Forced Librations in Longitude for Europa

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Introduction: Future attempts to map the gravity and topography of Europa, from spacecraft observations, will need improved models of the rotational dynamics of that body. The current IAU model of Europa's rotation [1] assumes that the spin pole is aligned with the orbit pole, and that the rotation rate is uniform. Both of those assumptions are good first approximations, but not good enough for future geodetic analysis. The present study is focused on providing an improved model of the rotation rate variations. Previous work on the finite obliquity variations [2,3] also needs improvement, but that will be treated elsewhere.

Forced librations of Europa are rotational responses to torques attempting to keep its axis of least inertia pointed toward Jupiter. The amplitude of the rotational response can be diagnostic of internal structure.

The present analysis uses two different approaches to model the response. One assumes an isolated binary orbit, involving Jupiter and Europa. Depending upon the initial conditions, there can be both persistent librations, at integer multiples of the orbital period, and transient librations with decaying amplitude and period set by the moments of inertia of the body.

In the other approach, orbital perturbations, from the oblate figure of Jupiter, other satellites, Saturn and the Sun all lead to more complex variations in orbital true longitude. In that case, the amplitude and phase of the librational response depends upon both the orbital forcing, which is well known, and the free libration period and viscous damping time. The rotation angle, as seen in an inertial frame, deviates from a linear trend by ±6° on decadal and centennial time scales.

Binary orbit case: The simple case in which Jupiter and Europa are moving in an isolated binary orbit allows development of the basic torque balance [4,5,6].

In a fixed elliptical orbit, with semimajor axis ***a*** and eccentricity ***e***, the distance of the satellite from the primary varies with true anomaly f according to

$$r[a,e,f] = a\left(\frac{1-e^2}{1+e\cos[f]}\right)$$

To conserve angular momentum, the angular rate is largest when the distance between bodies is least. If we denote the rotation angle by φ, then the torque balance has the form

$$\frac{d^2\varphi}{dt^2} = -\frac{\omega^2}{2}\left(\frac{a}{r}\right)^3 \sin\big(2\,(\varphi - f)\big)$$

where, for a body with principal moments of inertia (A<B<C), moving on an orbit with mean motion ***n***, the free libration rate parameter given by

$$\omega^2 = 3n^2\left(\frac{B-A}{C}\right)$$

Based upon estimates of the moments of inertia from the Galileo mission flyby encounters [7], the expected free libration period is 52.7 days [6]. As that is appreciably longer than the 3.55-day orbital period, the eccentricity driven librations are expected to be quite small [6]. However, as will be shown below, there are longer period perturbations which are appreciably larger

Perturbed orbit case: The orbit of Europa is far from isolated. Instead, it is significantly perturbed by its neighbors Io and Ganymede, via the Laplace resonance [8,9]. The oblate figure of Jupiter and distant perturbations from Saturn and the Sun are also important [10]. We now examine results of a linearized torque balance in which the main rotational perturbations are due to longer period variations in orbital mean longitude. Mean longitude is the sum of mean anomaly and longitude of periapsis. It ignores the small, short period variations in true anomaly, and also represents orbital position in an inertially fixed frame.

Figure 1 shows a 100-year time span of mean longitude variations with the best fitting linear trend removed. The most notable variations are at periods of 29.5 years (Saturn perturbation) and 1.19 years (a libration in the Laplace resonance). Not visible in this figure are other, higher frequency oscillations.

A linearized torque balance can be written as a forced and damped harmonic oscillator. If **L** is the mean longitude, the governing equation is

$$\frac{d^2\varphi}{dt^2} = -\omega^2(\varphi - L) - \gamma\frac{d}{dt}(\varphi - L)$$

where ω is the free libration rate and γ is a viscous damping rate. This model implies that, at long periods, the rotation angle accurately tracks the orbit angle, but due to inertial resistance, the rotation is unable to track high frequency oscillation. There is also a resonant peak in the response. If there is orbital forcing at periods close to the free libration period, the rotation response exceeds the orbital forcing.

