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Dynamical modelling of the Galilean moons for the JUICE mission

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A B S T R A C T

Radio tracking and astrometric data obtained by the JUICE mission, using the PRIDE, 3GM and JANUS instruments, will allow the dynamics of the Galilean moons to be measured to unprecedented accuracy. As a result, the dynamical models used for creating ephemerides from these data will most likely require the inclusion of various heretofore neglected physical effects.

To determine which effects will need to be included, we perform a sensitivity analysis of the influence on the dynamics of the system for a wide array of gravitational, tidal and rotational characteristics of the system. We estimate the dynamics of the Galilean moons with a given perturbation turned off, using ideal three-dimensional measurements of the satellites' positions generated with these perturbations turned on. In doing so, we assess the capabilities of the nominal dynamical model to absorb the influence of this perturbations. We analyze the dynamical behaviour over a period of five years, and limit our analysis to effects that may be observable from JUICE radio tracking and optical astrometry data. Our simulations comprise a short-period (5 years) sensitivity analysis of the dynamics of the moons, and *not* a simulation of the tracking data inversion for JUICE.

Our analysis indicates that the nominal dynamical model of the Galilean satellites can very efficiently absorb the influence of the current uncertainties in most of the physical parameters of the Jovian system, to a level where these uncertainties will not be influential for JUICE-derived ephemerides. An important exception is the influence of tidal dissipation: the k_2/Q of Io will be clearly observable by JUICE tracking data, which will be strongly correlated with the weaker effect of Jupiter's k_2/Q. The dissipation inside Europa may also be weakly constrained by JUICE tracking data. Without improvements in the Jovian gravity field from the Juno mission, the estimation of Jupiter zonal gravity field coefficients at degrees 2, 3 and 5 should be included in the ephemerides generation. The influence of the deviation from perfect tidal locking of the moons' rotation is at the limit of observability. Furthermore, we have verified that the present uncertainty in the *a priori* ephemeris of Jupiter will not influence the (Jupiter-centered) dynamics of the Galilean moons at an observable level.

1. Introduction

The dynamical behaviour of (a system of) planetary satellites holds key information on the properties of both the satellites themselves and the central body (e.g. Jacobson, 2004; Emelyanov, 2005; Lainey et al., 2007, 2012; Beauvalet et al., 2012; Folkner et al., 2014; Jacobson, 2014; Lainey et al., 2015). As a result, the dynamical model of these satellites can be used to infer information on their interior structure, composition and rheology, which in turn provides clues to the origin and evolution of both the system under consideration and (exo) planetary systems in general.

So far, the ephemerides of the Galilean system have been based on Earth-based astrometric and mutual event observations, supplemented by both radio tracking and optical data from spacecraft such as Pioneer 10 and 11, Voyager 1 and 2, and Galileo (Lieske, 1980, 1998; Jacobson, 2001; Lainey et al., 2004a, 2009). Optical astrometric observations of the Jovian system, which have an uncertainty of about 20–150 mas, translating to approximately 60–450 km in linear position, are available over a period of over 100 years. The creation of ephemerides from these data has allowed for an estimation of the tidal dissipation in both Jupiter and Io (Lainey et al., 2009).

The dynamical characteristic that dominates the behaviour of the system is the 1:2:4 Laplace mean motion resonance that Io, Europa and Ganymede are locked in. There are several theories on how this resonance came into being (Peale, 1999; Greenberg, 2010), with one key issue being whether the resonance is primordial (e.g., Greenberg, 1987; Peale and Lee, 2002) or whether the satellites evolved into the configuration as a result of tidal dissipation (e.g., Yoder and Peale,

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1981; Malhotra, 1991). Constraining the properties of both the Jovian moons and Jupiter, especially the tidal characteristics, will be crucial in furthering our understanding of the system's origin and evolution. Furthermore, the present configuration and properties of the Galilean moons can be used to shed insight onto the formation and evolution of the solar system (Deienno et al., 2014; Heller et al., 2015).

The Jupiter Icy Moons Explorer (JUICE) mission is set to arrive in the Jovian system in 2030, focusing on investigation of the Galilean satellites and culminating in a nine-month orbital phase around Ganymede, with a final altitude of 500 km (Grasset et al., 2013; Titov et al., 2014). The data collected by this mission will allow the dynamics of the system to be constrained to revolutionary accuracy. The main instruments that facilitate this are the Planetary Radio Interferometry and Doppler Experiment (PRIDE) (Gurvits et al., 2013) and Gravity and Geophysics of Jupiter and Galilean Moons (3 GM) (Iess, 2013), which will both provide active tracking data obtained from Earth-based radio telescopes. In addition to the Doppler data provided by both systems, 3GM will provide range measurements, which should have an uncertainty of down to 0.2 m. PRIDE will provide uniquely valuable lateral positions of JUICE in the International Celestial Reference Frame (ICRF). These measurements presently have a precision of about 1 nrad (Duev et al., 2012), which translates to a linear position uncertainty of about 750 m (at 5 AU). This could perhaps be improved to the 0.1 nrad level by the use of the Ka-band radio signal (as opposed to the typically used X-band signal) (Lanyi et al., 2007) or in-beam phase-referencing (Fomalont et al., 1999). It is these absolute measurements of range and lateral position that are most valuable for planetary ephemeris generation, as opposed to the Doppler data which are important for reconstructing the trajectory of the spacecraft itself, (e.g., Pitjeva, 2001; Fienga et al., 2009; Jones et al., 2015). The planetary satellite ephemeris generation can benefit from both the absolute and the Doppler data. The precise contribution of each data type will be investigated in future work.

