Viability of the early JUICE flyby trajectories to confirm ocean existence at Ganymede

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Key Points:

- Revisiting the Galileo flybys of Ganymede to compare the induction and quadrupole signals.
- Prediction of the strength and polarity of the induction signature at JUICE trajectories.
- Possible confirmation of Ganymede's subsurface ocean using the initial 3 low altitude JUICE flybys.

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Abstract

Ganymede is the largest moon in our Solar System, and unique in producing its own magnetic field, as well as possibly possessing a subsurface ocean. The measurements from the only spacecraft that visited the moon, Galileo, provided two models for the internal field- a dipole and quadrupole model or a dipole and induction model. The focus of the initial 3 close flybys of the JUpiter ICy moons Explorer (JUICE) mission is to differentiate between the two signals and confirm the existence of an ocean. We begin with an analysis of the JUICE and Galileo trajectories in different reference frames and predict the induction signal using the time-varying field of Jupiter. A comparison between the induction and quadrupole signatures for Galileo flybys shows that the former seems more likely. Finally, we present and discuss the importance of the 3 JUICE flybys to observe the induction field and hence confirm the ocean.

Plain Language Summary

The Jovian icy moons' interiors hold the key to understanding potential habitability and could serve as a prototype to comprehend similar bodies that might have the potential to sustain life. In particular, Ganymede is the largest moon of our Solar System and is capable of producing its own magnetic field. In addition, Jupiter's fast rotation and large magnetic field create a periodically varying field at the moon. If Ganymede has a conducting ocean in its interior, this changing field will produce currents through electromagnetic induction. However, separating the intrinsic field from the induced field is a difficult problem. Galileo provided in-situ measurements from the moon from which two internal field models were derived- a dipole and quadrupole model or a dipole and induction model. The JUpiter ICy moons Explorer (JUICE) mission will observe the moon with the aim of confirming the existence of the ocean and better constrain its internal characteristics. In this study, we use both the Galileo and JUICE trajectories to understand the induction field. For Galileo, we find that the induction signal matches closely with the quadrupole signal while for JUICE, we predict the induced signature and discuss the viability of the flybys to confirm the ocean.

1 Introduction

The Jovian system is a complex structure consisting of the largest planet, Jupiter (equatorial radius, 1 R_J = 71,492 km), its moons and the various interactions that take place between them. The Jovian magnetosphere has been visited by many spacecraft beginning with the Pioneer and Voyager flybys, followed by the Ulysses flyby and two orbiting spacecraft- Galileo and Juno, with Juno still presently in orbit around the planet. As a result, our understanding about the planet and its magnetosphere is comprehensive, but that of its moons less so. The only spacecraft that has observed the Jovian moons (in particular, the Galilean moons) at close distances and provided in-situ measurements is NASA's Galileo mission (Johnson et al., 1992). The magnetic observations from the spacecraft provided insights about the interior of the moons (e.g., Kivelson et al., 1999; Zimmer et al., 2000), with one of the major discoveries being that Ganymede has an internal magnetic field. Not only is Ganymede the largest moon in the Solar System (equatorial radius, 1 R_G = 2,634 km) but is unique in having its own magnetic field and magnetosphere (Kivelson et al., 1996, 1997). Modelling the internal field reveals that the dipole field has an equatorial strength of about 719 nT at the surface (Kivelson et al., 2002) with the magnetic axis having a tilt of about 176° relative to the spin axis displaying a south-north symmetry like the Earth.

Any spacecraft in the vicinity of Ganymede measures the magnetic field produced by 5 different magnetic sources. This includes the internal and external fields generated by the moon itself and the changing background field of Jupiter. The background field consists of Jupiter's dynamo and magnetodisk fields at the distance of Ganymede ($\sim$ 15

