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Updated Europa gravity field and interior structure from a reanalysis of Galileo tracking data

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# Updated Europa Gravity Field and Interior Structure from a Reanalysis of Galileo Tracking Data

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## Abstract

The Galileo radio tracking data were reanalysed exploiting the new knowledge of Jupiter obtained by the Juno mission, together with modern orbit determination techniques developed for the Cassini data analysis. Using Doppler data acquired during six encounters of Europa an updated gravity field of the moon was obtained, resulting in a value of  $C_{22}$  statistically different from the available literature. The new value suggests a thinner ice-water shell and a less dense interior.

Keywords: *Europa, Interiors, Orbit determination, Jupiter, satellites, Geophysics*

## 1. Introduction

The Galileo mission studied the Jovian system for eight years, from December 1995 to September 2003. One of the main mission objectives was the study of Europa, the smallest of the Jovian moons discovered by Galileo Galilei in 1610, and the sixth biggest moon of the entire solar system. Before the arrival of the Galileo spacecraft to the Jovian system, very little was known about Europa. The mission provided plenty of data



27 which dramatically increased our knowledge of the moon and resulted in the discovery of a subsurface ocean  
28 of liquid water (Carr et al., 1998; Kivelson et al., 2000; Zimmer et al., 2000), with important implications for  
29 its habitability.

30 The gravity field of a celestial body is crucial to understand its interior structure and composition. Using  
31 Galileo data, three different analyses of Europa's gravity field were performed. The first gravity field analysis,  
32 (Anderson et al., 1997), analysed independently the non-coherent radiometric data acquired during E4  
33 (December 1996) and E6 (February 1997), according to the numbering scheme used by the Galileo project,  
34 providing a weighted mean of the single orbital fits in which the hydrostatic equilibrium constraint ( $J_2/C_{22} =$   
35  $10/3$  for a relaxed, synchronously rotating, satellite) was applied. From the Radau relation the moment of  
36 inertia (MoI) factor was retrieved directly from the degree-2 gravity field coefficients, obtaining a MoI = 0.330  
37  $\pm 0.014$ . This analysis concluded that the measurements were compatible with a metallic core surrounded by  
38 a water ice-liquid outer shell. Subsequently (Anderson et al., 1998), performed a global fit using four Europa  
39 flybys, adding E11 (November 1997) and E12 (December 1997) to the previous solution, along with ground-  
40 based astrometric data and optical navigation observables from both Voyager and Galileo, applying the  
41 hydrostatic equilibrium as an a priori constraint. The analysis provided evidence that the Galilean moon is  
42 most likely differentiated into a metallic core surrounded by a rock mantle and a water outer shell in liquid  
43 or solid state. Finally, (Jacobson et al., 1999) reported on the reconstruction of Galileo's orbit during the  
44 prime mission and the estimation of Jupiter's satellite ephemerides by means of a global fit. The analysis  
45 used an extensive data set comprising Earth-based astrometry, Pioneer and Voyager radiometric and optical  
46 data, and Galileo radiometric data up to E19 (February 1999), also introducing the a priori equilibrium  
47 constraint between  $J_2$  and  $C_{22}$ . The estimated  $J_2$  and  $C_{22}$  coefficients were substantially smaller than those  
48 published in the last reference work (Anderson et al., 1998).

49 The entire Galileo mission included 11 encounters of Europa, 8 of which were close enough to provide  
50 information about its mass and gravity field. In this work, only the best 6 encounters, in terms of data quality  
51 and availability, are used. The main characteristics of Galileo's flybys of Europa are summarized in Table 1,

52 while Figure 1 shows the corresponding ground tracks. Unfortunately, all the encounters were nearly  
53 equatorial, so we do not expect a good accuracy in the determination of the  $J_2$  gravity coefficient (which is  
54 longitudinally symmetric). As can be seen in Table 1, the orbital distribution of the flybys in terms of mean  
55 anomaly of Europa around Jupiter, together with the non-negligible eccentricity of the Galilean satellite,  
56 suggest that in principle the tidal response to Jupiter could be inferred.

57 In this paper we present the reanalysis of Galileo tracking data acquired during the different encounters with  
58 the Galilean moon motivated by the future ESA's JUICE (Grasset et al., 2013) and NASA's Europa Clipper  
59 (Phillips et al., 2014) missions, which will study Ganymede, Europa, and Callisto, and by recent advancements  
60 in the knowledge of the Jupiter system.

61 First, NASA's Juno mission recently provided a new estimation of the gravity field of Jupiter, which drives the  
62 orbital motion of the moons, to an unprecedented level of accuracy (Folkner et al., 2017; Iess et al., 2018;  
63 Serra et al., 2019, Durante et al., 2020). The zonal harmonic coefficients up to degree 10 were determined  
64 up to 50 times more accurately than before and, for the first time, non-zero values for the odd zonal harmonic  
65 coefficients up to degree 9 were observed and related to Jupiter's wind dynamics (Kaspi et al., 2018, Guillot  
66 et al., 2018).

67 In addition, Juno provided new observations of the Io Plasma Torus (IPT), a toroidal cloud of plasma that  
68 orbits Jupiter (Iess et al., 2018), from which new models were derived (Phipps et al., 2018). The IPT introduces  
69 a non-dynamical, dispersive signal on the radiometric observables and becomes a source of bias in the gravity  
70 estimations, if not properly accounted for. The effect on the gravity analysis of the Galileo mission is critical,  
71 since the probe had to use the S-band, more affected by this dispersive phenomenon than higher frequency  
72 radio links currently used.

