Probing Europa's hidden ocean from tidal effects on orbital dynamics

Xiaoping Wu, Yoaz E. Bar-Sever, William M. Folkner, James G. Williams, and James F. Zumberge

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Abstract. Recent observations of Europa suggest that the Jovian satellite may have a liquid ocean underneath its icy surface. Geophysical models indicate that the tidal Love number k_2 has a strong dependence on the presence or absence of an ocean. The k_2 dependence on the ice shell thickness is also significant. Measurements of the static and tidal gravity fields through their dynamic effects on the trajectory of a low Europan orbiter can be essential in the detection of an ocean and inference of other internal structures. Covariance analyses have been carried out to assess accuracies using simulated Doppler tracking data. With 15 days of tracking from 2 Earth stations, the uncertainties for k_2, mantle libration amplitude and the epoch radial position of the spacecraft are expected to be 0.0004, 2.8 arcsec and 5.7 m, respectively. These tight constraints will strongly contribute to ocean detection and ice thickness determination when combined with altimeter measurements.

Introduction

Surface features from high resolution Galileo images, hydrodynamic modeling, and magnetic fields imply the possibility of a global liquid water ocean underneath Europa's icy surface shell [*Chapman,* 1999; *Kivelson et al.,* 2000]. The detection of such an ocean could have profound implications on potential existence of extra-terrestrial life. Since a body with internal fluid layer(s) deforms more under tidal forcing than an otherwise similar but solid body, one can measure the tidal response to infer the fluid layer [e.g., *Cassen et al.,* 1979; *Wu et al.,* 1995; *Yoder,* 2001]. Such an experiment is particularly interesting for Europa because of its intense tidal environment at 9.4 Jupiter radii, with an orbit eccentricity of 0.01 and a synchronous orbit/spin period of 3.55 days.

Current observational constraints on the Europan internal structure are the mean density and polar moment of inertia based on Doppler tracking of the Galileo spacecraft's four encounters and the hydrostatic equilibrium assumption [*Anderson et al.,* 1998]. A three layer Europa model has been proposed: a metallic core, a rocky mantle and a 80-170 km thick surface ice-water shell. While the constraints are very valuable, they cannot uniquely identify some key compositional or mechanical parameters (e.g., rigidity) inside Europa. An orbiter mission will provide more detailed information in this regard.

A Europa orbiter mission is planned by NASA for launch as early as in 2004. The spacecraft could begin science map-

ping around 2009 for a short duration (one month) under the hostile radiation environment. Confirmation of the existence of the ocean and characterization of the water/ice dimensions are among the top objectives of the mission. The tidal response of Europa and the possibility of inferring the interior structure will be discussed in the next section. Such inferences would require the determination of static and tidal topography and gravity fields, as well as the 3.55-day ice shell forced libration amplitude (see below). We carry out covariance analyses to address the issue of measurement accuracies for the static and tidal gravity fields using radio Doppler tracking to the orbiter. The topography and its tidal variations can be determined by a laser altimeter. The shell libration amplitude may also be measured by altimetry (B. Haines, personal communication, 1999), or by imaging. Although we do not include altimetry or imaging in this study, the topography and surface rotation measurements would be an important component of the mission. The orbit accuracy determined here from Earth to spacecraft tracking will be an important factor for these measurements.

Europan Tides

To assess detectability and measurement accuracies of a global liquid ocean on Europa, we will examine the 2nd-degree tide-raising potential by Jupiter V_2^J. The deformation of a spherical, non-rotating, and elastic Europa is proportional to the tide-raising potential. The deformation induced time-variable potential at the spacecraft position (r, ϕ, λ) and ground uplift are

$$\Delta V_2 = k_2 \left(\frac{R_e}{r}\right)^3 V_2^J, \text{ and } u_2 = \frac{h_2}{g}V_2^J, \qquad (1)$$

respectively. k_2 and h_2 are tidal Love numbers. R_e and g are the surface radius and gravity. The anelasticity and ocean friction can be represented by equivalent lag angles through complex Love numbers.

The Love numbers k_2 and h_2 depend on the mechanical properties of the interior of Europa. To investigate their sensitivity to a set of interior parameters, we numerically compute the Love numbers using a series of plausible Europan models with a four layer structure (*Anderson et al.* [1998]'s outer ice/water shell is separated into two layers). The mean density, dimensionless moment, and the radius of Europa are fixed at their nominal values as $\bar{\rho} = 2989$ kg m^{-3}, $C/MR_e^2 = 0.346$, and $R_e = 1565$ km.

