

Key Points:

- We perform an inversion of Galileo spacecraft magnetometer measurements to quantify Europa's subsurface ocean properties
- Our method considers the plasma interaction and the inhomogeneous background including their uncertainties
- With our model we provide quantitative constraints for the depth, thickness, and electrical conductivity of Europa's subsurface ocean

Correspondence to:

J. Winkenstein,
jwinken3@uni-koeln.de

Citation:

Winkenstein, J., Saur, J., & Cervantes, S. (2025). An inversion of magnetic field measurements to constrain the depth, thickness, and conductivity of Europa's ocean. *Journal of Geophysical Research: Planets*, 130, e2025JE009122. <https://doi.org/10.1029/2025JE009122>

Received 31 MAR 2025

Accepted 1 OCT 2025

An Inversion of Magnetic Field Measurements to Constrain the Depth, Thickness, and Conductivity of Europa's Ocean

Jason Winkenstein¹ , Joachim Saur¹ , and Sebastian Cervantes^{1,2} 

¹Institute of Geophysics and Meteorology, University of Cologne, Cologne, Germany, ²School of Cosmic Physics, DIAS Dunsink Observatory, Dublin Institute for Advanced Studies, Dublin, Ireland

Abstract The Galilean satellite Europa is a primary candidate for the study of ocean worlds. In anticipation of NASA's Europa Clipper and ESA's JUICE missions, we revisit the magnetic field measurements of the Galileo spacecraft. The ocean's induction response is governed by its induction amplitude and phase shift, which are a function of the ocean properties, i.e., its depth, thickness, and electrical conductivity. While prior work focused on deriving values for the former two by a qualitative comparison with measurements, this work emphasizes the characterization of Europa's ocean properties directly, including their uncertainties. For that, we perform an inversion of magnetic field measurements. Our model includes magnetic field contributions due to Europa's plasma interaction and the inhomogeneous field of Jupiter's magnetospheric plasma. We estimate the uncertainties of our plasma interaction model, our background field model, and the inducing field. Employing a chi-squared analysis, we utilize these uncertainties to quantify the ocean properties and their uncertainties. We apply this method to the E14 flyby, which is currently the best flyby for such an inversion. Using existing depth constraints from the literature, we find a minimum conductivity of 1.6 S/m at 20 km depth and 2.8 S/m at 35 km depth. At the derived maximum depth, 49 km, the required conductivity exceeds current estimates. Our work is a first step for the development of methods which quantitatively constrain the various magnetic field contributions around Europa in future measurements, including their uncertainties, and highlights the challenges of a quantitative characterization using magnetic sounding.

Plain Language Summary Jupiter's moon Europa is expected to host a subsurface ocean of liquid water below its icy surface layer. This notion has been supported especially by magnetic field measurements recorded with the Galileo spacecraft. While these measurements provided evidence for the existence of an ocean, a quantitative description of the ocean, i.e., information about its depth, thickness, and salinity or electrical conductivity, remains a question of current research. In this work, we develop a method that provides such quantitative constraints by performing an analysis of Galileo spacecraft magnetic field measurements. We present the resulting constraints and test their robustness, i.e., how stable the results are to changes of the input parameters. This work provides insights into how individual contributions to Europa's magnetic field environment influence our results, and thus our understanding of Europa's interior.

1. Introduction

Magnetic field measurements recorded with the Galileo spacecraft discovered strong evidence for the existence of a subsurface ocean harbored below the icy crust of Jupiter's moon Europa (e.g., Khurana et al., 1998; Kivelson et al., 1999, 2000). Jupiter's dipole axis is tilted by 10.25° with respect to its rotational axis (Connerney et al., 2022). In Europa's rest frame, this results in a time varying field oscillating at the synodic rotation period (approximately 11.23 hr at Europa). In a conductive body, these temporal variabilities induce eddy currents, which drive a secondary magnetic field, also called induced magnetic field or induction response. As such, magnetic field perturbations in the direct vicinity of Europa have been attributed to an induced magnetic field generated within its subsurface ocean.

The magnetic field in Europa's vicinity is additionally perturbed by the interaction between the Jovian magnetospheric plasma and Europa's atmosphere (see e.g., Blöcker et al., 2016; Harris et al., 2021; Neubauer, 1998; Saur et al., 1998; Schilling et al., 2008). This interaction must be taken into account in order to retrieve the ocean properties. In this work, we use a single-fluid magnetohydrodynamic (MHD) model to describe the magnetic field due to Europa's plasma interaction.

© 2025. The Author(s).

This is an open access article under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

The measured magnetic field provides a window into Europa's interior, as the induced magnetic field is a function of the ocean's depth d , thickness h , and electrical conductivity σ , assuming that the ocean can be described by a radially symmetric shell with homogeneous conductivity (Saur et al., 2010; Zimmer et al., 2000). Thus, the modeled induction response can be compared against the measurements to characterize the ocean's properties (e.g., Schilling et al., 2007; Zimmer et al., 2000). The values derived in prior studies, however, were obtained visually from fitting various ocean models to the measurements, and the parameter space has not been systematically constrained. An important aspect to consider is that with magnetic sounding, no direct information about the ocean properties, (d, h, σ) , had been retrieved traditionally, but rather about its induction amplitude A and phase shift ϕ^{ph} . The ocean properties are non-unique, that is, different sets of (d, h, σ) can result in the same values for A and ϕ^{ph} if only one frequency is available for the investigation. Motivated by the expected heterogeneity of Europa's icy crust, recent modeling work advanced away from the radially symmetric model, allowing for the consideration of local (Winkensstern & Saur, 2023) and global (Styczinski et al., 2022) conductivity anomalies within Europa's interior.

While the primary inducing signal is at Jupiter's synodic rotation period, additional inducing frequencies arise due to Europa's orbital motion and higher order synodics, as well as "beats" between the multiple inducing periods (e.g., Biersteker et al., 2023; Khurana et al., 2002; Seufert et al., 2011; Vance et al., 2021). A multi-frequency approach allows to decouple the ocean's thickness and conductivity. However, one still has to consider the ocean's depth as a third dimension of the induction problem. Furthermore, this approach requires exact knowledge of the induced field, while in reality, all contributions to the magnetic field are measured. Seufert et al. (2011) also studied the magnetic field induced within Europa's putative iron core, which is not observable in the presence of a highly conductive ocean (see Figure 9 in Seufert et al., 2011). In addition to the ocean's induction response to the temporal variabilities in the external field, electric currents are induced by flows within the ocean, resulting in additional induced fields (Šachl et al., 2024; Vance et al., 2021).

Despite these novel developments, a quantitative analysis to characterize Europa's subsurface ocean with magnetic sounding that includes the plasma interaction and the uncertainties of the various processes remained missing. Although Schilling et al. (2004) performed a joint inversion of four Galileo flybys, they only provided information about the induction amplitude. Biersteker et al. (2023) developed an approach to quantify the ocean properties using Markov-chain Monte Carlo. In their work, a plasma interaction field was used and scaled from 0–1 to represent incomplete plasma removal from the measurements. In addition, stochastic and systematic magnetometer noise sources were considered. However, no actual uncertainty was provided for, for example, the plasma interaction. This work aims to bridge the gap and provide such estimates for the uncertainties of the inducing field, the Jovian background field, and the plasma interaction, respectively, and perform an inversion of existing magnetic field measurements. The resulting output provides upper and lower limits of the ocean's depth d , thickness h , and electrical conductivity σ .

This paper is organized as follows, in Section 2, we introduce models for the Jovian magnetospheric background field, the inducing magnetic field, and the magnetic field due to Europa's plasma interaction, and we estimate their respective uncertainties. We utilize these uncertainties to characterize the properties of Europa's ocean and constrain them quantitatively using a chi-squared analysis, which we apply to the magnetic field measurements of Galileo's E14 and E04 flybys, respectively. The resulting constraints are presented in Section 3. In Section 4, we compare our derived constraints against existing estimates for the ocean properties and test the robustness of our method by slightly changing the model setup and comparing the resulting constraints against our reference model. We also briefly discuss the potential of a joint inversion and summarize our assumptions. We finish the paper with concluding remarks.

2. Model of Europa's Magnetic Field Environment

In this section, we first provide an outline of the method developed in this work to quantitatively compare a magnetic field model with observations. We introduce the models with which we describe the individual contributions to the modeled magnetic fields. Due to assumptions made within each model, these descriptions are an approximate representation of the real magnetic field in Europa's environment. We quantify the uncertainties that are introduced as a consequence of our assumptions. Afterward, we present a chi-squared analysis in which these uncertainties are used to characterize both the ocean properties and their uncertainties in a quantitative manner.

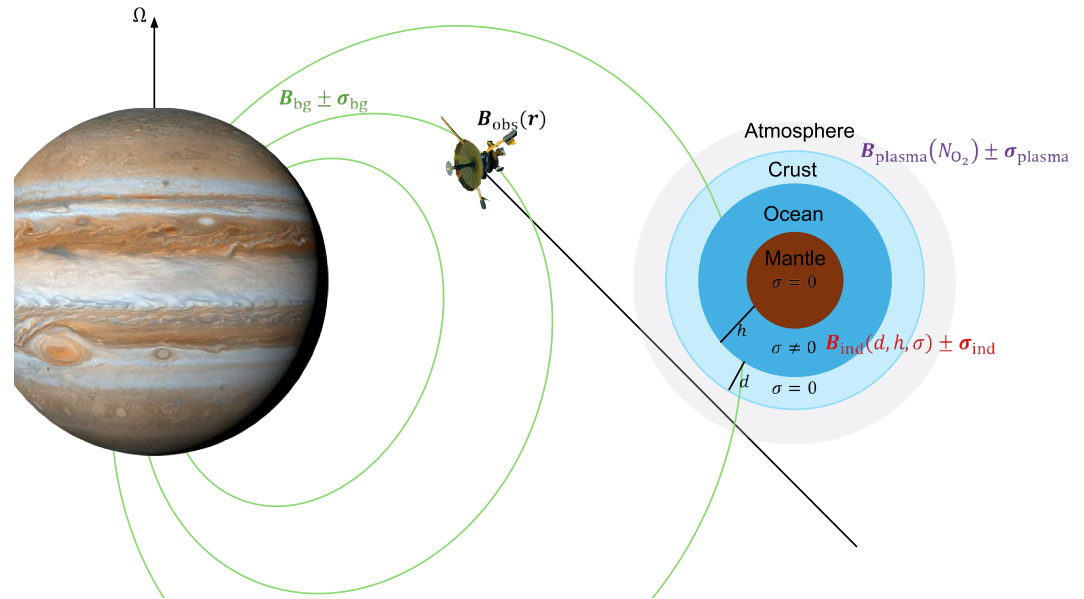


Figure 1. Sketch of the basic setup showing the contributions of our inversion model. The tilt of Jupiter's dipole component with respect to its rotational axis Ω causes time-variable magnetic fields in Europa's rest frame, which induce magnetic fields within Europa's subsurface ocean (dark blue) $\mathbf{B}_{\text{ind}}(d, h, \sigma)$, which is surrounded by a non-conductive icy crust (bright blue) and underlying mantle material (brown). The presence of a putative core is neglected for our conductive model, that is, it is assumed to be zero for simplicity (see Section 1). The induced field is a function of the ocean properties investigated in this work. Besides the induced field, Europa's magnetic field environment is additionally perturbed by the plasma interaction between Europa's atmosphere (gray layer) and the Jovian magnetosphere. The magnetic field due to plasma interaction is referred to as $\mathbf{B}_{\text{plasma}}$ and its strength varies with the O_2 column density N_{O_2} , among other factors. These three contributions build our magnetic field model, as described by Equation 1. To quantify the ocean's properties, we perform an inversion with the goal to minimize the misfit between the model and measurements made by the Galileo spacecraft along its trajectory $\mathbf{B}_{\text{obs}}(\mathbf{r})$ (black line). Due to assumptions in the model descriptions of background field, inducing field, and plasma interaction, uncertainties are introduced, which are utilized in deriving the ocean properties and their constraints by employing a chi-squared analysis, see Equation 3.

2.1. Inversion Strategy

We model the magnetic field $\mathbf{B}_{\text{model}}$ in Europa's vicinity as the sum of three contributions

$$\mathbf{B}_{\text{model}} = \mathbf{B}_{\text{bg}} + \mathbf{B}_{\text{ind}} + \mathbf{B}_{\text{plasma}}, \quad (1)$$

where $\mathbf{B}_{\text{bg}}$ is the Jovian magnetospheric background field, $\mathbf{B}_{\text{ind}}$ is the induced magnetic field generated within Europa's subsurface ocean, and $\mathbf{B}_{\text{plasma}}$ is the magnetic field due to Europa's plasma interaction. The modeled magnetic field is compared against observations recorded along the spacecraft's trajectory $\mathbf{B}_{\text{obs}}(\mathbf{r})$. A phenomenological sketch of the problem is shown in Figure 1.

Fitting all contributions to $\mathbf{B}_{\text{model}}$ at once would further increase the non-uniqueness of the induction problem when only one or a few flybys are used. It is thus sensible to disentangle these contributions by fitting them separately. This is done as follows. Jupiter's magnetospheric field is modeled using measurements recorded further away from the moon, that is, where contributions from plasma interaction and the ocean's induction response are negligibly small (Section 2.3). To decouple the induced magnetic field and plasma interaction field different components are used for each contribution, that is, the B_z -component is used to fit the plasma interaction model to the observations (Section 2.4) and the B_x and B_y -components are used to describe the ocean's induction response (Section 2.5).

Subtracting the background and plasma fields from the observed magnetic field, we assume the residual field represents the induced field within the measurements, referred to in this study as the “observed induction response” $\mathbf{B}_{\text{obs,ind}}$

$$\mathbf{B}_{\text{obs,ind}} = \mathbf{B}_{\text{obs}} - \mathbf{B}_{\text{bg}} - \mathbf{B}_{\text{plasma}}. \quad (2)$$

Using the ocean properties as model parameters, we perform an inversion to determine which combinations of depth d , thickness h , and conductivity σ appropriately reproduce the measurements. Therefore, we minimize the difference of the modeled field $\mathbf{B}_{\text{model}}(d, h, \sigma)$ and the observed field $\mathbf{B}_{\text{obs}}$ including the uncertainties of the individual contributions. This is done by performing a chi-squared analysis in which the difference between $\mathbf{B}_{\text{model}}$ and $\mathbf{B}_{\text{obs}}$ is weighted against calculated uncertainties

$$\chi^2(d, h, \sigma) = \frac{1}{2N - m} \sum_{i=1}^N \frac{\|\mathbf{B}_{\text{model}}(d, h, \sigma, \mathbf{r}_i) - \mathbf{B}_{\text{obs}}(\mathbf{r}_i)\|^2}{\sigma_{\text{plasma}}^2 + \sigma_{\text{bg}}^2 + \sigma_{\text{ind}}^2} \quad (3)$$

along the spacecraft's trajectory $\mathbf{r}$ with number of measurements N and number of model parameters $m = 3$. With a resolution on the order of 10^{-2} nT (Kivelson et al., 1992), the uncertainties of the magnetic field measurements are negligible. Thus, it is the assumptions in the model descriptions of the individual contributions that control the overall uncertainty used to calculate χ^2 . The criterion of $\chi^2 \leq 1$ quantifies models that are in agreement with the measurements within the one-sigma uncertainties (e.g., Bevington & Robinson, 2003). This criterion subsequently also characterizes the uncertainty and ambiguity of the ocean properties in the form of a range, for example, $d \in [d_{\text{lower}}, d_{\text{upper}}]$, in which these properties can lie.

2.2. Inducing and Induced Magnetic Field Model

The induced field is the electromagnetic response to the inducing field. As such, any uncertainty in the model of the inducing field directly propagates into the uncertainty of the induced field. In this section, we present our inducing field model and quantify its underlying uncertainty. We also investigate the uncertainty propagation into the induced field.

2.2.1. Inducing Field Model

We first define the coordinate system used in this study. We employ the right-handed Europa IAU body-fixed reference frame, where the prime meridian, that is, x points approximately toward Jupiter, z is aligned with Europa's rotational axis, and y completes the right-handed system (Archinal et al., 2018). Previous modeling of magnetic field data was mostly done in EPhiO coordinates (e.g., Schilling et al., 2004, 2007; Zimmer et al., 2000), where z is parallel to Jupiter's rotational axis and y points toward Jupiter in a plane perpendicular to z . This coordinate system, however, is not strictly body-fixed due to the eccentricity and inclination of Europa's orbit. To allow for easier comparability to existing studies on the Galileo flybys, we rotate the xy -plane of the IAU coordinates to approximately align with the EPhiO coordinate system, $x_{\text{IAU}} \rightarrow y_{\text{EPhiO}}$ and $-y_{\text{IAU}} \rightarrow x_{\text{EPhiO}}$, similar to the approach used for magnetic sounding of Enceladus in Saur et al. (2024). After rotation, the angle between the prime meridians of the EPhiO and the rotated IAU coordinate system is approximately 2° for the E14 flyby.