73 During the last years, several authors reported evidence of water plumes emerging from Europa (Roth et al.,  
74 2014; Sparks et al., 2016). More recently, (Jia et al., 2018) performed a reanalysis of Galileo magnetometer  
75 data acquired during E12, suggesting the presence of a plume, localized around  $245^\circ$  W and  $5^\circ$  S, in a region

76 with high surface temperature (Spencer et al., 1999). This plume may have influenced the motion of the  
77 Galileo spacecraft during the encounter, potentially biasing the gravity field analysis.

78 Moreover, the current analysis is performed using new orbit determination codes and techniques extensively  
79 used for the Cassini radio science experiment, in order to provide an update on the gravity field of the moon  
80 and report on its internal structure implications.

81 This manuscript is organised as follows: Section 2 describes the data analysis; Section 3 provides the gravity  
82 field results; Section 4 details the implications on the interior structure of Europa; finally, Section 5  
83 summarizes the main conclusions of this work.

## 84 **2. Data Analysis**

85

86 The gravity field of Europa can be estimated through reconstruction of Galileo's trajectory during encounters  
87 with the moon, exploiting the Doppler shift of a highly stable microwave signal induced by the relative motion  
88 between the tracking stations of the Deep Space Network (DSN) and the Galileo spacecraft.

89 During the different flybys of the Galileo probe with Europa, Doppler data at S-Band (2.3GHz) were acquired  
90 by the 70-m antennas at the DSN complexes of Goldstone, Madrid and Canberra. The Galileo spacecraft  
91 operated using only the low-gain antenna at S-band, because Galileo's umbrella-like High Gain Antenna  
92 (HGA), which supported X-band, failed to correctly deploy. Therefore, the spacecraft downlink data rate was  
93 significantly reduced, limiting the mission science return, and the spacecraft tracking was carried out using  
94 the S-band link, which has larger noise and thus lower performances (less et al., 2012).

95 From all the available data (E4, E6, E11, E12, E14, E16, E19, and E26) we only used the 6 flybys that had  
96 accessible both tropospheric and ionospheric calibrations, leaving E4 and E26 out of the analysis. The actual  
97 length of each arc is determined by the available data in the vicinity of each encounter (Table 1).

98 Data selection was performed by preferring two-way data over three-way, if an overlap occurs. During E19  
 99 we used also one-way data acquired during the closest approach, due to the large sensitivity to the gravity  
 100 field and the exceptional observed data quality of the obtained residuals. To account for a possible drift of  
 101 the on-board clock, we estimated a constant bias and linear drift during the one-way tracking pass. Moreover,  
 102 an additional solution was generated without using one-way data to assess the stability of the retrieved  
 103 results, obtaining a compatible solution within  $1-\sigma$ .

104 Data acquired with an elevation angle, as viewed from the DSN complex, lower than  $15^\circ$  were discarded to  
 105 avoid potential biases coming from incorrect troposphere or ionosphere calibrations.

106 The HGA failure prevented the use of multi-frequency link calibration systems (Bertotti et al., 1993; Mariotti  
 107 et al., 2013), which could have been used to remove the systematic signal due to dispersive media. Since S-  
 108 band data are significantly affected by dispersive noise, we studied in detail two sources of dispersive noise,  
 109 the ionosphere of Europa and the IPT, that potentially could have introduced a bias in the gravity results. To  
 110 do so, we generated the expected Doppler shift induced by these dispersive sources using reference models  
 111 (Kliore et al., 1997; Phipps et al., 2018), finding that the ionosphere could have corrupted the one-way data  
 112 acquired during the closest approaches of E4, E6, and E26, and that the IPT could explain some strong  
 113 signatures found in the two-way tracking data of E26. Since the models cannot be used to calibrate the  
 114 observables at the required level of accuracy, we decided to remove from the analysis about 12 minutes of  
 115 possibly corrupted, non coherent, data of E6, whereas E4 and E26 were not used at all, to prevent errors in  
 116 the gravity solution.

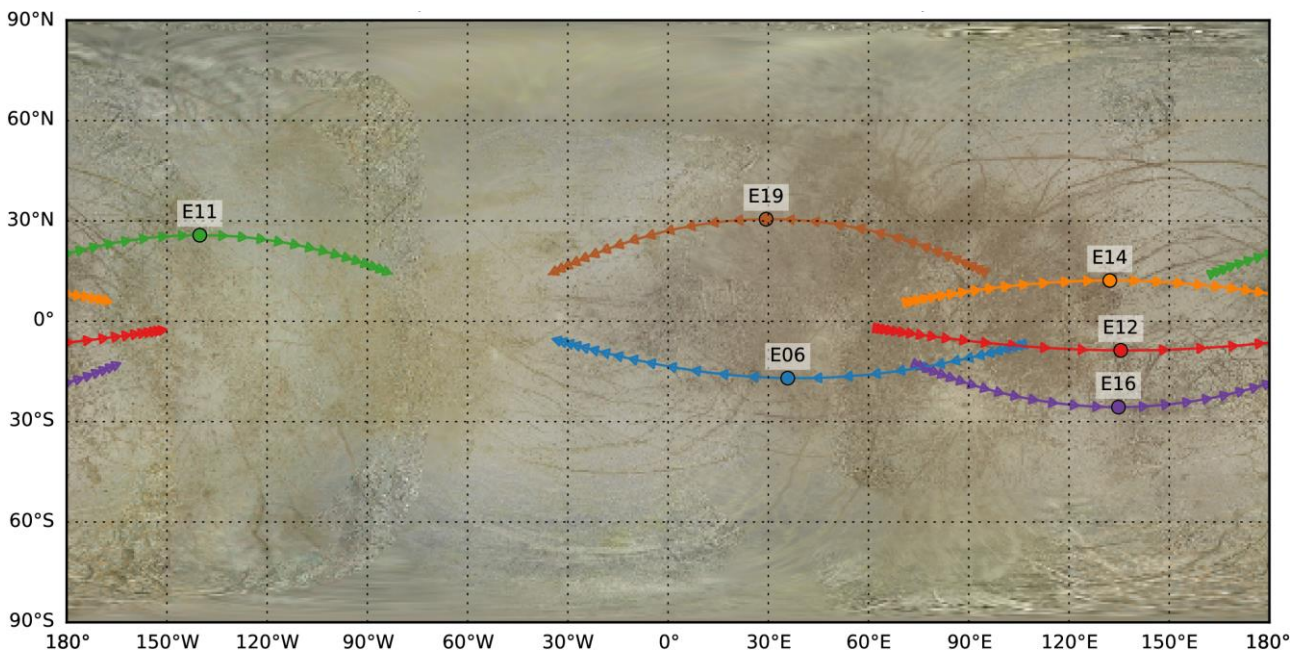
	Date of C/A	Altitude (km)	Rel. Velocity (km/s)	Inclin. ( $^\circ$ )	Mean anomaly ( $^\circ$ )	SEP ( $^\circ$ )	Number of points	RMS at 60 s (mm/s)
E4	19 Dec. 1996	693.0	5.75	178	-137	25	N/A	N/A
E6	20 Feb. 1997	587.0	5.77	162	-142	25	2189	0.869



