}\right)\left(\hat{\mathbf{h}}_0\cdot\hat{\mathbf{g}}\right)+\sum_{j=1}^{k}\frac{\mu_j}{r_j^3}\left(\hat{\mathbf{h}}_j\cdot\hat{\mathbf{s}}\right)\left(\hat{\mathbf{h}}_j\cdot\hat{\mathbf{g}}\right)\right] \quad (1)$$