Geodetic investigations of the mission concept MAGIC to reveal Callisto's internal structure

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Abstract

Geodetic and geophysical investigations of the Galilean moon Callisto address fundamental questions regarding the formation and evolution of the Jovian system. Callisto's evolution and internal structure appear to significantly differ from the other Jovian satellites. Similarly-sized Ganymede is a highly evolved ice-rock moon with a differentiated interior, intrinsic magnetic field, and abundant surface evidence of internal activity. In contrast, Callisto's surface is ancient, and Galileo spacecraft data suggest its interior is only incompletely differentiated, despite the presumed presence of a sub-surface ocean. These properties make Callisto uniquely able to constrain the timing and nature of the Jovian system formation. The Magnetics, Altimetry, Gravity, and Imaging of Callisto (MAGIC) mission concept is conceived to fully characterize the properties of this enigmatic moon from its deep interior to the icy shell. Three main instruments are included as a scientific payload. Highly accurate measurements of Callisto's topography, magnetic field, and morphology are obtained by the onboard laser altimeter, magnetometer, and camera, respectively. The telecommunication system supports an additional gravity and radio science investigation. Long- and short-wavelength gravity anomalies afford powerful constraints on internal differentiation and the properties of the hydrosphere (water and ice). Comprehensive numerical simulations and covariance analyses of MAGIC mission scenarios presented in this paper show that the gravitational degree-2 normalized coefficients and the pole obliquity enable the determination of the moment of inertia with an accuracy better than 0.015%. The combination of gravity and altimetry measurements acquired by MAGIC plays a key role in the characterization of Callisto's interior if the gravity degree-2 includes non-hydrostatic terms. MAGIC's radio science data yield the estimation of Callisto's gravity field with spatial resolutions of < 100 km. The combination of gravitational and deformation tides that are retrieved by the radio science and altimetry investigations, respectively, leads to the recovery of the rigid ice shell thickness to within ~3 km. Together these datasets would resolve ambiguities inherent in Galileo flyby data, revealing Callisto's interior structure as well as the existence and properties of its postulated internal ocean.

Keywords: Callisto, Geodesy, Geophysics, Gravity and Radio Science, Deep Interior, Tides

1. Introduction

The exploration of the Jovian system is a key science theme for future space missions. Accurate knowledge of the internal structure of the Galilean moons is fundamental to understanding Jovian system formation and the moons' differing evolutions. The inner three Galilean moons – Io, Europa, and Ganymede – are highly geologically evolved bodies with differentiated interiors. In contrast, Callisto's surface appears mainly untouched by internal processes and its interior is inferred to be incompletely differentiated [1]. Thus, it is Callisto that best preserves the record of its formation and ancient past.

In the 2030's, the NASA flagship mission Europa Clipper will explore the icy moon Europa with ~50 flybys, reaching altitudes of 25 km at the closest approach [2]. During the same decade, the ESA L-class mission JUICE will conduct reconnaissance of Europa and Callisto with 2 and 12 flybys (baseline tour), respectively, prior to going into orbit around Ganymede [3]. The JUICE spacecraft will host onboard instrumentation to provide accurate measurements of surface and interior properties, although Callisto data will be limited to that acquired during flyby encounters.

Our current knowledge of Callisto's internal structure is uncertain, due to poor resolution of the Galileo spacecraft data acquired during its five flybys in the late 1990's [4]. Hints of a subsurface liquid ocean beneath Callisto's icy surface were provided by Galileo measurements of an induced magnetic field [5], [6], although the presence of its ocean remains uncertain due to the confounding effects of Callisto's time-variable ionosphere. An estimate of Callisto's moment of inertia (MoI) of 0.3549 ± 0.0042 derived from Galileo radio tracking data indicates that its internal structure is not fully differentiated into a rocky deep interior and a rock-free hydrosphere [1]. This would require that portions of Callisto never became warm enough for rock to separate from ice, which, if true, places powerful constraints on the timing, rate, and nature of Galilean satellite formation, as well as on early bombardment history.

Because of the sparse surface coverage of Galileo's flybys, the measured MoI was obtained through the Radau-Darwin Approximation (RDA), that is, by assuming a hydrostatic interior to enable the combined estimation of the gravity field coefficients J_2 and C_{22}. This *a priori* constraint enforces a ratio of ~10/3 between the zonal and sectoral degree–2 unnormalized harmonic coefficients. A departure from the hydrostatic equilibrium was measured for Titan [7], for example, and may likely exist for Callisto, leading to significant errors in the MoI value derived with the RDA [8]. An independent and separate estimate of the gravitational coefficients J_2 and C_{22} is crucial to accurately determine the internal differentiation state.

JUICE's flybys will help to improve our knowledge of Callisto's evolution by using imaging [9], altimetry [10], gravity [11] and magnetometry [12] measurements. The spatial resolution of these data, however, will be limited by the altitude of the closest approaches, between 200 and 400 km, and by temporal and spatial coverage limits inherent to flyby measurements. A thorough characterization of Callisto's surface and internal structure can only be obtained through a dedicated orbital mission enabling highly accurate geodetic, geophysical, and multi-frequency inductive field measurements. This would provide the needed complement to the high-accuracy datasets of Europa Clipper at Europa and JUICE at Ganymede in the Jovian system.

The Magnetics, Altimetry, Gravity, and Imaging of Callisto (MAGIC) mission is conceived to address outstanding objectives regarding the properties of the moon's interior, ocean, and ice shell [13]. This paper focuses on the gravity and radio science investigation that significantly contributes to fulfil the main mission science objectives. In Section 2, we describe the science instrumentation and measurements to accomplish the scientific goals. In Section 3, numerical simulations of the gravity investigation are presented to report the expected accuracies of the geophysical measurements. The discussion and summary of the results are reported in Sections 4 and 5, respectively.