As this work focuses on showcasing the inversion technique and the underlying uncertainties, we make certain assumptions about the inducing field, noting that this method will still be applicable in general cases as well. For one, we consider only the synodic rotation period as an inducing signal. Additionally, we neglect the inducing signal in the B_z -component. Both of these assumptions will be further discussed in Section 4.

Considering only the inducing frequency ω corresponding to the synodic rotation period $T = 11.23$ hr, we assume that the inducing field is primarily confined to lie within the orbital plane of Europa (Kivelson et al., 1999). Furthermore, we assume that the inducing field is homogeneous in Europa's vicinity (Khurana et al., 1998). Thus, the temporal variability of the inducing field, also sometimes referred to as exciting or primary field, can be described using external Gauss coefficients q_1^1 and s_1^1

$$\begin{aligned} B_x^e(t) &= -q_1^1(t) = -\Re\{q_0 e^{i(\omega t - \phi_0 - \phi_x)}\} \\ B_y^e(t) &= -s_1^1(t) = -\Re\{s_0 e^{i(\omega t - \phi_0 - \phi_y)}\}. \end{aligned} \quad (4)$$

Table 1
Inducing Amplitude at the Synodic Rotation Period

	Seufert et al. (2011)	Vance et al. (2021)
$B_{x,0}^e$ (nT)	66.3	75.55
$B_{y,0}^e$ (nT)	216.6	209.78

Note. Values between the two references vary as different models for the internal and external contributions to Jupiter's magnetic field have been used.

with the inducing amplitudes $q_0 = -B_{x,0}^e$ and $s_0 = -B_{y,0}^e$, phase of the inducing field $\phi_0 = 200^\circ$ (Schilling et al., 2007), and additional phases of the individual components $\phi_x = 90^\circ, \phi_y = 0^\circ$.

This study focuses on the measurements recorded during the E14 flyby. As such, we fit Equation 4 to the magnetospheric model by Khurana (1997) and choose values for $B_{x,0}^e$ and $B_{y,0}^e$ that best reproduce the values at System III longitude at which the E14 flyby occurred ($\lambda_{III} = 184.3^\circ$). For that, we took the model values at $\lambda_{III} = 184.3^\circ$ (see Zimmer et al., 2000, Table I) and

calculated the required amplitudes using Equation 4. From this approach, it follows $B_{x,0}^e = 37\text{nT}$ and $B_{y,0}^e = 222\text{nT}$.

2.2.2. Uncertainty of the Inducing Field

The values for the inducing field amplitudes $B_{x,0}$ and $B_{y,0}$ are estimated using a magnetospheric model which includes both Jupiter's intrinsic field, as well as contributions from magnetospheric currents, rather than exclusively the dipole term of Jupiter's intrinsic field. The strength of the inducing amplitude at a given period can be determined by performing a Fourier analysis of the modeled magnetic field over a long time series as was done by Seufert et al. (2011) and Vance et al. (2021). Their respective values for the inducing amplitude at the synodic rotation period are given in Table 1. As a simple first order estimate of the uncertainty of the inducing amplitude at the synodic rotation period ($\sigma_{B_{x,0}^e}, \sigma_{B_{y,0}^e}$), we use the difference between the values obtained by Seufert et al. (2011) and Vance et al. (2021), which yields $\sigma_{B_{x,0}^e} = 9.3\text{ nT}$ and $\sigma_{B_{y,0}^e} = 6.3\text{ nT}$.

2.2.3. Induced Field Description

The internal Gauss coefficients (g_1^1, h_1^1) of the induced field are related to the external Gauss coefficients via

$$\begin{aligned} g_1^1 &= Qq_1^1 \\ h_1^1 &= Qs_1^1, \end{aligned} \quad (5)$$

with the Q -response $Q = Ae^{i\phi^{\text{ph}}}$. For a conductive shell with outer radius r_0 and inner radius r_1 , the Q -response can be obtained by considering the ratio between the complex coefficients of the induced and inducing field (Zimmer et al. (2000) for degree $l = 1$, Saur et al. (2010) for arbitrary l)

$$Q_l = -\frac{l}{l+1} \frac{\xi J_{l+3/2}(r_0 k) - J_{-l-3/2}(r_0 k)}{\xi J_{l-1/2}(r_0 k) - J_{-l+1/2}(r_0 k)}, \quad (6)$$

with

$$\xi = \frac{r_1 k J_{-l-3/2}(r_1 k)}{(2l+1)J_{l+1/2}(r_1 k) - J_{l-1/2}(r_1 k)}, \quad (7)$$

where k is the complex wave number with $k^2 = i\mu_0\omega\sigma$ and $J_\nu(z)$ are the Bessel functions of first kind and order ν with complex argument z . This solution assumes that both the icy crust and mantle have a conductivity of $\sigma = 0$. We note that the usage of the wave number $k^2 = -i\mu_0\omega\sigma$ in Parkinson (1983) results in the modified Bessel differential equation, for which the solutions are the modified Bessel functions $I_\nu(z)$. Parkinson (1983), however, used the standard Bessel functions, resulting in positive values for the phase shift. From Equation 6, the induction amplitude and phase shift can be calculated as $A = (l+1)/l \text{abs}(Q)(r_0/R_E)^3$ and $\phi^{\text{ph}} = \arg(Q)$, respectively. The induction amplitude ranges from 0 to $(r_0/R_E)^3$ on the surface of Europa. With our definition of the wave number k , the phase shift is negative, ranging from $-\pi/2$ to 0. For a conductor extending to the surface of the satellite with radius R_E and $\sigma \rightarrow \infty$, $A = 1$, and $\phi^{\text{ph}} = 0$.

In this work, we assume that the conductivity of Europa's space environment is zero. In this case, the induced field is transported via the electromagnetic mode and additional variations due to the propagation with MHD modes are neglected (Strack & Saur, 2024). Thus, the induced field can be described by a potential Φ of the form

$$\Phi(r, \theta, \phi) = R_E \left(\frac{R_E}{r} \right)^2 \sin \theta (g_1^1 \cos \phi + h_1^1 \sin \phi), \quad (8)$$

with Europa's mean radius $R_E = 1561$ km (Nimmo et al., 2007), colatitude θ , and longitude ϕ . The individual components are calculated via $\mathbf{B}_{\text{ind}} = -\nabla \Phi$ and read

$$\begin{aligned} B_{\text{ind},r}(r, \theta, \phi) &= 2 \left(\frac{R_E}{r} \right)^3 \sin \theta (g_1^1 \cos \phi + h_1^1 \sin \phi) \\ B_{\text{ind},\theta}(r, \theta, \phi) &= - \left(\frac{R_E}{r} \right)^3 \cos \theta (g_1^1 \cos \phi + h_1^1 \sin \phi) \\ B_{\text{ind},\phi}(r, \theta, \phi) &= \left(\frac{R_E}{r} \right)^3 (g_1^1 \sin \phi - h_1^1 \cos \phi) \end{aligned} \quad (9)$$

2.2.4. Uncertainty of the Induced Field

Assuming Gaussian error propagation, the uncertainty of the external Gauss coefficients propagates into the internal Gauss coefficients via Equation 5 as

$$\begin{aligned} \sigma_{g_1^1} &= Q \sigma_{q_1^1} \\ \sigma_{h_1^1} &= Q \sigma_{s_1^1}. \end{aligned} \quad (10)$$

Their uncertainty propagates further into the induced magnetic field. The uncertainty for the j th component of the induced field reads

$$\sigma_{\text{ind},j}(r, \theta, \phi) = \sqrt{\left(\frac{\partial B_{\text{ind},j}(r, \theta, \phi)}{\partial g_1^1} \right)^2 (\sigma_{g_1^1})^2 + \left(\frac{\partial B_{\text{ind},j}(r, \theta, \phi)}{\partial h_1^1} \right)^2 (\sigma_{h_1^1})^2}. \quad (11)$$

As a conservative measure, we characterize the uncertainty of the induced field due to the inducing field as $\max(\sigma_{\text{ind}})$ along the entire trajectory. This also ensures that parts of the measurements, where the uncertainty of the induced field would approach zero because the local induced magnetic field is zero, are not weighted more than measurements taken around closest approach.

For System III longitude of the E14 flyby, the internal Gauss coefficients g_1^1 and h_1^1 and their associated uncertainties are given in conductivity-thickness space at the top of the ocean, that is, distance effects are neglected (Figures 2c–2f). As the uncertainties $\sigma_{g_1^1}$ and $\sigma_{h_1^1}$ depend solely on the inducing field amplitude, they follow the same trends as their respective internal coefficients. In Figures 2a and 2b, we also show the induction amplitude A and phase shift ϕ^{ph} to highlight their aforementioned non-uniqueness.

2.3. Jovian Magnetospheric Background Field

To compare the modeled induced magnetic field with the data, the Jovian background field must be removed from the measurements. We approximate Jupiter's contribution to the measured magnetic field by fitting a second degree polynomial to the portions of the flyby in which the perturbations due to induction and plasma interaction are negligible and can solely be described by Jupiter's magnetospheric background field $\mathbf{B}_{\text{bg}}$ (Figure 3). The plasma magnetic field perturbations due to the interaction with Europa's atmosphere are calculated with an MHD model presented in Section 2.4. The choice of parameters for the MHD model output shown in Figure 3 are based on default values also presented in Section 2.4.

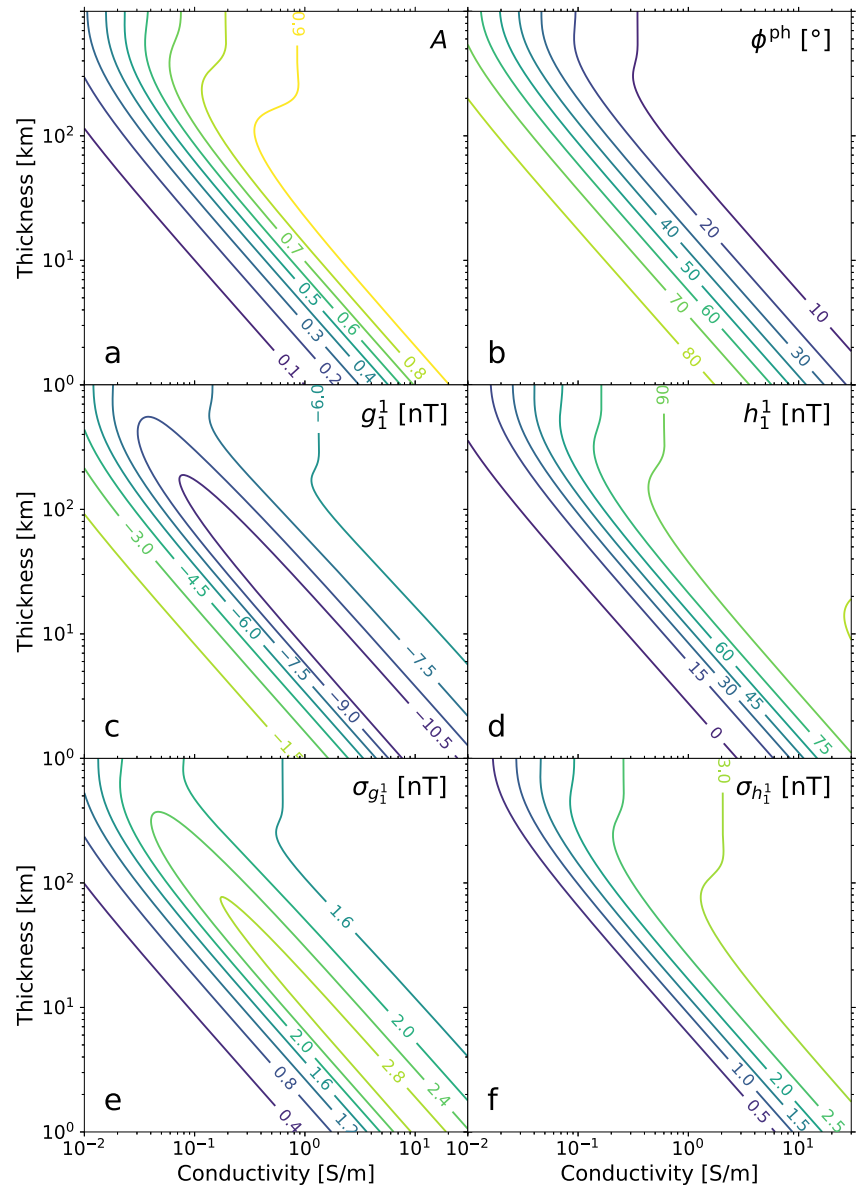


Figure 2. (a) Induction amplitude A and (b) phase shift $|\phi^{\text{ph}}|$ for degree $l = 1$ in conductivity-thickness space calculated at the top of the ocean. The internal Gauss coefficients g_1^1 (c) and h_1^1 (d), as well as their uncertainties σ_g (e) and σ_h (f) are given in nT. The Gauss coefficients and their uncertainties were calculated for System III longitude $\lambda_{\text{III}} = 184.3^\circ$.

As a quantitative threshold for the start and end of the window excluded from the polynomial fit, we choose a benchmark value of 1.5 nT in each component. Values greater than 1.5 nT would result in larger plasma magnetic fields within the fitting window and generate a fit that is less representative of the background field. A value lower than 1.5 nT would extend the overall time span of considered measurements due to the increased length of the excluded window around closest approach. This would decrease the quality of our fit, as a polynomial fit cannot reproduce the periodicity of the Jovian background field.

To assess the length of the intervals used to calculate the background fit, we consider the root-mean-square deviation (rms) between the data and background fits calculated with varying interval lengths from 10 to 60 min (Figure 4)

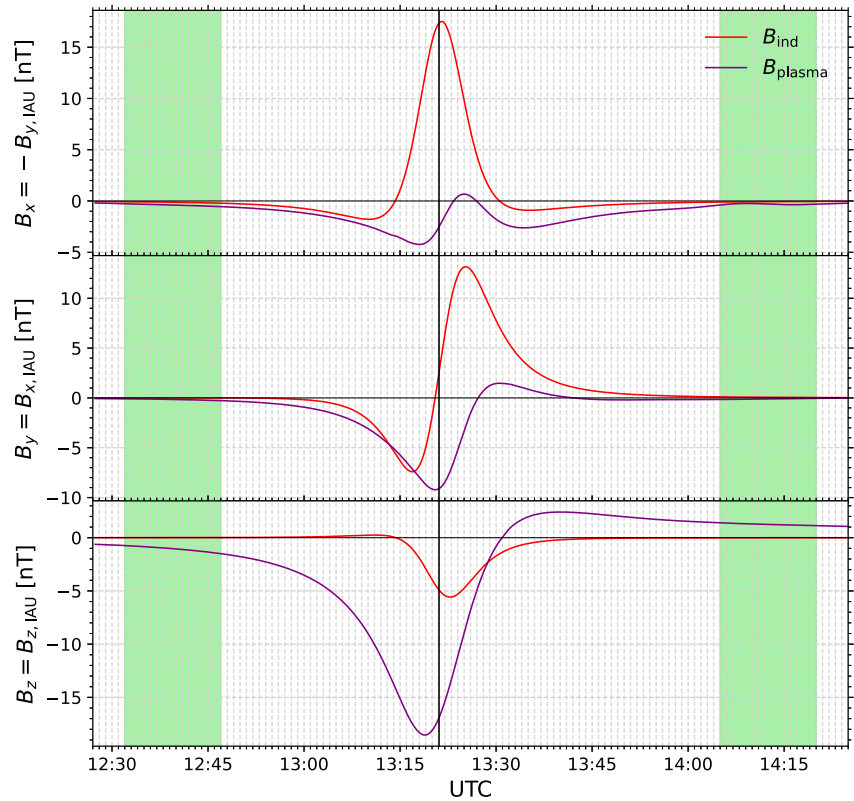


Figure 3. Modeled magnetic field due to plasma interaction with Europa's atmosphere (purple) and induction response (red) for the E14 flyby. Moving outward from closest approach (black vertical line), the green regions begin when the modeled plasma and induced magnetic fields are smaller than 1.5 nT and cover a range of 15 min.

$$\text{rms}_{\text{bg}}(\Delta t) = \sqrt{\frac{1}{3N} \sum_{i=1}^N (\mathbf{B}_{\text{obs}}(\mathbf{r}_i) - \mathbf{B}_{\text{bg}}(\mathbf{r}_i, \Delta t))^2}, \quad (12)$$

where N is the number of measurements, $\mathbf{r}_i$ is the spacecraft position at the time t_i of the i th measurement, and $\mathbf{B}_{\text{bg}}(\mathbf{r}_i, \Delta t)$ is the background fit calculated with interval length Δt . Here, we also show the resulting rms for a third degree polynomial used to fit the background. We find that, for short window lengths, the difference between the two is minor, motivating the choice of a second degree polynomial as the extra degree could introduce additional 'kinks' in the resulting fit.