R_J), where the large fields of Jupiter and the planet's fast rotation create a periodically varying field (Khurana et al., 1998; Neubauer, 1999). From Galileo and telescope observations, it is likely that Ganymede has a liquid water ocean beneath its surface which is capable of generating an induced field due to electromagnetic induction (Kivelson et al., 2002; Saur et al., 2015). The present magnetic models for Ganymede cannot differentiate between the induced and dynamo quadrupole signatures due to lack of a sufficient amount of data and possibly similar magnitudes of the two signals. Since a dipole plus induction model provides similar residuals but with less number of parameters as compared to a dipole plus quadrupole model, the former model is favoured (Kivelson et al., 2002). However, the problem of separating the field from different sources has always been a challenge in planetary studies (Olsen et al., 2010). Moreover, a recent study by Plattner et al. (2023) using Galileo and Juno observations states that any constraints on Ganymede's quadrupole terms and subsequently its dynamo cannot be achieved adequately with available data.

This highlights the importance of the JUpiter ICy moons Explorer (JUICE) mission with one of its focus being an understanding of the interior of Ganymede (Grasset et al., 2013). The scientific objectives of JUICE are twofold- it aims to explore the habitable zone at Jupiter with an emphasis on Ganymede, Callisto and Europa; and examine the Jupiter system as an archetype for gas giants. JUICE was launched on 14th April 2023 from the European Space Agency's (ESA) spaceport at French Guiana, with the spacecraft reaching Jupiter's orbit in 2031, after an interplanetary cruise of almost 8 years. It will be the first spacecraft to orbit two bodies- Jupiter and Ganymede, in its lifetime. Following Jupiter orbit insertion and prior to Ganymede orbit insertion, there will be numerous flybys around Ganymede and Callisto, and 2 flybys around Europa. The first 3 flybys at Ganymede are close flybys, which occur at distances of $\sim$400 km above the surface of the moon, enabling observations and modelling of the internal fields. The final part of the mission is an orbital phase around Ganymede which is the first time a spacecraft will orbit a moon other than our own.

Although the Ganymede orbital phase will enable a detailed analysis of the interior structure of the moon through high multipole spherical harmonic modelling, the flyby phase will prove equally important in terms of better understanding the various magnetic signals observed at the moon. While global coverage data from the orbits will efficiently let us separate the contribution from the different magnetic sources, the early close flybys will potentially allow us to confirm the existence of the subsurface ocean in the initial mission phase. The main dilemma from the Galileo observations was being able to distinguish between the quadrupole and induction signals which the first 3 JUICE flybys may resolve, and hence an early confirmation of the ocean is possible. In addition, the results from the flyby phase will aid in modelling the data in the orbital phase.

In this study, we focus on the first 3 close flyby trajectories of the JUICE mission at Ganymede to understand the induction response. Simultaneously, we visit the Galileo era to aid in early ocean existence and obtain its characteristics as well as provide comparison with JUICE. In Section 2, we begin with a discussion of both the spacecraft trajectories in different coordinate systems with respect to (wrt) Ganymede, and observe the position of Ganymede wrt Jupiter and the latter's field at those times. We predict the induction signals that would be produced due to Jupiter's background field at both the JUICE and Galileo locations in Section 3. For Galileo, we compare them with the quadrupole signal using the model of Kivelson et al. (2002) while for JUICE, we discuss the viability of the trajectories to detect the signal. We also focus on predicting features like the strength and structure at the JUICE orbits. We interpret and discuss the results in connection with Ganymede's interior in Section 4 and summarise our results in a short conclusion in Section 5.

2 JUICE and Galileo trajectories

Our discussion about the viability of the JUICE flybys to confirm an ocean using magnetic observations begins with an analysis of the trajectories in the frame of reference of Ganymede. For JUICE, our focus is the first 3 flybys around Ganymede- 1G1 and 2G2 with closest approach above the surface at 397 km and 3G3 which has an altitude of 485 km. The next 2 flybys around the moon, 4G4 and 5G5 are not considered since they are quite high in altitude (> 1,000 km). After 5G5, there are Callisto and Europa flybys and JUICE visits Ganymede the sixth time only in the twenty-sixth (26G6) flyby. Therefore, we use the first 3 flybys occurring within a year of reaching the Jovian system with an aim of confirming the ocean and understanding the induction signal produced from them.

