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Expected precision of Europa Clipper gravity measurements

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ABSTRACT

The primary gravity science objective of NASA's Clipper mission to Europa is to confirm the presence or absence of a global subsurface ocean beneath Europa's Icy crust. Gravity field measurements obtained with a radio science investigation can reveal much about Europa's interior structure. Here, we conduct extensive simulations of the radio science measurements with the anticipated spacecraft trajectory and attitude (17F12v2) and assets on the spacecraft and the ground, including antenna orientations and beam patterns, transmitter characteristics, and receiver noise figures. In addition to two-way Doppler measurements, we also include radar altimeter crossover range measurements. We concentrate on ± 2 h intervals centered on the closest approach of each of the 46 flybys. Our covariance analyses reveal the precision with which the tidal Love number k_2, second-degree gravity coefficients $\bar{C}_{20}$ and $\bar{C}_{22}$, and higher-order gravity coefficients can be determined. The results depend on the Deep Space Network (DSN) assets that are deployed to track the spacecraft. We find that some DSN allocations are sufficient to conclusively confirm the presence or absence of a global ocean. Given adequate crossover range performance, it is also possible to evaluate whether the ice shell is hydrostatic.

1. Introduction

The spacecraft mission design process at NASA relies on design requirements that flow from measurement requirements, which themselves flow from science objectives. The Europa Clipper mission has a set of compelling science objectives (e.g., Pappalardo et al., 2017) that emerged out of strategic planning documents (e.g., National Research Council, 1999, 2011) and other studies. Here we investigate some of the measurement requirements that may be needed to enable a gravity science investigation. Gravity science experiments provide powerful data for investigating the physical state of planetary bodies. Examples include mapping the gravity field, estimating the rotational state, and probing the internal structure of Mercury (e.g., Smith et al., 2012; Mazarico et al., 2014; Verma and Margot, 2016), Venus (e.g., Sjogren et al., 1997; Konopliv et al., 1999), Mars (e.g., Smith et al., 1999; Konopliv et al., 2011), and Titan (e.g., Iess et al., 2010).

In 2015, NASA appointed a Gravity Science Working Group (GSWG) to help refine science objectives for the Europa Clipper mission (then known as the Europa Multiple Flyby Mission). NASA's charge to the GSWG included the following statement: "The GSWG will define and recommend to the science team science investigations related to understanding the response of the satellite to gravity, specifically, but not limited to, understanding the tidal distortion of Europa, its internal structure, precession, and moments of inertia." The GSWG produced a report (Gravity Science Working Group, 2016) that specifies the precision with which certain quantities must be measured in order to meet specific science objectives (Table 1). The GSWG focused primarily on measurements that pertain to the ice shell and the presence of an ocean.

One of the primary objectives of a mission to Europa is to confirm the presence of a global ocean. A gravity science investigation can address this objective in a number of ways (Gravity Science Working Group, 2016). Here, we focus on measurements of the tidal Love number k_2. An alternate approach consists of measuring the tidal Love number h_2, as examined by Steinbrügge et al. (2018). Calculations by Moore and Schubert (2000) indicate that k_2 is expected to range from 0.14 to 0.26, depending on the thickness and strength of the ice shell, if a global ocean is present underneath the ice shell. In contrast, k_2 is expected to be less than 0.015 if there is no global ocean. Therefore, a measurement of k_2 is sufficient to test the global ocean hypothesis (Park et al., 2011, 2015; Mazarico et al., 2015), provided that the uncertainties do not exceed the 0.06 level recommended by the GSWG.

Another important objective of a gravity science investigation is to confirm whether the ice shell is in hydrostatic equilibrium.

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Table 1
A subset of possible measurement objectives for a Europa Clipper gravity science investigation (Gravity Science Working Group, 2016). The rightmost column specifies the one-standard-deviation precision with which geophysical parameters must be measured in order to meet gravity science objectives. The GSWG recommended multiplying formal uncertainties of fitted parameters by a factor of two to arrive at realistic one-standard-deviation uncertainties – see Section 4.4. The spherical harmonic coefficients in the representation of the gravity field are 4π-normalized. In this work, we focus on the first three objectives.

Objective	Quantity	Required precision
Confirm the presence of an ocean	Tidal Love number k	$k_2 < 0.06$
Verify whether ice shell is hydrostatic	Gravitational harmonics	$\bar{C}_{20} <$ 8e-6 and $\bar{C}_{22} <$ 9e-6
Measure shell thickness (to $\pm 20\%$)	Gravitational harmonics	$\bar{C}_{30} <$ 4e-7 and $\bar{C}_{40} <$ 4e-7
Confirm the presence of an ocean	Tidal Love number h	$h_2 < 0.3$
Confirm the presence of an ocean	Obliquity	$\theta < 0.01°$
Measure elastic shell thickness (to ± 10 km)	Tidal Love numbers	$k_2 < 0.015$ and $h_2 < 0.015$
Confirm ice shell is decoupled from interior	Amplitude of longitude libration	<50 m at tidal period