Although the rms increases with increased window length for the E14 flyby, it should be noted that very short fitting windows produce background fits that are not representative of the variabilities of the Jovian background field on scales of the flyby as the fitting window would be significantly smaller than the interval that the resulting fit is extrapolated in. Furthermore, residual plasma interaction in the fitting window might not be averaged out if the chosen interval length is smaller, as $B_{\text{plasma}} \leq 1.5$ nT at the start of our fitting window. This could result in a fit that is not solely controlled by the Jovian background field. For those reasons, we argue for a window length of 15 min as a reasonable choice, despite the rms not being at minimum.

The resulting background fit is shown in Figure 5, with $\text{rms}_{\text{bg}} = 0.67$ nT across all three components. The rms characterizes the uncertainty of the

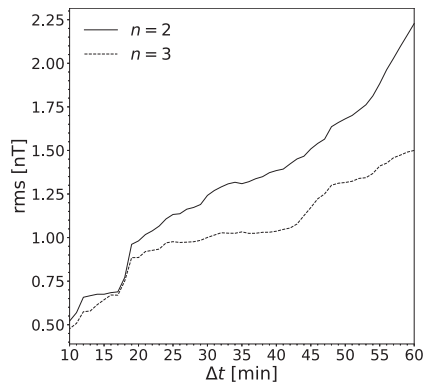


Figure 4. Root-mean-square deviation (rms) of background fits calculated with a second degree (solid line) and third degree (dashed line) polynomial for the E14 flyby with varying window length Δt before and after closest approach, respectively. The rms has been calculated across all three components of the magnetic field. For the E14 flyby, the excluded window begins at 12:47:00 and ends at 14:05:00.

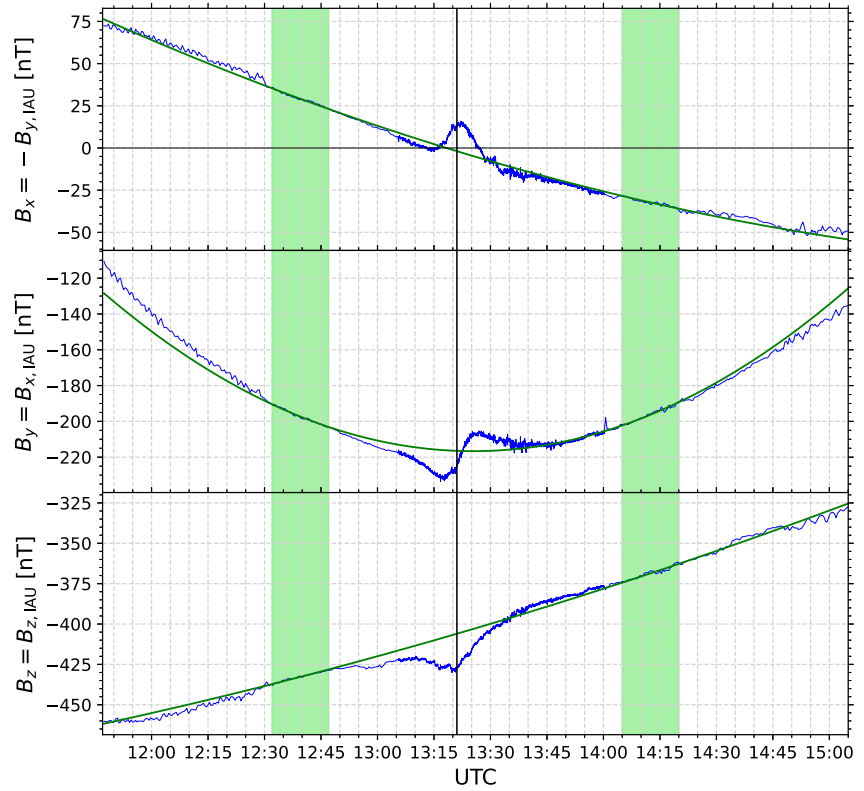


Figure 5. Polynomial fit (green) to the components of the measured magnetic field (blue). The light green area indicates the respective 15-min windows used to calculate the fit.

background model, $\sigma_{bg} = \text{rms}_{bg}$. In Figure 5, we also recognize a magnetospheric “quiet” interval between 12:30 to 12:45, coinciding with the 15-min window before closest approach. Around 12:30, a jump occurs in the magnetic field, particularly noticeable in the B_x and B_y -components, and the magnetospheric fluctuations increase compared to the aforementioned quiet interval. This point will be discussed further in Section 4.3.

2.4. Plasma Interaction Model

To model the plasma interaction at Europa, we solve the three-dimensional single-fluid magnetohydrodynamic (MHD) equations for the conditions during the E14 flyby using the PLUTO code (Mignone et al., 2007). This code has been used by Duling et al. (2022) to model the plasma interaction of Ganymede.

2.4.1. Model Setup

The MHD equations govern the plasma mass density ρ , plasma bulk velocity $\mathbf{v}$, magnetic field $\mathbf{B}$, and the total energy E_t . For each variable, an evolution equation is stated with

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = P m_n - L m_L, \quad (13)$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[\rho \mathbf{v} \mathbf{v} - \frac{1}{\mu_0} \mathbf{B} \mathbf{B} + \mathbf{I} \left(p + \frac{1}{2} \frac{B^2}{\mu_0} \right) \right] = -(L m_L + \nu_n \rho) \mathbf{v}, \quad (14)$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0, \quad (15)$$

$$\frac{\partial E_t}{\partial t} + \nabla \cdot \left[\left(E_t + p + \frac{1}{2} \frac{B^2}{\mu_0} \right) \mathbf{v} - \frac{1}{\mu_0} \mathbf{B} (\mathbf{v} \cdot \mathbf{B}) \right] = -\frac{1}{2} (L m_L + \nu_n \rho) v^2 - \frac{3}{2} (L m_L + \nu_n \rho) \frac{p}{\rho}$$

$$+\frac{3}{2}(Pm_n + \nu_n \rho) \frac{k_B T_n}{m_n}. \quad (16)$$

with plasma production and loss rates P and L , respectively, ion-neutral collision frequency ν_n , thermal pressure p , average ion mass m_L , and average neutral mass m_n . The initial values of the magnetic field and bulk velocity are $\mathbf{B}_0 = (5, -213, -409)$ nT and $v_0 = 100$ km/s in corotational direction. Our model includes electron impact ionization as the dominant ionization process in Europa's atmosphere (Saur et al., 1998), and we assume an ionization frequency of $f_{\text{imp}} = 10^{-6} \text{ s}^{-1}$, in the lower limit of the range provided by Smyth and Marconi (2006). This results in a production rate P of

$$P = f_{\text{imp}} n_n, \quad (17)$$

where n_n is the neutral O_2 number density. Therefore, in the model we take into account the production of singly charged O_2^+ and furthermore assume $m_n = m_L = 32$ u. We consider a radially symmetric atmosphere and describe its number density profile $n_{\text{O}_2}(z)$ as

$$n_{\text{O}_2}(z) = n_{0,\text{O}_2} e^{-z/H}, \quad (18)$$

with surface number density n_{0,O_2} , height above surface z , and scale height $H = 150$ km. We consider plasma loss due to dissociative recombination between ions and electrons, where we employ a recombination rate coefficient of

$$\alpha_{\text{rec},\text{O}_2^+} = 2 \cdot 10^{-7} \left(\frac{300}{T_e} \right)^{0.7} \text{ cm}^3/\text{s}, \quad (19)$$

which has also been used in, for example, Saur et al. (1998) and Blöcker et al. (2016). For the electron temperature T_e , we use the ionospheric electron temperature of 0.5 eV. Analogous to Duling et al. (2022), we employ the following expression for the loss rate L

$$L = \begin{cases} \alpha \rho (\rho - \rho_0) m_L^{-2} & \text{for } \rho > \rho_0 \\ 0 & \text{for } \rho < \rho_0 \end{cases}. \quad (20)$$

We model collisions between ions and neutrals using the collision frequency $\nu_{\text{O}_2} = \sigma_{\text{O}_2} v_0 n_{\text{O}_2}$, where $\sigma_{\text{O}_2} = 2 \cdot 10^{-15} \text{ cm}^2$ is the O_2 cross section, similar to Saur et al. (1998). Lastly, the MHD model includes electromagnetic induction in Europa's subsurface ocean through boundary conditions given by Duling et al. (2014). These boundary conditions state that toroidal contributions to the magnetic field need to vanish at the insulating boundary and furthermore use a first order differential equation for the poloidal contributions.

2.4.2. Column Density and Uncertainty of the Plasma Interaction Model

As Figure 3 indicates, the perturbations in the B_z -component are dominated by plasma interaction compared to induction in the icy moon's interior. This is because the inducing field is primarily confined to the xy -plane and the E14 flyby occurred near the equatorial plane. As such, our fit to the measured B_z -component is primarily controlled by Europa's plasma interaction and we use the best fit for B_z as the best prediction for the B_x and B_y -components of the plasma interaction. Similar assumptions have also been made in the induction studies by Zimmer et al. (2000) for Europa and Khurana et al. (2011) for Io.

For given upstream parameters, the strongest influence on the strength of the plasma interaction at Europa stems from Europa's atmosphere. For simplicity of the parameter space, we assume a radially symmetric model and describe the atmospheric content through the column density $N_{\text{O}_2} = n_{0,\text{O}_2} H$. We use the B_z -component to assess which column density best describes the measurements of the E14 flyby. For that, we consider the variance between the “observed plasma perturbation” $\mathbf{B}_{\text{obs,plasma}} = \mathbf{B}_{\text{obs}} - \mathbf{B}_{\text{bg}} - \mathbf{B}_{\text{ind}}$ and the model

$$\sigma_{\text{plasma}}^2 = \frac{1}{N} \sum_{i=1}^N (B_{\text{obs,plasma},z}(\mathbf{r}_i) - B_{\text{plasma},z}(\mathbf{r}_i))^2, \quad (21)$$

where $\mathbf{B}_{\text{plasma},z}$ is the modeled plasma interaction field. The plasma interaction has been modeled for fixed column densities ranging from $N_{\text{O}_2} = 1 - 8 \cdot 10^{14} \text{ cm}^{-2}$ in integer steps. This approach yields a minimum variance at an O_2 column density of $N_{\text{O}_2} = 4 \cdot 10^{14} \text{ cm}^{-2}$. The variance σ_{plasma}^2 is also used as a proxy to estimate the uncertainty of the MHD model. We confine the calculation of the MHD model uncertainty to measurements where Galileo was within four Europa radii relative to the satellite's center. The uncertainty σ_{plasma} is assumed to be equal in all three components. Note that this uncertainty measure requires us to specify the ocean properties in order to subtract the induced field in the B_z -component. As such, the estimate for the plasma uncertainty is specific to the ocean model.

2.5. Chi-Squared Analysis

After evaluating the individual contributions and their uncertainties, we perform a chi-squared analysis to find all induction models that appropriately reproduce the observed induction response described by Equation 2. We construct a 3D parameter space for the ocean's depth d , thickness h , and conductivity σ . For each combination of (d, h, σ) , we calculate the ocean's induction amplitude, phase shift, and the resulting induced magnetic field. We evaluate the corresponding chi-squared value using

$$\chi^2(d, h, \sigma) = \frac{1}{2N - m} \sum_{i=1}^N \left(\frac{(B_{\text{obs,ind},x}(\mathbf{r}_i) - B_{\text{ind},x}(d, h, \sigma, \mathbf{r}_i))^2}{\sigma_{\text{bg},x}^2 + \sigma_{\text{plasma}}^2 + \sigma_{\text{ind},x}^2(\mathbf{r}_i)} + \frac{(B_{\text{obs,ind},y}(\mathbf{r}_i) - B_{\text{ind},y}(d, h, \sigma, \mathbf{r}_i))^2}{\sigma_{\text{bg},y}^2 + \sigma_{\text{plasma}}^2 + \sigma_{\text{ind},y}^2(\mathbf{r}_i)} \right), \quad (22)$$

where N is the number of measurements and $m = 3$ the number of model parameters. We only use the B_x and B_y -components to evaluate χ^2 , as we used the B_z component to constrain the plasma interaction, and we only include measurements where Galileo was within four Europa radii relative to Europa's center, as suggested by Kivelson et al. (2023). Any combination of values for (d, h, σ) that results in $\chi^2 \leq 1$ is labeled a good fit to the data, given the considered uncertainties (Bevington & Robinson, 2003). Assuming Gaussian distributed errors, a $\chi^2 \leq 1$ will mean that our fit, on average, deviates less than one standard deviation from the measurements. The resulting parameter space for (d, h, σ) that fulfills $\chi^2 \leq 1$ gives us constraints on the properties of Europa's subsurface ocean.

2.6. Model Parameter Space (d, h, σ)

We calculate χ^2 as a function of the ocean properties, that is, its depth d , thickness h , and conductivity σ . We do so in a prescribed parameter space, spanning a 3D grid with $d \in [1, 150] \text{ km}$, $h \in [1, 150] \text{ km}$, and $\sigma \in [0.01, 10] \text{ S/m}$. We employ 50 log-spaced grid points along the thickness and conductivity axes and 100 along the depth axis. The parameter space is aimed to explore the range of existing estimates of the total thickness of the H_2O shell (Anderson et al., 1998), as well as the ocean's electrical conductivity (Pan et al., 2020, 2021; Schilling et al., 2007; Vance et al., 2021; Zimmer et al., 2000). Our prescribed depth covers a broad range of estimates (e.g., Tobie et al., 2003; Turtle & Pierazzo, 2001; Wakita et al., 2024). We note that conductivities above 10 S/m are possible if the salt content of Europa's ocean is near the solubility limit (Hand & Chyba, 2007), the required salinity however lies above 100 g/kg.

3. Results

In this section, we present the results from our chi-squared analysis. First, we provide a short overview of the E14 flyby, followed by a review of the uncertainty estimates for that flyby. Taking into account these uncertainties, we show the observed induction response and all induced magnetic fields that lie within $\chi \leq 1$. Afterward, we investigate the parameter space of depth d , thickness h , and conductivity σ and derive their limits. We take additional geophysical estimates of the ocean's depth into account to further constrain the ocean properties. We

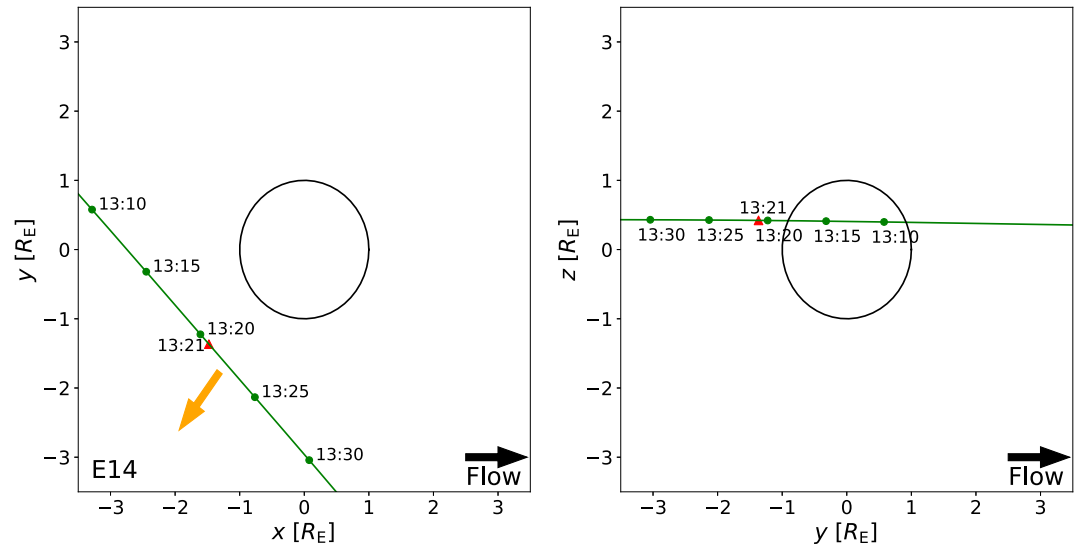


Figure 6. Trajectory of the Galileo spacecraft during the E14 encounter in the xy (left) and yz -plane (right), respectively. The red triangle marks the time and location of closest approach. The yellow arrow points toward the sun.

also apply our method to the E04 flyby. Finally, we test the robustness of our method by slightly varying the model setup and compare the resulting constraints against the reference model.

