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Bright prospects for radar detection of Europa's ocean

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ABSTRACT

The surface of Europa has been hypothesized to include an ice regolith layer from hundreds of meters to kilometers in thickness. However, contrary to previous claims, it does not present a significant obstacle to searching for Europa's ocean with radar sounding. This note corrects prior volume scattering loss analyses and expands them to includes observational and thermo-mechanical constraints on pore size and regolith depth. This provides a more physically realistic range of potential ice-regolith volume-scattering losses for radar sounding observations of Europa's ice shell in the HF and VHF frequency bands. We conclude that, for the range of physical processes and material properties observed or hypothesized for Europa, volume scattering losses are not likely to pose a major obstacle to radar penetration.

1. Introduction

In his 2004 *Icarus* note, *Dim prospects for radar detection of Europa's ocean*, Eluskiewicz attempted to fill a perceived gap in the published analyses of radar attenuation in Europa's ice crust by providing a quantitative treatment of volume scattering by spherical pores in an ice regolith layer (Eluszkiewicz, 2004). Using a scattering optical depth approximation to model volume scattering losses and compaction rates to constrain regolith thickness, he argued that layers as thin as 1 km with porosities as low as 1 % would produce scattering losses great enough to pose an "insurmountable obstacle" to searching for Europa's ocean using radar sounding. This note, which is a response to Eluskiewicz's 2004 original, presents evidence that his analysis was "unduly pessimistic" (as he allowed it might be Eluszkiewicz, 2004) by providing corrected scattering calculations and improved geophysical constraints on regolith depths for the 2004 sounding scenario. Radar sounding has long been proposed as a method of sensing the deep subsurface of icy satellites (Blankenship et al., 1999; Chyba et al., 1998; Kofman et al., 2010). It provides the potential of sensing kilometers below the surface without landing and is especially attractive for exploring icy moons because of ice's near-total transparency to radar at low temperatures (MacGregor et al., 2007; Moore, 2000). Two current missions; NASA's Europa Clipper and ESA's JUpiter Icy Moon Explorer (JUICE) are planned to explore the subsurfaces of Europa and Ganymede using ice penetrating radars (Bruzzone et al., 2013; Phillips and Pappalardo, 2014). These are the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) operating both a 60 MHz VHF band and 9 MHz HF band and the Radar for Ice Moon Exploration (RIME) operating a 9 MHz band respectively (Blankenship et al., 2009; Bruzzone et al., 2013; Grima et al., 2015). Given this continued interest in using radar sounding to detect shallow subsurface water and a global ocean at Europa (Schmidt et al., 2011), this updated (and more physically appropriate) implementation of the Eluszkiewicz (2004) analysis, along with its attendant revisions of his original conclusion, is relevant, timely, and needed for planning radar observations at Europa.

2. Scattering losses

In his original note, Eluszkiewicz modeled scattering losses in Europa's ice regolith as a layer of of ice with thickness d populated by vacuum-filled pores with radius r and porosity (by volume) of ϕ, which lay above a layer of solid ice and a liquid ocean (Fig. 1A). To estimate losses from propagating through the regolith, he implemented a model based on the scattering optical depth τ_s for a collection of Mie scatters (Eluszkiewicz, 2004). However, his reported scattering efficiency of $Q_s = 2.2$ for vacuum pores (index of refraction values of $n_{pore} = 1$) within an ice shell ($n_{ice} = 1.78$) would only be possible for pore radii greater than 3 m (Fig. 1B) rather than the 1 m claimed in the 2004 note. This error results in a dramatic overestimate of scattering losses. We address this error by redoing the calculations from original note using the correct

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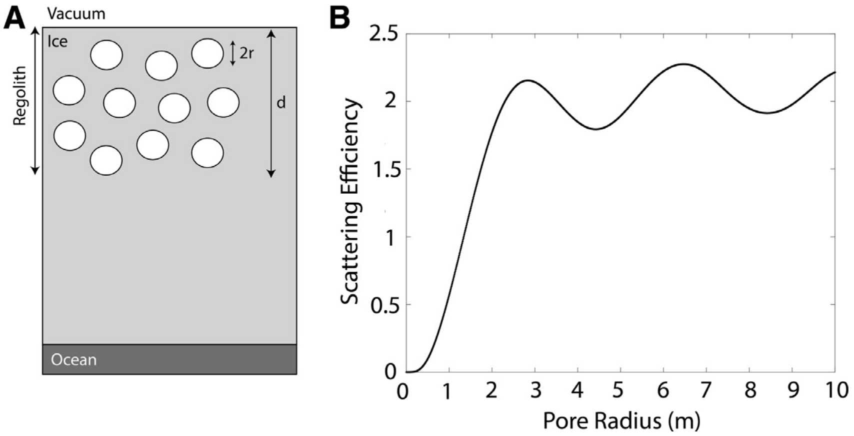

Fig. 1. (A) Cartoon of a radar scattering ice regolith composed of pores with radii r and porosity ϕ in a layer of thickness of d above solid ice and a liquid ocean. (B) Scattering efficiency for the 50 MHz radar sounding case considered by Eluszkiewicz (2004)

scattering efficiencies for a range of potential pore radius (r) and porosity (ϕ) values.