2. Mission Design

2.1 *Scientific Payload*

The MAGIC spacecraft is conceived to host three main instruments devoted to a comprehensive geophysical investigation of the Galilean moon Callisto. A 2-laser multi-beam altimeter draws heritage from successful planetary lidars (*e.g.*, MOLA [14], LOLA [15], MLA [16]) and will enable accurate measurements of the surface topography with a radial accuracy of 10 cm [17]. A dual fluxgate magnetometer system (*e.g.*, [18], [19]) is designed to provide high quality data sensitive to the time-varying magnetic field from Jupiter, Callisto's non-uniform and temporally varying ionosphere, and any induction signal from an internal ocean. To observe the moon's surface, a framing camera system (*e.g.*, [20], [21]) will provide high-resolution images. A global coverage (~99%) of the surface is expected at $\leq$ 100 m/pixel and local areas (~22%) at 25 m/pixel.

An important contribution to the determination of Callisto's internal structure is given by the spacecraft telecommunication system to be used for gravity and radio science investigation. Two configurations of the radio science system for deep space tracking are accounted for in this concept. A baseline instrument scheme includes a high-gain antenna (HGA) and a deep space transponder (DST) [22] to enable X-band two-way coherent radio links with ground stations of the NASA's Deep Space Network (DSN). An additional transponder (*e.g.*, KaT [23]) may be included to enable Ka-band downlink capabilities (increase the returned data volume) with the benefit of calibration of the dispersive medium (*e.g.*, solar plasma, ionosphere) [24]. The relative velocity and position of the spacecraft with respect to the ground station will be observed by measuring the Doppler shift (*range-rate*) and the time delay (*range*) of the radio signal, respectively. The precise orbit determination (POD) of the spacecraft trajectory based on the processing of the radio tracking data will enable highly accurate measurements of Callisto's gravity field to constrain its internal structure.

2.2 *Orbital Configuration*

The science phase of the MAGIC mission is based on a low-altitude near-circular polar orbit. After its arrival in the Jovian system, the spacecraft will be placed in a preliminary mapping orbit (PMO) with an inclination of ~90° and eccentricity ~0, and a mean altitude of 100 km. This initial phase is planned to obtain the primary global datasets with the instrumentation onboard the MAGIC spacecraft. The gravity investigation will provide a precise characterization of the low degree spherical harmonics of Callisto's gravity field. The main perturbation acting on the spacecraft orbit at altitudes lower than 100 km is associated with gravitational anomalies. MAGIC can utilize available gravity results retrieved by JUICE flybys. However, JUICE results will be limited by the uneven coverage of the moon's surface due to the geometry of the flybys, and may not be accurate enough for MAGIC mission planning. An accurate knowledge of the zonal gravity coefficients is important to enable safe operations at low altitudes and prevent unplanned spacecraft impact with the moon's surface. The data collected during the three months of the MAGIC's PMO will allow us to determine Callisto's gravity field with much higher accuracy, fully characterizing gravitational perturbations on the spacecraft and enabling a thorough design and optimization of a stable, low-altitude orbit for its subsequent science primary phases in line with the engineering requirements.

Orbit correction maneuvers will then be used during a transition phase that will lead the spacecraft to a 50×100 km polar orbit. This phase will last two months, and it will allow to safely lower the spacecraft altitude. The mapping orbit will be reached after five months from the orbit insertion, and its nominal timespan is one year (Fig. 1). The low-altitude science MAGIC orbit will provide highly accurate measurements at global and local scales (see Section 4). Gravity, magnetic field, and topography data will reveal Callisto's extent of internal differentiation, the thickness and density of the ice shell, and the existence and properties of a subsurface ocean (see Section 5). Numerical simulations were carried out to support our expected estimates of Callisto's gravity field, and geophysical parameters that will constrain with high accuracy the properties of its internal structure and orientation.

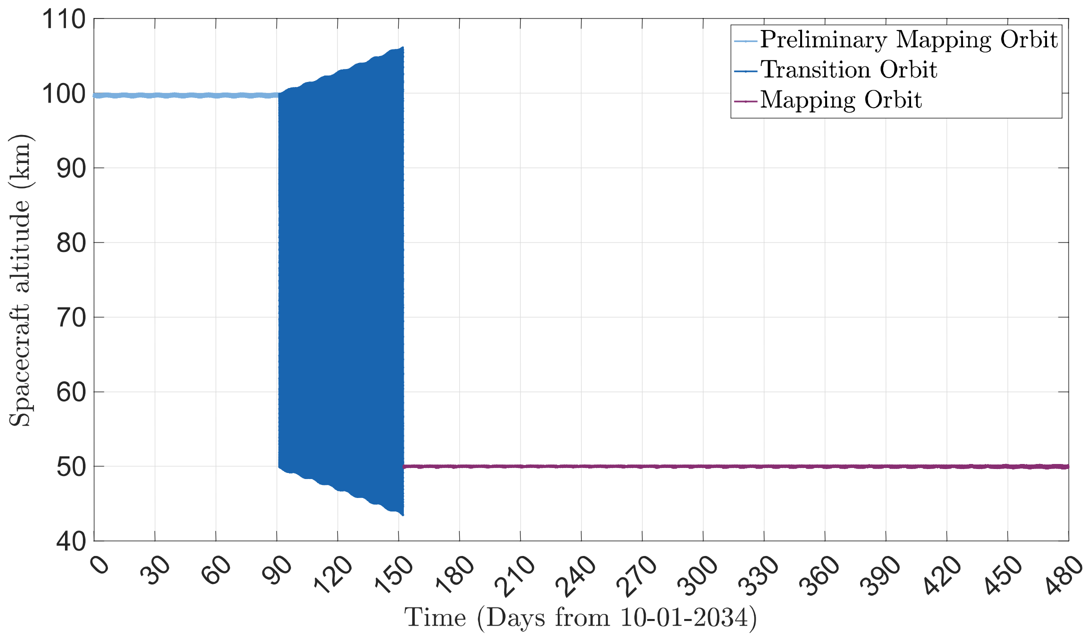

Figure 1 Evolution of the spacecraft orbital altitude during the three main mission phases: preliminary mapping (**cyan**), transition (**blue**), and mapping orbit (**purple**).