For Galileo, there are only 3 out of 8 available orbits that can be considered close to the planet (< 1,000 km), namely orbits O1, O2 and O28. The closest approach of the 3 flybys, also the only orbits used by Kivelson et al. (2002) to model Ganymede's internal magnetic field, are 835 km, 261 km and 808 km respectively. The spacecraft Juno also visited Ganymede but at an altitude of about 1,045 km. While it can be suitable for studying the magnetospheric field at Ganymede (e.g., Duling et al., 2022; Hansen et al., 2022), we ignore the flyby in our focus on comprehension of the induction field. A summary of the six chosen flybys in terms of position in Ganymede centered frames is provided in Table 1.

Table 1. Details about the closest approach of the 3 chosen Galileo and JUICE trajectories.

Orbit	Date	Time (UT)	Alt (km)	Lat (° PC)	Lon (° PC)	Lat (° PO)	Lon (° PO)
O1	27 Jun 1996	06:29:06	835.00	30.37	246.46	30.60	338.89
O2	06 Sep 1996	18:59:34	261.42	79.22	235.23	79.50	328.45
O28	20 May 2000	10:10:10	808.74	-18.96	92.70	-19.16	184.69
1G1	21 Jul 2031	07:08:09	397.20	1.80	238.71	1.80	330.93
2G2	13 Feb 2032	23:03:55	397.20	25.08	234.08	25.08	326.22
3G3	11 Apr 2032	04:14:51	485.50	32.23	245.14	32.23	337.31

2.1 In Ganymede centered system

The SPICE kernels for JUICE provide the position of the spacecraft relative to the centre of Ganymede in various different coordinate systems. The two Ganymede-centered coordinate systems useful for us are the Planetocentric (PC) and Phi ZOrb (PO) systems. In the spherical PC system, r is the radial component that points away from Ganymede, θ is the co-latitude measured from the rotation axis and ϕ is the azimuthal component measured from the Jupiter facing meridian. In the cartesian PO system, the Y axis points in the direction of Jupiter, the X axis is in the direction of corotation or the plasma flow while the Z axis is along the Jovian spin axis and completes the right-handed system. Comparing both the coordinates in the cartesian system, we have-

$$B_x\ (PO) \approx -B_y\ (PC) \qquad B_y\ (PO) \approx B_x\ (PC) \qquad B_z\ (PO) \approx B_z\ (PC) \tag{1}$$

Figures 1a and 1b display the 3 Galileo and JUICE trajectories wrt Ganymede for both PC and PO spherical coordinates respectively. The first JUICE orbit, 1G1 will fly over Ganymede's equator and observe the field present. The orbits 2G2, 3G3 and O1 are