The radio tracking data will be supplemented by the JANUS camera system on JUICE (Jaumann et al., 2013), which will collect astrometric observations of the Jovian moons. This supplements the data available for ephemeris generation, as is done for the generation of Saturnian satellite ephemerides from Cassini data (Lainey et al., 2015). Furthermore, the Gaia mission will provide revolutionary accuracy of the background star catalogue, improving the quality of both past and future ground-based optical astrometry (Arlot et al., 2012). This will result in uncertainties that are no longer limited by the catalogue. This will result in improved uncertainties down to the 10–20 mas level for absolute Earth-based astrometry (Arlot et al., 2012; Robert et al., 2015), a significant improvement over the present state-of-the-art in astrometric data reduction (e.g. Robert et al., 2011). Moreover, the new denser catalogue will allow additional plates to be reduced, for which there are presently insufficient reference stars. Mutual event data, which have a smaller uncertainty than the absolute data, will not be improved as significantly by the Gaia catalogue. However, mutual event data is only sparsely available (once every 6 years), while there is a large volume of historical absolute astrometry. JANUS astrometry will not be improved by the Gaia catalogue, as the uncertainty in its astrometric observables is dominated by the center-of-figure to center-of-mass correction, as discussed by e.g. Pasewaldt et al. (2012). Finally, we note that an improved background catalogue will also be crucial in applying the recently proposed *mutual approximations* in optical astrometry (Morgado et al., 2016) for ephemeris creation. An analysis of the quantitative influence of the Gaia catalogue on all facets of optical astrometry data and the associated improvement in ephemerides and tidal dissipation is yet to be performed, however.

Our goal in this article is to identify the parameters to which the Jovian system may be dynamically sensitive over time scales that are relevant for JUICE observations (nominally 3.5 years). In doing so, we identify those parameters that should or should not be included in the inversion of these data. This will be crucial in optimizing the science observation planning and maximizing the mission's science return. Furthermore, our results provide a guideline for further developments in dynamical modelling of the Galilean moons that may be needed for a robust inversion of the tracking data, in particular those related to tidal and/or rotational properties. We analyze the behaviour of the dynamics over a somewhat longer period of 5 years, to provide a broader context for the results, and improve the robustness of the results on excludability of a given parameter. Also, it allows for a preliminary analysis of the influence of a (short) putative mission extension.

We stress that the analysis in this paper does *not* provide any uncertainties of the physical parameters of the Jovian system that can be estimated using tracking data from the JUICE mission. Such an analysis requires the detailed investigation of the influence of the various tracking data types, mission geometry, observation cadence, etc. Instead, we analyze for which parameters the influence may be visible in the tracking data analysis of the JUICE mission, and for which parameters the influence will be too small and/or indistinguishable from the influence of a change in the initial positions of the moons.

Consequently, we remain independent of any specific tracking observable in this paper, instead analyzing the influence of variations in the system's properties to the overall dynamical behaviour of the moons. In doing so, we build a generic basis upon which future analyses of Jovian-system ephemeris-generation can build, with a focus on the JUICE mission. Nevertheless, our analysis is also relevant for the science return of other planned/proposed missions to the Jovian system, such as Europa Multiple-Flyby Mission (EMFM), (formerly known as Europa Clipper) see (Park et al., 2015) and the Io Volcano Explorer (IVO), discussed by McEwen et al. (2014).

We start in Section 2 by describing our dynamical model. Subsequently, we discuss the approach we use for the sensitivity analysis in Section 3. We present and discuss the results of the sensitivity of the dynamics of the Galilean satellites to the system's physical properties, over a timespan and observational accuracy relevant to JUICE, in Section 4 and summarize our overall conclusions in Section 5.

2. Dynamical models

In this section, we describe the dynamical model we use for the Galilean moons, which is extended from the one used by Lainey et al. (2004b). We limit ourselves to the effects that we expect to be visible at a level that may be relevant for the JUICE mission (Section 3.3).

In Section 2.1, we review the model for mutually gravitationally interacting extended bodies. Subsequently, we present the rotation models we use in Section 2.2 and the model for the tides raised on both Jupiter and the satellites in Section 2.3. Finally, we summarize the present and expected near-future uncertainty in the knowledge of the characteristics of the Jovian system in Section 2.4.

For indices denoting the bodies of the Jovian system, we use i=0 for Jupiter, $i = 1\ldots4$ for the Galilean moons (Io, Europa, Ganymede and Callisto, respectively) and $i = 5\ldots7$ for Amalthea, Thebe and Himalia, respectively. We propagate the Jovian moons w.r.t. the center of mass of Jupiter, with the orientation fixed w.r.t. the ICRF (J2000). As the initial condition, we use the state of the Galilean moons on January 1, 2030 from the Spice kernel (Acton, 1996) provided by IMCCE (2010), created using the model of Lainey et al. (2009). We use the DE431 solar system ephemeris (Folkner et al., 2014) for positions of the planets and the Sun. We use an extended version (Dirkx, 2015) of the Tudat software toolkit[1] for our numerical simulations.

2.1. Gravitational interaction

Following Lainey et al. (2004b), we denote the potential of a point

[1] http://www.github.com/tudat.