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Radar Characterization of Salt Layers in Europa's Ice Shell as a Window Into Critical Ice-Ocean Exchange Processes

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Key Points:

- Salt layers formed through the process of cryoconcentration represent radar-detectable structure in Europa's ice shell
- Ice-penetrating radar measurements of salt layer thickness can help to determine if ice shell reservoirs are sourced through injection of ocean water
- The salinity of Europa's ocean can be bounded through combined constraints on maximum initial reservoir thickness and salt layer thickness

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The potential habitability of Jupiter's moon Europa has motivated two missions: NASA's Europa Clipper and ESA's JUpiter ICy moons Explorer (JUICE). Both missions are equipped with ice-penetrating radars which will transmit radio waves into the subsurface, recording reflections from interfaces defined by contrasts in ice shell dielectric properties. Assuming an $MgSO_4$ ocean, we show that salt layers, formed through the freezing of subsurface liquid water reservoirs, can be detected by ice-penetrating radar instruments on Europa Clipper and JUICE. Furthermore, because these features are thermodynamically stable within the minimally attenuating portion of Europa's ice shell, referred to here as the "pellucid region," they could produce brighter reflections than deeper liquid water interfaces. We demonstrate how ice-penetrating radar measurements of salt layer thickness could establish lower bounds on the parameter space of possible initial reservoir thickness and salinity, constrain the origin of reservoirs (ice shell melt vs. ocean injection), and—if sourced through ocean injection—the ocean salinity.

Plain Language Summary Europa, one of Jupiter's moons, is thought to have the conditions necessary to support life as we know it. Europa is going to be explored by two missions: NASA's Europa Clipper and ESA's JUpiter ICy moons Explorer (JUICE). Both missions will use radar to look beneath the icy surface to search for liquid water and structures formed from liquid water freezing. In this work we show that salt layers, mixtures of salt and ice formed when salty water freezes into a solid, can be seen by radars on Europa Clipper and JUICE. These layers could give us clues about the water's original size and saltiness, and how these underground reservoirs formed—either from melting ice or ocean water pushing up into the ice shell. This research could help us understand more about Europa's ocean and its potential for life.

1. Introduction

Jupiter's moon Europa is believed to harbor a global ocean beneath an icy crust tens of kilometers thick (Billings & Kattenhorn, 2005; Howell, 2021; Kivelson et al., 2000). Features observed at Europa's surface (e.g., domes, pits, and chaos) hint that shallow liquid water could have existed, or may still exist, within the ice shell at depths on the order of kilometers (Chivers et al., 2021, 2023; Collins & Nimmo, 2009; Culberg et al., 2022; Dombard et al., 2013; Manga & Michaut, 2017; Michaut & Manga, 2014; Schmidt et al., 2011). Liquid water within the ice shell is hypothesized to be emplaced by injection of ocean water through basal fractures (Manga & Michaut, 2017; Michaut & Manga, 2014) or by melting of the ice shell through diapirism, convection, and/or tidal heating (Collins & Nimmo, 2009; Schmidt et al., 2011; Soderlund et al., 2020). Extant water is a high priority astrobiological target and could be critical for understanding exchange processes between the ocean and ice shell; however, even if the ice con impurities that depress the freezing temperature, liquid water is only thermodynamically stable where Europa's ice shell is warm, above the eutectic temperature (Wolfenbarger et al., 2022a, 2022b).

Therefore, regardless of whether these water bodies are sourced from ice shell melt or from ocean injection, they will thermally equilibrate with the surrounding ice shell and trend toward freezing (Chivers et al., 2021; Lesage et al., 2022). As these water bodies freeze, the remaining liquid decreases in volume, causing impurities in the water to concentrate and evolve into a progressively richer brine (i.e., cryoconcentration). Freezing concludes

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Key Points:

- We present systematic measurement results of the frequency-dependent complex permittivity of ilmenite-bearing lunar regolith analogs
- We make our measurements over a broad range of frequencies between 100 MHz and 8.5 GHz
- These results provide new frequency-dependent constraints on the attenuation of radar in the lunar regolith

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Determination of Broadband Complex EM Parameters of Powdered Materials: 2. Ilmenite-Bearing Lunar Analogue Materials

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Abstract We present systematic measurements of the frequency-dependent complex dielectric permittivity of lunar regolith analogue samples with increasing amounts of the mineral ilmenite along with Bayesian model fits using a one-pole Cole-Cole model. We use these results to calculate a lower bound for the attenuation of radar signals in dB/m based on ilmenite content. We compare our measurement results with previous efforts to use Earth-based radar maps to calculate the effect of ilmenite on radar attenuation and find that they are in agreement. We also revisit the ilmenite-dependent loss tangent relationships of Carrier III et al. (1991) and demonstrate the significant frequency-dependent effect of ilmenite content on signal attenuation as well as the effect of minor variations in loss tangent for depth-to-feature determinations. The results presented here are the first systematic laboratory measurements investigating the effect of ilmenite on radar attenuation and show future promise for the application of dielectric spectroscopy, or the identification of materials based on their electromagnetic properties in the radar and microwave range.

Plain Language Summary We measure and model the electrical parameters that are responsible for absorbing and reflecting radar signals in powdered rocks that have a similar composition to the surface of the Moon. We show that knowing the abundance of the mineral ilmenite is important for knowing how much of the signal gets absorbed. We also show that the frequency (or wavelength) of the signal is important. We do this by measuring samples with more and more ilmenite at different frequencies. We find that adding more ilmenite causes the material to absorb more signal. By knowing how much more signal at specific frequencies gets absorbed with increasing ilmenite, we can better understand both the surface and below the surface of the Moon using radar data. For example, if we see in radar data that something might be buried beneath the surface of the Moon, we can use this information to try to find out how deep it is.

