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Juno and General Relativity

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Abstract

The recently approved Juno mission will orbit Jupiter for one year in a highly eccentric ($r_{\rm min} = 1.06R_{\rm Jup}$, $r_{\rm max} = 39R_{\rm Jup}$) polar orbit ($I = 90$ deg) to accurately map, among other things, the jovian magnetic and gravitational fields. Such an orbital configuration yields an ideal situation, in principle, to attempt a measurement of the general relativistic Lense-Thirring effect through the Juno's node Ω which would be displaced by about 570 m over the mission's duration. Conversely, by assuming the validity of general relativity, the proposed test can be viewed as a direct, dynamical measurement of the Jupiter's angular momentum S which would give important information concerning the internal structure and formation of the giant planet. The long-period orbital perturbations due to the zonal harmonic coefficients $J_\ell, \ell = 2, 3, 4, 6$ of the multipolar expansion of the jovian gravitational potential accounting for its departures from spherical symmetry are, in principle, a major source of systematic bias. While the Lense-Thirring node rate is independent of the inclination I, the node zonal perturbations vanish for $I = 90$. In reality, the orbit injection errors will induce departures δi from the ideal polar geometry, so that, according to a conservative analytical analysis, the zonal perturbations may come into play at an unacceptably high level, in spite of the expected improvements in the low-degree zonals by Juno. A linear combination of Ω, the periJove ω and the mean anomaly $\mathcal{M}$ cancels out the impact of J_2 and J_6. A two orders of magnitude improvement in the uncanceled J_3 and J_4 would be needed to reduce their bias on the relativistic signal to the percent level; it does not seem unrealistic because the expected level of improvement in such zonals is three orders of magnitude. More favorable conclusions are obtained by looking at single Doppler range-rate measurements taken around the closest approaches to Jupiter; numerical simulations of the classical and gravito-magnetic signals for this kind of observable show that a $0.2-5\%$ accuracy would be a realistic goal.

1 Perspectives in testing General Relativity with the Juno mission

The node Ω of Juno, a recently approved spacecraft aimed to orbit Jupiter along a highly eccentric ($r_{\rm min} = 1.06R_{\rm Jup}$, $r_{\rm max} = 39R_{\rm Jup}$), polar ($I = 90$ deg) trajectory during one year to accurately map, among other things, its gravitational field, will be displaced by the general relativistic gravito-magnetic Lense-Thirring effect by about 572 m over the entire duration of the mission.

We, first, explored the possibility of a high accuracy measurement of such an effect by performing analytical calculations and interpreting them in a rather conservative fashion. A meter-level accuracy in determining the jovicentric orbit of Juno should not be an unrealistic goal to be reached. Equivalently, the gravitomagnetic node precession of Juno amounts to 68.5 mas yr^{-1}, while the accuracy in measuring its node and periJove precessions should be of the order of $0.5-1$ mas yr^{-1}, given the expected improvements in our knowledge of the departure of the jovian gravitational field from spherical symmetry. If the Juno's orbit was perfectly polar, the long-period node precessions induced by the zonal harmonics $J_\ell, \ell = 2, 3, 4, 6, ...$ of the non-spherical jovian gravitational potential would vanish, thus removing a major source of systematic alias on the Lense-Thirring secular precession. In reality, unavoidable orbit injection errors will displace the orbital plane of Juno from the ideal polar geometry; as a consequence, the mis-modeled part of the node zonal precessions would overwhelm the relativistic signal for just $\delta I = \pm 1$ deg, in spite of the expected improvements in $J_\ell, \ell = 2, 4, 6$ of three orders of magnitude. A suitable linear combination of the node, the periJove ω and the mean anomaly $\mathcal{M}$ will allow to cancel out the effect of J_2 and J_6; the remaining uncanceled J_3 and J_4 will have an impact on the Lense-Thirring combined precessions which should be reduced down to the percent level or better by the improved low-degree zonals.

Instead of looking at the cumulative, secular effects over the entire duration of the mission, we also followed an alternative approach by looking at single Doppler range-rate measurements over time spans six hours long centered on the the probe's closest approaches to Jupiter; it turned out that, in this way, the perspectives are even more favorable. We numerically simulated the characteristic Lense-Thirring pattern for a single science pass by finding a maximum value of the order of hundreds μm s^{-1}, while the expected precision level in Juno's Doppler measurements is of the order of one μm s^{-1}. Thus, by exploiting about 25 of the planned 33 total passes of the mission it would be possible to reach a measurement accuracy below the percent level. We repeated our numerical analysis also for the Doppler range-rate signals of J_2 and J_4 by finding quite different patterns with respect to the gravitomagnetic one; moreover, for a level of mismodeling of the order of $2 - 3 \times 10^{-10}$ in such zonals the maximum value of their biasing Doppler signals is about $1 - 1.5$ μm s^{-1}. Our numerical analysis also shows that a departure from the nominal polar orbital geometry as large as 1 deg would not compromise the successful outcome of the measurement of interest, contrary to the conservative conclusions of our analytical analysis. Thus, this approach shows that there is not a high correlation between the Lense-Thirring parameter and the jovian gravity field parameters, although a covariance analysis would be needed to prove it. However, such a covariance analysis is outside the scope of the present paper.

2 Conclusions

In conclusion, the potential error in the proposed Juno Lense-Thirring measurement is between 0.2 and 5 percent. Conversely, if one assumes the existence of gravito-magnetism as predicted by general relativity, the proposed measurement can also be considered as a direct, dynamical determination of the jovian proper angular momentum S by means of the Lense-Thirring effect at the percent level.