ON RADAR SOUNDING APPLICATIONS FOR ENCELADEAN ICE

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1. INTRODUCTION

Though recent observations by the Cassini spacecraft have shed new light on the surface of Enceladus, Saturn's sixth-largest moon, the mechanisms that drive its resurfacing remain unclear, a fact that may be rectified through discovery of the states and processes of its subsurface. Radar sounding is a very useful tool in characterizing the depth-wise dimension of its target body. The depth of Enceladus' ice shell, its structure, thickness, and the nature of its possible subterranean reservoir or ocean have yet to be determined. Low temperature water ice is very transparent at radar wavelengths [9]; conveniently, Enceladus' surface is dominated by water ice, with some CO2 and a few other light organics [3]. At a basic level, Enceladus' surface can be broken up into two basic regions: the south polar "tiger stripe" terrain (TST), and the rest of the moon. The composition of the TST is largely crystalline ice, with CO2 and simple organics trapped along the tiger stripes themselves. Most likely in this region, the CO2 is complexed with the water ice, with free CO2 existing north of the tiger stripe terrain, where temperatures are lower. There are several hypotheses leading to an explanation of the activity seen at the moon, including strike-slip faulting, ridge spreading, and the possibility of a convecting ice layer, which "carries" mobile surface lids. Certainly, radar sounding of a thick ice shell, like the one that may exist at Enceladus, could prove difficult, but with enough power, it is not implausible. Indeed, sounding would not only characterize the ice structure, but may additionally be used to observe the possible convection that occurs beneath the surface by detecting the topsides of the individual upwellings, or the convective layer as a whole at the interface. McKinnon (2005) [9] suggests this possibility at some of the Jovian satellites.

2. ON THE EFFECTIVENESS OF RADAR SOUNDING

The usefulness of radar depends on the ability to penetrate the surface. As is obvious from the continuous developments in technology and design requirements for radar systems, there are many issues that must be considered prior to the application of such a system. These issues include the physical appearance of the observable surface, and in Enceladus' case, one must take into account the layering and ridges and other features formed during resurfacing events; the size of the radar spot on the surface; reflection off of steep-relief features due to highly off-nadir orientation, such as ridges that may occur on the surface; and, among others, the actual ability to penetrate through the surface deep enough to characterize interior processes. And so, although there are many issues, we focus on the plausibility of penetrating the Enceladean ice crust.

The rate of attenuation of electromagnetic waves in ice was given by Evans (1965) (in dB m^{-1}):

$$\alpha = 0.129\sqrt{\varepsilon_r}\, f\left[\sqrt{(1+\tan^2\delta)}-1\right]^{1/2} \qquad (1)$$

The term $\tan\delta = \varepsilon_i/\varepsilon_r$, where ε_i and ε_r are the imaginary and real parts of the ice's permittivity, or dielectric constant. Also, f is the frequency in MHz. Moore (2000) indicates that this expression may be simplified by assuming that in low loss materials, such as ice at radar frequencies, $\delta \ll 1$ [10], so it can be re-written as

$$\alpha = 0.0009\sigma. \qquad (2)$$

Additionally, Corr, et al. give the ice conductivity σ as [5]

$$\sigma = \sum_{i=1}^{3} C_i \exp\left[\frac{E_i}{k}\left(\frac{1}{T}-\frac{1}{T_r}\right)\right] \qquad (3)$$

Equation (3) shows that the electrical conductivity of ice can be expressed in terms of the temperature of the ice and the varying number of impurities within it (C). Radar losses also occur at polarization interfaces; additionally, scattering occurs when the wave interacts with a material of different impedance.

To calculate an estimate of the radar absorption in the ice, essential data are needed: surface temperature, the ice temperature profile, and the chemical composition of the ice. Chyba et al. estimated the temperature profile of Europan ice with the expression

$$T(z) = T_s \exp\left[{}^{z}\!/_{h}\right] \qquad (4)$$

To compute the temperature profile in Enceladus' ice, we consider Cassini CIRS data that showed a surface temperature variation between approximately 65 K and around 85 K (global and south polar terrain, respectively). The temperature T_b at the bottom of the ice layer is taken to be 273 K [2], and the thickness of the ice shell is taken to be between 30 and 90 km [2], assuming a convective scheme. We have modeled temperature profiles for b = 30, 50, 70, and 90 km. In terms of ice conductivity (Eqn. (3)), Andersson, et al. (2004) give the relevant values as C = 4.5 $\mu S\ m^{-1}$ and activation energy (E) of CO_2-complexed water ice as 0.26eV [1]. Figure 1a shows the temperature profile of Enceladus with an ice layer with a depth of 90 km, with surface temperature between 65 K and 85 K. Also plotted is a scheme in which the ice layer is topped by a 5 km "convective lid", a scheme that we have been studying. Barr (2008) notes that convection will start for an ice crust thickness of at least 5 km.

For the temperature profiles calculated, we can compute radar wave attenuation using Equation (1) above (or use the approximation in Eqn. (2)). As noted in Chyba et al. (1998), the ice activation energy drops by more than half at colder temperatures, i.e., from 0.571 eV to .23 eV at temperatures below 220 K. This means that the top few kilometers of ice may be relatively clear, assuming Cassini observations of the surface water ice and lack of contaminants carries throughout the upper layers of the ice. Figure 1b shows the attenuation of radar waves in ice (in dB/m) for the ice layer.