Following Eluszkiewicz, we calculate the scattering optical depth (τ_s) for the ice regolith layer as

$$\tau_s = \frac{3\phi d}{4r} Q_s \tag{1}$$

and the two-way scattering losses L as

$$L = e^{-2\tau_s}. \tag{2}$$

We calculate Q_s as a function of r, n_{pore}, n_{ice}, and the radar wavelength (λ) by using a numerical Mie scattering solver from Ulaby and Long (2014).

3. Regolith properties

According to current theories, Europa could possess one of two types of regolith: impact-generated, or tidal (Moore et al., 2009). For the former, analogies are fairly well-established, especially those based on Earth's Moon (Moore et al., 2009). For tidal regolith, there are no good analogs and it is not clear that such a regolith even exists. However, if it does exist, it can be expected to be less fractured than the impact regolith, because the surface layer containing impact regolith is also affected by tidal stresses (Moore et al., 2009). In his original note, Eluszkiewicz did not distinguish between impact-generated and tidally-generated ice regoliths (which will have different ranges of potential depth, porosity, and radius values) and invoked a single regolith compaction vs generation model to constrain potential regolith depths (Eluszkiewicz, 2004). To address the limitations (and geologically unrealistic corner-cases) of this model, we treat impact and tidal regolith independently and place improved observational or theoretical constraints on the properties of each.

For impact regolith, Black et al.'s used Earth-based radar observations of Europa to estimate near-surface ice-regolith pore radii between 5 cm and 75 cm and porosities up to 80 %(Black, 2001; Black et al., 2001) . However, because impact regolith is expected to extend no more than several meters below the surface (Moore et al., 2009) (Black et al. estimate less than a meter (Black, 2001)), the two-way losses from impact regolith are expected to be between 10^{-3} dB (for $d = 0.5$ m, $\phi = 0.8$, and $r = 5$ cm) and 16 dB (for $d = 5$ m, $\phi = 0.8$, and $r = 75$ cm) at 60 MHz and between 10^{-6} dB (for $d = 0.5$ m, $\phi = 0.8$, and $r = 5$ cm) and 0.03 dB (for $d = 5$ m, $\phi = 0.8$, and $r = 75$ cm) at 9 MHz. Much of this range is negligible and none of these values pose an "insurmountable obstacle" to ocean detection.

For tidal regolith losses, d, r, and ϕ are unknown parameters. However, the first can be constrained based on the latter two. At depth d, ice will creep to close any pores, limiting the depth of the regolith to this closure depth. At the closure depth and below, the creep rate for ice will exceed the tidal strain rate that opens pores (and creates tidal regolith). Since the creep rate of ice is temperature dependent, this condition will be met for ice above a critical temperature (T_c) of ~ 170 K (Petrenko and Whitworth, 1999). Therefore, estimating the regolith depth is really a matter of determining the thermal profile of the cold, upper portion of Europa's ice crust and identifying the depth to which temperatures remain below T_c. We follow the approach that Sleep (2012) applied to Enceladus and solve for a profile that satisfies Fourier's Law

$$Q = -k\nabla T \tag{3}$$

where Q is heat flow, T is the ice temperature, and k is the thermal conductivity. For k, we use the thermal conductivity model for porous ice from Luikov et al. (1968) with coefficients of 0.005 for microrelief-particle size ratio, $k_k = 1.75$, and $k_n = 0.75$, and estimates of Europa's heat flow (Pappalardo et al., 2009). This approach assumes that heat flow is constant with depth, as tidal heat production is expected to be significant only in the lower and warmer part of the ice crust (Pappalardo et al., 2009; Sotin et al., 2009). We use the resulting temperature profiles to estimate the closure depth (and therefore regolith depths) shown in Table 1. The corresponding two-way scattering losses at the 60 MHz VHF band center frequency of REASON and 9 MHz HF band center frequency of both RIME and REASON are shown in Tables 2 and 3 respectively. These match or exceed the full range of pore radius (1 mm to 1 m) and porosity (1% to 5%) values considered by Eluszkiewicz (2004). We see that the prohibitive losses invoked in that note (e.g. "ten orders of magnitude") only occur in the VHF band (the frequency range considered in the 2004 note) for the corner case of regoliths with the largest radius values in the parameter space. Although the meter-scale pore radii considered are geologically implausible (Moore et al., 2009), porosities as high as 20 % for smaller radius pores (in the sub-decimeter range) are much more likely (Moore et al., 2009) but result minimal losses (Table 2). In the HF band all potential losses (including implausible corner cases) are trivial (Table 3).

4. Discussion

These revised analyses show that scattering losses can be expected to be modest in the likely case that meter-radius pores