3. Measurement and Force Modeling

To conduct a covariance analysis of the MAGIC radio science and gravity investigation, accurate models of the data noise and perturbative forces are accounted for in our POD software GEODYN II [25]. Different noise sources are studied to define the measurement requirements based on single- (X-band) and triple-link (X/X, X/Ka, Ka/Ka) configurations. The spacecraft design includes a high gain antenna (HGA) that prevents high thermal noise in the radio data. Errors of the deep space radio tracking observations are mainly associated with the Earth's troposphere and the solar plasma. By assuming a mission time span between 2034 and 2035, we computed the contribution of each perturbation. Tropospheric effects show annual variations related to the season at the ground station, which was assumed to be the NASA Deep Space Station (DSS) 25 Goldstone. The dominant noise source is the solar plasma that leads to extremely high errors in the radio tracking data at low Sun-Earth-probe (SEP) angles (< 30º shown in red in Fig. 2-a). Data that are acquired in proximity of superior solar conjunctions (SEP< 30º) are not included in the POD solutions of the mission scenario with a single-frequency radio system. Figure 2-b reports in black the total noise budget of the radio tracking data by assuming an integration time of 60 s and a single-link configuration based on X-band only [24]. The average rms of the radio tracking data is expected to be between 0.07 and 0.1 mm s^{-1} at 10-s integration time. A triple-link configuration allows to compensate the solar plasma leading to a more constant noise model that mainly depends on thermal and tropospheric effects [26]. The synthetic Doppler data in our numerical simulations are generated with a sampling time of 10 s and perturbed by a white Gaussian noise with a standard deviation that is fixed to 0.03 mm s^{-1} for a triple-link system and varies as a function of the SEP angle (black dots in Fig. 2-b) for X-band only [26].

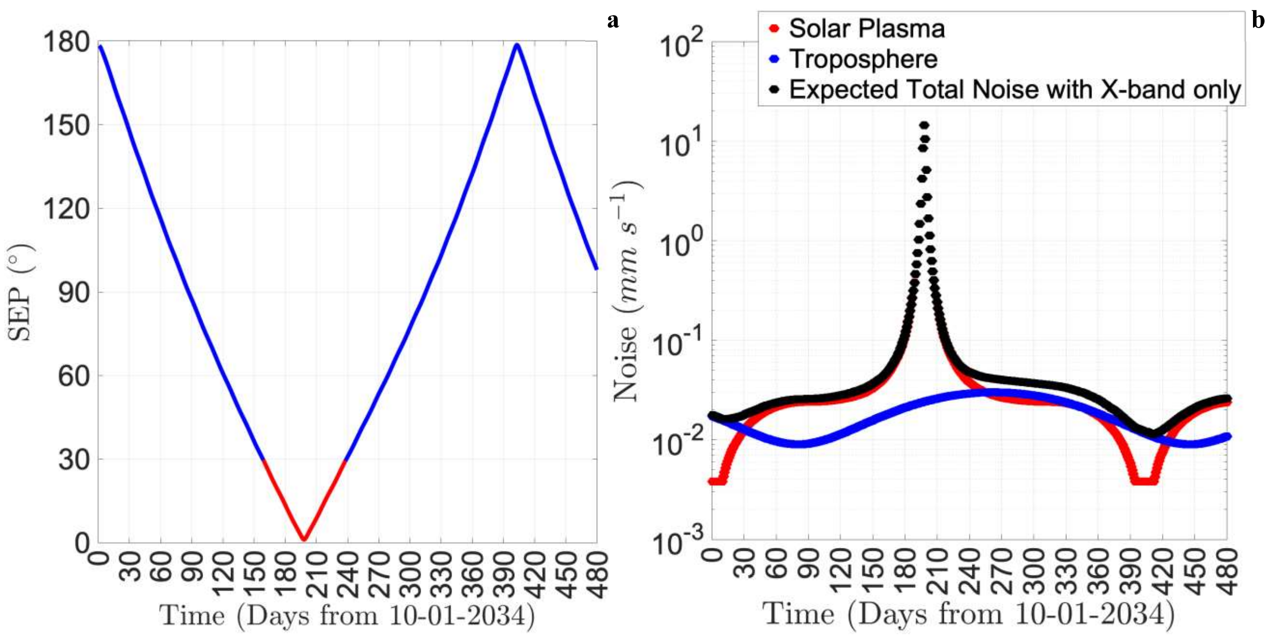

Figure 2 (**a**) Sun-Earth-probe angle and (**b**) noise budget of the radio tracking data with single link configuration for the entire mission time span, assuming an orbit insertion on October 1st, 2034.

The integration of the spacecraft trajectory considers both gravitational and non-conservative forces. The gravitational effects of the Sun and the main celestial bodies in the solar system, including Jupiter and the other Galilean moons Io, Europa and Ganymede, were accounted for in our dynamical model. For the non-conservative forces, a simplified cannonball model was assumed by using thermo-optical properties, mass and cross-sectional area consistent with the mission design. The non-conservative forces included in our numerical simulations are solar radiation pressure, as well as Callisto's albedo and thermal infrared radiation pressures. By assuming a mean surface albedo of 0.22 [27], a global mosaic of images collected by Voyager 1 and 2, and Galileo archived at https://astrogeology.usgs.gov/maps/callisto-voyager-galileo-global-mosaics was used to determine regional variations of the albedo (Figure 3-a). To account for non-conservative force mismodeling, a radiation pressure scale factor is estimated each day. The uncertainties retrieved for these parameters are ~10%.

The main forces acting on the spacecraft are associated with Callisto's gravity field. To model these perturbations, the gravitational field is expanded in spherical harmonics to degree and order 180. Our current knowledge of Callisto's gravity is limited to degree 2 because of the sparse resolution provided by the Galileo flyby data [1]. To simulate the entire spectrum of the gravity field, we assumed Titan's gravity coefficients scaled with the ratio of the moons' radii for the degree 3 [7], and gravity induced by topographic relief [28] for higher-degree coefficients. The gravity from topography is computed by assuming an ice shell density of 1000 kg m^{-3}, and topographic relief based on Titan's global map [29] scaled accordingly to Callisto's shape. Figure 3-b shows the gravitational anomalies computed from the simulated gravity field from degree 3 to degree 180. This simplified model does not account for the gravity signal generated by the mantle-ocean or mantle-shell boundary that is expected to be dominant up to degrees 50-60 [30]. The scope of the numerical simulations is to determine the gravity resolutions that are expected with MAGIC radio science investigation, assuming that the gravity signal at degrees larger than 60 are caused by the surface topography.