E11	06 Nov. 1997	2044.6	5.72	26	41	89	1324	0.317
E12	16 Dec. 1997	201.9	6.27	9	127	55	1309	0.509
E14	29 Mar. 1998	1644.9	6.42	12	-149	26	1506	0.871
E16	21 Jul. 1998	1835.2	6.22	26	-63	120	1285	0.165
E19	1 Feb. 1999	1440.5	5.83	149	36	46	994	0.334
E26	3 Jan. 2000	351.3	11.3	133	-143	103	N/A	N/A

117

118 **Table 1:** Main characteristics of the different Galileo encounters of Europa. The table reports on the date of the  
 119 closest approach (C/A), the minimum altitude, the relative velocity of the spacecraft, the orbital inclination, the  
 120 mean anomaly in Europa's orbital frame, the Sun-Earth-Probe (SEP) angle, the number of Doppler points used, and  
 121 the Root Mean Square (RMS) of the Doppler residuals at 60 s. Note that E4 and E26 data were not used in the  
 122 analysis.



123

124 **Figure 1:** Ground tracks of Galileo during the different Europa encounters 15 minutes before and after the C/A. The  
 125 C/A is indicated by a circle and the separation between the different markers is equal to 60 s. The equatorial region  
 126 of the moon is well sampled, while the higher latitudes are not covered. The ground tracks are represented over a  
 127 map of Europa produced by Björn Jónsson (Planetary Society) using Galileo and Voyager images (NASA, JPL).

128





129 The range-rate data were compressed at 60 second integration time, as a balance between spatial resolution  
130 and numerical considerations (Zannoni and Tortora, 2013), and were weighted on a pass-by-pass basis, using  
131 the root mean square of their residuals. The data were analysed with JPL's orbit determination code MONTE  
132 (Evans et al., 2018), which adopts a Batch-Weighted Least Squares information filter (Bierman 1977), that  
133 allows to generate iterative corrections to an a-priori dynamical model.

134 The dynamical model included the gravitational acceleration due to the Sun and the planets of the Solar  
135 system, including Jupiter and its Galilean satellites. For Jupiter, we used the latest gravity solution obtained  
136 by the Juno gravity team up to the 10th degree (less et al., 2018), while for the other Galilean satellites we  
137 used the 2nd degree and order gravity fields reported by the Radio Science Team and summarized in  
138 (Schubert et al., 2004). For Europa, we adopted a perfectly-synchronous rotational model, in which the  
139 moon's long axis points to the empty focus of the orbit, and set the obliquity equal to zero. The diurnal  
140 libration on Europa is expected to be  $\sim 150$  m (Van Hoolst et al. 2013), or  $0.005^\circ$ , and the librations related to  
141 deviations from a Keplerian orbit can be of the order of  $0.05^\circ$  (Rambaux et al. 2011). The obliquity is predicted  
142 to be  $0.05^\circ$  (Baland et al. 2012, Chen et al. 2014). These angles are much smaller than the retrieved  
143 uncertainty on the misalignments between the body-fixed frame and the inertia axes and neglecting them  
144 does not affect our conclusions in a detectable way. For Jupiter we used the rotational model used to  
145 generate the JUP310 ephemerides (The satellite ephemerides of Jupiter can be retrieved from  
146 <ftp://ssd.jpl.nasa.gov/pub/eph/>). We included the non-gravitational acceleration due to Solar Radiation  
147 Pressure (SRP) acting on the spacecraft, estimated to be around  $3.3 \text{ nm/s}^2$  during the Jupiter approach phase  
148 (Antreasian et al., 1997). In addition, as a stability test, we introduced the possible drag produced by a plume  
149 during E12 (discussed in Section 3), and the non-isotropic acceleration of the Radioisotope Thermal  
150 Generators (RTG's), modelled using an exponential acceleration.

