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Improved Galilean Moon Ephemerides - Reanalysis of Astrometry and Contribution of JUICE mission

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1. Introduction

The dynamics of giant planet satellites provides key information on the physical properties of both the satellites and the planet, in particular due to the signature of tidal dissipation. For the Jovian system, tidal dissipation in both Io and Jupiter (at Io's forcing frequency) has been determined concurrently with the satellites' ephemerides by [Lainey et al., 2009] using astrometric data. This analysis was based purely on astrometric data over a time interval of >100 years. Tidal dissipation in Saturn has been determined at several forcing frequencies by [Lainey et al., 2017] using Cassini data.

The Jupiter Icy Moons Explorer (JUICE) mission will perform detailed measurements of the properties of the Galilean moons, with a nominal mission duration of 2030-2033. Using both the radio tracking data, and (Earth- and JUICE-based) optical astrometry, the dynamics of the moons will be measured to unprecedented accuracy. An analysis of the contribution of the data from JUICE only was done by [Dirkx et al., 2016, Dirkx et al., 2017]. Their results indicated that, although the ephemeris of Ganymede in particular will be determined to extremely high accuracy, the improvement of dissipation parameters may be limited, due to the short time span of the mission. In addition, JUICE's lack of direct obervations at Io, and very limited observations at Europa (for the purposes of ephemerides) strongly reduce the quality of the solutions.

Here, we present a reanalysis of the existing astrometric data, combined with simulated astrometric data between the present day and 2030 (arrival of JUICE) and simulated JUICE tracking data, to obtain a full picture of what the various data sets will contribute to the determination of both the ephemerides and the dissipation parameters.

2. Methodology

Our presented work combines past efforts by [Lainey et al., 2004, Lainey et al., 2009, Dirkx et al., 2016, Dirkx et al., 2017]. The existing astrometric data is reanalyzed, and fitted to our dynamical model. This results in updated estimates of satellite initial states and physical parameters of the system, as well as a covariance matrix for these parameters (formal errors and correlations). For the simulated data (both astrometric and radiometric) we limit ourselves to a covariance analysis.

To obtain the combined uncertainty, we merge the astrometric data sets and the simulated radio data at the normal-equations level:

$$P = \left(H^T W H\right)^{-1} \tag{1}$$

This equation produces the covariance matrix P for the estimated parameters. Here, H is the design matrix, and W the weights matrix. For H, we have:

$$H = \frac{\partial \mathbf{h}}{\partial [\mathbf{x}(t_0); \mathbf{p}]} \tag{2}$$

with $\mathbf{h}$ the vector of observations, $\mathbf{x}(t_0)$ the states of the estimated bodies at the initial time t_0, and $\mathbf{p}$ the physical parameters that are estimated, most notably the dissipation parameters k_2/Q. The initial times of the two data sets will be different, and consequently our two H matrices (for astrometric and radiometric data) will be mapped to a common epoch before combining the data sets.

Our analysis of the JUICE data will follow the approach of [Dirkx et al., 2017], splitting the spacecraft orbit determination and ephemeris calculation. For this setup, the estimation settings for the satellites have been calibrated with a dedicated JUICE orbit determination effort. The analysis of the astrometric data follows the methodology by [Lainey et al., 2004, Lainey et al., 2009]. The data sets are analyzed with separate software packages (NOE for astrometry, Tudat for JUICE data).

The results of our analysis will provide robust insight into the contributions made by the long astrometric time series, and the short radiometric JUICE time series. It will provide predictions for the uncertainty of the Galilean satellite ephemerides, both before, during and after the JUICE mission. Crucially, we will provide improved estimates of the uncertainties of dissipation estimates following the JUICE mission, and identify any critical issues that may need to be adressed for this determination to proceed successfully.

The determination of dissipation parameters in giant planets and their satellites is critical to understand the evolutionary paths of icy satellite systems. It provides key input to (thermal-orbital) evolution studies of the system by reducing the model freedom of the system's physical parameters and current architecture, as dissipation is one of the driving factors in the system's long-term evolution.

For Jupiter, the value of k_2/Q at only a single forcing frequency (Io) has been determined. For Saturn, k_2/Q has been determined for multiple forcing frequencies, and was found to vary over several orders of magnitude. This is most likely the result of the fluid dynamic response of the planet's interior to tidal forcing, the so-called dynamical tide [Ogilvie and Lin, 2004]. This causes a strongly nonlinear dependence between dissipation and forcing frequency. The dynamical tide is key in the concept of resonance locking [Fuller et al., 2016], in which a migrating satellite can be 'locked' onto a peak in the planet's dissipation spectrum.

There is a tantalizing proposition by [Fuller et al., 2016] that Callisto may currently be in such a resonant lock. The JUICE data would be ideally suited to contributing to the determination of such an effect, as the estimation of Callisto's dynamics does not correlate strongly with the inner three satellites, allowing signatures on its dynamics to be more robustly extracted. In our work, we analyze the signature of Jupiter's k_2/Q at Callisto's forcing frequency in the current data, and place upper limits to the level to which it could potentially be constrained by the JUICE mission.

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