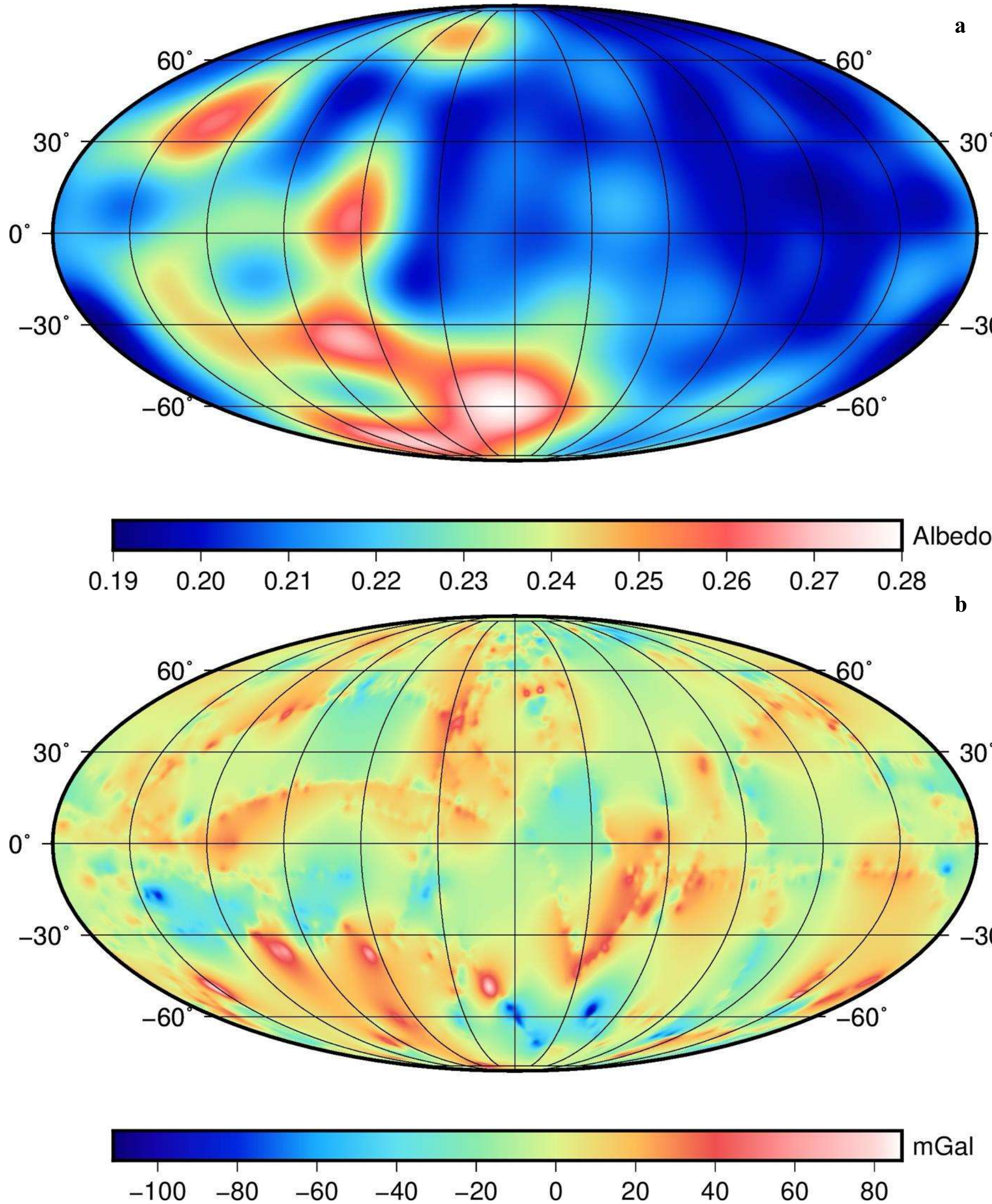

Figure 3 Map of (**a**) surface albedo and (**b**) gravitational anomalies for the simulated model of Callisto's field.

4. Geodetic Results

Numerical simulations of JUICE flybys and MAGIC orbit about Callisto were carried to compare the expected results of the gravity and radio science investigations. Our geophysical results are based on the processing of the simulated radio tracking data through our POD software GEODYN II [25]. By minimizing the difference between observed and computed observables (*residuals*), a least-squares filter enables the accurate estimation of the parameters of interest [31]. To reduce the effects associated with propagation errors, the spacecraft trajectory is integrated in different arcs that are finally combined through a global inversion. The local parameters adjusted in each arc are the spacecraft state vector and a solar radiation scale factor. The gravity inversion that is based on the combination of all the arcs yields the estimation of the field to degree and order 7-10 for JUICE, and 120 for MAGIC, the coordinates of the pole (right ascension, α_0, and declination, δ_0), the Love number k_2 and, for MAGIC only, the gravitational tidal phase lag. All solutions are based on an unconstrained approach: no *a priori* uncertainties are applied to the gravity field.