1. Introduction

Earth-based, orbital, and ground radar systems in addition to microwave radiometers have all been used or are being used on the Moon to study its subsurface structure and composition; however, the lack of information on the complex relative permittivity ($\epsilon_r^* = \epsilon_r' - i\epsilon_r''$) and loss tangent ($\tan\delta = \epsilon_r''/\epsilon_r'$) of the surface and near-surface materials hinders detailed quantitative analysis of lunar radar data. Such analysis includes determining the precise depth of radar-detected subsurface features as well as refining estimates of the abundance of subsurface materials such as the mineral ilmenite ($(Fe,Mg)TiO_3$), which is known to attenuate radar and microwave signals (e.g., B. A. Campbell & Hawke, 2005; B. A. Campbell et al., 1997; Ghent et al., 2005; Fa & Wieczorek, 2012; Schaber et al., 1975) and may be responsible for bright basal radar reflections at the south pole of Mars ((Grima et al., 2022)). Ilmenite is the most abundant oxide mineral in lunar rocks, with ilmenite content being proportional to the amount of TiO_2 in the originating magma (Papike et al., 1991). Significant work has made use of the fact that ilmenite attenuates radar signals to conduct geologic studies of, for instance, lava flow emplacement dynamics and regolith thickness variations in the lunar maria (e.g., Morgan et al., 2016). For example, Figure 1 shows two Earth-based same-sense circular polarization (SC) imaging radar datasets (P band (430 Mhz, 70 cm) and S band (2.38 GHz, 12.6 cm) overlain on a shaded terrain image in Mare Imbrium. Same-sense, or depolarized, radar refers to the circular polarization state of the backscattered radar signal. For the signal to return to Earth with the same polarization state as the emitted signal, either non-specular (diffuse, not mirror-like) surface reflection or volumetric scattering (multiple scattering events in a medium with scatterers) is required. SC radar

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Revising the Basal Permittivity of the South Polar Layered Deposits of Mars With a Surficial Dust Cover

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Key Points:

- We re-assess the radar inversion of the south polar layered deposits (SPLD) basal permittivity by incorporating the recently characterized dust layer mantling the ice
- The inverted basal permittivity is highly sensitive to the property of the surficial dust layer
- Better characterization of the dust layer is necessary in discriminating the nature of the SPLD bright basal reflector

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Bright basal reflections from the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) have been proposed to be consistent with permittivities characteristic of a wet material beneath the south polar layered deposits (SPLD). The characterization of a recently formed impact crater highlight the existence of a several meters thick ice-poor layer associated to a unit blanketing a large portion of the SPLD. We revise the radar propagation model used to invert the basal permittivity by including a surficial thin layer. We find that the inverted basal permittivity is highly sensitive to the properties of such a layer, with solutions ranging from common dry rocks to an unambiguously wet base. We advocate toward a better characterization of the surficial cover to assess the wet or dry nature for the base, and possibly reconcile most of the literature on the topic.

Plain Language Summary A localized bright radar reflection has been detected from the base of the Southern Martian polar cap. This reflection has been attributed to salty water infiltrating the material present beneath the ice. However, this result is not yet reconciled with other radar analyses and a debate has emerged on how liquid brine could be sustained at Martian conditions. Recently a 5-m thick layer of dust blanketing the surface of the ice cap has been detected from a recent crater excavation. This layer would act like a thin coating material that alters the apparent property of what is seen through a coated glass. At radar wavelengths, it can significantly modify the basal composition inferred from radar echoes. The bulk property of this layer is still unknown and a better characterization is necessary to inform the debate over a wet or dry base below the ice cap.

1. Introduction

Anomalous, isolated bright basal reflections have been detected at Planum Australe, beneath the south polar layered deposits (SPLD) of Mars by the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) onboard the Mars Express spacecraft (Lauro et al., 2020; Orosei et al., 2018). There, the normalized basal echo (Ψ), defined as the basal echo strength relative (P_{ss}) to the surface echo strength (P_s), reaches positive median values, that is, the buried interface is brighter than the surface. Under the assumption of signal propagation through a homogeneous vertical column of 205 K SPLD ice with 10% dust content, Orosei et al. (2018) derived a median real basal permittivity of 30, 33, 22 at 3, 4 and 5 MHz, respectively. The results at 4 MHz are usually those considered for further investigation because they derived from a more statistically representative set of measurements (Lauro et al., 2019, 2020; Orosei et al., 2018). Laboratory measurements and dielectric models indicate that such high permittivity on Mars could only be reached in a mixture including salty liquid water such as perchlorate brines (Mattei et al., 2022; Stillman et al., 2022). Frequency dispersion of Ψ between the 3, 4, and 5 MHz MARSIS frequency bands argue for a loss tangent of the ice higher than previously considered, leading to basal permittivity of ∼40 when attenuation is accounted for in the vertical propagation model (Lauro et al., 2022).

The hypothesis of a wet basal material at the SPLD is not reconciled with current understanding of polar geothermal state, however. Basal liquid water is thought to be unsustainable under the present-day Martian geothermal conditions, even with large amounts of salts that would depress the ice melting point (Sori & Bramson, 2019). The southern highlands are inferred to have a low geothermal heat flux (Broquet et al., 2021; Ojha et al., 2021) and thermophysical evolution modeling from the known composition of the SPLD does not predict conditions for sustainable basal liquid water to be reached.