3.1. The E14 Flyby

During the E14 flyby, Galileo approached Europa upstream, crossing near its equatorial plane with a closest approach (C/A) altitude of 1,684.1 km (Figure 6). Europa was situated above the plasma sheet during the encounter with a magnetic latitude of $\Psi_m = 9.1^\circ$ (Kurth et al., 2001).

To evaluate if a flyby is suitable for the quantitative study of the ocean properties, we first compare the induction response of a perfectly conducting ocean with $A = 1$ and $\phi^{ph} = 0$ to the measurements. For the E14 flyby, this is shown in Figure 7. The B_x -component is well reproduced by only taking the ocean's induced field into account. While we expect the plasma interaction to contribute noticeably to the B_y -component, the induced field is the dominating contribution in both the B_x and B_y -components (see Figure 3). If the plasma interaction were to be stronger, the resulting magnetic field would obscure the induction response and thus hamper our ability to quantitatively constrain Europa's subsurface ocean, as our model would be primarily controlled by Europa's plasma interaction. Thus, the E14 flyby is a good candidate for our quantitative study.

The induction response of a perfectly conducting ocean has also been compared to the measurements of the flybys E04, E12, E19, and E26 (Appendix A). For the cases of the E12 and E26 flybys, the induction response is obscured by strong plasma magnetic fields of up to 100 nT. During the E19 flyby, the magnetometer stopped recording shortly after closest approach. This complicates the fitting of the Jovian background field and thus the overall inversion process. The E04 flyby was a wake crossing and had plasma magnetic fields on a similar strength to the induced field. Of the five flybys discussed, the E04 was deemed the second most suitable for the exploration of Europa's ocean.

3.1.1. Uncertainties During the E14 Flyby

In Section 2, we provided the equations to estimate the uncertainties for the inducing magnetic field, Jupiter's background field, and the plasma interaction at Europa (see Equations 11, 12, and 21, respectively). The uncertainty of the background field is calculated for each component individually and is constant across the entire flyby, with $\sigma_{bg} = (0.61, 0.62)$ nT for the B_x and B_y -components. In the case of a perfectly conducting ocean, $A = 1$ and $\phi^{ph} = 0$, the uncertainty of the inducing field results in an induced field uncertainty of $\sigma_{ind} = (0.48, 0.42)$ nT. With $\sigma_{plasma} = 1.60$ nT, the plasma uncertainty is the dominating contribution to the overall uncertainty, which can be described with $\sigma_{tot} = \sqrt{\sigma_{bg}^2 + \sigma_{ind}^2 + \sigma_{plasma}^2} = (1.78, 1.77)$ nT. The plasma

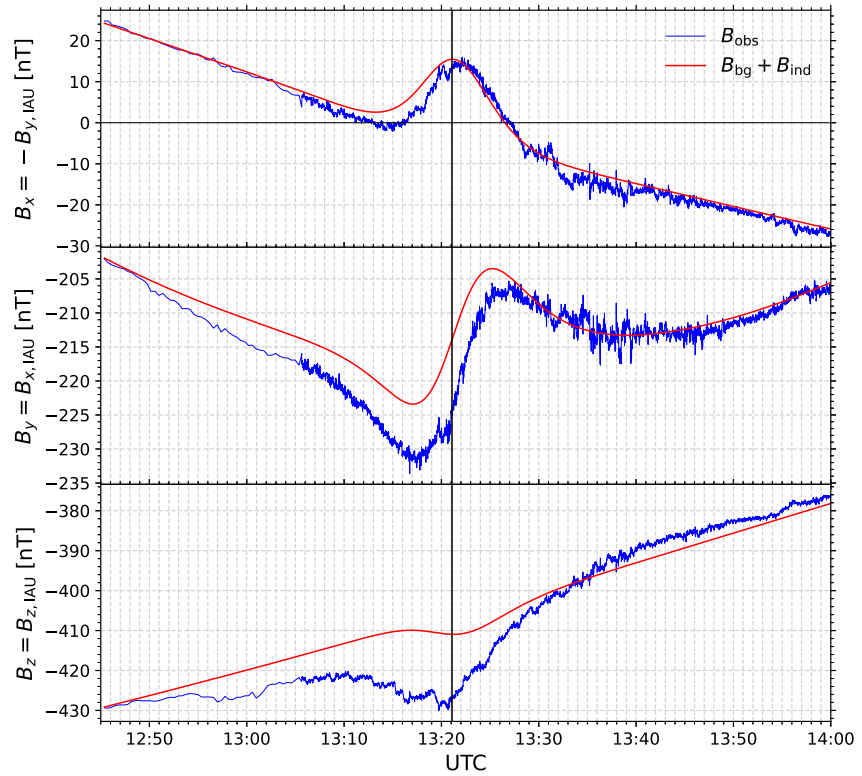


Figure 7. Magnetic field measurements of the E14 flyby (blue) and the induction response of a perfectly conducting ocean with $A = 1$ and $\phi^{\text{ph}} = 0$ (red) in rotated IAU (=approximately EPhiO) coordinates defined in Section 2.2.1. The vertical black line marks the closest approach.

uncertainty is assumed to be the same in both components as we assume that the uncertainty in the B_z -component translates to B_x and B_y . While the uncertainty of the background field is calculated once, the uncertainties of the induced field and plasma model change with the ocean model. As such, σ_{tot} is not constant but also varies with the specific ocean model. The plasma uncertainty remains the primary contribution to the total uncertainty throughout the prescribed parameter space. Having obtained our uncertainty estimates, we can now perform the chi-squared analysis to derive the ocean properties and their constraints.

3.1.2. Chi-Squared Analysis of the E14 Flyby

Figure 8 shows the “observed induction response” $\mathbf{B}_{\text{obs,ind}}$ as calculated with Equation 2. In addition, all induction models that lie within $\chi \leq 1$ are presented. We are able to reproduce the trend of the observed induction response in the B_x - and B_y -components, although underestimating the amplitude of the perturbation in the B_x -component around closest approach. This could be a result of the single-frequency approach used in this work. At System III longitude of the E14 flyby, the half-synodic period would produce an inducing signal of approximately 15 nT. At the altitude of the E14 flyby, this could result in an induced field around 1.5 nT, depending on the ocean's induction amplitude.

The best fit to the measurements is a highly conductive, shallow ocean ($d = 1$ km, $h = 26$ km, $\sigma = 10$ S/m), indicated as a red solid line in Figure 8. This fit, however, is on equal footing with any other fit with $\chi \leq 1$ in terms of agreement with the measurements due to the calculated uncertainties. The $\chi \leq 1$ criterion provides a direct method to obtain upper and lower limits for the ocean's depth, thickness, and conductivity, above or below which χ^2 would be greater than one, and thus not an appropriate fit. The limits are derived by considering the $\chi = 1$ isocontour.

In Figure 9, we show the χ -isocontours in conductivity-thickness space for three fixed values for the ocean's depth. With magnetic sounding (of the E14 flyby), we are unable to resolve a lower limit on the ocean's depth. Thus, we consider depth constraints from the literature, employing a lower limit of 20 km. This value

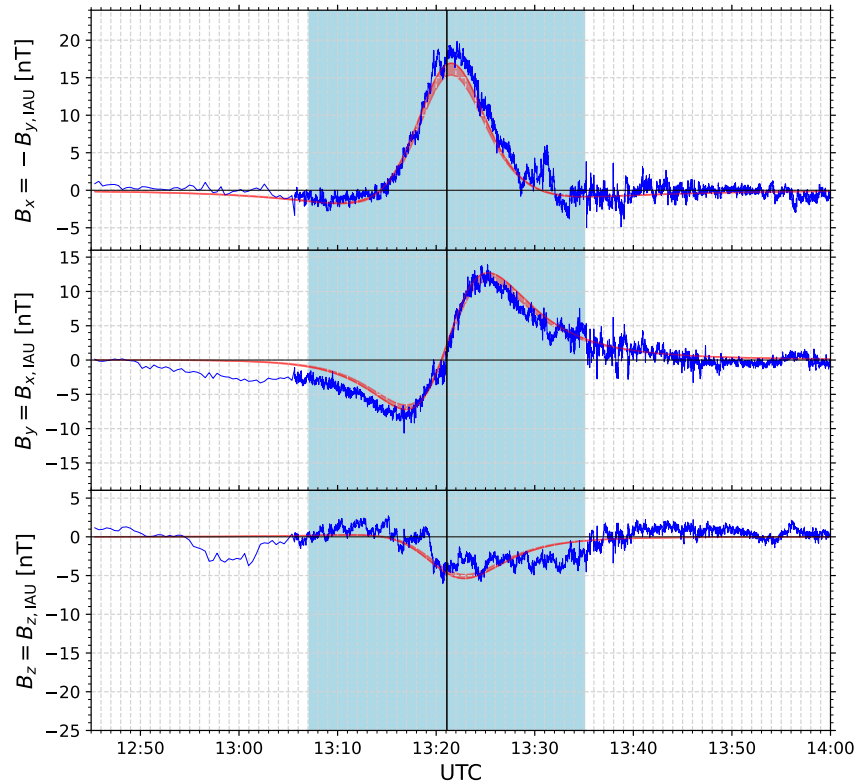


Figure 8. Observed induction response $\mathbf{B}_{\text{obs,ind}}$ (blue) for the E14 flyby in rotated IAU (=approximately EPhiO) coordinates. The light red band shows all induction models with $\chi \leq 1$. The red solid line is our best fit with $\chi^2 \approx 0.62$ at $d = 1$ km, $h = 24$ km, and $\sigma = 10$ S/m. The interval of the trajectory where Galileo was within 4 Europa radii relative to Europa's center is highlighted in light blue.

corresponds roughly to the icy crust thickness that has been estimated from both tidal heating (Tobie et al., 2003; Walker & Rhoden, 2022), as well as impact crater simulations (Schenk, 2002; Wakita et al., 2024). Additionally, we consider a value of 35 km, which corresponds to the estimated depth in a recent study using JUNO's microwave radiometer (Bolton et al., 2024; Voosen, 2024).

At $d = 20$ km, we find a minimum conductivity around 1.6 S/m and minimum thickness of $h > 6$ km. As the depth increases, the space of possible values for thickness and conductivity below the $\chi = 1$ isocontour decreases. Thus, at 35 km, we find lower limits for the thickness and conductivity of 8.6 km and 2.8 S/m,

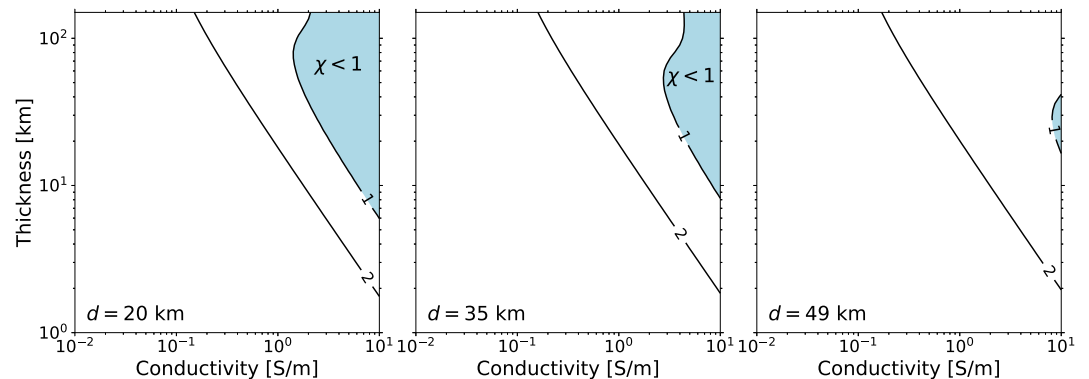


Figure 9. χ -isocontours in conductivity-thickness space for (left) $d = 20$ km, (middle) $d = 35$ km, and (right) $d = 63$ km. The blue shaded region marks the parameter space in agreement with the E14 flyby, that is, with $\chi < 1$.

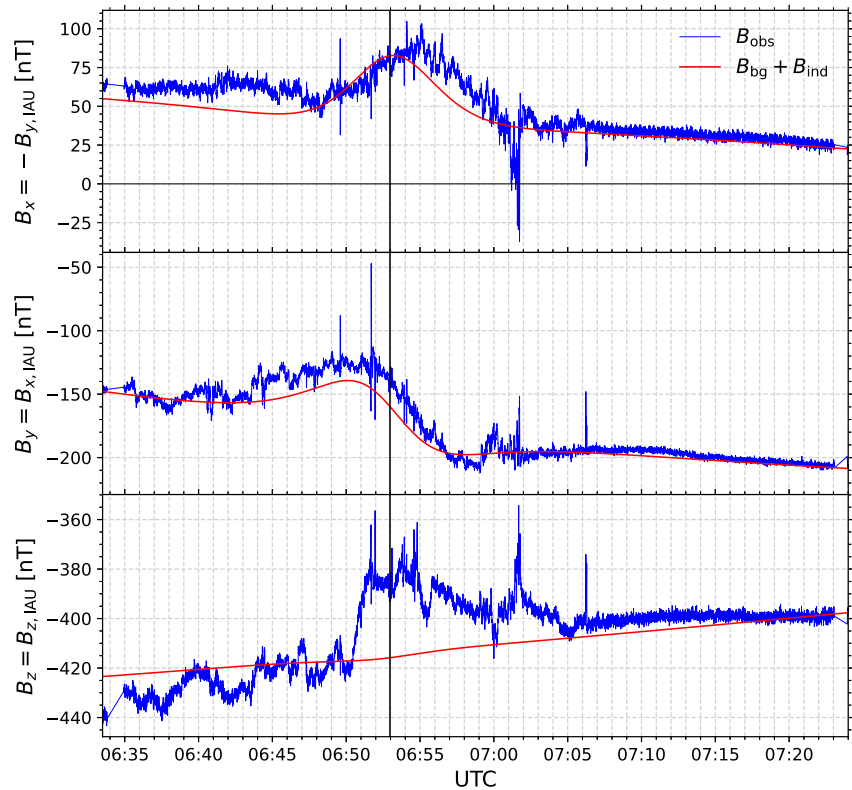


Figure 10. Magnetic field measurements of the E04 flyby (blue) and the induction response of a perfectly conducting ocean with $A = 1$ and $\phi^{\text{ph}} = 0$ (red) in rotated IAU (=approximately EPhiO) coordinates. The vertical black line marks the closest approach.

respectively. For both properties, magnetic sounding (of the E14 flyby) is unable to provide upper limits as the induction response goes into saturation.

The lowest depth that still lies within $\chi \leq 1$ is approximately 49 km. However, the required conductivity at that depth lies around 7 S/m. This conductivity would require a highly saline ocean above 100 g/kg, considering temperatures around 273 K (Pan et al., 2020, 2021; Vance et al., 2021). It is important to note that the limits for an ocean property are given for specified values for the other two properties, for example, a conductivity of 1.6 S/m is only a valid solution if $d = 20$ km and $h \approx 100$ km. This cross-correlation between the ocean properties complicates the quantification of their uncertainties.

3.2. The E04 Flyby

While this work focuses primarily on the magnetic field measurements of the E14 flyby, we also apply our chi-squared analysis to the E04 flyby at Europa. This equatorial flyby occurred at a C/A altitude of 696 km while Europa was outside the Jovian plasma sheet. A noticeable difference to the E14 flyby is that the E04 was a downstream flyby, crossing Europa's wake. Figure 10 shows the observed magnetic field, as well as the induction response of a perfectly conducting ocean with $A = 1$ and $\phi^{\text{ph}} = 0$. While this comparison indicates that the general trend of the perturbation is reproduced by the induced field, there are several additional structures in the measurements not accounted for.