The Geodesy and Geophysics of Jupiter and the Galilean Moons (3GM) instrumentation onboard the JUICE spacecraft will provide range-rate and range measurements with accuracies of 14 $\mu m\ s^{-1}$ at 60 integration time and 20 cm [32], respectively. These highly accurate data will enable an estimate of the global gravity field with a resolution in spherical harmonics between degrees 7 and 10 [33], depending on Callisto's gravity power and JUICE Jovian tour. We simulated the radio science observations of the JUICE mission during Callisto flybys that are based on the tours released with the Consolidated Report on Mission Analysis (CReMA) versions 3.2 and 5.0 [34]. Each JUICE flyby is simulated and processed by using a 1-day arc with the closest approach in its middle. Multiple tracking passages were accounted for in each arc to enable a continuous data coverage, which is, however, affected by few occultation events due to Jupiter and Callisto. Figure 4 shows the power spectra of the simulated field and the formal uncertainties of the gravity field estimated by assuming JUICE tours from CReMA 3.2 and 5.0. The original mission baseline was the 141a tour from CReMA 3.2 that enables 12 flybys of Callisto, which are well-suited for retrieving the gravity field to degree and order 7. An enhanced coverage of the icy moon is guaranteed by the new baseline tour released with CReMA 5.0 that includes 21 flybys of Callisto, yielding a better mapping of the gravitational anomalies (Fig. 4-b). Our results show that the uncertainty in the degree-2 field ($\sim 1.5 \times 10^{-7}$ for CReMA 5.0) will improve on that of Galileo data, which had a normalized C_{22} uncertainty of 4.65×10^{-7} [6]. Table 1 reports the formal uncertainties of the geophysical quantities, including the pole obliquity and Love number k_2, that were estimated with our numerical simulations of JUICE tour based on CReMA 5.0.

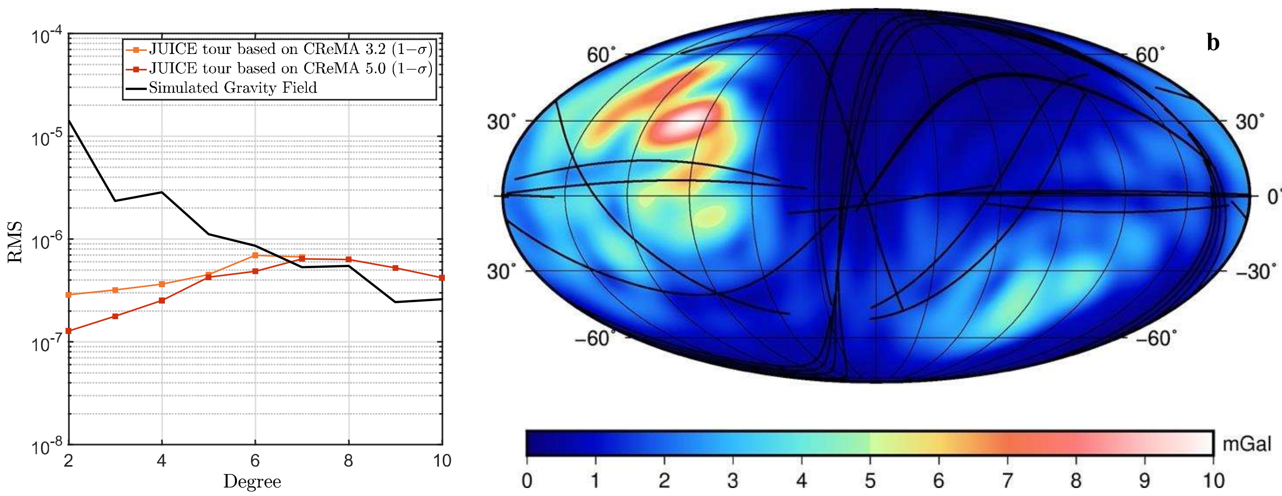

Figure 4 (**a**) Power spectra of the simulated gravity field and one standard deviation formal uncertainties retrieved with the numerical simulations of JUICE flybys. (**b**) Map of the gravity anomaly uncertainties and JUICE ground tracks covered by radio tracking passages (**black lines**) based on CReMA 5.0.

The numerical simulations of the MAGIC mission are based on three different cases with a total timespan of 1 year that is partitioned in 4-day arcs. A first simulation scenario assumed a 1-year mapping orbit at 100 km. Figure 5 shows the formal uncertainties obtained from the gravity inversion by assuming a radio science system with a single link in X-band only. The analysis of the radio tracking data of this mission phase yields enhancements in the low degree formal uncertainties by ~3 orders-of-magnitude compared to JUICE expectations. The global resolution of the gravity field is l~70 in spherical harmonics which corresponds to a spatial resolution of ~108 km.

Assuming a dedicated instrumentation for a triple-link configuration, we reran the numerical simulation of the MAGIC gravity investigation for 1 year at 100-km altitude. The improved data quality leads to even lower formal uncertainties for the entire power spectrum (Fig. 5, cyan dot-line).

Higher resolutions of the gravity field are achievable with a single-link radio science system and a mapping orbit at 50-km altitude. This scenario was selected as the nominal science phase of the MAGIC mission concept. Our numerical simulations of this case support a global resolution of l~100 that is spatially about 75 km (Figure 5, blue dot-line). To better understand the local accuracy of the gravity field, we used the degree strength metric [35]. By comparing the predicted gravity acceleration profiles with the uncertainties from the covariance matrix at each location, we determine locally the resolution of the gravity field in spherical harmonics. Since the orbit is polar, the highest resolution is at the poles (l>100), and an average spatial resolution of ~95 km is obtained at mid-latitude and equatorial regions. Figure 6 shows the resulting degree-strength map for a 1-year nominal mission at 100 and 50 km altitudes and a X-band radio system. Our simulations are based on 8-h tracking passes per day with DSS 25. The use of multiple Earth's ground stations may enable an improved coverage of areas of scientific interest. The ground stations schedule would then be planned accordingly to the mission scientific goals, which include an even coverage of the entire moon surface.

