Very-Low-Frequency (VLF) Radio Sounding to Probe Brittle-Lid Temperatures on Europa and Enceladus

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Synopsis

- **Brittle-lid thicknesses are key information for modeling ice shell dynamics.**
- **Dielectric properties of impure (chloride-laden) water ice (Ih) vary strongly with temperature at 10-100kHz frequency.**
- **Radio waves at 10-100 kHz are therefore reflected by 'warm' ice at depth in a brittle lid.**
- **For lid thicknesses of ~ 0.1 – 7 km and radio frequencies of ~ 10-100 kHz, reflections from the ice/vacuum interface and the subsurface interfere, so…**
- **Radio reflection from the lid varies with lid thickness.**
- **Reflection measurement using 2 or more small spacecraft may be feasible.**
- **Planetary radio emission and plasma-wave environments at Europa and Enceladus may be challenging, or might present opportunities.**

Science Background

- **The length- and time-scales of processes that resurface icy moons are critically uncertain.[1-4]**
- **Heat flow through the coldest, uppermost layer of an icy moon must be conductive (the ice being too cold to convect on relevant time-scales).[1]**
- **Thickness of the so-called brittle lid is a key parameter for modeling mechanics of ridge formation[2,3] and spreading and initiation of subduction.[4]**
- **We aim to enable remote sensing of brittle lid thickness by measuring the temperature gradient within the upper hundreds to thousands of meters of ice.**

Next Steps

Development and comparative evaluation of mission concepts based on the physics shown here – possibly including:

(1) active sensing using 1 or more small spacecraft,

(2) passive sensing utilizing planetary radio emission or local plasma-wave excitation, or

(3) (just possibly) sensing on a lander.

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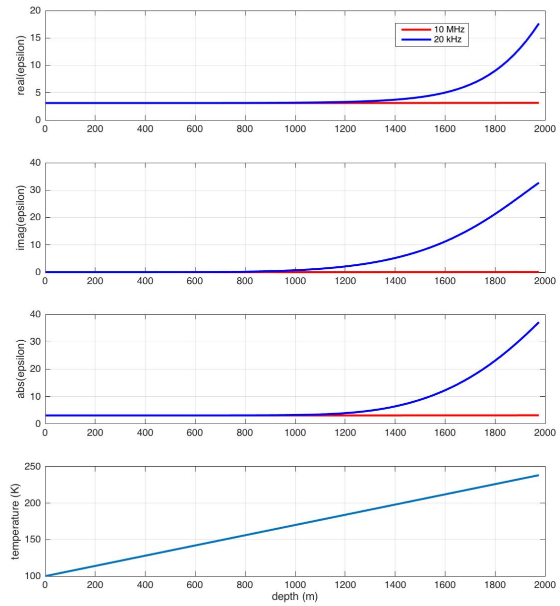
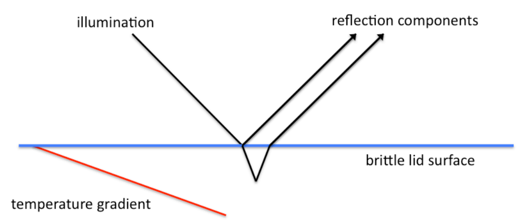
VLF Dielectric Properties of Impure Ice vs. Temperature



Real and imaginary parts (upper two panels) and magnitude (third panel) of the complex relative permittivity of impure water ice (50 micromolar chloride concentration)[5,6], versus depth, in a 2 km-thick brittle lid model with a linear temperature gradient (lower panel). Note strong dielectric variation at 20 kHz, vs. little variation at typical radar sounding frequencies (e.g., 10 MHz).

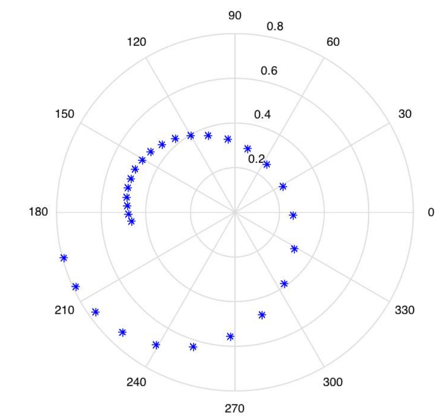


Strong dielectric variation with depth leads to reflection from the subsurface, in addition to that from the dielectric transition at the ice/vacuum interface. Wavelengths near 20 kHz are only a few kilometers in ice, so the two reflection components interfere, yielding an overall reflection that varies with the depth of the subsurface reflection.

Some Advantages at VLF

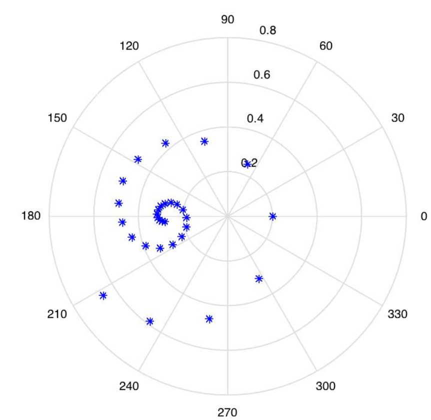
- Free-space wavelengths of 10-20 km are long compared to vertical relief on surfaces of Europa or Enceladus – so effects of scattering by surface roughness are nil, or nearly so.
- The same wavelengths in ice are short enough for interference between reflections from the ice surface and those from the subsurface -- interference causes the overall reflectivity to vary usefully with the temperature gradient (see column at right), and thus with brittle lid thickness.
- The rich assortment of electromagnetic radiation near icy moons (freely propagating, or plasma waves)[7] may offer illumination (or interference).

Reflection from a Linear Temperature Gradient (with Depth) in Ice



Reflection coefficients (magnitudes and phases, on a polar plot) at vertical incidence on the ice for which dielectric properties at shown at left, for 20 kHz frequency. (Computed using numerical integration of coupled first-order ordinary differential equations for electric- and magnetic-field components parallel to the ice surface, based on the method of Born and Wolf[8] .)

Each point indicates a distinct value for the thickness of ice in which the temperature gradient is linear – beginning (at reflection magnitudes near 0.8 and phase 195 degrees) with 250 m thickness, and proceeding in 250 m increments to 7 km thickness.



Reflection coefficients as above except at 90 kHz frequency, and with depths beginning at 100 m (at magnitude near 0.65 and phase near 210 degrees) and proceeding in 100 m increments to 3000 m thickness.

The choice of 90 kHz is motivated by observations of the typical plasma frequency near Europa, which varies from 80-100 kHz[7]. Thus observations of freely propagating electromagnetic waves reflected from the European surface would be limited to frequencies near this frequency or above. 90 kHz reflection varies usefully only for lid thicknesses up to perhaps 2 km, in contrast to 20 kHz reflection (which may serve to probe thickness up to ~6 km). 90 kHz reflection may serve to find 'hot spots', where warm ice occurs relatively near the surface.