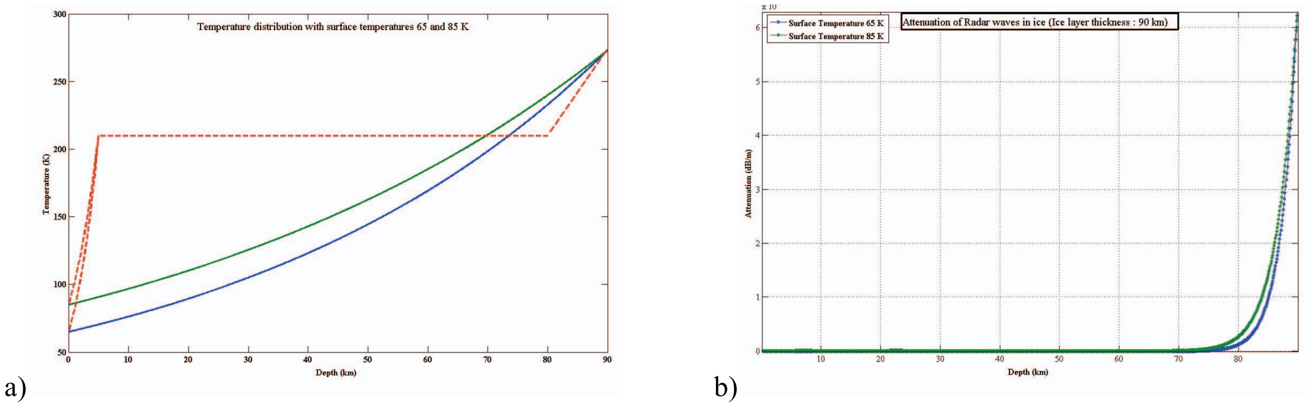

Figure 1. Simple models. a) Green (65K) and blue (85K) (solid) lines show the temperature distribution in an ice layer with a 90-km thickness from surface to base (an upper limit). Red dotted line shows the profile including a 5-km thick frozen ice "cap" with an isothermal convecting layer beneath it. b) The attenuation of a 50 MHz radar signal in ice, assuming relatively clean Enceladean surface ice.

3. SOUNDING DEPTH AND GOALS FOR RADAR SOUNDING AT ENCELADUS

Chyba et al. use the radar equation (Gudmansen, 1971)

$$\frac{P_r}{P_t} = \frac{G^2 \lambda^2 L_{vi}^2 L_{iw} g_r}{(4\pi)^2 \left[2(h_a + b)\right]^2 L_{2i}} \qquad (5)$$

to estimate the possible sounding depth of a radar at Europa. The Europan ice crust is similar to that of Enceladus, i.e., it is mostly "dirty" water ice. Enceladus features colder surface temperatures and likely a thicker ice crust, but a similar approximation as the one completed by Chyba et al. (1998) could be modeled for Enceladus to determine the usefulness of a radar there. Chyba et al. suggest that a radar at Europa would most likely require a detection limit of 50 dB (with a possible increase to 80 dB). Based on current observations of the Enceladean surface, the water-ice dominated crust would feature little absorption losses until the radar waves penetrate into the subsurface layers that contain what has been hypothesized to be a possible water reservoir or a rocky-ice sublayer. At present, we are in the beginning stages of modeling a system using Equation (5).

There are a fair few phenomena at Enceladus that could be uniquely addressed by radar sounding. The ice lid thickness at Enceladus has been difficult to characterize, and though it has been constrained to approximately 30 to 90 km at the south pole, powerful radar technology could be applied to detect the ice thickness (with enough penetration strength). Additionally, the presence of water plumes at the south pole has spurred the discussion of a possible water reservoir or ocean supply. Sounding of the area could shed light on the source of the water (and other species) that has been detected emanating from the region. It has been hypothesized that the subsurface may consist of rock, instead, which may also be sounded. Is the subsurface of the south polar terrain the same or different from the rest of the moon? The question of characterization of the plume reservoir could be answered with a powerful enough sounder. Indeed, another issue altogether is the mechanism that actually drives the plume formation. This group, as well as Barr (2008), and others have been studying the possibility of mobile lid convection (i.e., convection in the icy subsurface) as a cause; McKinnon (1999) suggests that convection cells beneath the surface of Europa may be detected by a radar sounder, as warmer upwelling would image differently than would colder downwellings – this may be true at Enceladus also. Additionally, signal losses could also indicate useful information about surface and subsurface impurities, including correlating Cassini's recent detection of salt [10].

4. ONGOING AND FUTURE STUDY

Radar sounding of Enceladus' ice crust and subsurface would contribute greatly to the understanding of the clearly dynamic but little understood moon. As evident in this paper and others, the range of radar penetration of the target ice sheet is of great importance. Moore (1999) concludes that calculation of radar absorption of Europan ice is poorly constrained at present and could be improved through laboratory testing. Surely, the same applies to Enceladean ice, and for that reason, this research team intends to conduct experiments on laboratory ice at the Jet Propulsion Laboratory in the spring of 2010 to better constrain the properties and behaviors of ice at conditions relevant to Enceladus. A radar investigation of Enceladus would provide a chance of characterizing the moon's subsurface structure and therefore its internal dynamics, and the relevant geophysical interface, whether it's an ocean, convection cells, or a rocky sublayer. It could also assist in the discovery of possible convecting cells as the mechanism driving the TST activity, as hypothesized by McKinnon (2005) [9] for the Jovian moons. And so, in addition to laboratory work, our intention is to continue to model the radar applicability at Enceladus, taking into account different ice thicknesses, compositions, rheologies, etc. Since Enceladean ice has been characterized as relatively clean, it is possible that application of radar at Enceladus could be compared with the generally successful radar sounding of ice sheets on the Earth.

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