Reconstruction of localized gravity anomalies of Callisto with 3GM gravity experiment

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Introduction: The JUpiter Icy Moons Explorer (JUICE), an ESA mission launched on 14 April 2023, will reach the Jovian system in July 2031. It aims to study Jupiter and its icy moons using ten instruments. The mission involves flybys of Europa, Callisto, and Ganymede, concluding with a 9-month orbit around Ganymede. The 3GM experiment on board will leverage precise radiometric measurements to determine the moons' orbit, gravity field, and tidal deformation, essential for accurate internal structure modeling. Twenty-one Callisto flybys will yield gravity field data up to degree and order 9, moon ephemerides, and information on Jupiter-induced tidal effects, aiding in distinguishing the presence of an internal ocean. These constraints will inform the development of interior models for the moon.

Methodology: The mass and mass distribution of celestial bodies can be indirectly determined by observing their dynamical effects on test masses. For the Galilean satellites, we will deduce the gravity field by precisely determining the orbit of the JUICE spacecraft. This involves adjusting gravity coefficients, along with other model and observation parameters, to minimize differences between predicted and observed observables, forming a vector of residuals. The gravitational potential of a celestial body is modeled using a spherical harmonic expansion with normalized coefficients ($\bar{C}_{lm}, \bar{S}_{lm}$) of degree l and order m, as represented by the equation:

$$U(r,\lambda,\phi) = \frac{GM}{r}\left(1 + \sum_{l=2}^{\infty}\sum_{m=0}^{n}\left(\frac{a_E}{r}\right)^n \bar{P}_{lm}\,(\sin\phi) \cdot [\bar{C}_{lm}\cos m\lambda + \bar{S}_{lm}\sin m\lambda]\right)$$

where G is the gravitational constant, M is the planet or satellite mass, $\bar{P}_{nm}$ are the fully normalized associated Legendre polynomials, a_e is the reference radius of the body, while ϕ, λ, and r are, respectively, latitude, longitude, and radial distance. This approach is valid for quasi spherical objects and when the spacecraft offers a global coverage of the moon. With a flyby mission this is not the case. Slepian functions and the mass concentration (mascon) approach are favored over spherical harmonics for local reconstructions of gravity anomalies due to their enhanced localization properties. Slepian functions, also known as spherical Slepian functions or concentration functions, are specifically designed to offer optimal concentration of energy within a prescribed spatial region. This property allows for a more precise localization of gravity anomaly information within a targeted area, making them particularly suitable for capturing localized features in gravity field variations.

Similarly, the mascon approach is advantageous for local gravity anomaly reconstructions as it is tailored to emphasize local signals while minimizing the influence of distant variations. By focusing on the mass distribution within a specified region, the masscon method provides a more localized representation of gravity anomalies, which is beneficial when analyzing geophysical phenomena in specific areas of interest. Unlike spherical harmonics, which may spread information across a broader spatial extent, Slepian functions and the masscon approach excel in capturing and isolating gravity anomalies within defined local regions, enhancing the accuracy and applicability of local gravity field modelling (see Figure 2).

The observational model's mathematical formulation, as detailed in [1], involves estimating gravity coefficients through iterative weighted least-square differential corrections with a priori information, presented at the k-step according to [2]:

$$\delta\hat{\mathbf{x}}_k = \left(H_k^T W_k H_k + \bar{P}_k^{\;-1}\right)^{-1}\left(H_k^T W_k \delta\hat{\mathbf{y}}_k + \bar{P}_k^{\;-1}\delta\bar{\mathbf{x}}_k\right)$$

Here, x is the unknown n-dimensional vector of parameters to be estimated (solved-for parameters), and $\delta\hat{\mathbf{x}}_k$ is the vector of differential corrections. H is the p×n design matrix (p is the number of observables), containing partial derivatives of observables with respect to solved-for parameters. $\delta\bar{\mathbf{x}}_k$ and $\bar{P}_k$ represent the a priori estimate deviation and covariance of x, respectively. $\delta\hat{\mathbf{y}}_k$ is the vector of residuals (differences between observed and computed observables), and W is the corresponding weighting matrix. The n×n matrix $P_k = \left(H_k^T W_k H_k + \bar{P}_k^{\;-1}\right)^{-1}$ represents the covariance matrix of solved-for parameters, coinciding with the minimum variance estimate.