151 To analyse the data, we adopted a multi-arc approach (Milani et al., 2010), a well-known technique used in  
152 the analyses of radio science data of several deep space missions (less et al., 2012; less et al., 2014; Modenini  
153 & Tortora, 2014; Tortora et al., 2016; less et al., 2019; Durante et al., 2019; Zannoni et al., 2018, Zannoni et



154 al., 2020, Lainey et al., 2020), in which radiometric data obtained during non-contiguous orbital segments,  
155 called arcs, are jointly analysed to produce a single solution of a set of global parameters, which affect all the  
156 arcs, and a set of local parameters that influence only one single arc.

157 In some of these previous analyses, the orbit of the moon under study was integrated for the entire time  
158 span of the data, in order to ensure the coherency of the observed data with the satellite trajectory. However,  
159 Durante et al. (2019), highlighted that this kind of analysis is sensitive to errors, mis-modelling or missing  
160 models in the ephemeris integration. Since the generation of a coherent Europa ephemeris set was beyond  
161 the scope of this work, the state of Europa was treated as a local parameter, updating the orbit of the moon  
162 for each encounter, as done in (Durante et al., 2019; Zannoni et al., 2020). This introduces an over-  
163 parametrization that can absorb the modelling errors of the ephemerides, avoiding biases in the gravity field.

164 Our global parameters included Europa's mass and the full gravity field of degree 2, while our local  
165 parameters included the initial state vectors of Galileo and Europa. The a priori values of Galileo's state  
166 vectors were taken from the last reconstruction of the Galileo navigation team (Retrieved from  
167 <https://naif.jpl.nasa.gov/pub/naif/GLL/kernels/spk/>) with an a priori uncertainty large enough to not  
168 constrain the solution. The a priori values of Europa's state vector were retrieved from the latest available  
169 Jupiter system ephemerides (JUP310), using a conservative approach for the a priori uncertainty. In addition,  
170 we estimated a scale factor for the SRP acceleration for each arc, Doppler biases for three-way data (caused  
171 by asynchronous clocks at the transmitting and receiving stations), and a Doppler bias and a drift for the one-  
172 way pass of E19. There were not enough data to estimate the rotational parameters of Europa, thus the  
173 rotational model is supposed perfectly known.

### 174 3. Gravity field results

175

176 The estimated set of parameters was sufficient to fit the data to the noise level (Figure 2). Table 2 reports  
177 the estimated gravity field coefficients of Europa for two interesting cases. SOL-A represents the  
178 unconstrained solution, obtained without imposing the hydrostatic equilibrium ratio  $J_2/C_{22} = 10/3$ . The

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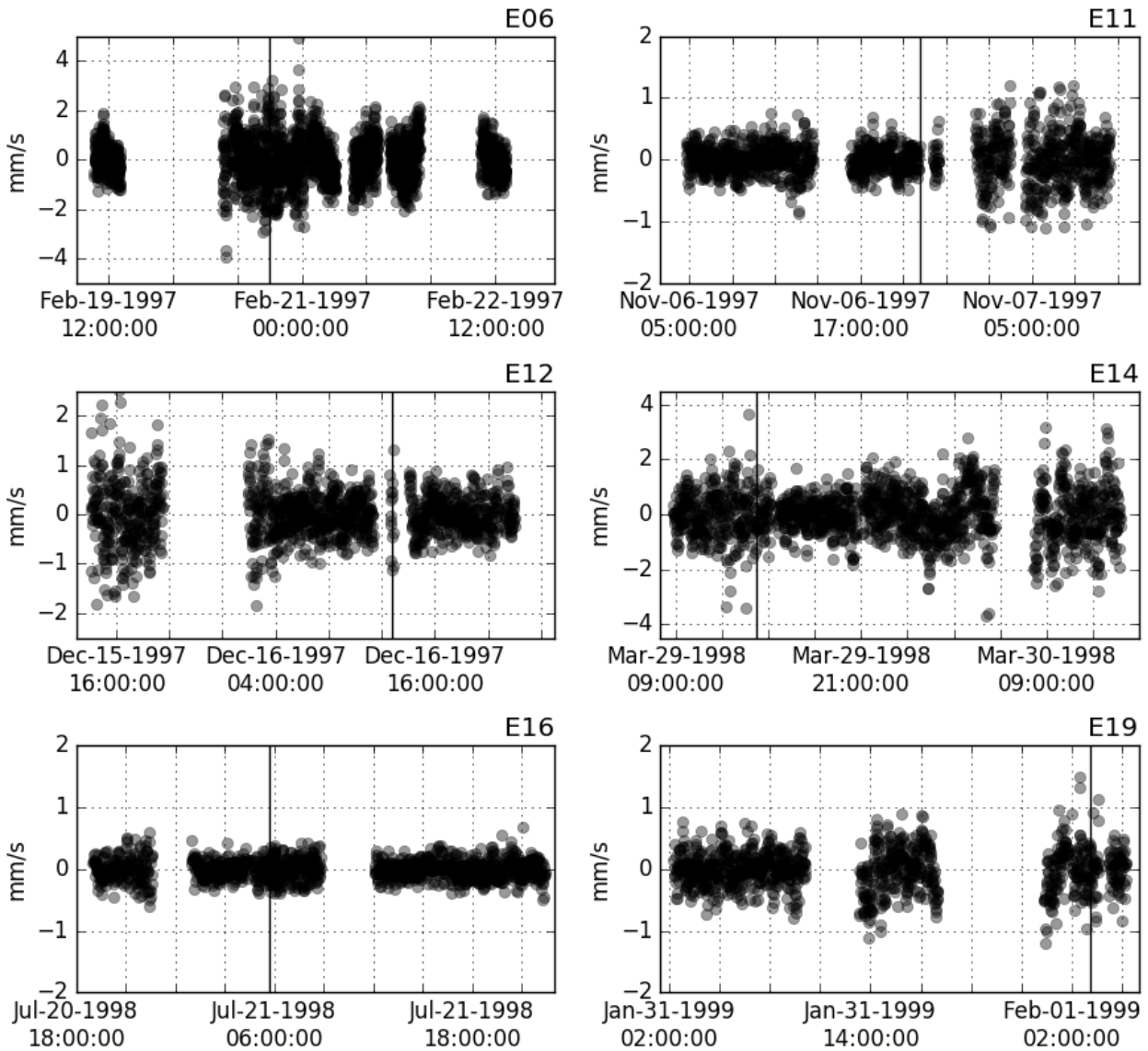
<http://creativecommons.org/licenses/by-nc-nd/4.0/>