We model the magnetic field due to the plasma interaction using a column density of $N_{\text{O}_2} = 10^{14} \text{ cm}^{-2}$ and derive a plasma uncertainty of $\sigma_{\text{plasma}} \approx 7.1 \text{ nT}$, approximately five times higher than our estimate for the E14 flyby. The column density for the E04 flyby is four times smaller than for the E14 flyby. A column density equal to that of the E14 flyby would significantly overestimate the perturbations in the B_z component. The different column densities between the two flybys motivates potential spatial variabilities of Europa's atmosphere. While Galileo traversed the night side of Europa during the E04 flyby, the E14 flyby occurred toward the sunlit hemisphere, where an

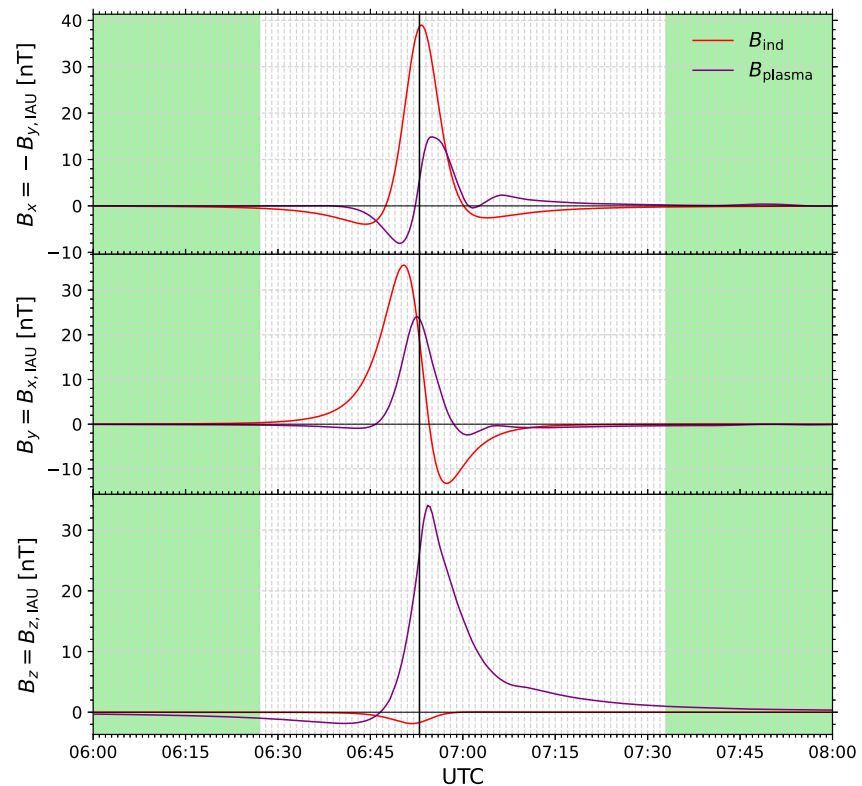


Figure 11. Modeled magnetic field due to plasma interaction with Europa's atmosphere (purple) and induction response (red) for the E04 flyby. Moving outward from closest approach (black vertical line), the green regions begin when the magnetic field signatures are smaller than 1.5 nT and cover a range of 30 min, respectively.

increased sputtering yield is expected to generate a denser atmosphere (Plainaki et al., 2013). Additional variations have been observed upstream and downstream of Europa (Hansen et al., 2005), further increasing the difference in expected column density between the two flybys.

Figure 11 compares the plasma magnetic field and the induced magnetic field, similar to Figure 3 for the E14 flyby. While the induced field is the primary source of magnetic field perturbation in the B_x and B_y -components, plasma magnetic fields are larger for the conditions of the E04 flyby compared to those of the E14 flyby. The induced field is stronger compared to the E14 flyby, due to the lower altitude.

To fit the background field, we used a polynomial fit of degree $n = 2$ and window length $\Delta t = 30$ min (Figure 12). This deviates from the 15 min used in the E14 flyby, as for the E04, the rms was minimum at 30 min. This can be explained by larger magnetospheric fluctuations between 06:15 and 06:30, resulting in an increased rms at smaller window lengths.

Comparing the observed induction response obtained for the E04 flyby (Figure 13) to that of the E14 flyby (Figure 8), larger residuals in the B_z component become apparent. These indicate that the plasma interaction model used here is less representative of the real environment than compared to the E14 flyby. In addition, small-scale fluctuations are stronger throughout the encounter compared to those of the E14 flyby. These high frequency perturbations can be seen throughout the measurements and are possibly a result of kinetic effects (see Blöcker et al., 2016). Another noteworthy feature is the continuous offset in the B_x component while approaching Europa, on the order of 10–20 nT. These strong deviations from our model result in a rms of approximately 10 nT for our best fit model obtained in the analysis of the E04 flyby. This value is 10 times larger than that of the E14 flyby, which was 1.44 nT. The chi-squared analysis yields $\chi > 1$ across the entire parameter space, with a minimum of 1.8.

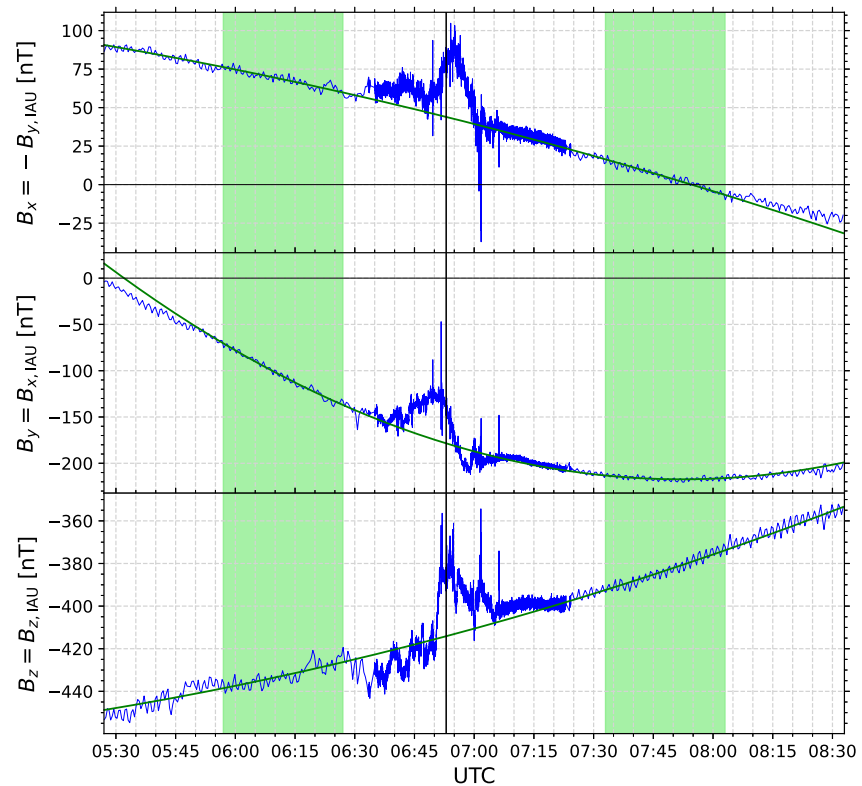


Figure 12. Polynomial fit (green) to the components of the measured magnetic field (blue). The light green area indicates the respective 30-min windows used to calculate the background fit. For the E04 flyby, the window that includes induction and plasma effects, that is, the window excluded from the background fit begins at 06:27:00 and ends at 07:33:00.

4. Discussion

Here, we discuss the quantitative constraints on Europa's interior derived with the chi-squared analysis of the E14 flyby. We compare the results of the E04 flyby against the E14 and comment on the potential of a joint inversion. Afterward, we investigate our method's robustness, highlighting the complexity of the inversion process and important aspects to consider in future work. Finally, we discuss the assumptions that were made in estimating the model uncertainties. We also mention additional sources of uncertainty that were not considered in this work.

4.1. Ocean Properties Derived With the E14 Flyby

The primary motivation of this work is to introduce an approach to quantitatively characterize and constrain the depth, thickness, and electrical conductivity of Europa's subsurface ocean. As most existing constraints originating from electromagnetic induction have been derived qualitatively from visual comparison, this study emphasizes the development of a method using a quantitative measure, in the form of a chi-squared analysis, where the squared deviation between the modeled induction response $\mathbf{B}_{\text{ind}}$ and the observed induction $\mathbf{B}_{\text{obs,ind}}$, described by Equation 2, is weighed against the sum of model uncertainties described by Equations 11, 12 and 21. We applied this method to the E14 flyby due to its ideal conditions for magnetic sounding, that is, a strong inducing field and quiet plasma environment. Here we found a minimum conductivity of approximately 1.6 S/m, assuming the icy crust is at least 20 km thick. This value is larger than the constraint obtained by Schilling et al. (2007), who estimated the minimum conductivity to be 0.5 S/m. Zimmer et al. (2000) suggested a minimum conductivity of 0.06 S/m. Compared to the value derived in this study, our method provides a tighter constraint on the conductivity. It is worth noting that the cited constraints were not derived quantitatively, but only qualitatively on the basis of visually comparing various ocean models to the measurements. Retrieval of the ocean's conductivity is tightly coupled to its salinity and can provide insights about the ocean's composition. By providing constraints on the ocean's conductivity, our method may benefit the assessment of Europa's ocean composition, a key goal of the Europa Clipper mission (for more information see Vance et al., 2023). The large amount of data collected by the

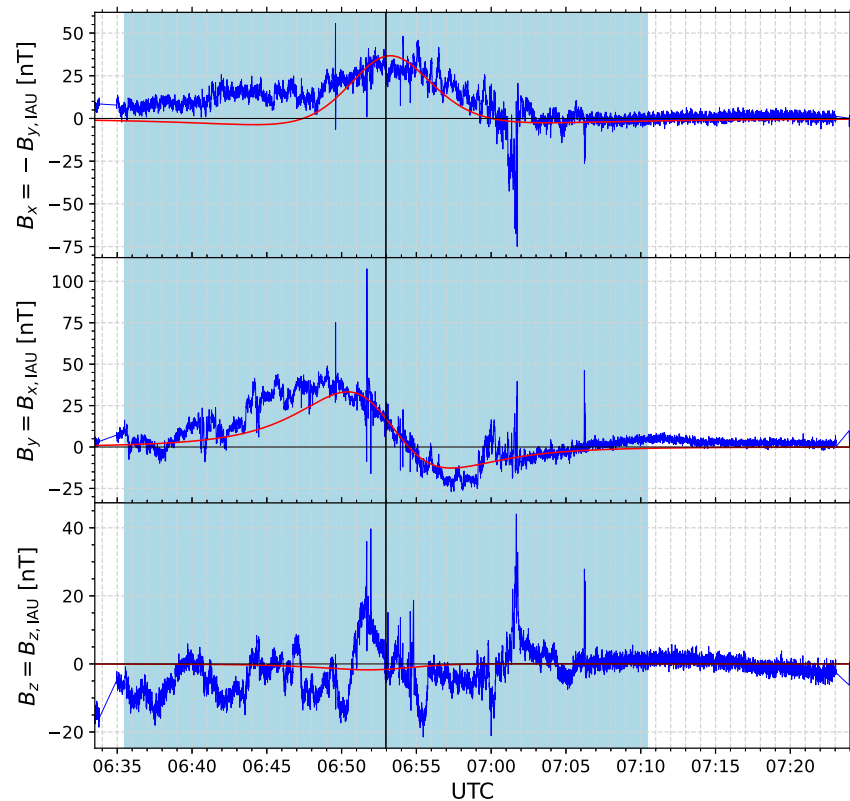


Figure 13. Observed induction response $\mathbf{B}_{\text{obs,ind}}$ (blue) for the E04 flyby in rotated IAU coordinates. The red solid line shows the best fit induced magnetic field obtained from our analysis of the E14 flyby. The blue region highlights the portion of the trajectory where Galileo was within 4 Europa radii relative to the moon's center. The vertical black line marks the closest approach.

Europa Clipper spacecraft over multiply flybys unlocks the potential of joint inversions, thus increasing the potential to tighten the conductivity constraints and inform about the ocean's salinity and composition.

While our inversion of magnetic field data favors an ocean that lies at a shallow depth, with $d = 1$ km for the best fit, such small values conflict with geological and geophysical estimates from tidal heating and crater simulations, where larger icy crust thicknesses in the range of 20–35 km are suggested. Turtle and Pierazzo (2001), for instance, derive a minimum thickness of 3–4 km, excluding a near-surface ocean as would be the case in our best fit. Assuming a conductivity of 10 S/m, we derived a depth constraint on Europa's ocean, according to which it lies at most 49 km below the icy surface. This value lies outside the uncertainties on the icy crust thickness derived by Petricca et al. (2023), where they suggest a thickness of at most 35 km. In their work, induction amplitudes of $A = 0.97 \pm 0.02$ and $A = 0.92 \pm 0.02$ are considered. The uncertainty of the induction amplitude is taken from Schilling et al. (2004), who, however, did not perform a systematic analysis of their model uncertainties. The cited value thus likely underestimates the range of possible values for the induction amplitude. As a comparison, our lowest value for the induction amplitude is $A = 0.86$. This comparison highlights the varying constraints that can be derived under consideration of different uncertainties and, more importantly, emphasizes the necessity of a systematic error analysis.

An inversion considering only magnetic sounding does not yield information about the ocean's minimum depth. Additional measurements, such as the gravity data recorded by Galileo, could be used to further constrain the parameter space of possible ocean characteristics, similar to the approach used in Petricca et al. (2023). Casajus et al. (2021) provided an updated analysis of Galileo gravity data, suggesting a hydrosphere thickness of 138.7 ± 7.7 km for an H_2O density of $1,000 \text{ kg/m}^3$.

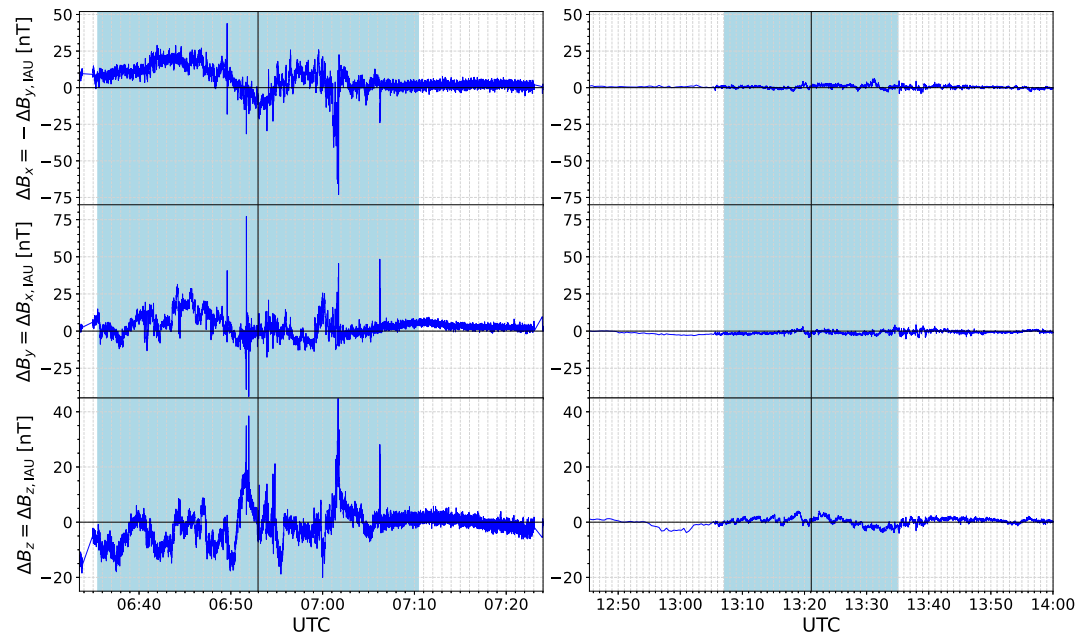


Figure 14. Residuals $\Delta \mathbf{B} = \mathbf{B}_{\text{obs,ind}} - \mathbf{B}_{\text{ind}}$ for (left) the E04 flyby and (right) the E14 flyby.

4.2. Galileo's E04 Flyby and Potential of a Joint Inversion

Figure 14 shows the residuals $\Delta \mathbf{B} = \mathbf{B}_{\text{obs,ind}} - \mathbf{B}_{\text{ind}}$ in all three components for the E04 and E14 flyby. Non-zero residuals are visible in both flybys across all components, although for the E04 flyby they are on the order of 10 nT. In comparison, the residuals for the E14 flyby lie consistently below 10 nT throughout the flyby. This direct comparison emphasizes that the observations during the E04 flyby have stronger contributions from effects that are not considered in our model for Europa's magnetic field environment.

Our chi-squared analysis for the E04 flyby results in $\chi^2 > 1$ across the entire parameter space. Two possible explanations for this result are (a) underestimating our uncertainties and (b) our model of the Europa's magnetic field environment is missing a physical contribution and thus does not fully capture the measured magnetic field. Particularly, the latter reason plays a role during the E04 flyby, as shown in Figure 14. Residuals oscillating around zero indicate that our model describes the general structure of the observations well, with the exception of the small-scale fluctuations, as is the case for the E14 flyby. However, in the E04 flyby, these fluctuations are not only stronger, but there are also noticeable offsets from the zero line on the order of 10 nT, indicating that larger structures of the observations are mismodeled. This could result from an incomplete plasma interaction model. Thus, the E04 flyby is a good example to highlight that flybys with smaller plasma interaction are crucial to gain quantitative insights about Europa's interior from magnetometer measurements, but it also emphasizes the need for accurate modeling of the plasma perturbed magnetic fields around Europa. The Europa Clipper spacecraft is equipped with the Plasma Instrument for Magnetic Sounding (PIMS) instrument, monitoring the plasma environment to correct the magnetometer measurements for plasma perturbed fields (Westlake et al., 2023). These corrections should allow for better removal of plasma magnetic fields from observations, which in turn will improve retrieval of ocean properties, but also increase the number of measurements that can be used in the inversion.