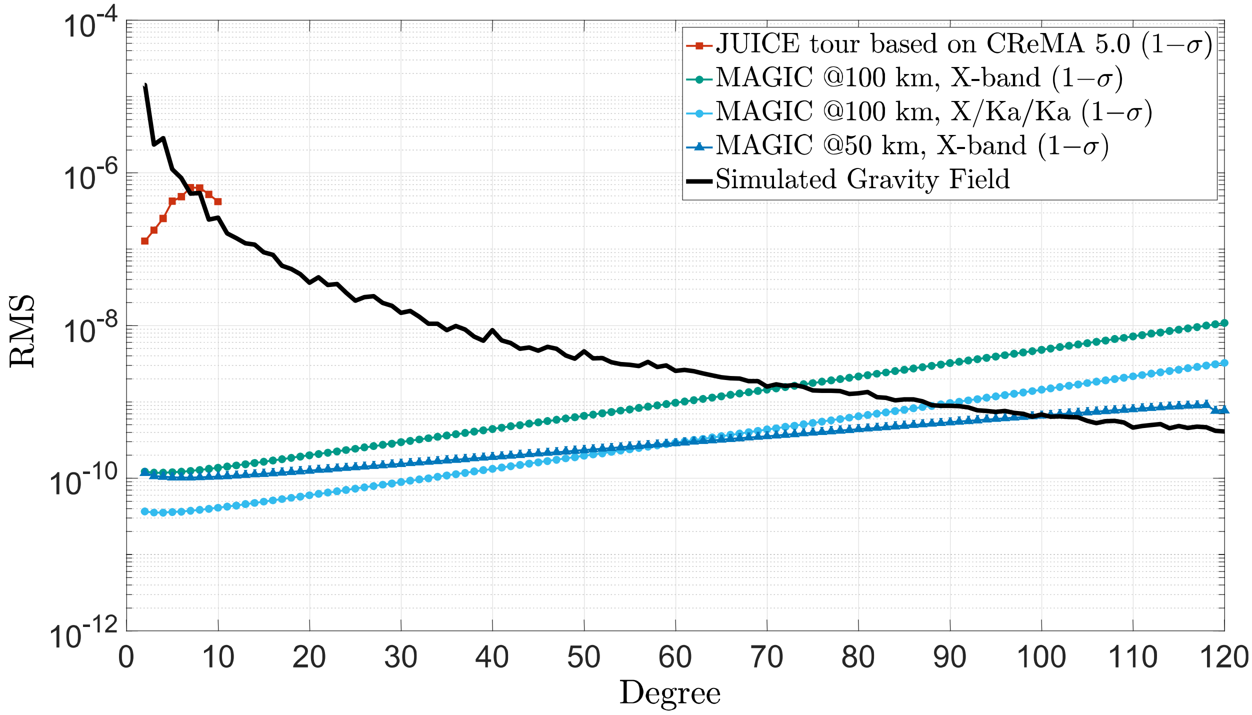

Figure 5 Power spectra of the simulated gravity field and one standard deviation formal uncertainties of the estimated solutions based on the analysis of JUICE and MAGIC datasets. Three mission scenarios of the 1-year mapping phase are simulated for the MAGIC mission.

The main objective of the MAGIC gravity and radio science investigation is the characterization of Callisto's internal structure. An accurate measurement of the MoI is crucial to determine the level of internal differentiation and to what extent rock and ice remain well-mixed within Callisto's interior. MAGIC measurements of the geophysical parameters allow us to determine the MoI with two independent techniques. An accurate estimation of the degree-2 coefficients J_2 and C_{22} will help test the hydrostatic equilibrium condition that is the main assumption of the RDA method. These coefficients are estimated independently leading to extremely low correlations (*i.e.*, <0.1). If the hydrostatic ratio of ~10/3 is verified, by applying the RDA formula, we retrieve an uncertainty of the MoI of ~7×10^{-6}. Non-hydrostatic terms may be compensated by using the shape degree-2 coefficients that will be precisely measured by the onboard laser altimeter. By computing the ratio of the non-hydrostatic gravity to the non-hydrostatic topography (*i.e.*, degree-2 admittance), a unique MoI factor is detected if this ratio is isotropic. Similar approaches were successfully used at Titan [36] and Dione [37].

Synchronous rotating bodies enable an alternative method to recover the MoI. The Galilean moons are expected to be in an equilibrium state in which the spin, orbital and Laplace poles are co-planar (*i.e.*, a Cassini state). A combined estimation of the spin axis right ascension (α_0) and declination (δ_0) with a precision of 0.2-0.25 arcsec (Table 1) and Callisto's ephemeris will allow us to demonstrate whether the icy moon is in one of the four Cassini states. If this assumption is confirmed, a relationship between the pole obliquity ϵ and MoI allows for an independent estimation of the moon's internal mass distribution [38]. The formal uncertainty of the MoI that is yielded by combining the degree-2 gravity coefficients and the pole obliquity is ~5×10^{-5} (~0.015% by assuming a MoI of 0.355).