179 solution is compatible with a body in hydrostatic equilibrium within  $1\text{-}\sigma$ , but the uncertainty in  $J_2$  is very large,  
180 due to the poor latitudinal coverage of the flybys. Hence, solution SOL-B was generated applying the  
181 hydrostatic equilibrium constraint. We note that this is an assumption, which may or may not turn out to be  
182 correct; the main reason for doing so is to allow comparison with previous works, all of which made the same  
183 assumption.

184 For the same reason, we imposed the hydrostatic equilibrium constraint equal to the classical value of  $10/3$ ,  
185 as in the previous solutions available in literature. However, using the more correct value of 3.324, adopted  
186 in Section 4, which takes into account the relatively rapid rotation of Europa (Tricarico 2014), the estimated  
187 quadrupole coefficients change by less than  $0.02\text{-}\sigma$ .





188

189 **Figure 2:** Range-rate residuals around the closest approach of E06, E11, E12, E14, E16 and E19 encounters  
 190 (vertical line), in mm/s. Range-rate residuals are obtained scaling the Doppler residuals by the coefficient  
 191  $136.27 \text{ mm/s} \times 1/\text{Hz}$ .

192

193 As shown in Figure 3, both solutions are compatible within  $1-\sigma$ , but SOL-B has smaller uncertainties (as  
 194 expected, due to the hydrostatic constraint), up to about 1 order of magnitude for  $J_2$  and by 3.7 % for  $C_{22}$ .

195 Given the estimated values of  $C_{21}$ ,  $S_{21}$  and  $S_{22}$  and following MacCullagh's theorem we can extract the  
 196 misalignment between the Europa body fixed frame and its principal axes of inertia. The obtained values



197 correspond to rotations of  $-3.1 \pm 5.0^\circ$  and  $0.1 \pm 1.2^\circ$  around the x and y axes, respectively. Both are compatible  
 198 with zero within  $1-\sigma$ . On the other hand,  $S_{22}$  translates to a misalignment of the minimum inertia axis with  
 199 respect to prime meridian of  $1.3 \pm 0.6^\circ$ , that vanishes within  $2.1-\sigma$ .

Coefficient ( $\times 10^6$ )	(Anderson et al., 1998; Schubert et al., 2004)	(Jacobson et al., 1999)	SOL-A (Unconstrained)	SOL-B (Hydrostatic eq.)
$J_2$	$435.50 \pm 8.2$	$417.0 \pm .6.0$	$437.59 \pm 77.47$	$461.39 \pm 7.84$
$C_{21}$	$-1.4 \pm 6.0$	$-1.3 \pm 3.8$	$1.26 \pm 15.21$	$4.25 \pm 11.73$
$S_{21}$	$14 \pm 12$	$11.0 \pm 10.0$	$9.01 \pm 11.38$	$7.425 \pm 10.16$
$C_{22}$	$131.5 \pm 2.5$	$125.0 \pm 2.0$	$138.62 \pm 2.44$	$138.42 \pm 2.35$
$S_{22}$	$-11.9 \pm 2.9$	$-10.0 \pm 2.0$	$-6.21 \pm 2.90$	$-6.65 \pm 2.51$
$J_2/C_{22}$	$3.3118 \pm 0.0097$	10/3	$3.16 \pm 0.57$	10/3
$\mu$	0.993	1.0	-0.17	1.0

200

201 **Table 2:** Europa's unnormalized gravity field coefficients and its associated  $1-\sigma$  uncertainty, corresponding to a  
 202 reference radius of 1565 km, estimated using two different approaches. SOL-A corresponds to the unconstrained  
 203 solution, while in SOL-B the hydrostatic equilibrium constraint was applied. In addition, the table shows both  
 204 previous reference solutions, the  $J_2/C_{22}$  ratio and the correlation ( $\mu$ ) between both  $J_2$  and  $C_{22}$  coefficients.

205 The retrieved uncertainties in all the coefficients, except  $J_2$  for SOL-A, are comparable to the ones obtained  
 206 in the old solutions (Anderson et al., 1998; Jacobson et al., 1999). The difference in the  $J_2$  uncertainty in SOL-  
 207 A comes from the fact that the hydrostatic equilibrium constraint was not applied. This large uncertainty was  
 208 expected since the encounters were nearly equatorial (see Figure 1).