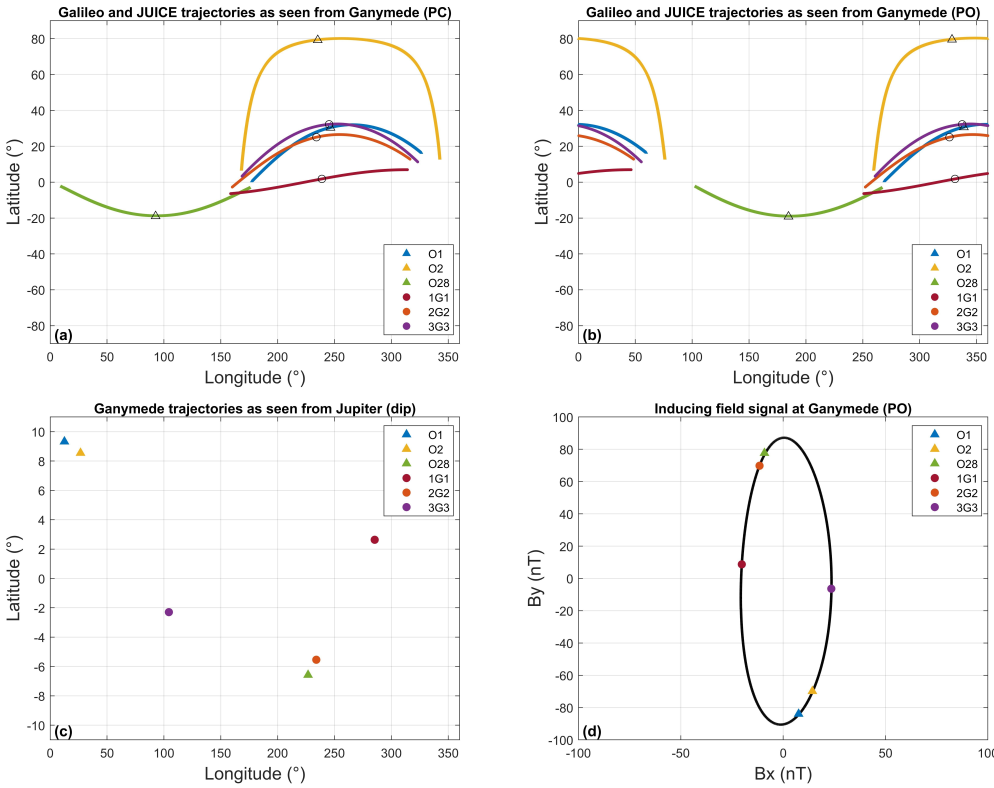

Figure 1. The trajectories of the Galileo and JUICE orbits in (a) Planetocentric and (b) Phi ZOrb spherical coordinates. (c) The position of Ganymede at the times of the 6 flybys closest approach wrt Jupiter in magnetic dipole spherical coordinates. (d) The background field of Jupiter over one complete rotation at the position of Ganymede (black line) in PO cartesian coordinates. The triangles and circles represent the closest approach for Galileo and JUICE orbits respectively.

quite close to each other spatially, providing an efficient way to understand any temporal variations over a 35 year period as well as a shorter 2 month period. O2 is the only orbit that observes data near the pole (north) while O28 expands our reach in the other hemispheres. Combining data from all of the 6 orbits will better characterise and model the moon's internal field.

2.2 In Jupiter centered system

The position of the spacecraft or Ganymede wrt Jupiter should also be considered in order to understand whether an induction signal can be resolved. If Ganymede is at the centre of the Jovian magnetodisk during the flybys, it will be difficult to obtain an induction signal (e.g., Weber et al., 2022). This is because in a dipole approximation, the field is strongest at the poles and weakest at the equator. This is better understood in a Jupiter centered PC reference frame but where the Z axis is along the magnetic dipole axis of Jupiter instead of the spin axis. Figure 1c displays the position of Ganymede in this space where the movement of Ganymede wrt Jupiter's latitude is confined between $\pm 11°$.

The induction signature is dependent on the periodically varying background field of Jupiter observed by Ganymede at its position. To calculate the field, we use the internal and magnetodisk models of Jupiter and predict the measurements at the location and time of the 6 orbits. For the internal dynamo field, we use the model by Sharan et al. (2022) defined up to spherical harmonic degree and order 16. Using or ignoring the secular variation model negligibly changes the predicted field of Jupiter at the distance of Ganymede. For the magnetospheric field, we use the magnetodisk model by Connerney et al. (2020) utilising the analytical equations defined in Edwards et al. (2001). Figure 1d shows the background field at Ganymede over a 10.53 hour period in the Ganymede centered PO coordinates as well as the values of the field at the closest approach for the 6 orbits. In terms of the PO coordinates of Ganymede, the B_y component can be considered the opposite of Jupiter centered B_r component while the B_x component is nearly equal to Jupiter centered B_ϕ component. The B_θ component of Jupiter's field is almost constant at the distance of the moon and hence does not contribute to the periodic field. The maximum variation is observed in the B_y component that drives the induction.