As shown in Figure 1, with two ice rigidity values, the Love number k_2 becomes strikingly smaller when the ice shell thickness equals 160 km, because then there is no liquid ocean (in this model). k_2 also depends significantly on the thickness and rigidity of the ice shell (Figure 1), the
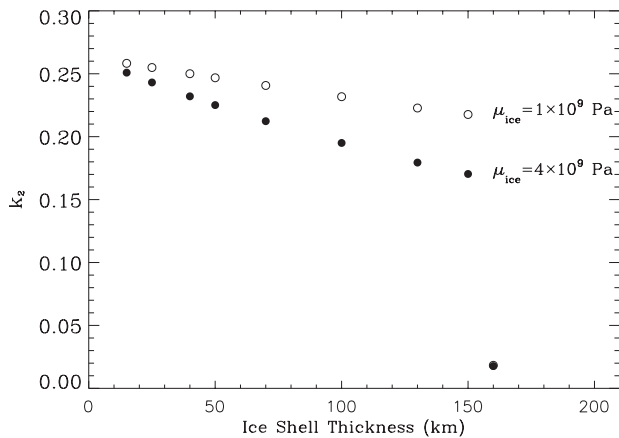
Figure 1. k_2 as a function of thickness of the ice shell. Total ice and water thickness is assumed to be 160 km. Solid circles: ice rigidity = 4×10^9 Pa; open circles: ice rigidity = 1×10^9 Pa.

rigidity of the mantle and the density of the liquid ocean (not shown). On the other hand, k_2 does not depend (at the 0.002 level) on the thickness of the liquid ocean. Also, k_2 is relatively insensitive to the densities of the mantle, core, or the ice shell. The presence of a fluid core or outer core with a radius of 800 km can increase k_2 by about 0.02 while reducing the ratio of Love numbers, h_2/k_2 by about 0.3. This effect on the two Love numbers seems to be indistinguishable from that of a smaller mantle rigidity.

Yoder [2001] pointed out that the ratio of h_2/k_2 can be used to constrain the rigidity of a soft mantle, and that the rigidity of the ice and the density contrast between the liquid ocean and the ice shell may be constrained by ice shell libration and high degree (>20) static topography/gravity measurements, respectively. Since k_2 depends on these parameters, it should be combined with the 3 measurements to infer the interior. Assuming accurate shell libration and topography measurements from the altimeter and gravity measurements from the Doppler tracking, one can use the two Love numbers to infer the ice shell thickness and mantle rigidity. A simple covariance analysis shows roughly equal contributions from k_2 and h_2 noise to the uncertainty of the ice shell thickness. Uncertainties of 0.002 in both Love numbers would correspond to 1-km error in the ice shell thickness in the quasi-linear inference. The inference about mantle rigidity, however, is highly non-linear. Around our reference Europan structure, k_2 error affects the rigidity determination more than h_2. Thermal models of the Europan interior will greatly improve when the tidal phenomena are better measured and understood since tidal friction is a major heating source. These could constrain the state of the core and the mantle. The determination of tidal lag angles would also be desirable for this purpose.

Covariance Analyses

For our simulation study, the Europa orbiter is placed in a 200-km altitude orbit with eccentricity $e = 0.01$. The mass of the spacecraft is assumed to be 400 kg. The orbital period is about 2.3 hours. The orbital inclination is assumed to be $83°$. The longitude of node is $220°$, and the argument of periapsis is $30°$. For our main case study, Four 3.55-day arcs

of X-band Doppler tracking data are simulated from 2 Deep Space Network (DSN) stations (Goldstone and Madrid). A $15°$ minimum elevation angle and a two-way range rate uncertainty of 9×10^{-2} mm s^{-1} for 30 second count interval are used.