209 The analysis provides a  $C_{22}$  coefficient significantly larger than the one retrieved in the old solutions and  
 210 shown in Figure 3. The differences are  $2.84-\sigma$  with respect to (Anderson et al., 1998) and  $5.58-\sigma$  with respect

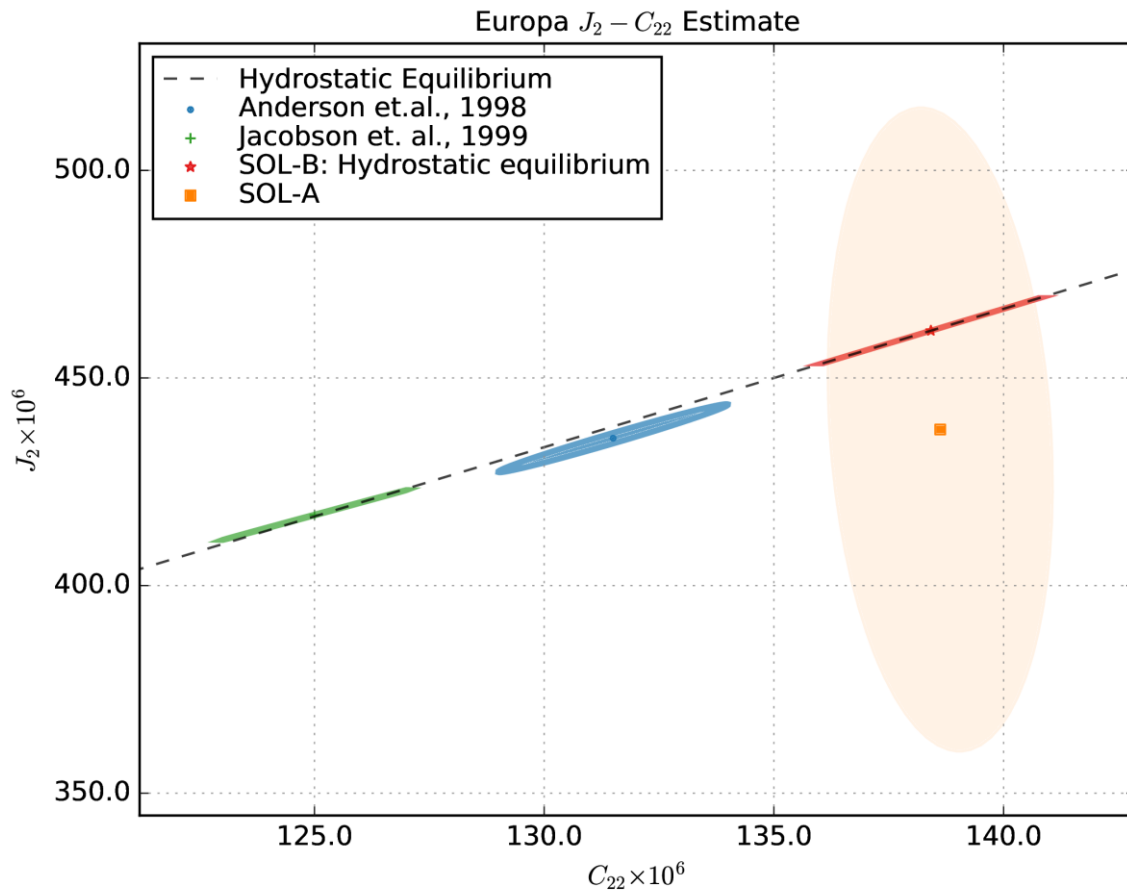
211 to (Jacobson et al., 1999). These differences may come from the use of a different data pre-processing and  
212 data-selection and the different orbit determination techniques used in this work, such as the use of MONTE  
213 or the local ephemeris update. For example, a detailed inspection of the residuals published in (Jacobson et  
214 al., 1999) showed that previous analyses used all the available data without removing the measurements at  
215 low elevation angles. Following the same approach, we obtained a value of  $C_{22}$  compatible with (Anderson  
216 et al., 1998) within  $0.8\text{-}\sigma$ . This is an indication that the previous published solutions might be biased due to  
217 the wrong calibration of the Earth's atmosphere and ionosphere at low elevation angles.

218 Among the Galilean satellites, Europa has the highest eccentricity. This fact together with the good coverage  
219 of Galileo's flybys along Europa's orbital frame supported the addition of the tidal parameter  $k_2$  to the  
220 estimated parameters set. We found  $k_2 = 0.29 \pm 0.46$  (SOL-A) and  $k_2 = 0.15 \pm 0.28$  (SOL-B),  $1\text{-}\sigma$  uncertainties.  
221 In both cases the retrieved uncertainty is too large to extract any conclusions and only provides upper limits  
222 to Europa's tidal response.

223 A full degree 2 gravity field was sufficient to fit the data. Higher degrees cannot be determined with enough  
224 accuracy, but the addition of the full degree 3 and 4 coefficients to the estimated parameters did not bias  
225 the solution. The a priori uncertainties of the degree 3 and 4 normalized coefficients were set using the  
226 Kaula's rule,  $K/l^2$  (Kaula, 1963), that describes the gravity power spectra of terrestrial planets. The K factor,  
227 obtained fitting Titan's gravity field (Durante et al., 2019), was scaled to Europa using the scaling law provided  
228 by (Bills et al., 2014), retrieving  $K = 2 \cdot 10^{-5}$ . Since there is no evidence that the Kaula's rule can be applied to  
229 ocean worlds, to assess the stability of the solution we generated other solutions setting the a priori  
230 uncertainty of the degree 3 and 4 using  $0.1 \cdot K$  and  $10 \cdot K$ . The obtained solutions were always compatible within  
231  $1\text{-}\sigma$ .