The Galileo orbits O1 and O28 are located at the narrower ends of the loop, where the B_y field is almost at its highest value making them great candidates for induction studies. However, their altitudes are more than 800 km which results in a weak induction signal. Similarly, though the O2 flyby is very close to the planet ($\sim$ 260 km) at a high inducing field value, it is quite close to the north pole which minimises the induction signature. The JUICE 2G2 orbit shows a similar value for the background field while the 1G1 and 3G3 orbits are located where B_y is less and B_x is at its maximum. Even though the B_y component is low for the latter two orbits, the advantage with JUICE is the low altitude of the flybys, which has a better chance of measuring the signals even if they are weak. The 2G2 and 3G3 flybys are very close together spatially in Ganymede centered frames (Figure 1a,b) and will provide a good comparison between the measurements made. Similar to O28, 2G2 is at a prime location that will provide high induction signals. 3G3 is close to the magnetic equator and should have minimum induction signal and therefore the only internal source for the field would be the intrinsic field. A comparison between the two flybys would independently yield an accurate structure of the quadrupole and induction signals.

3 Induction signature

In the previous section, we calculated the primary inducing signal $\mathbf{B}_0$ which is the periodic 10.53 hour background field of Jupiter. For a first approximation, other frequencies such as the eccentricity of the orbit can be ignored due to their small contribution (Zimmer et al., 2000). Assuming a nearly infinite conductivity case that is spherically symmetric, the probable induction signal is (Saur et al., 2010) -

$$B_{ind}(t) = \frac{\mu_0}{4\pi} \frac{(3(\mathbf{r} \cdot \mathbf{M}(t))\mathbf{r} - r^2\mathbf{M}(t))}{r^5} \tag{2}$$

where,

$$\mathbf{M}(t) = -\frac{2\pi}{\mu_0}\mathbf{B}_0(t)r_0^3 \tag{3}$$

t and $\mathbf{r}$ are the time and position respectively where the induction field is measured and μ_0 is the permeability of free space. For finite conductivity, an amplitude and phase factor $Ae^{i\theta}$ would be included in Equation 3 where A is the cubic power of the ratio between the radius of the conductive region and the radius of the entire conducting body (r_0 or here, 1 R_G). However, for the results we display, we use a simple case where Ganymede acts like a superconductor (A = 1 and $\theta = 0$).

3.1 For Galileo

We predict the induction signal that would be observed by the 3 Galileo flybys due to the inducing field of Jupiter. Simultaneously, we predict the quadrupole field at the same locations using the internal field model of Kivelson et al. (2002). Figure 2 shows both the induction and quadrupole fields for the 3 trajectories in Ganymede's rest frame for the PO coordinates. As expected, the maximum amplitude for both signals is observed for the second flyby which was at altitudes of about 260 km above the surface. The other two flybys at higher altitudes also show good induction signals as predicted from our analysis of their position on the inducing field graph (Figure 1d). However, what is remarking here is the fact that the quadrupole signal calculated using a spherical harmonic model is very similar to the induction signature estimated independently. The polarity and variation in the components as well as the amplitude of the two fields closely match each other.

3.2 For JUICE

We use the same method to calculate the induction field due to Jupiter's inducing field for the JUICE trajectories. Figure 3 displays the cartesian components of the field in PO coordinates and the amplitude of the 3 signals wrt the number of data points considered. Since the first and third flybys occur when Ganymede is present close to the Jovian magnetic equator (Figure 1c), we observe a weak induction signal while the second flyby displays the maximum field. It is even higher than the second close altitude flyby of Galileo. Analysis of the 2G2 flyby will provide a good approximation of the induction field and hence information about the ocean existence and characteristics. On the other hand, comparison between the second and third flybys will independently resolve the quadrupole and induced signatures due to their overlapping spatial locations (Figure 1a) but different inducing field locations (Figure 1d).