The spacecraft orbit dynamics include static and tidal gravity, third body attraction by Jupiter, solar radiation pressure, Europa albedo and infra-red thermal radiation, a conical shadow model, and the 3.55-day forced libration in longitude. The obliquity is taken to be $0.17°$. The detection of an ionosphere by the Galileo spacecraft indicates a possible sparse Europan atmosphere. To simulate possible air drag on the low orbiter, we have also included a constant and a once-per-revolution along-track accelerations for the spacecraft. The kinematic model of the inter-planetary tracking contains the rotation of Europa and Earth, simplified Keplerian orbits for the Earth and Europa, light time solution for the radio signal, Earth orientation, and the troposphere refraction. The solar wind plasma effect on the Doppler observable is lower than the noise level assumed above and is ignored here provided solar elongation angle is greater than $60°$ (J. Armstrong, personal communication, 2000).

The estimated common parameters are GM of Europa, separate gravity contributions from the ice shell and from the mantle to harmonic degree/order 50, the Love number k_2, the tidal lag angle ν, the average reflectivity parameters of the spacecraft body and antenna, and the librational amplitudes of the ice shell and rocky mantle. Our estimated arc-dependent parameters consist of epoch radial, along-track and normal position (X, Y, Z) and velocity vectors of the spacecraft, six Keplerian elements for Europan orbital motion, and the constant and once-per-revolution along-track spacecraft accelerations for air-drag. A set of so-called "considered parameters", not solved for in the estimation process but the effects of their uncertainties on the estimated parameters are evaluated by the analyses, are chosen to be: unestimated gravity coefficients up to degree 60, a constant range rate bias of 6×10^{-3} mm s^{-1}, Europa's surface absorption coefficient, spacecraft emissivity and reflectivity parameters, Earth orientation parameters, DSN station coordinates, and zenith troposphere delay. The uncertainties for the considered gravity contribution from the mantle on down are computed using Kaula's rule, a planetary factor and a decay factor due to the surface layer of ice and water. The uncertainties for the considered ice shell gravity contribution are derived from a compensated topography (including the underside) formula, with the coefficient calibrated by 0.2 km height variation at a wavelength of 800 km.

With a planet-wide ocean, the ice shell and rocky mantle may librate separately in longitude with respective amplitudes of 10 and 20 arcsec. The librations will also produce time-dependent variations in the external gravitational potential due to non-zonal mass anomalies attached to the two frames. We therefore estimate separate static gravity contribution coefficients from the shell and the mantle along with their amplitudes of libration. Since we cannot separate out all components of the separate gravity contributions, to prevent the estimates being way out of range, a priori uncertainties (constraints) are applied at the level of 10 times the expected amplitudes to the estimated gravity contribu-

tions. For the ice shell gravity contribution, such uncertainties at degree 2 correspond to about 30 km topographic variation. The uncertainties assumed here are much larger than altimeter or imaging noises. They should be sufficient to accommodate possible inaccuracies of the theory used to link gravity to topography. Therefore, the results of the covariance analyses would not be compromised by realistic uncertainties in the ice shell gravity contributions. No other a priori constraints are applied to the estimated parameters except for 100-km ephemeris knowledge of Europa.

Results and Discussion

The perturbing effects of the radiation force uncertainties are very small in the Europan environment. This leaves the high degree gravity coefficients to be the dominant source of uncertainty if available data do not permit a sufficiently high resolution recovery of the gravity field. For our main case analysis, the resolution in the gravity field is high enough so that the covariance results are not notably affected by uncertainties in the considered parameters such as short-wavelength ice shell and mantle gravity contributions. The resulting uncertainties for the most relevant estimated parameters are listed in Table 1.

If the librational motion of the ice shell and rocky mantle is attached in absence of a liquid ocean, covariance analysis uncertainties for the total gravity coefficients, tidal parameters and mantle libration amplitude do not differ notably from the detached motion studied in the main case. We have also carried out a case analysis with the same tracking data set as the main case but with 12-hour arcs for the possibility of daily spacecraft reaction wheel momentum dumps and uncertain dynamic sources. The shorter arc results in an increase in the uncertainties of most parameters by a factor of about 4 (Table 1). For a shorter mission, with only one 4-day arc, the k_2 uncertainty becomes 0.0008 with tracking from all 3 DSN stations. If only 2 DSN stations are used during the short mission, k_2 uncertainty would go up to 0.0024.