Figure 2 shows forced librations in longitude, over the same time span as is shown in Figure 1. The calculations used a free libration period of 52.7 days and a damping time of 100 years.

Figure 3 compares the orbital mean longitude variations (in blue), with the estimated forced librations (in red) over a time span which covers the nominal Europa Clipper operations. Times of flyby encounters are shown as black vertical grid lines. Combining the dynamic model presented here with observations of surface points with the EIS instrument [11] should allow estimation of an improved rotation model for Europa. That will be helpful in geophysical analyses of gravity and topography.

If the librations are not properly modeled they will result in what appear to be time variations in gravity and topography, which might otherwise be attributed to tidal deformation.

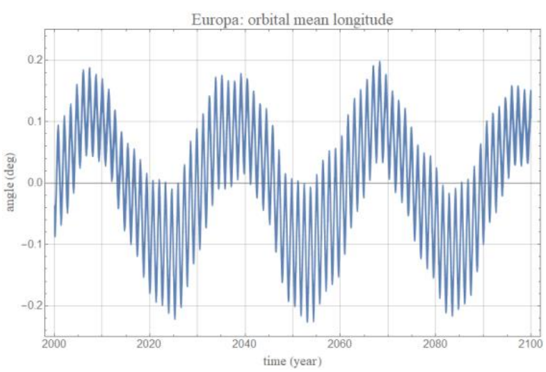

Figure 1. Europa mean longitude variations

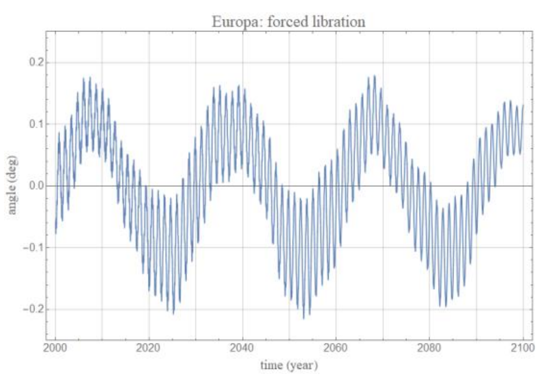

Figure 2. Europa forced libration response

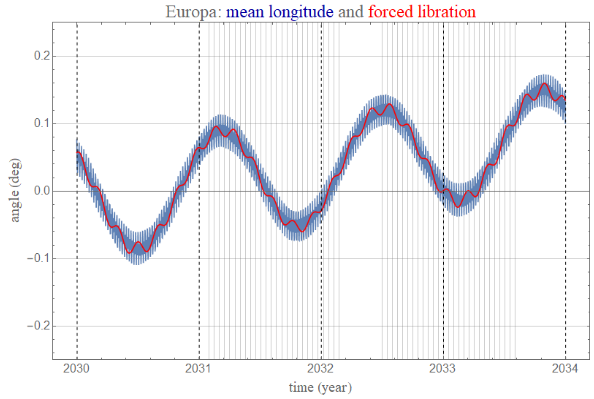

Figure 3. Europa orbit and rotation angles

References: [1] Archinal B.A. et al. (2018), CMDA, 130, 22 [2] Bills B.G. and Ray R.D (2000), JGR 105, 292777-29282. [3] Bills B.G. (2005), Icarus, 175, 233-247. [4] Eckhardt, D.H. (1981), Moon Plan. 25, 3-49. [5] Comstock, R.L. and Bills B.G. (2003), JGR, 108, 5100. [6] Bills B.G. et al. (2009), Europa, pp 119-134. [7] Anderson, J.D. et al. (1998), Science 281, 2019-2022. [8] de Sitter, W. (1930), MNRAS, 91, 706-738. [9] Celletti, A. et al. (2018), CMDA, 130, UNSP 15. [10] Lieske, J.H (1998), Astron. Astrophys Supp. Ser., 129, 205-217. [11] Turtle, E.P. et al. (2016) LPSC abs. 1903.