4 Discussion

For the Galileo flybys, we have the induction field at its location from Jupiter's background field and the modelled quadrupole field. Using the amplitudes of the quadrupole field and varying the induction signal by changing the depth of the ocean, we find the optimum depth value where the standard deviation between the two signals is minimum (Figure 4). To do this, we estimate the induced field by multiplying different values of A in equation 3. For O1, this value is at 0.8, or 190 km depth and for O28, this is 0.7, or about 295 km depth. The O2 flyby shows the lowest error between the signals at the surface. However, being very close to the surface and near the north pole, the signal from this flyby probably contains more of the quadrupole field than the induced field. Averaging the three depths yields a value of 0.83 which coincides with the induction model of Kivelson et al. (2002), reiterating their result that a 84% inductive response along with the dipole field describes the measurements equally well to that using a dipole and quadrupole field. However, the probability of two signals being so close in structure is statistically very low. The induction field we predict independently from Jupiter's field is very close in amplitude, polarity and variation to the field modelled using the quadrupole terms. A potential outcome could be that the quadrupole signal is either not present or is too low to be detected during the Galileo flybys. The Galileo trajectories, which were very well placed to observe the induction signal, measures the field generated by the subsurface ocean with depth estimates between 0 to 295 km indicating a shallow ocean. Assuming a penetration depth of 150 km (d) from the inducing signal of a 10.53 (T) hour period, we obtain conductivity (σ) near 0.42 S/m using $d = \sqrt{T \,/\, \sigma\mu\pi}$. While the JUICE orbits around Ganymede will resolve these properties accurately, the flybys would be able to clarify our ambiguities about the strength of the quadrupole signature and the existence of the ocean.