The multitude of flybys performed by the Europa Clipper spacecraft will generate an unprecedented amount of measurements, filling gaps in System III longitudinal coverage as well as uniformly covering the true anomaly phase (Cangahuala et al., 2025; Pappalardo et al., 2024), therefore allowing the investigation to characterize the anomalous and nodal orbital periods of 84.6 and 85.2 hr, respectively. This mission will provide a great opportunity to apply this method in a joint inversion of multiple flybys. Due to the large residuals in the E04 flyby, a joint inversion was not performed in this work. While the consideration of further data generally tightens constraints placed on the ocean characteristics (see, Biersteker et al., 2023; Cochrane et al., 2025), the difference in the 'quality' between the measurements recorded during the E04 and E14 flybys warrants an exception to this

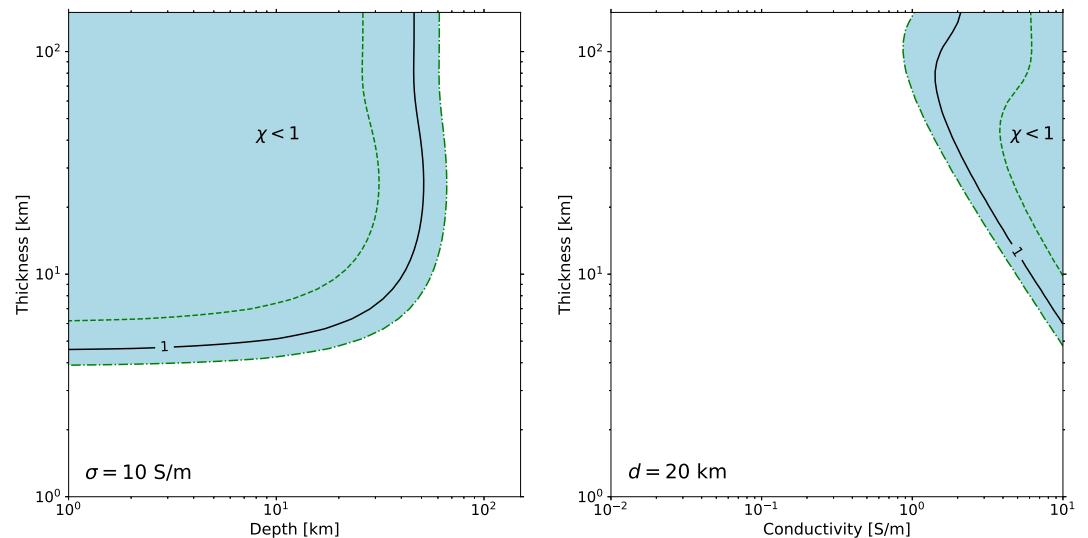


Figure 15. $\chi = 1$ -isocontours of the reference model presented in Section 3.1.2 (solid), a model with degree $n = 3$ background fit (dash-dotted, green), and a model with interval length $\Delta t = 20$ min background fit (dashed, green). The left figure presents the isocontours in depth-thickness space for a conductivity of $\sigma = 10$ S/m, highlighting variations in the derived depth constraints. The right figure shows the isocontours in conductivity-thickness space for a depth of $d = 20$ km to highlight the robustness of our derived conductivity constraints. Note that for the asymmetric atmospheric model the entire parameter space lies outside the $\chi < 1$ regime and is thus not shown in this figure.

rule. A smaller pool of measurements that is described well by our plasma interaction model allows for better retrieval of ocean properties than a larger sample size, where our model leads to larger deviations and systematic uncertainties due to insufficiently constrained plasma interaction, resulting in larger residuals. A joint inversion with a method similar to the one employed in this work would be of interest if multiple flybys with conditions similar to the E14 flyby existed, that is, a low C/A altitude (< 1800 km), large distance to the plasma sheet, magnetic field perturbations dominated by the induced field, and small high-frequency fluctuations throughout the measurements.

4.3. Robustness of Our Method

The constraints derived in this work are influenced by the assumptions in our individual models for the inducing field, the background field, and the magnetic field due to Europa's plasma interaction, as well as the values for the input parameters, for example, the degree of the background fit and the O_2 column density. In three additional runs, we introduce changes to our model parameters to assess the robustness of our derived constraints, only varying one parameter at a time. If our approach is robust, the derived limits on the ocean properties will be similar compared to the reference model. The variations to our model that we consider are

- a background fit of degree $n = 3$,
- a background fit with interval length $\Delta t = 20$ min,
- a background fit with interval length $\Delta t = 30$ min,
- and an asymmetric O_2 atmosphere that includes both upstream-downstream asymmetry and a day-night asymmetry.

In each case, we estimate the resulting uncertainties and calculate χ^2 across the prescribed parameter space. The resulting $\chi = 1$ -isocontours for all four models are shown in Figure 15 in depth-thickness and conductivity-thickness space, respectively. In the following subsections, we will compare the resulting background and plasma interaction fields and demonstrate the robustness of our analysis.

4.3.1. Robustness Against Background Field Variations

Figure 16 shows the four background fits used in this study compared to the measured data. Particularly in the B_x -component, the 20-min fit is around 1 nT smaller than our reference fit around closest approach. This in turn will

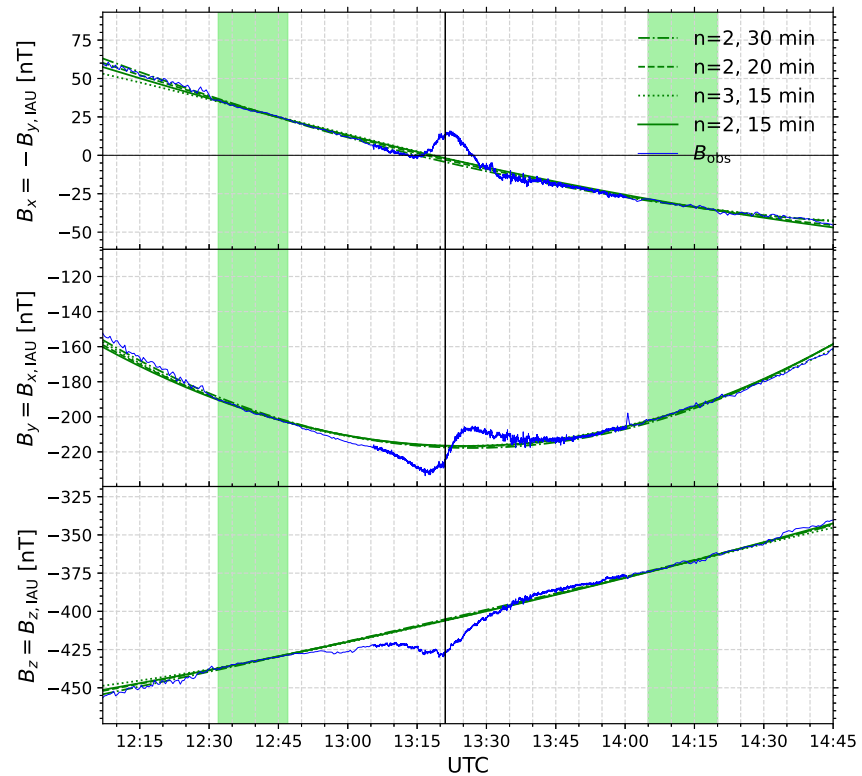


Figure 16. Magnetic field measurements of the E14 flyby (blue) and background fits calculated with (solid green) degree $n = 2$ and window length $\Delta t = 15$ min, (dashed green) $n = 2$ and $\Delta t = 20$ min, (dotted green) $n = 3$ and $\Delta t = 15$ min, and (dash dotted green) $n = 2$ and $\Delta t = 30$ min. The light green area indicates the respective 15-min intervals.

result in an “observed induction response” that is approximately 1 nT larger than in the reference case. As a consequence, the required induction amplitude to stay within $\chi < 1$ increases, while the required phase decreases. This results in more restrictive limits on the ocean properties. In contrast, the background fit with degree $n = 2$ is shown to be fairly insensitive to changes in the degree of the polynomial fit from $n = 3$. This indicates that the background is captured mostly by a linear or quadratic fit within the considered frame of measurements. We also performed the inversion technique using a 30-min background fit. This fit, however, resulted in a $\chi > 1$ throughout the prescribed parameter space. The observed induction response resulting from this fit is shown in Figure 17 and compared against the possible solutions presented in Figure 8. Here, we see a striking offset from zero in the B_x -component. Assuming that our plasma interaction model is reasonably accurate, this means that the resulting background fit is not physically representative of Jupiter's magnetic field in Europa's vicinity. This can be explained by the abrupt jump in the magnetic field observed around 12:30 in the B_x and B_y -components. The magnetospheric field measured by Galileo before 12:30 is likely not indicative of Europa's space environment.

The background fit is involved in multiple instances of our method, that is, its uncertainty σ_{bg} , the uncertainty of the plasma interaction σ_{plasma} , and the observed induction response. Particularly the last point is not exclusive to our work, but pertains to the principle of magnetic sounding in general, and emphasizes the importance of the fit of Jupiter's background field.

4.3.2. Robustness Against Variations in the Atmospheric Model

While a radially symmetric atmosphere was used to obtain the results in Section 3.1.2, simulations by Plainaki et al. (2013) on the generation of Europa's exosphere show spatial variability due to the time-varying orientations of solar illumination and the incident plasma direction. Additional variabilities between the trailing and leading hemispheres of Europa have been observed (Hansen et al., 2005). In this section, we employ an atmosphere model that includes both an upstream-downstream and day-night asymmetry to test how a varying atmosphere model

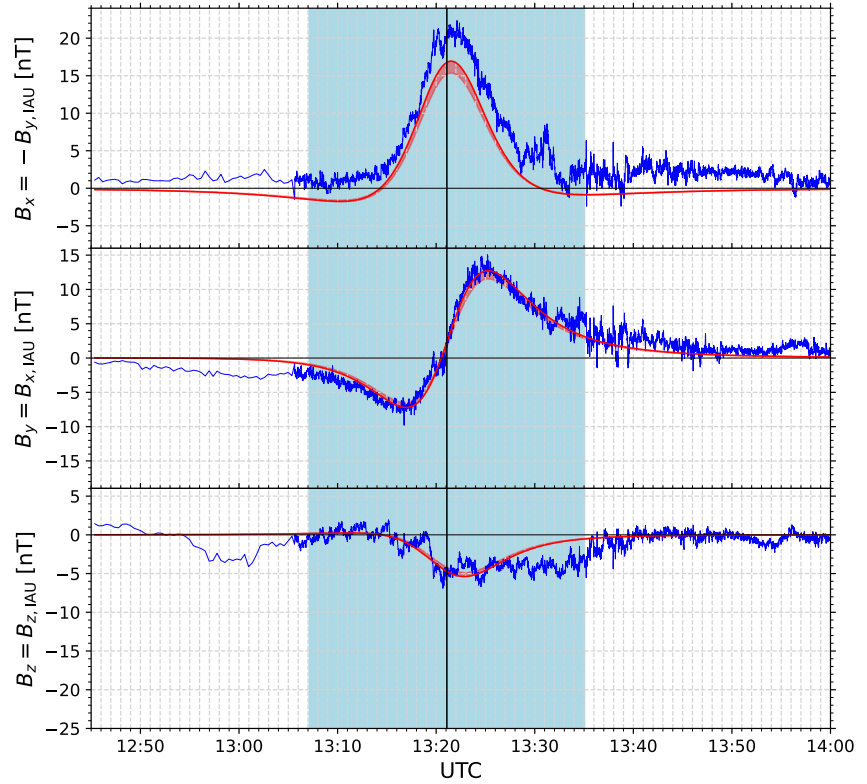


Figure 17. Observed induction response $B_{\text{obs,ind}}$ (blue) for the E14 flyby in rotated IAU coordinates when a background fit with interval length $\Delta t = 30$ min is subtracted. The light red band shows induction models with $\chi \leq 1$ retrieved from the reference model.

influences the derived limits of Europa's ocean properties. For that, the surface density is described with a longitudinal variability following

$$n_{\text{O}_2}(\phi, \theta) = n_{0,\text{O}_2} \sin \theta \begin{cases} (1 + k \sin \phi)(1 + k' \cos(\phi - \phi_{\text{sp}})) & \text{if } \frac{\pi}{2} < \phi < \frac{3\pi}{2} \wedge |\phi - \phi_{\text{sp}}| < \frac{\pi}{2} \\ (1 + k \sin \phi) & \text{if } \frac{\pi}{2} < \phi < \frac{3\pi}{2} \wedge |\phi - \phi_{\text{sp}}| > \frac{\pi}{2} \\ (1 + k' \cos(\phi - \phi_{\text{sp}})) & \text{if } -\frac{\pi}{2} < \phi < \frac{\pi}{2} \wedge |\phi - \phi_{\text{sp}}| < \frac{\pi}{2} \\ 1 & \text{else,} \end{cases} \quad (23)$$

with n_{0,O_2} resulting in a column density of $N_{\text{O}_2} = 10^{14} \text{ cm}^{-2}$ and ϕ_{sp} being the longitude of the subsolar point. The density decays exponentially with height z , following Equation 18. Here, we use $k = 1$ and $k' = 1$ to reproduce the perturbations in the B_z -component from the symmetric model, which results in a maximum column density of $4 \cdot 10^{14} \text{ cm}^{-2}$, assuming the subsolar point aligns with the trailing hemisphere apex. The resulting plasma interaction field for the conditions of the E14 flyby is shown in Figure 18. As the B_z -component does not vary much between both model runs, the uncertainty σ_{plasma} of our MHD model changes by roughly 5%, with $\sigma_{\text{plasma}} = 1.60 \text{ nT}$ in the reference model and $\sigma_{\text{plasma}} = 1.61 \text{ nT}$ for the asymmetric atmosphere model in the case of a perfectly conducting ocean. Since the uncertainty is slightly smaller in the asymmetric description of Europa's atmosphere, we would expect tighter constraints on the ocean properties, assuming the B_x and B_y -components are unchanged. If the plasma interaction fields from the asymmetric case would be in better agreement with the

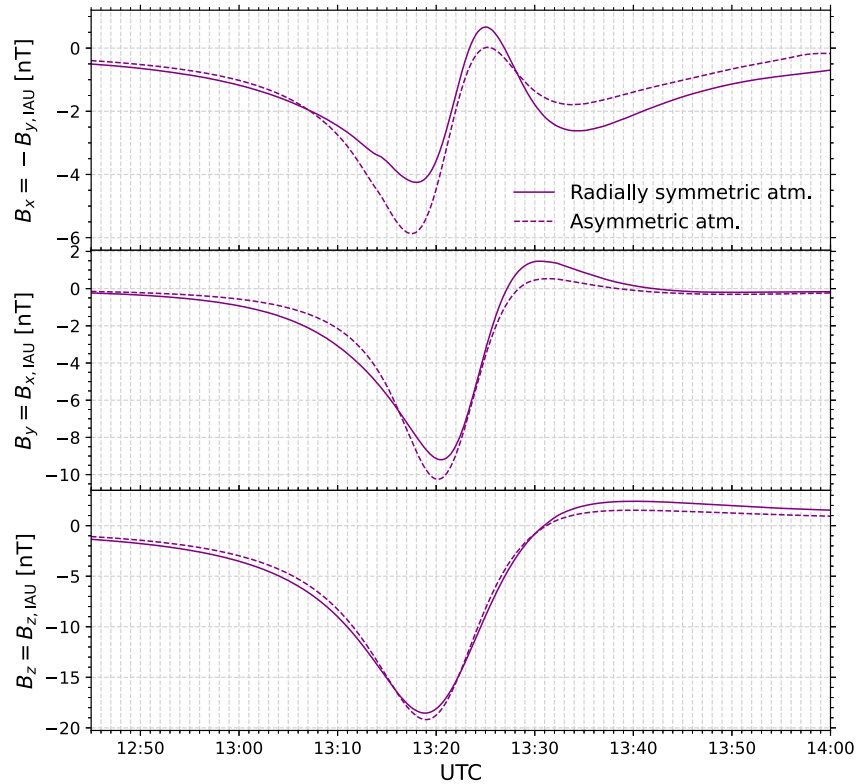


Figure 18. Plasma perturbed magnetic field resulting from (solid) a symmetric atmosphere with column density $N_{O_2} = 4 \cdot 10^{14} \text{ cm}^{-2}$ and (dashed) an asymmetric atmosphere with upstream-downstream and day-night asymmetries, following Equation 23.

observations in the B_x and B_y -component, the misfit between $\mathbf{B}_{\text{model}}$ and $\mathbf{B}_{\text{obs}}$ would decrease, thus increasing the combination of ocean properties that fulfill $\chi^2 \leq 1$.