The uncertainties for the total static gravity coefficients are shown in Figure 2 for the main and short arc cases. The
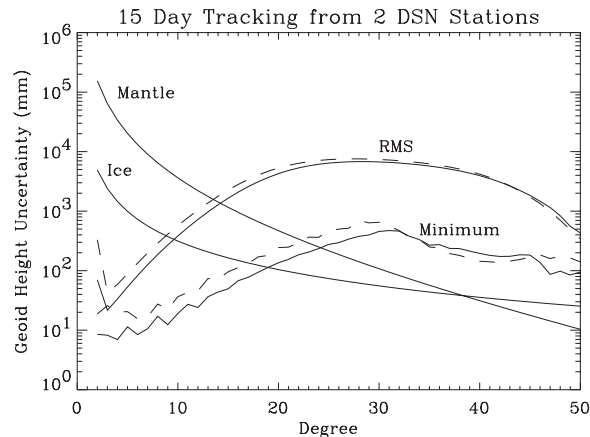
Figure 2. RMS and minimum uncertainties for Europan geoid harmonic coefficients per degree. Solid and dashed curves show results using 3.5 day and 12 hour arcs respectively. Also shown are expected amplitudes of the mantle and ice shell geoid contributions

RMS uncertainty for each degree goes above the expected amplitude at degree 15. But significant information can be obtained even beyond degree 24. The epoch position of the spacecraft is determined to a few meters. Two-meter radial accuracy is possible with more tracking data from 3 DSN stations. This should allow meter-level altimetry measurements for topography and shell libration. The uncertainties of the orbital elements of Europa from our analyses correspond typically to 1-km position accuracy.

The analyses show that with a reasonable tracking configuration, the k_2 Love number should be determined to about 0.0004. The tidal lag angle uncertainty of $0.03°$ is significantly smaller than the expected phase lag of 0.06 to $1.2°$ [*Yoder*, 2001]. These should strongly contribute to the detection of a liquid ocean as well as to constraining the ice shell thickness, mantle rigidity, and tidal friction on Europa. For example, if h_2 and ice shell libration are determined to sufficient accuracies, the k_2 uncertainty of 0.0004 translates to an ice thickness uncertainty between 200 m and 1 km, subject to minor contaminations from uncertainties in other interior parameters such as the ice shell density. Moreover, the high measurement accuracy for the static k_2 raises the hope that resonance effects of free-ocean-nutation, free-mantle-nutation, and internal ocean modes are also detectable, which may reveal more about the ocean and other internal structures. The uncertainty in the amplitude of forced mantle libration depends on the strength of the non-zonal gravity contribution. For our reference gravity coefficients, the uncertainty in the mantle libration amplitude is 2.8 arc seconds. This is also very close to the uncertainty in the attached ice shell libration amplitude. Less than 1.0 arc second uncertainty can be achieved with 15 days of tracking from 3 stations on the Earth. Accurately measured mantle and ice shell librations could discern any detached motions and provide additional crucial evidence for a global liquid ocean. Mantle libration measurement could also contribute to constraining the size of a possible fluid core and the depth of the ocean-mantle interface.

Table 1. Uncertainties Resulting from Covariance Analyses (15-Day Tracking from 2 Stations)

Parameter	Uncertainty	
	3.5-day arc	12-hour arc
Europa GM (km^3/s^2)	3×10^{-2}	1.2×10^{-1}
Stokes coefficient $\bar{C}_{20}$	3.8×10^{-8}	1.9×10^{-7}
Stokes coefficient $\bar{C}_{21}$	1.2×10^{-8}	2.5×10^{-8}
Stokes coefficient $\bar{S}_{21}$	5.4×10^{-9}	1.2×10^{-8}
Stokes coefficient $\bar{C}_{22}$	6.2×10^{-8}	2.9×10^{-7}
Stokes coefficient $\bar{S}_{22}$	6.7×10^{-8}	3.1×10^{-7}
Love number k_2	0.0004	0.0016
Lag angle ν ($°$)	0.03	0.16
Mantle libration β_m ($''$)	2.8	*
Ice shell libration β_i ($''$)	11	*
RMS epoch SV pos. X (m)	5.7	22
RMS epoch SV pos. Y (m)	4.2	25
RMS epoch SV pos. Z (m)	8.6	47
RMS Europa s.m. axis (km)	1.0	2.8

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Y. E. Bar-Sever, W. M. Folkner, J. G. Williams, X. Wu, and J. F. Zumberge, Jet Propulsion Laboratory, 4800 Oak Grove Dr. MS 238/600, Pasadena, CA 91109. (e-mail:Xiaoping.Wu@jpl.nasa.gov)