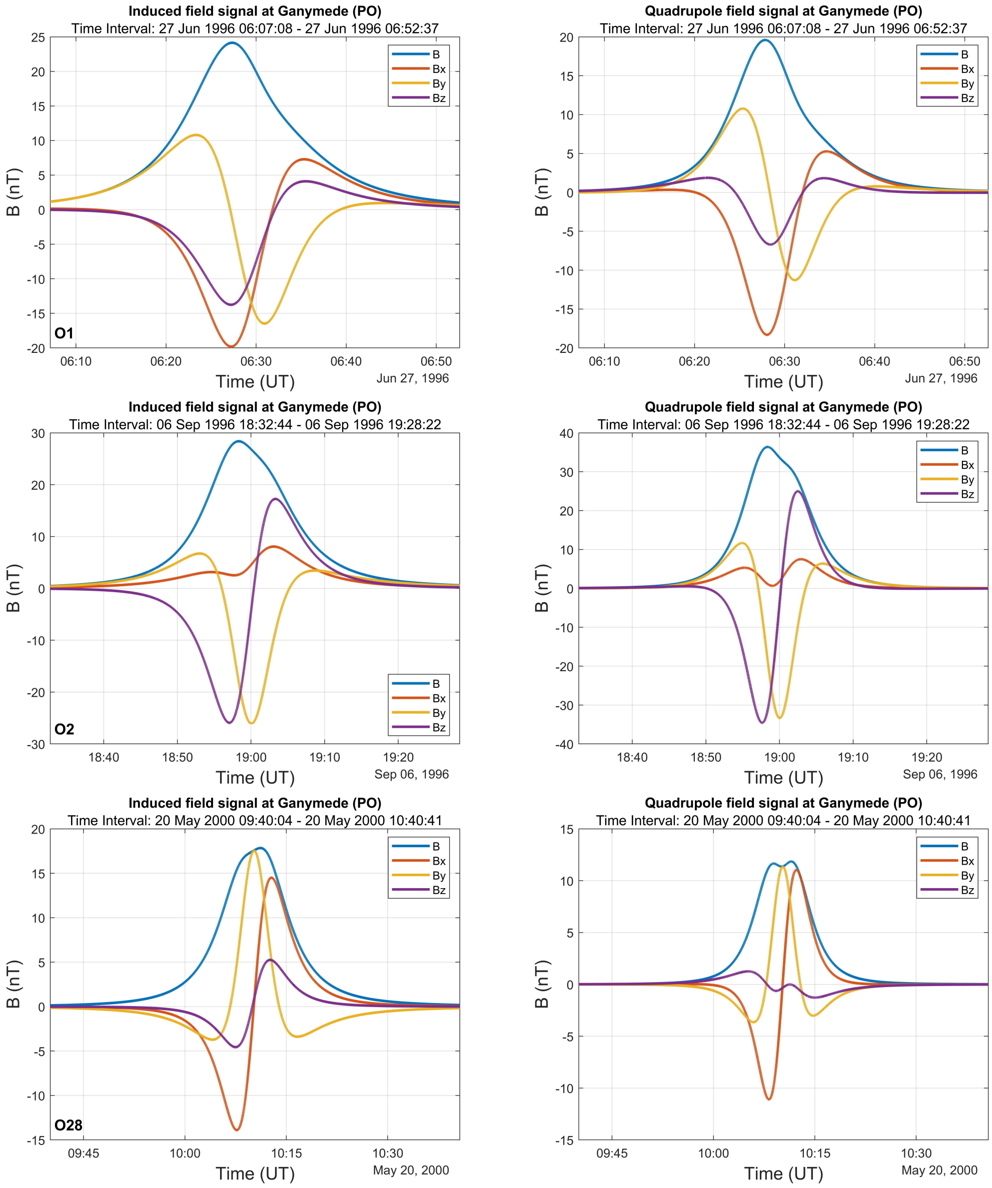

Figure 2. Comparison between the predicted induced (left) and quadrupole (right) field signals for the Galileo flybys. The quadrupole field is estimated using the model of Kivelson et al. (2002).

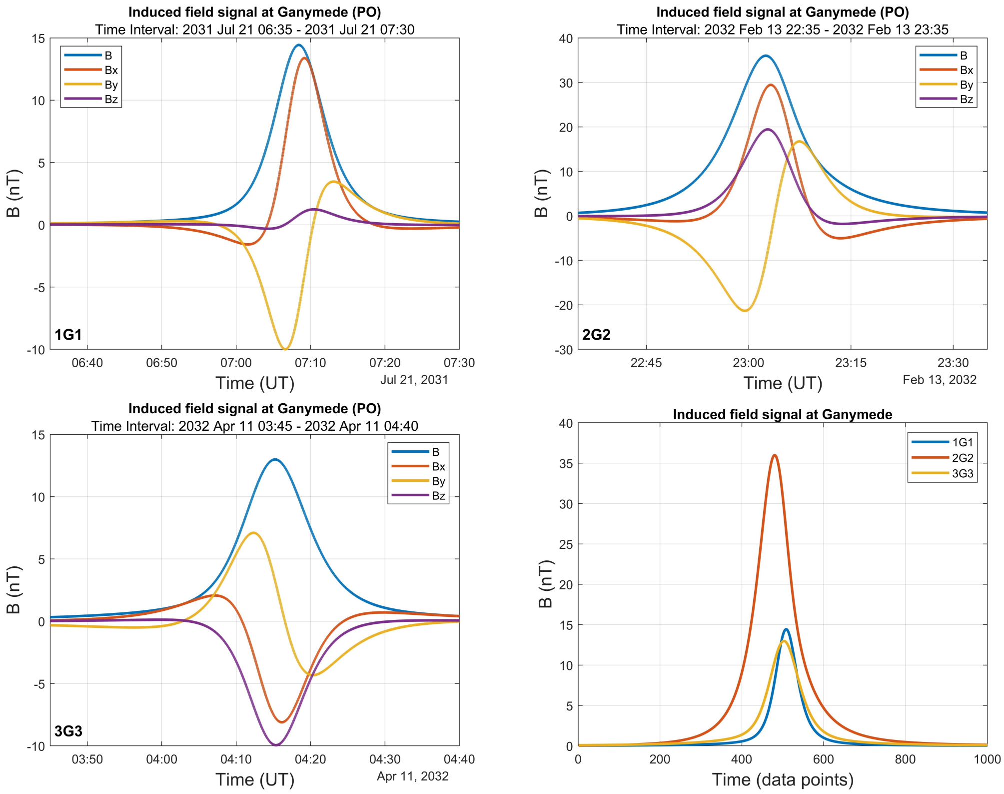

Figure 3. The induction field prediction for the JUICE flybys at Ganymede and their amplitude comparison.