The changes in the magnetic field due to plasma interaction, which were introduced by consideration of an asymmetric atmosphere, result in a $\chi > 1$ throughout the entire parameter space. This is a consequence of the reduced MHD model uncertainty on one hand, i.e., the asymmetric model reproduces the B_z -component more accurate than the radially symmetric model. On the other hand, its fit to the B_x and B_y -components is worse compared to a radially symmetric atmosphere, further increasing χ^2 . This investigation indicates the importance of the plasma correction in the retrieval of the ocean properties. We emphasize that these findings are specific to the atmosphere model considered in this study, and furthermore a result of the chosen strength of the asymmetry, with $k = 1$ and $k' = 1$.

We cannot extrapolate this conclusion to changes in the overall setup of our MHD model, as we kept additional parameters affecting the plasma interaction (e.g., ionization frequency f_{imp}) unchanged. Therefore, additional tests are required to study the robustness of the retrieved ocean properties to changes in the various input parameters of the MHD model. In general, the results of any inversion will be specific to the plasma interaction model used in the description of Europa's magnetic field environment.

4.4. Assumptions in the Uncertainty Estimates and Additional Sources

In this work, we estimated the uncertainties that are introduced by our models for the inducing field at Europa, the Jovian magnetospheric background field, and the magnetic field due to plasma interaction in Europa's vicinity. These uncertainties are specific to the conditions of a given flyby. The uncertainty of the inducing field, and thus of the induced field, varies with System III longitude. We characterized the uncertainty of the inducing field

amplitudes ($\sigma_{B_{x,0}^e}, \sigma_{B_{y,0}^e}$) as the difference of the inducing amplitude of the synodic rotation period obtained from two various models. This approach provides only a rough approximation, as the uncertainty of the inducing field requires a separate study. Additional uncertainties of the phase of Jupiter's magnetospheric field, ϕ_0 , were not taken into account. For a comprehensive quantitative characterization of Europa's ocean, it is important to analyze the multiple inducing frequencies of Jupiter's inducing field and their respective uncertainties individually.

To assess the justification of our assumptions, we performed an analysis of the two important additional inducing frequencies. First, the half-synodic rotation period at $T = 5.62$ hr, which is primarily pronounced in the B_x and B_y -components. Analyzing this signal for the E14 flyby has shown that the strength of the inducing signals at the given System III longitude was $B_x^e(T = 5.62 \text{ h}, \lambda_{\text{III}} = 184.3^\circ) \approx 15 \text{ nT}$ and $B_y^e(T = 5.62 \text{ h}, \lambda_{\text{III}} = 184.3^\circ) \approx 6 \text{ nT}$. At the distance of the closest approach during the E14 flyby, this inducing field could generate an induction response with a strength of up to 2 nT, depending on the ocean's induction amplitude, potentially accounting for our underestimation of the B_x -component (see Figure 8). The second signal are the nodal and anomalistic orbital periods at 85.2 and 84.6 hr, respectively. The former causes an inducing signal in the B_x and B_y -components, which however was negligibly small during the E14 flyby, with $B_x^e(T = 85.2 \text{ h}) \approx 1 \text{ nT}$ and $B_y^e(T = 85.2 \text{ h}) \approx 3 \text{ nT}$. The anomalistic orbital period affects the B_z -component, producing a signal of roughly 10 nT during the E14 flyby. We, however, neglect an inducing signal in the B_z -component, as both the E14 and E04 flyby occurred near the equatorial plane. We conclude that, within the scope of this work, these assumptions are valid and do not affect the interpretation of the results. In a thorough analysis, however, these additional inducing signals must be taken into account.

The uncertainties of the background field and the plasma magnetic field are characterized by the rms, following Equations 12 and 21. As such, an increased misfit between our model and the observations will naturally increase these two uncertainties as well. Such increased misfits can occur during flybys where small-scale fluctuations are larger than, for example, during the E14 flyby, as they are not included in our model description of Europa's magnetic field environment (see Section 4.2).

We estimate the uncertainty of the plasma model using the B_z -component and assume that this uncertainty translates into the B_x and B_y -components. At flybys near the equatorial plane, the B_x and B_y -components of the plasma interaction are very small (and even exactly zero in case the interaction would be symmetric with respect to the equatorial plane, e.g., Neubauer (1998)), while the B_z -component resulting mostly from the fast mode represents the plasma interaction (Saur, 2021). Deviations from these symmetries, particularly in Europa's wake where electron beams have been detected to contribute to ionization (Allegrini et al., 2024), need to be considered in future inversions using data obtained downstream of Europa.

In this work, we were able to disentangle the individual contributions to the modeled magnetic field by fitting the magnetic field due to plasma interaction using the B_z -component, followed by an inversion of the induction response using the B_x -component and B_y -component. This approach works particularly well for the E04 and E14 flybys, as they occurred near the equatorial plane, resulting in a very small induction signal in the B_z -component. As a consequence, the plasma uncertainty changes by only 1 nT throughout our parameter space. For polar flybys, this difference will be larger.

It should be noted that this work does not cover all uncertainties and is confined to single-frequency magnetic sounding. While the consideration of additional frequencies, for example, higher order synodics and Europa's orbital period, can provide useful additional insights (Biersteker et al., 2023; Khurana et al., 2002; Seufert et al., 2011; Vance et al., 2021), we consider these outside the scope of this work.

5. Summary

In this paper, we developed a method to quantitatively derive the depth, thickness, and electrical conductivity of Europa's subsurface ocean, as well as lower and upper limits of these properties. For that, we performed an inversion where we compared the modeled magnetic field against the observations of the Galileo spacecraft. The magnetic field model in this work is described as the sum of the Jovian background field, the induced magnetic field generated within Europa's subsurface ocean, and the plasma magnetic field. Each contribution to the magnetic field was modeled individually and has an uncertainty associated with it, for which we introduced estimates.

These estimates were used in a chi-squared analysis to derive the ocean properties. Any combination of depth d , thickness h , and conductivity σ that resulted in a magnetic field model with $\chi > 1$ was classified as an inappropriate fit to the observations and thus considered outside the regime of possible values for the ocean properties. This way, the $\chi = 1$ isocontour provided constraints on the range of (d, h, σ) .

We showcased the method using the magnetic field measurements of Galileo's E14 flyby, as the plasma environment was 'quiet' during the encounter and the inducing field was near its maximum, resulting in a strong electromagnetic response. For comparison, we also applied the method to the E04 flyby. While the observations of three other flybys, E12, E19, and E26, were also discussed as potential candidates for the inversion, we ultimately decided against further consideration of those measurements for varying reasons, as stated in Section 3.1.

After performing the chi-squared analysis, we took additional estimates of the ocean's depth into account to further constrain the electrical conductivity and thickness. For that, we considered a minimum depth of 20 km, such as suggested in the literature. Under consideration of the additional depth constraint, we derived a minimum conductivity of 1.6 S/m. An upper limit on the conductivity could not be resolved, as the induction amplitude saturates. For the thickness, no upper constraint was found within our prescribed parameter space, considering thicknesses up to 150 km. However, our analysis yielded a minimum thickness of 6 km at a depth of 20 km.

The Jovian background field is commonly approximated by a polynomial fit to the measurements of the specific flyby considered. The degree of the fit, as well as the interval length and its start and end, however, are ambiguous and usually not well documented in the previous literature. In this work, we have shown the effect that varying background fits have on the derived ocean properties, emphasizing the need to adequately choose and document background fitting in future work to ensure reproducibility. This includes the degree of the polynomial, the start and end of the excluded window, as well as the interval length. While we motivated a background fit with interval length of 15 min and degree $n = 2$ for the E14 flyby, it is not the best fit if measured solely by the rms. The E14 flyby also presents an abrupt change in the magnetospheric field shortly before the first 15-min window, further motivating this choice. It is worth noting that, measured by the rms, the optimal interval length varies between flybys, as the magnetospheric behavior is variable between individual flybys. We conclude that accurate magnetospheric models are imperative for magnetic sounding and further analysis of the periodic and non-periodic variations of the magnetospheric field is required.

We also compared the constraints resulting from two different descriptions for Europa's atmosphere. Here, the derived constraints were the least robust due to the increased misfit between the model and measurements in the B_x and B_y -components, while the plasma uncertainty decreased. Although the conditions of the E14 resulted in comparably small plasma magnetic field contributions in the B_x and B_y -components, this does not hold for any arbitrary flyby, as shown in our application to the E04 flyby, emphasizing the necessity for complementary observations of the plasma environment and atmosphere in addition to the magnetometer measurements on board of ESA's JUICE and NASA's Europa Clipper spacecraft (Kivelson et al., 2023; Masters et al., 2025). Both missions are equipped with instruments monitoring the plasma environment (Wahlund et al., 2025; Westlake et al., 2023). Complementary measurements of the plasma environment and Europa's atmosphere will be provided by the UVS instruments (Davis et al., 2021; Retherford et al., 2024). The framework we present in this study provides a useful method to analyze existing and future spacecraft data recorded with the two aforementioned spacecrafts. We also delivered first estimates to quantify uncertainties introduced by our models for the individual contributions to Europa's magnetic field environment.

Appendix A: Measurements of the E12, E19, and E26 Flybys

For the sake of completeness, we present the measurements of the E12 (Figure A1), E19 (Figure A2), and E26 flybys (Figure A3), compared against the induction response of a perfectly conducting ocean with $A = 1$ and $\phi^{\text{ph}} = 0$.

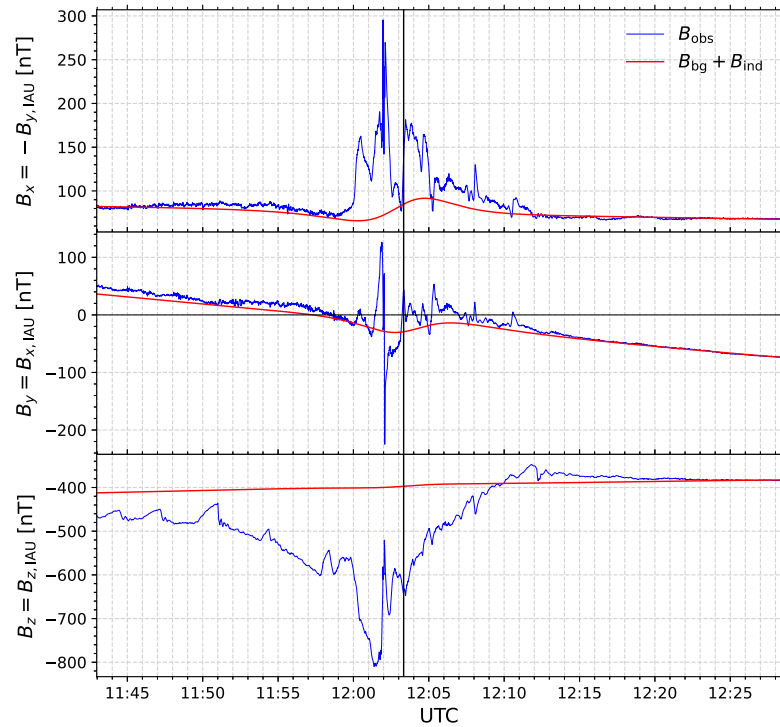


Figure A1. Magnetic field measurements of the E12 flyby (blue) and the induction response of a perfectly conducting ocean with $A = 1$ and $\phi^{ph} = 0$ (red) in rotated IAU (=approximately EPhiO) coordinates. The vertical black line marks the closest approach.

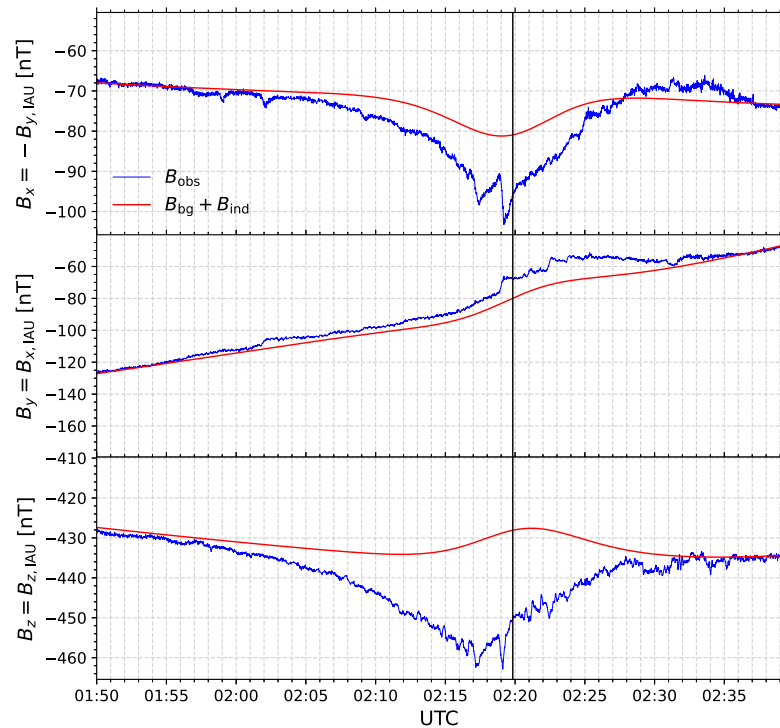


Figure A2. Magnetic field measurements of the E19 flyby (blue) and the induction response of a perfectly conducting ocean with $A = 1$ and $\phi^{ph} = 0$ (red) in rotated IAU (=approximately EPhiO) coordinates. The vertical black line marks the closest approach.

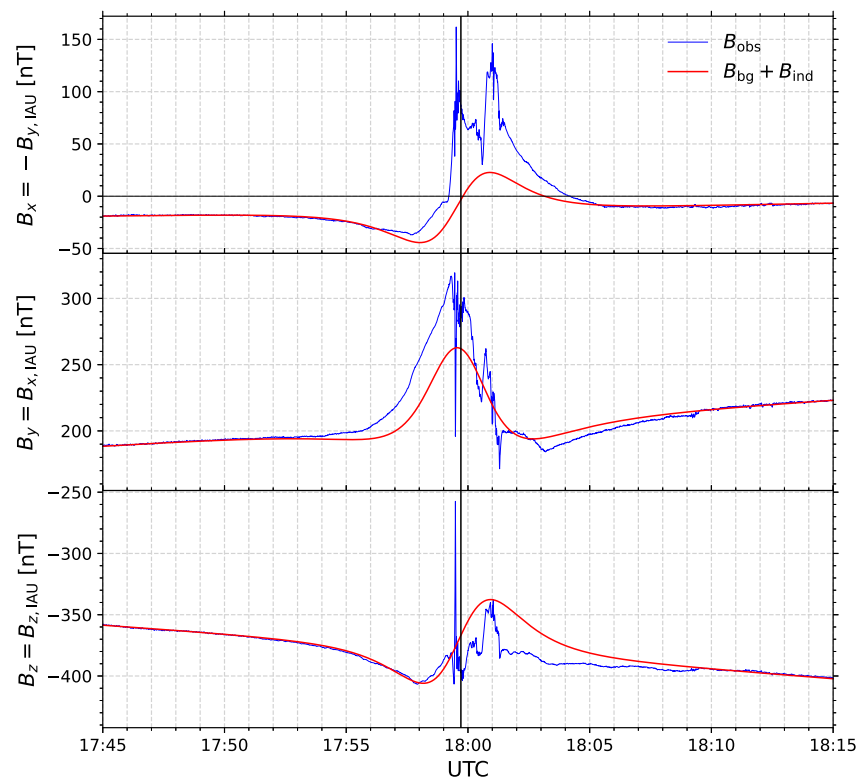


Figure A3. Magnetic field measurements of the E26 flyby (blue) and the induction response of a perfectly conducting ocean with $A = 1$ and $\phi^{\text{ph}} = 0$ (red) in rotated IAU (=approximately EPhiO) coordinates. The vertical black line marks the closest approach.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Magnetic field measurements of the Galileo spacecraft are available in the Planetary Data System: Planetary Plasma Interaction node (Kivelson et al., 2024a, 2024b). Both high and low resolution data were used in this work. The plasma interaction was modeled using the PLUTO code (Mignone et al., 2007) available at <https://plutocode.ph.unito.it/>. The simulation output is available using the following link <https://zenodo.org/records/15113801> (Winkenstern et al., 2025).

Acknowledgments

The authors thank their colleague David Strack for his insightful comments and helpful discussion. This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement no. 884711). This project used computing resources of the Deutsches Klimarechenzentrum (DKRZ), granted by its Scientific Steering Committee (WLA) under project ID 1350. Open Access funding enabled and organized by Projekt DEAL.