232 The possible plume emerging from Europa during the E12 encounter, reported in (Jia et al., 2018), could have  
233 perturbed the motion of the Galileo probe, inducing a bias in the solution. For this reason, following a similar  
234 approach used for Cassini's flybys close to Enceladus's plumes (Iess et al., 2014), we modelled the  
235 perturbation of a plume as an impulsive change in velocity of the spacecraft at the C/A, estimating the three

236 components of this impulse, using an a priori uncertainty of 5 mm/s. The retrieved component along Galileo's  
 237 velocity is  $\Delta V_{\text{plume}} = 0.22 \pm 4.93$  mm/s (SOL-A) and  $\Delta V_{\text{plume}} = 0.19 \pm 4.93$  mm/s (SOL-B), showing that the  
 238 plume cannot be estimated using the radio tracking data and that therefore it does not represent a bias in  
 239 the solution.



240  
 241 **Figure 3:** Obtained  $J_2$  and  $C_{22}$  and its  $1-\sigma$  associated error ellipses of SOL-A (unconstrained) and SOL-B (applying the  
 242 hydrostatic equilibrium). In addition, the figure shows both the solutions of (Anderson et al., 1998) and (Jacobson  
 243 et al., 1999), for comparison purposes. The previous published solutions are not compatible with the gravity update  
 244 within  $1-\sigma$ .

## 245 4. Interpretation

246

247 Given a measurement of either  $J_2$  or  $C_{22}$  and assuming hydrostatic equilibrium, the gravity coefficients can  
 248 then be used to directly infer the Mol of the body (e.g. Schubert et al., 2004). Below we will compare the Mol  
 249 results obtained from the three different gravity measurements of  $C_{22}$  using the hydrostatic assumption. First  
 250 we will briefly digress to discuss the assumption itself.

251 If Europa is hydrostatic, then  $C_{22}$  can be converted directly to a Mol via the Radau equation (e.g. Schubert et  
 252 al. 2004). However, we do not *know* that Europa is hydrostatic, because we do not have an independent  
 253 measurement of  $J_2$ . Without further observations, it is unclear whether Europa is likely to be hydrostatic or  
 254 not. However, the icy moon Titan provides a useful example. Titan's gravity is well-determined (Iess et al.  
 255 2010) and the deviation of the ratio  $J_2/C_{22}$  is only 2-4% away from the expected hydrostatic ratio. Europa is  
 256 likely to be more hydrostatic than Titan, being more strongly tidally-heated and having a thinner ice shell. We  
 257 thus regard the hydrostatic assumption as reasonable, though we caution the reader that future gravity  
 258 measurements may prove it to be incorrect.

259 Table 3 presents the inferred Mol derived from the three independent solutions. Here we have taken into  
 260 account the small correction required by Europa's relatively rapid rotation (Tricarico, 2014), the result of  
 261 which is to modify the ratio  $J_2/C_{22}$  from  $10/3$  to 3.324. The effect of the slightly larger  $C_{22}$  coefficient we  
 262 estimate is to yield a slightly higher Mol, indicating a less differentiated Europa.

Quantity	(Anderson et al., 1998; Schubert et al., 2004)	(Jacobson et al., 1999)	This Work
$C_{22}$ ( $\times 10^6$ )	$131.5 \pm 2.5$	$125.0 \pm 2.0$	$138.42 \pm 2.35$
Mol	$0.3475 \pm 0.0026$	$0.3405 \pm 0.0022$	$0.3547 \pm 0.0024$
H <sub>2</sub> O thickness (1 g/cm <sup>3</sup> ) (km)	$161.8 \pm 8.4$	$184.5 \pm 7.2$	$138.7 \pm 7.7$
H <sub>2</sub> O thickness (0.95 g/cm <sup>3</sup> ) (km)	$157.7 \pm 8.2$	$179.7 \pm 7.0$	$135.2 \pm 7.5$
Core density (g/cm <sup>3</sup> )	$3.790 \pm 0.049$	$3.928 \pm 0.046$	$3.658 \pm 0.043$





H <sub>2</sub> O mass fraction (%)	8.6 ± 0.4	9.7 ± 0.4	7.5 ± 0.4
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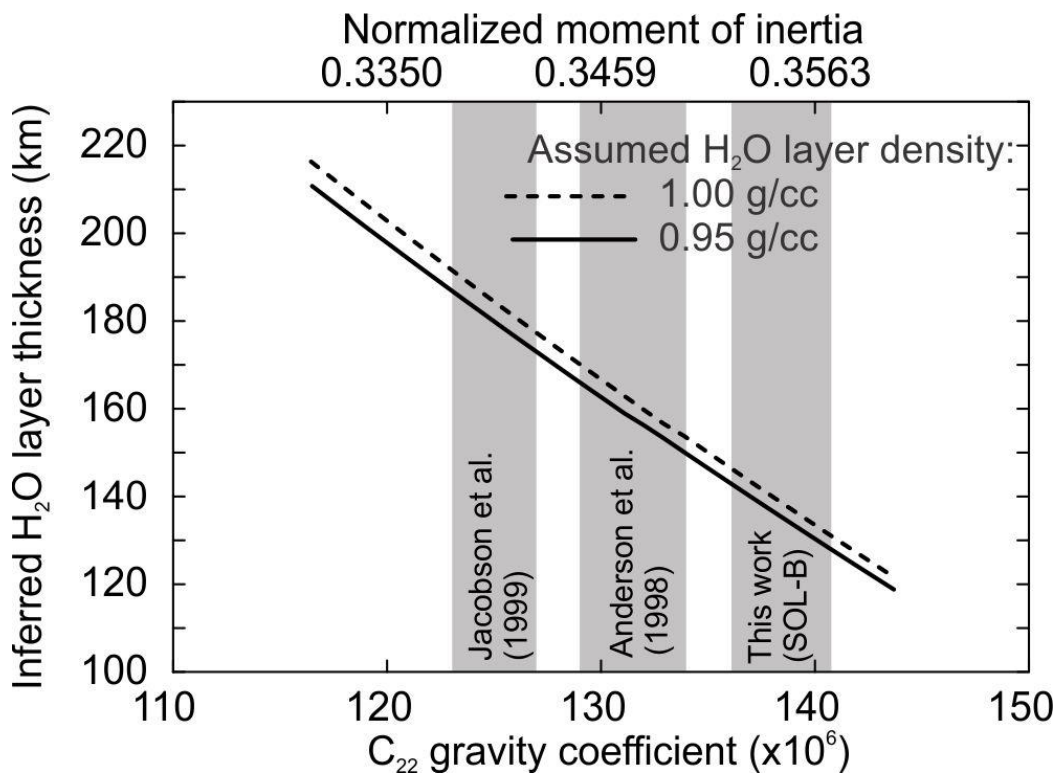
263 **Table 3.** Geophysical parameters derived from  $C_{22}$  measurements (see text). Thicknesses and densities are  
 264 derived assuming a two-layer Europa with a bulk density of  $3.013 \text{ g/cm}^3$ . The final two rows assume an H<sub>2</sub>O  
 265 density of  $0.95 \text{ g/cm}^3$ .