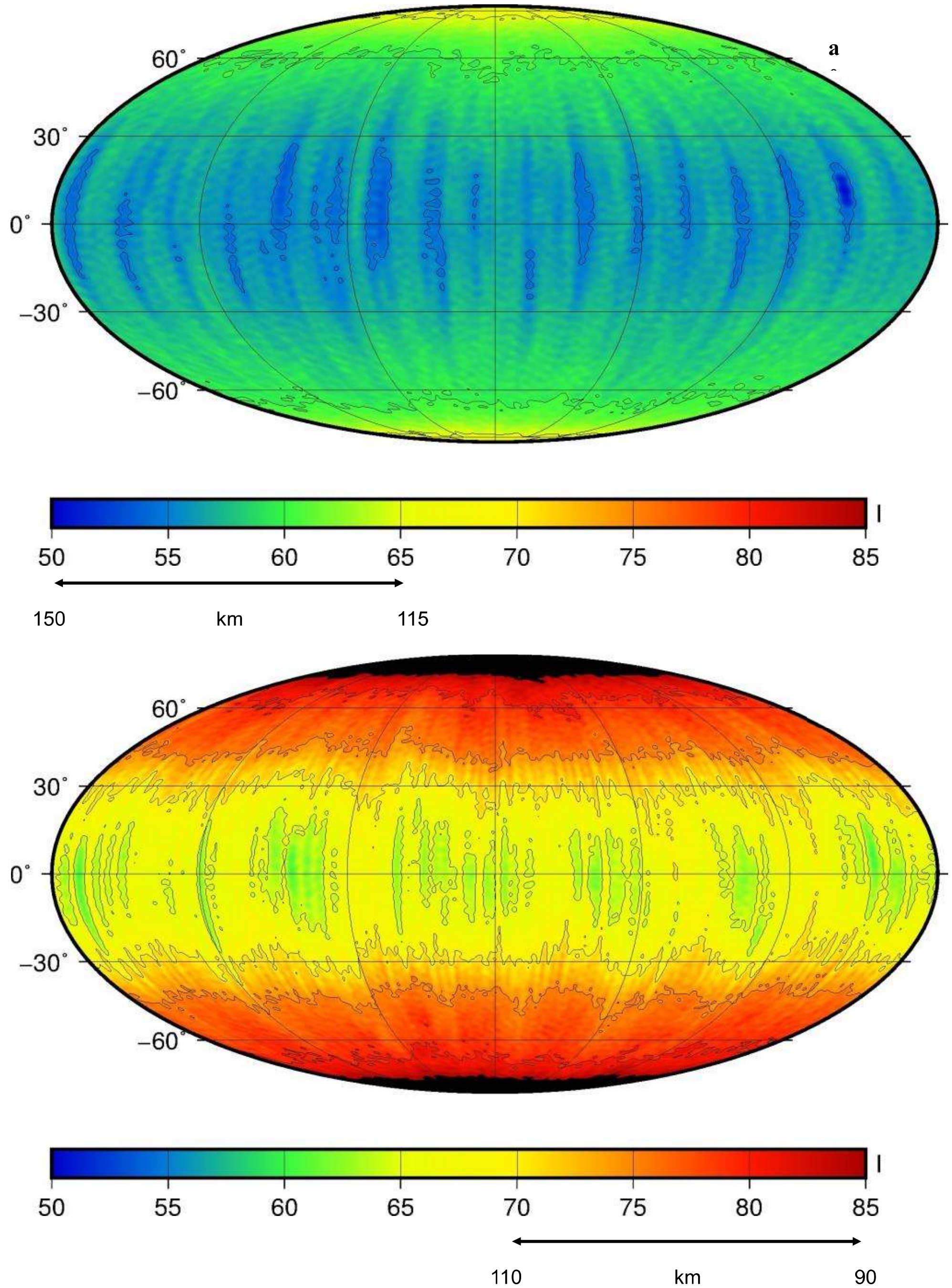

Figure 6 Degree strength map of Callisto's gravity field retrieved with 1-year nominal mission at (**a**) 100-km and (**b**) 50-km altitude and a single-link radio science system. The corresponding spatial resolutions are shown in km.

Another key geophysical parameter that will be measured by MAGIC gravity investigation is the Love number k_2. A precise measurement of this quantity provides crucial information on the gravitational tidal response, which strongly depends on Callisto's interior. The presence of a water ocean underneath the icy shell would lead to large gravitational tides. MAGIC radio observations constrain the amplitude of the Love number k_2 to an accuracy of 10^{-4}. The phase lag associated with Jupiter's gravitational effects is also detectable with an uncertainty of <0.05°, as supported by our numerical simulations.

Table 1 Formal uncertainties of the geophysical parameters based on the current knowledge [1] and MAGIC numerical simulations. The gravity field coefficients are unnormalized. Note that α_0, δ_0 and ϵ have never been directly measured; the values given in column 2 of this table are estimates based on the definition of the north pole as the axis above the invariant plane of the solar system [39].

	Current Knowledge				
Geophysical Parameter	**Value**	**Uncertainty**	**Ref.**	**JUICE* $(1-\sigma)$**	**MAGIC $(1-\sigma)$**
$\mathbf{J_2}$ $(\times 10^7)$	327	8.0		1.5	0.002
$\mathbf{C_{22}}$ $(\times 10^7)$	102	3.0	[1]	0.6	0.005
MoI *determined with RDA*	0.3549	4×10^{-2}		8×10^{-3}	7×10^{-6}
$\boldsymbol{\alpha_0}$ (deg)	268.72°			0.26	6×10^{-5}
$\boldsymbol{\delta_0}$ (deg)	64.83°		[39]	0.08	7×10^{-5}
$\boldsymbol{\epsilon}$ (deg)	~0.3°	—		0.1	6×10^{-5}
MoI *determined with pole obliquity*				0.07	4×10^{-5}
$\mathbf{k_2}$	—		—	0.08	10^{-4}
$\boldsymbol{\phi_{k_2}}$ *due to Jupiter*				—	<0.05°

*These results are obtained by accounting for JUICE flybys tour reported in CReMA 5.0 and by estimating Callisto's gravity field to degree and order 10 with no *a priori* constraint.

5. Discussion

The gravity and radio science investigation of the MAGIC concept contributes significantly to the main science objectives of the mission. Accurate estimates of the low degree gravity coefficients and the pole obliquity provide definitive constraints on Callisto's internal differentiation, which are well-suited to address fundamental questions regarding the formation and evolution of the Galilean moons. The rotational state of Callisto is also an objective of altimetry and imaging investigations (*e.g.*, [40], [41]). Independent gravity and surface-related measurements of the moon's orientation further inform on the decoupling mechanisms between the rocky interior and the icy shell.