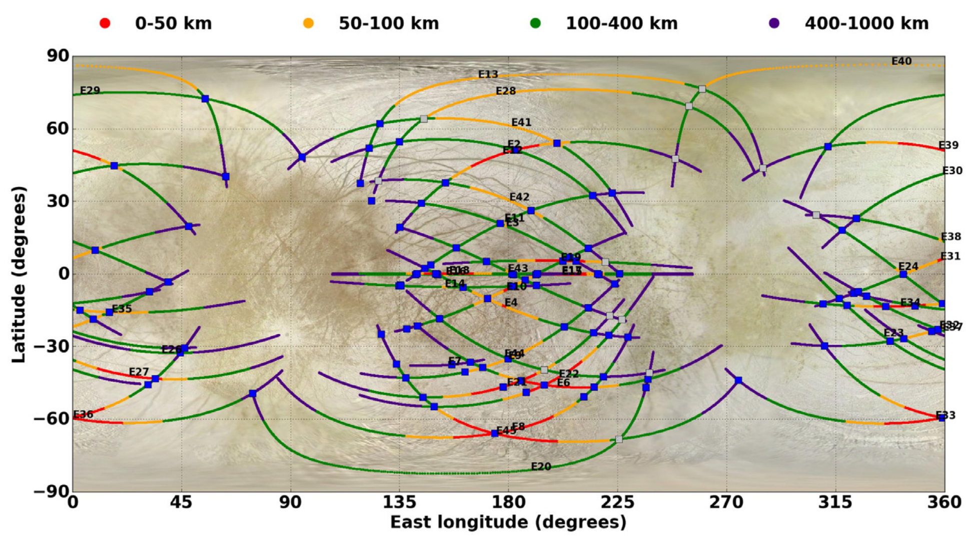

Fig. 1. Ground tracks (solid lines) and crossover locations (squares) corresponding to trajectory 17F12v2. Ground tracks are color-coded by altitude and crossovers are color-coded in blue (when Europa's surface is illuminated by the Sun) or silver (when the surface is in darkness). Only crossovers that occur when both altitudes are below 1000 km are shown.

Galileo-based estimates of second-degree gravity coefficients rely on the assumption of hydrostatic equilibrium (Anderson et al., 1998), but it is unclear whether hydrostatic equilibrium applies. It is possible to test the hydrostatic equilibrium hypothesis by measuring the second-degree gravitational harmonic coefficients, $\bar{C}_{20}$ and $\bar{C}_{22}$, to the level prescribed by the GSWG (Table 1). Trajectories being designed for the Clipper mission offer promising prospects for measuring these quantities.

In Section 2, we provide an overview of the anticipated Clipper trajectory. In Section 3, we review measurements, uncertainties, and model assumptions. Our dynamical model, solution strategy, and estimated parameters are discussed in Section 4. In Section 5, we discuss our covariance analysis results. Our conclusions are provided in Section 8.

2. Spacecraft trajectory and attitude

Europa Clipper will orbit Jupiter and execute repeated close flybys of Europa, Ganymede, and Callisto with science observations at Europa and gravitational assists at Ganymede and Callisto (Lam et al., 2015). To achieve the science goals of the mission, Clipper trajectories are designed to obtain globally distributed regional coverage of Europa with multiple low-altitude flybys (Pappalardo et al., 2017). The current trajectory, named 17F12v2, includes 46 flybys with altitudes as low as 25 km (Fig. 1) and 126 crossovers below 1000 km altitude. Crossovers are locations where two ground tracks intersect and where altimetric measurements are particularly valuable.

We examined the suitability of trajectories 15F10, 16F11, and 17F12v2 for gravity science investigations, with a particular emphasis on 17F12v2. All of these trajectories were designed to obtain globally distributed regional coverage of Europa with 42, 43, and 46 flybys, respectively (Table 2).

An important consideration for a gravity science investigation is the distribution of sub-spacecraft latitudes when the spacecraft is at closest approach. Trajectory 17F12v2 provides an adequate distribution for gravity science purposes (Table 3). Details about the spacecraft's anticipated trajectory and orientation in space (attitude) are available at ftp://naif.jpl.nasa.gov/pub/naif/EUROPACLIPPER in the form of SPICE kernels (Acton et al., 2017).

3. Measurements

The gravity science investigation will utilize a radio link between Earth-based stations and the spacecraft's radio frequency telecommunications subsystem to provide range and Doppler measurements (see Section 3.2) and solve for Clipper's trajectory. These data will yield measurements of Europa's gravity field and tidal response. The investigation will also rely on spacecraft-to-Europa ranging data from the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) instrument (Blankenship et al., 2014). Analysis of REASON data may be enhanced with digital elevation models obtained by stereo imaging from the Europa Imag-