266 With the known bulk density of Europa ( $3.013 \text{ g/cm}^3$ ) and a measurement of its Mol, we can place constraints  
 267 on its internal structure (e.g. Schubert et al. 2004). The simplest approach is to assume a two-layer structure,  
 268 with an H<sub>2</sub>O layer (ice or water) above a rock/iron core. For an assumed H<sub>2</sub>O density (which should be  
 269 intermediate between that of water and ice), we can deduce the H<sub>2</sub>O layer thickness, which is also tabulated  
 270 in Table 3. While this is undoubtedly an oversimplified model of the real Europa, the point of these  
 271 calculations is to illustrate how differences in the measured  $C_{22}$  value translate into differences in the  
 272 structures inferred. The higher Mol results in an H<sub>2</sub>O layer that is thinner by ~20-40 km than previous  
 273 estimates. Figure 4 presents these same results graphically, showing how the measured  $C_{22}$  values can be  
 274 mapped to Mol and H<sub>2</sub>O layer thickness values.

275 The same analysis also yields estimates of the core density and H<sub>2</sub>O mass fraction (Table 3). Our density is  
 276 lower than the previous estimates, suggesting a smaller and/or less dense iron component of the rock/iron  
 277 core. Similarly, the total H<sub>2</sub>O mass fraction is a little lower. Although none of these differences are very large,  
 278 a thinner H<sub>2</sub>O layer, as suggested here, would slightly increase the gravitational effect of the mantle, and  
 279 could in principle slightly shift the characteristic period of tidally-driven resonant oscillations (Matsuyama et  
 280 al. 2018). The upper-bound SOL-B solution on  $k_2$  of 0.43 is not diagnostic: estimates of Europa's  $k_2$  are typically  
 281 0.26 or less (Moore & Schubert 2000). Such a high value would require an ocean density of at least  $1500$   
 282  $\text{kg/m}^3$ , if resonant enhancement of tidal flow in the ocean is neglected (e.g. Matsuyama et al. 2018).

283





284

285 **Figure 4.** Inferred H<sub>2</sub>O layer thickness as a function of C<sub>22</sub> gravity coefficient (see text), for two different  
286 assumed H<sub>2</sub>O layer densities. Shaded regions denote coefficient estimates made by three different groups.

287

288 While more complicated (e.g. three-layer) models can be produced (e.g. Schubert et al. 2004), they require  
289 additional assumptions to be made. As an example, models which include an iron core or allow an ocean  
290 denser than the ice typically result in H<sub>2</sub>O thicknesses that are lower than in Table 3 by up to several tens of  
291 kilometers. The main point of Table 3 and Figure 4 is to illustrate how different estimates of the gravity  
292 coefficients map into different internal structures. The relative differences in, for example, H<sub>2</sub>O thickness  
293 between the different gravity models will be preserved, even if more complex structures are invoked.

294

## 295 5. Conclusions

296

297 In view of the future missions JUICE and Europa Clipper and motivated by the new knowledge of the Jupiter  
298 system given by Juno, we reanalysed the radio tracking data of Galileo acquired during the Europa flybys. The  
299 analysis considered effects neglected in previous analyses, such as the IPT, Europa's ionosphere, and the  
300 recently detected plume of E12, that may have affected the retrieved gravity field. In addition, this work  
301 adopted modern orbit determination techniques previously used in the gravity analyses of Cassini and Juno.  
302 We obtained a satisfactory fit of the Doppler data, estimating a full degree and order 2 gravity field. The  
303 retrieved gravity field is compatible with the hydrostatic equilibrium without imposing the a priori hydrostatic  
304 equilibrium constraint ( $J_2/C_{22} = 10/3$ ), as done in the past in the reference analyses. The obtained  $C_{22}$   
305 coefficient is slightly different from previous results and suggests a thinner water ice shell and a less dense  
306 core, that could have implications on the characteristic period of tidally-driven resonant oscillations.

307 Three research groups obtained contrasting solutions of the gravity field of the Galilean satellite using  
308 unequal data sets and orbit determination techniques, with slightly different implications on Europa's  
309 internal structure. Further insights into Europa's structure and evolution will come from the gravity  
310 measurements of the incoming Europa Clipper and JUICE missions. Both of them will allow to estimate the  
311 gravity field and the love numbers of the icy moon up to an unprecedented level, shedding light on the  
312 interior structure of this body.

313

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315

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