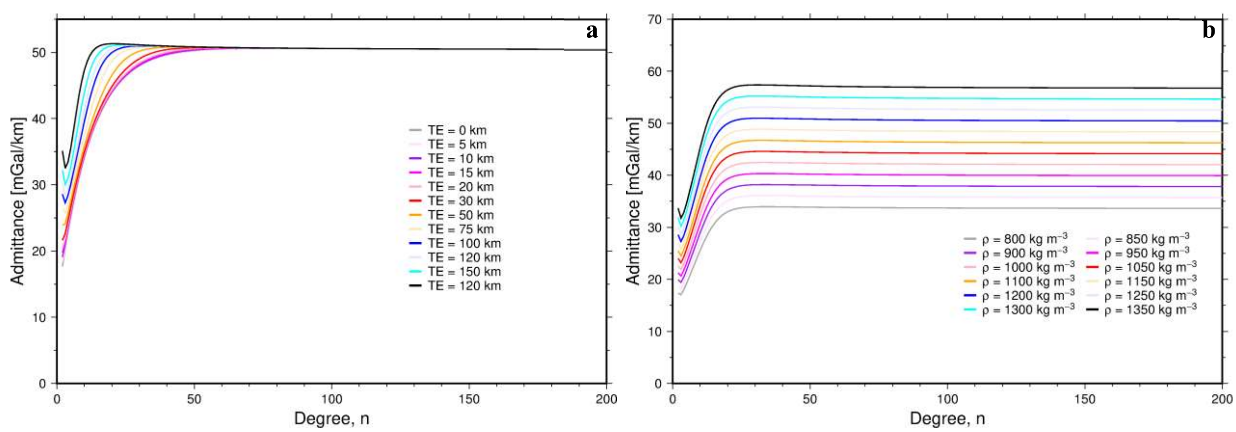

Figure 7 (**a**) Admittances for ice shell thickness = 200 km, ice shell density = 1200 kg m^{-3}. (**b**) Admittances for ice shell thickness = 200 km, elastic thickness = 100 km. Admittance level depends only on crustal density, and this is how we can obtain the crustal density.

To study the properties of Callisto's hydrosphere, gravity and topography are compared through the computation of the gravity from the topographic relief (*i.e.*, Bouguer correction) [28]. By subtracting this synthetic field from the observed gravity, we determine the Bouguer anomalies that are used to constrain the lateral variations of the ice shell thickness through an iterative method [28]. Additional information that can be obtained from the combination of gravity and topography measurements is the ice density. Short-wavelength gravity anomalies correlate with topography at high degrees, where the signals associated with the lithosphere and the mantle-ocean interface are attenuated. To support these hypotheses, we computed gravity/topography admittance profiles with theoretical models of Callisto's interior by varying ice shell thickness and density, and the lithosphere thickness (*e.g.*, [42]). Figure 6 shows that at l~60 the admittance becomes independent from elastic thickness, and the admittance level depends on the ice shell density only. An accurate knowledge of the gravity field to degree and order l>80 is sufficient to fully characterize the ice shell density.

Determining the Love numbers k_2 and h_2 provides a means to reveal the existence of the ocean. The laser altimeter enables highly accurate measurements of the tidal displacement. The crossover technique, which consists of a differential observation obtained by the comparison of two tracks of altimetric measurements collected in the same area at two different epochs, will provide accuracies smaller than 30 cm on the tidal amplitude. Figure 8 shows the number of altimetric crossovers that are collected in the first six months of MAGIC's mapping phase. The vertical difference of each crossover is a direct measurement of the temporal changes associated with the tides (*e.g.*, [43]). A formal uncertainty σ_{h_2}~0.012 is obtained after two months of the nominal mission through the combination of 2 million laser altimeter crossovers.

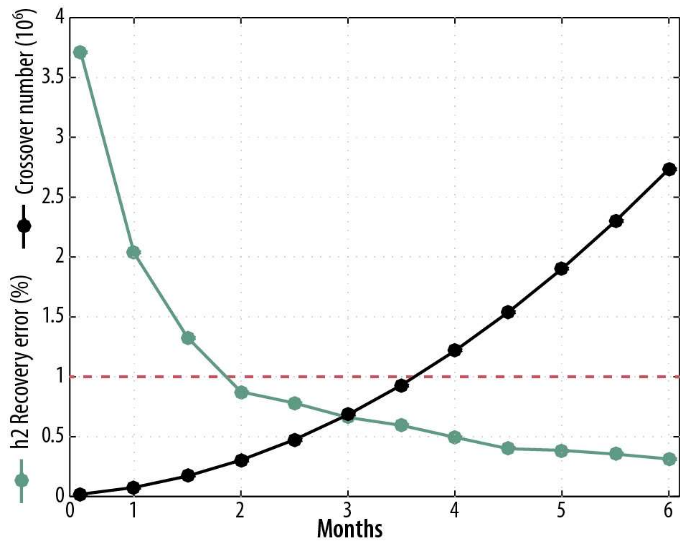

Figure 8 Number of altimetric crossovers (**black**) and Love number h_2 recovery error (**green**) for the first six months of the MAGIC mission.

By assuming a mean ice shell thickness of 100 km, the expected values for the Love numbers k_2 and h_2 are ~0.4 and ~1.2, respectively [44]. The expected magnitude of the solid tides at the equator is then ~30 m. MAGIC's uncertainty in k_2 and h_2 at the end of the nominal mission are 0.03% $\left(\sigma_{k_2}\sim 10^{-4}\right)$ and 0.33% $\left(\sigma_{h_2}\sim 4\times 10^{-3}\right)$, respectively. The linear combination $\Delta_2 = 1 + k_2 - h_2$ yield an accurate estimation of the ice shell thickness (~3%) [45]. MAGIC is expected to resolve the rigid ice shell thickness to within ~3 km.

To yield constraints on the viscosity of the ice shell and the ocean, the Love number k_2 phase lag associated with the gravitational response induced by Jupiter is estimated, enabling a comprehensive characterization of the hydrosphere properties.

6. Summary

A mission concept devoted to study the internal structure of Callisto is presented in this study with a detailed description of the orbit configuration, the space system, and the radio science investigation. The mapping phase consists of a low-altitude orbit to enable extremely high-resolution measurements of gravity, topography, and magnetic field. At 50-km altitude, the onboard camera would provide unprecedented images of the moon's surface with 25m/pixel resolution. The synergy between the three main instruments and the radio science investigation enables a thorough characterization of Callisto's interior from the rocky core to the hydrosphere.

MAGIC's radio science is conceived to provide precise gravity measurements to address fundamental science objectives of the mission. A precise estimation of the low degree harmonic coefficients J_2 and C_{22}, and the pole obliquity can allow us to definitively determine the MoI by using complementary techniques. Short-wavelength gravity anomalies provide information on the icy shell thickness and density, constraining the dynamical processes that led to the evolution of the outer layers. The combination of gravitational and deformation tides can confirm the presence of

Callisto's internal ocean, providing constraints on its depth and composition. An orbital mission at Callisto represents a unique opportunity to complement the outstanding investigations in the Jovian system that will be conducted by the NASA mission Europa Clipper at Europa and the ESA mission JUICE at Ganymede.

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