Estimating the gravity field of Callisto using data from distant flybys faces challenges such as inaccuracies in the dynamical model, numerical rounding errors in orbit propagators, and the impact of orbit maneuvers on spacecraft trajectory coherence. These challenges are addressed through a multiarc approach [3], wherein the JUICE trajectory is divided into shorter arcs, and dynamical parameters are categorized into global (common to all arcs, e.g., gravity coefficients) and local (specific to individual flybys, e.g., spacecraft initial state).

Simulation setup: The simulation setup for the 3GM gravity experiments on the JUpiter Icy Moons Explorer (JUICE) mission involves careful consideration of the primary observables, range, and Doppler (range-rate) data. Leveraging the capabilities of the JUICE multi-frequency radio system, which provides radiometric data minimally affected by solar plasma, we adopted a constant range-rate accuracy of 0.003 mm/s at 1000 s for all solar elongation angles. This corresponds to $\sigma_y \sim 10^{-14}$.

To simulate realistic conditions, we incorporated additive white Gaussian noise with a decrease as $\sigma_y \propto \tau^{-0.5}$ with integration time. Consequently, we set the simulated noise on observables to 12 mm/s at a 60 s integration time, aligning our approach with findings from BepiColombo and Juno missions [4]. The contribution of range data to the final covariance matrix was investigated, factoring in the link budget, resulting in an expected range jitter of 4 cm with a 300 s integration time. However, the availability of range data during flybys is uncertain due to potential signal-to-noise ratio limitations in the link budget.

Given the nature of estimating gravity coefficients as part of an orbit determination solution, acquiring data solely during the closest approach is insufficient. Our strategy involves relying on one pass at the closest approach, where the gravity signal is strongest, and two adjacent inbound and outbound arc segments, termed 'wings,' to reduce correlation between the state vector and gravity coefficients. Challenges posed by dynamical perturbations and wheel desaturation maneuvers led us to anticipate a conservative, guaranteed quiet period of approximately 30 hours, resulting in a simulation with three non-contiguous tracking windows lasting 6 hours each. These windows are centered at -12, 0, and +12 hours from the closest approach, as illustrated in the following Figure 1.

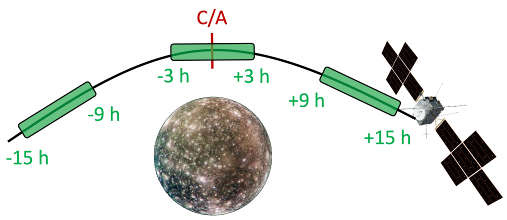

Figure 1 3GM operations timeline during Callisto flyby

Implicit in our simulation is the assumption that 3GM measurements are consistently supported by three ground stations with Ka-band link capabilities. Synthetic observables were simulated with a minimum spacecraft elevation angle of 15°, accounting for potential errors in low-elevation calibration data for the Earth's troposphere and any occultation of the radio link caused by Jupiter and the Galilean moons.

In this work, we compare the gravity anomaly reconstruction obtained by using the classical spherical harmonic approach with the Slepian approach and the mascon approach. With the different approaches we estimate different set of parameters to represent the gravity field.

Current knowledge: The current numerical simulations utilized spherical harmonics functions for the representation of the Callisto gravity field. Figure 2 depicts a map illustrating the degree strength of Callisto alongside JUICE ground-tracks [5]. It is apparent that certain areas remain unobserved, whereas others are traversed by the JUICE trajectory multiple times. In such instances, employing Slepian functions and/or the mascon approach could prove beneficial in extracting crucial information regarding the density distribution and surface structure of interest, such as craters. These alternative methods are well-suited for enhancing the precision of local reconstructions and capturing specific features within the gravity field.

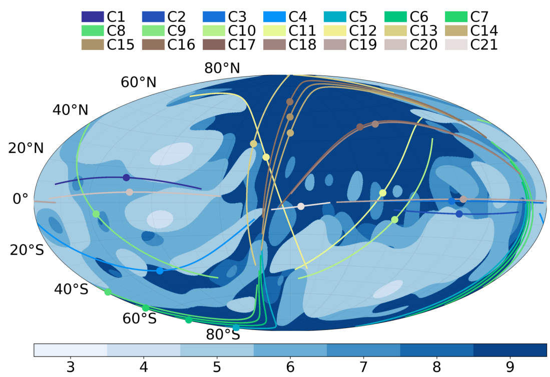

Figure 2 Callisto degree strength and JUICE ground-tracks

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