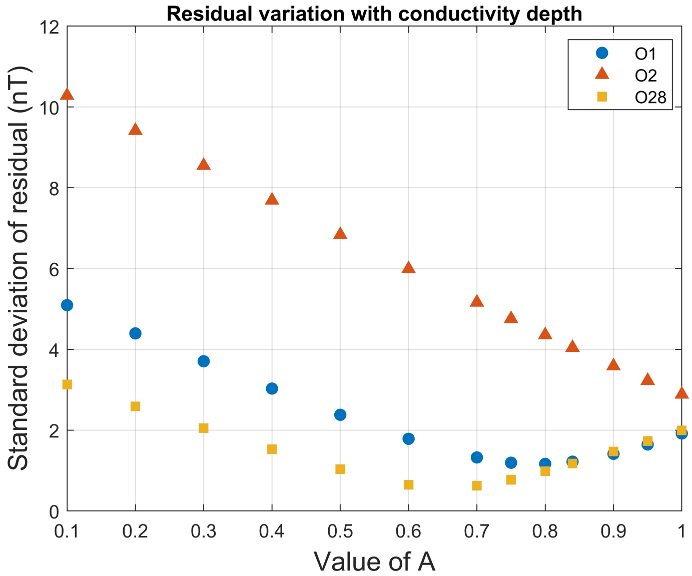

Figure 4. Standard deviation of the difference between the amplitudes of the induced signals at different depths and the quadrupole signal for the Galileo flybys.

Using our results, we expect JUICE to detect and provide us some ocean characteristics in its initial science phase. The 2G2 and 3G3 flybys work in principle similar to a ground observatory, given their locations as seen from the centre of Ganymede. While the flyby with a large magnitude of Jupiter's radial field should obtain high induction signals, the other with a lower radial field should provide little to no induction. It will be interesting to compare their real time data and use them to distinguish between the induced and quadrupole signals and obtain the field estimates. Adding to that the 1G1 flyby, we will be able to confirm the measurements by comparison, especially of 3G3 since they have almost the same inducing field signal.

Further on in the mission, the orbital phase of JUICE will clear our understanding and confirm many of the assumptions we have about the interior of Ganymede. The internal field will be modelled up to a high spherical harmonic degree and order using the global data distribution. The first 3 flybys of JUICE are hence important to understand the internal field sources of Ganymede. This will help to separate the fields efficiently and enable modelling of the interior in the orbital phase.

5 Conclusion

One of the important open questions for Ganymede concerns the ocean beneath the surface. Its confirmation, through electromagnetic induction studies will be one of the first highlights of the JUICE mission. In particular, the initial close flybys of Ganymede will clarify our uncertainties about its interior using magnetic field observations.

This study highlights the importance of the first 3 flybys of JUICE for induction studies and in preparation for the Ganymede orbital phase. We present the JUICE trajectories in Ganymede centered reference frames and compare them to the Galileo flybys. We then understand and estimate the induction signal observed at those locations due to the periodically varying background field of Jupiter. We find that the Galileo induction signal closely resembles the quadrupole signal indicating that the modelled quadrupole signal might actually just be the induction signal. In terms of predicting the induction signal during the JUICE flybys, we observe that the second flyby will result in a large induction signal while the other 2 flybys will help to differentiate between the induction and quadrupole signals. Though the first 3 JUICE orbits will not resolve the ocean characteristics independently in terms of depth and conductivity estimates, the work to date suggests a high conductivity and shallow depth for the ocean. Moreover, we will better understand the different sources for Ganymede's internal field which will prove important for field separation and modelling during the orbital phase of JUICE around the moon.

Data Availability Statement

The JUICE trajectories can be extracted from the SPICE kernals that are publicly available on the ESA website at https://www.cosmos.esa.int/web/spice/juice. The Galileo magnetometer data used here are publicly available on NASA's Planetary Data System (PDS) at the Planetary Plasma Interactions (PPI) node at https://pds-ppi.igpp.ucla.edu/search/?sc=Galileo&t=Jupiter&i=MAG. The model coefficients for Jupiter's internal field are available at https://doi.org/10.5281/zenodo.6564162.

Acknowledgments

The authors are supported by the Royal Society Funding with S.S by an Enhancement Grant, M.K.D. by a Research Professorship Grant and A.M by a University Research Fellowship. We acknowledge AGU's data policy.

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