References

- Allegrini, F., Saur, J., Szalay, J., Ebert, R., Kurth, W., Cervantes, S., et al. (2024). Electron beams at Europa. *Geophysical Research Letters*, 51(13), e2024GL108422. <https://doi.org/10.1029/2024gl108422>
- Anderson, J., Schubert, G., Jacobson, R., Lau, E., Moore, W., & Sjogren, W. (1998). Europa's differentiated internal structure: Inferences from four Galileo encounters. *Science*, 281(5385), 2019–2022. <https://doi.org/10.1126/science.281.5385.2019>
- Archinal, B., Acton, C., A'hearn, M., Conrad, A., Consolmagno, G., Duxbury, T., et al. (2018). Report of the IAU working group on cartographic coordinates and rotational elements: 2015. *Celestial Mechanics and Dynamical Astronomy*, 130, 1–46.
- Bevington, P. R., & Robinson, D. K. (2003). *Data reduction and error analysis for the physical sciences*. McGraw-Hill.
- Biersteker, J. B., Weiss, B. P., Cochrane, C. J., Harris, C. D., Jia, X., Khurana, K. K., et al. (2023). Revealing the interior structure of icy moons with a Bayesian approach to magnetic induction measurements. *The Planetary Science Journal*, 4(4), 62. <https://doi.org/10.3847/psj/acc331>
- Blöcker, A., Saur, J., & Roth, L. (2016). Europa's plasma interaction with an inhomogeneous atmosphere: Development of Alfvén winglets within the Alfvén wings. *Journal of Geophysical Research: Space Physics*, 121(10), 9794–9828. <https://doi.org/10.1002/2016ja022479>
- Bolton, S., Zhang, Z., Brown, S., Levin, S., Ermakov, A., Akiba, R., et al. (2024). *Juno microwave radiometer observations into the subsurface of the ice shells of Io, Europa and Ganymede (technical report)*. EPSC. <https://doi.org/10.5194/epsc2024-291>
- Cangahuala, L. A., Campagnola, S., Bradley, B. K., Boone, D. R., Buffington, B. B., Ludwinski, J. M., et al. (2025). Europa Clipper mission design, mission plan, and navigation. *Space Science Reviews*, 221(1), 22. <https://doi.org/10.1007/s11214-025-01140-2>

- Casajus, L. G., Zannoni, M., Modenini, D., Tortora, P., Nimmo, F., Van Hoolst, T., et al. (2021). Updated Europa gravity field and interior structure from a reanalysis of Galileo tracking data. *Icarus*, 358, 114187. <https://doi.org/10.1016/j.icarus.2020.114187>
- Cochrane, C. J., Vance, S. D., Castillo-Rogez, J. C., Styczinski, M. J., & Liuzzo, L. (2025). Stronger evidence of a subsurface ocean within Callisto from a multifrequency investigation of its induced magnetic field. *AGU Advances*, 6(1), e2024AV001237. <https://doi.org/10.1029/2024av001237>
- Connerney, J., Timmins, S., Oliverson, R., Espley, J., Joergensen, J., Kotsiaros, S., et al. (2022). A new model of Jupiter's magnetic field at the completion of Juno's prime mission. *Journal of Geophysical Research: Planets*, 127(2), e2021JE007055. <https://doi.org/10.1029/2021je007055>
- Davis, M. W., Gladstone, G. R., Retherford, K. D., & Persyn, S. C. (2021). The JUICE ultraviolet spectrograph: A next-generation compact UVS for ESA's JUICE mission. In *International conference on space optics—ICSO 2020* (Vol. 11852, pp. 919–929).
- Duling, S., Saur, J., Clark, G., Allegrini, F., Greathouse, T., Gladstone, R., et al. (2022). Ganymede MHD model: Magnetospheric context for Juno's PJ34 flyby. *Geophysical Research Letters*, 49(24), e2022GL101688. <https://doi.org/10.1029/2022gl101688>
- Duling, S., Saur, J., & Wicht, J. (2014). Consistent boundary conditions at nonconducting surfaces of planetary bodies: Applications in a new Ganymede MHD model. *Journal of Geophysical Research: Space Physics*, 119(6), 4412–4440. <https://doi.org/10.1002/2013ja019554>
- Hand, K. P., & Chyba, C. F. (2007). Empirical constraints on the salinity of the European Ocean and implications for a thin ice shell. *Icarus*, 189(2), 424–438. <https://doi.org/10.1016/j.icarus.2007.02.002>
- Hansen, C. J., Shemansky, D. E., & Hendrix, A. (2005). Cassini UVIS observations of Europa's oxygen atmosphere and torus. *Icarus*, 176(2), 305–315. <https://doi.org/10.1016/j.icarus.2005.02.007>
- Harris, C. D., Jia, X., Slavin, J. A., Toth, G., Huang, Z., & Rubin, M. (2021). Multi-fluid MHD simulations of Europa's plasma interaction under different magnetospheric conditions. *Journal of Geophysical Research: Space Physics*, 126(5), e2020JA028888. <https://doi.org/10.1029/2020ja028888>
- Khurana, K. K. (1997). Euler potential models of Jupiter's magnetospheric field. *Journal of Geophysical Research*, 102(A6), 11295–11306. <https://doi.org/10.1029/97ja00563>
- Khurana, K. K., Jia, X., Kivelson, M. G., Nimmo, F., Schubert, G., & Russell, C. T. (2011). Evidence of a global magma ocean in Io's interior. *Science*, 332(6034), 1186–1189. <https://doi.org/10.1126/science.1201425>
- Khurana, K. K., Kivelson, M. G., & Russell, C. T. (2002). Searching for liquid water in Europa by using surface observatories. *Astrobiology*, 2(1), 93–103. <https://doi.org/10.1089/153110702753621376>
- Khurana, K. K., Kivelson, M. G., Stevenson, D., Schubert, G., Russell, C., Walker, R., & Polansky, C. (1998). Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto. *Nature*, 395(6704), 777–780. <https://doi.org/10.1038/27394>
- Kivelson, M. G., Jia, X., Lee, K. A., Raymond, C. A., Khurana, K. K., Perley, M. O., et al. (2023). The Europa clipper magnetometer. *Space Science Reviews*, 219(6), 48. <https://doi.org/10.1007/s11214-023-00989-5>
- Kivelson, M. G., Khurana, K. K., Stevenson, D., Bennett, L., Joy, S., Russell, C., et al. (1999). Europa and Callisto: Induced or intrinsic fields in a periodically varying plasma environment. *Journal of Geophysical Research*, 104(A3), 4609–4625.
- Kivelson, M. G., Khurana, K. K., Means, J., Russell, C., & Snare, R. (1992). The Galileo magnetic field investigation. *Space Science Reviews*, 60, 357–383. https://doi.org/10.1007/978-94-011-2512-3_15
- Kivelson, M. G., Khurana, K. K., Russell, C., Walker, R., Joy, S., & Mafi, J. (2024a). *Galileo MAG high resolution*. NASA Planetary Data System. <https://doi.org/10.17189/nyak-9259>
- Kivelson, M. G., Khurana, K. K., Russell, C., Walker, R., Joy, S., & Mafi, J. (2024b). *Galileo MAG low resolution*. NASA Planetary Data System. <https://doi.org/10.17189/fq45-wv97>
- Kivelson, M. G., Khurana, K. K., Russell, C. T., Volwerk, M., Walker, R. J., & Zimmer, C. (2000). Galileo magnetometer measurements: A stronger case for a subsurface ocean at Europa. *Science*, 289(5483), 1340–1343. <https://doi.org/10.1126/science.289.5483.1340>
- Kurth, W., Gurnett, D., Persoon, A., Roux, A., Bolton, S., & Alexander, C. (2001). The plasma wave environment of Europa. *Planetary and Space Science*, 49(3–4), 345–363. [https://doi.org/10.1016/s0032-0633\(00\)00156-2](https://doi.org/10.1016/s0032-0633(00)00156-2)
- Masters, A., Modolo, R., Roussos, E., Krupp, N., Witasse, O., Vallat, C., et al. (2025). Magnetosphere and plasma science with the Jupiter Icy Moons Explorer. *Space Science Reviews*, 221(2), 24. <https://doi.org/10.1007/s11214-025-01148-8>
- Mignone, A., Bodo, G., Massaglia, S., Matsakos, T., Tesileanu, O. e., Zanni, C., & Ferrari, A. (2007). PLUTO: A numerical code for computational astrophysics. *The Astrophysical Journal - Supplement Series*, 170(1), 228–242. <https://doi.org/10.1086/513316>
- Neubauer, F. M. (1998). The sub-Alfvénic interaction of the Galilean satellites with the Jovian magnetosphere. *Journal of Geophysical Research*, 103(E9), 19843–19866. <https://doi.org/10.1029/97je03370>
- Nimmo, F., Thomas, P. C., Pappalardo, R. T., & Moore, W. B. (2007). The global shape of Europa: Constraints on lateral shell thickness variations. *Icarus*, 191(1), 183–192. <https://doi.org/10.1016/j.icarus.2007.04.021>
- Pan, Y., Yong, W., & Secco, R. A. (2020). Electrical conductivity of aqueous magnesium sulfate at high pressure and low temperature with application to Ganymede's subsurface ocean. *Geophysical Research Letters*, 47(21), e2020GL090192. <https://doi.org/10.1029/2020gl090192>
- Pan, Y., Yong, W., & Secco, R. A. (2021). Electrical conductivity of aqueous NaCl at high pressure and low temperature: Application to deep subsurface oceans of icy moons. *Geophysical Research Letters*, 48(17), e2021GL094020. <https://doi.org/10.1029/2021gl094020>
- Pappalardo, R. T., Buratti, B. J., Korth, H., Senske, D. A., Blaney, D. L., Blankenship, D. D., et al. (2024). Science overview of the Europa clipper Mission. *Space Science Reviews*, 220(4), 1–58. <https://doi.org/10.1007/s11214-024-01070-5>
- Parkinson, W. D. (1983). Introduction to geomagnetism.
- Petricca, F., Genova, A., Castillo-Rogez, J. C., Styczinski, M. J., Cochrane, C. J., & Vance, S. D. (2023). Characterization of icy moon hydro-spheres through joint inversion of gravity and magnetic field measurements. *Geophysical Research Letters*, 50(17), e2023GL104016. <https://doi.org/10.1029/2023gl104016>
- Plainaki, C., Milillo, A., Mura, A., Saur, J., Orsini, S., & Massetti, S. (2013). Exospheric O₂ densities at Europa during different orbital phases. *Planetary and Space Science*, 88, 42–52. <https://doi.org/10.1016/j.pss.2013.08.011>
- Retherford, K., Becker, T., Gladstone, G., Greathouse, T., Davis, M., Velez, M., et al. (2024). Europa ultraviolet spectrograph (Europa-UVS). *Space Science Reviews*, 220(8), 89. <https://doi.org/10.1007/s11214-024-01121-x>
- Šachl, L., Kverka, J., Čadek, O., & Velínský, J. (2024). Magnetic field induced by convective flow in Europa's subsurface ocean. *Icarus*, 429(2), 116375. <https://doi.org/10.1016/j.icarus.2024.116375>
- Saur, J. (2021). Overview of Moon–magnetosphere interactions. In *Magnetospheres in the solar system* (pp. 575–593).
- Saur, J., Duling, S., Grayver, A., & Szalay, J. R. (2024). Analysis of Enceladus's time-variable space environment to magnetically sound its interior. *The Planetary Science Journal*, 5(11), 245. <https://doi.org/10.3847/psj/ad8130>
- Saur, J., Neubauer, F. M., & Glassmeier, K.-H. (2010). Induced magnetic fields in solar system bodies. In *Planetary magnetism* (pp. 391–421). Springer.

- Saur, J., Strobel, D., & Neubauer, F. (1998). Interaction of the Jovian magnetosphere with Europa: Constraints on the neutral atmosphere. *Journal of Geophysical Research*, 103(E9), 19947–19962. <https://doi.org/10.1029/97je03556>
- Schenk, P. M. (2002). Thickness constraints on the icy shells of the Galilean satellites from a comparison of crater shapes. *Nature*, 417(6887), 419–421. <https://doi.org/10.1038/417419a>
- Schilling, N., Khurana, K. K., & Kivelson, M. G. (2004). Limits on an intrinsic dipole moment in Europa. *Journal of Geophysical Research*, 109(E5), 5006. <https://doi.org/10.1029/2003je002166>
- Schilling, N., Neubauer, F. M., & Saur, J. (2007). Time-varying interaction of Europa with the Jovian magnetosphere: Constraints on the conductivity of Europa's subsurface ocean. *Icarus*, 192(1), 41–55. <https://doi.org/10.1016/j.icarus.2007.06.024>
- Schilling, N., Neubauer, F. M., & Saur, J. (2008). Influence of the internally induced magnetic field on the plasma interaction of Europa. *Journal of Geophysical Research*, 113(A3), A03203. <https://doi.org/10.1029/2007ja012842>
- Seufert, M., Saur, J., & Neubauer, F. M. (2011). Multi-frequency electromagnetic sounding of the Galilean moons. *Icarus*, 214(2), 477–494. <https://doi.org/10.1016/j.icarus.2011.03.017>
- Smyth, W. H., & Marconi, M. L. (2006). Europa's atmosphere, gas tori, and magnetospheric implications. *Icarus*, 181(2), 510–526. <https://doi.org/10.1016/j.icarus.2005.10.019>
- Strack, D., & Saur, J. (2024). The spatiotemporal structure of induced magnetic fields in Callisto's plasma environment due to their propagation with MHD modes. *arXiv preprint arXiv:2411.15938*, 129(12), e2024JA033235. <https://doi.org/10.1029/2024ja033235>
- Styczinski, M. J., Vance, S. D., Harnett, E. M., & Cochrane, C. J. (2022). A perturbation method for evaluating the magnetic field induced from an arbitrary, asymmetric ocean world analytically. *Icarus*, 376, 114840. <https://doi.org/10.1016/j.icarus.2021.114840>
- Tobie, G., Choblet, G., & Sotin, C. (2003). Tidally heated convection: Constraints on Europa's ice shell thickness. *Journal of Geophysical Research*, 108(E11), 5124. <https://doi.org/10.1029/2003je002099>
- Turtle, E. P., & Pierazzo, E. (2001). Thickness of a European ice shell from impact crater simulations. *Science*, 294(5545), 1326–1328. <https://doi.org/10.1126/science.1062492>
- Vance, S. D., Craft, K. L., Shock, E., Schmidt, B. E., Lunine, J., Hand, K. P., et al. (2023). Investigating Europa's habitability with the Europa Clipper. *Space Science Reviews*, 219(8), 81. <https://doi.org/10.1007/s11214-023-01025-2>
- Vance, S. D., Styczinski, M., Bills, B., Cochrane, C., Soderlund, K., Gómez-Pérez, N., & Paty, C. (2021). Magnetic induction responses of Jupiter's ocean moons including effects from adiabatic convection. *Journal of Geophysical Research: Planets*, 126(2), e2020JE006418. <https://doi.org/10.1029/2020je006418>
- Voosen, P. (2024). Surprisingly thick ice on Jupiter's moon Europa complicates hunt for life. *Science*, 375(6585), 1076–1077. <https://doi.org/10.1126/science.adb1918>
- Wahlund, J.-E., Bergman, J. E., Åhlén, L., Puccio, W., Cecconi, B., Kasaba, Y., et al. (2025). The Radio & Plasma Wave Investigation (RPWI) for the JUPITER ICy moons Explorer (JUICE). *Space Science Reviews*, 221(1), 1–134.
- Wakita, S., Johnson, B. C., Silber, E. A., & Singer, K. N. (2024). Multiring basin formation constrains Europa's ice shell thickness. *Science Advances*, 10(12), ead8455. <https://doi.org/10.1126/sciadv.adj8455>
- Walker, M. E., & Rhoden, A. R. (2022). Tidal heating at Europa using the multifrequency analysis of tidal heating toolkit. *The Planetary Science Journal*, 3(7), 149. <https://doi.org/10.3847/psj/ac6df0>
- Westlake, J. H., McNutt Jr, R., Grey, M., Coren, D., Rymer, A., Cochrane, C., et al. (2023). The plasma instrument for magnetic sounding (PIMS) on the Europa clipper Mission. *Space Science Reviews*, 219(8), 62. <https://doi.org/10.1007/s11214-023-01002-9>
- Winkenstern, J., & Saur, J. (2023). Detectability of local water reservoirs in Europa's surface layer under consideration of coupled induction. *Journal of Geophysical Research: Planets*, 128(10), e2023JE007992. <https://doi.org/10.1029/2023je007992>
- Winkenstern, J., Saur, J., & Cervantes, S. (2025). Data for “An inversion of magnetic field measurements to constrain the depth, thickness, and conductivity of Europa's ocean” by Winkenstern et al. (2025) [Dataset]. *Zenodo*. <https://doi.org/10.5281/ZENODO.15113801>
- Zimmer, C., Khurana, K. K., & Kivelson, M. G. (2000). Subsurface oceans on Europa and Callisto: Constraints from Galileo magnetometer observations. *Icarus*, 147(2), 329–347. <https://doi.org/10.1006/icar.2000.6456>