Magnetotelluric Sounding of Europa's Ice Shell. R.E. Grimm[1], G.T. Delory[2], J.R. Espley[3], and D.E. Stillman[1], [1]Planetary Science Directorate, Southwest Research Institute, 1050 Walnut St. #300, Boulder CO 80302, grimm@boulder.swri.edu; [2]Space Sciences Laboratory, University of California Berkeley, Berkeley CA; [3]Goddard Space Flight Center, Greenbelt, MD.

Introduction. Electromagnetic (EM) sounding has revealed subsurface oceans on the three icy Galilean satellites [1-3] and a magma ocean on Io [4]. An additional objective for a Europa Lander is to detect any water layers within the ice shell [5]. However, a magnetometer alone is insufficient for this task, because the source strength and geometry are indeterminate at the higher frequencies required to resolve intra-shell structure. By measuring the horizontal components of the electric field and comparing them to the magnetic field, electrical conductivity structure can be determined without any additional information This is the magnetotelluric method, which has been used on Earth for more than a half-century [6].

EM Methods. We parameterize the EM response by the apparent conductivity σ_a, which is the conductivity of uniform half-space having the same EM response as the target. Then EM sounding can be considered simply in terms of exploiting the skin-depth effect to invert true conductivity $\sigma(z)$ from $\sigma_a(f)$, where z is depth and f is frequency. Alternatively, the complex impedance Z can used when considering measurement methods: the familiar Ohm's Law Z=V/I calls for two independent quantities to determine the impedance, and the same applies to EM sounding.

There are two approaches to determining Z that are relevant to Europa [7,8]. The Transfer Function (TF) compares the magnetic field at or near a planetary body (the sum of source and induced fields) to a known, distant source field. The Galileo induction studies can be considered a special case of the TF, wherein the source field is modeled a priori [9]. In the Magnetotelluric Method (MT), the horizontal electric field E and the magnetic field B are used to form Z. Because E supplies the required second piece of information, the source field is not needed separately.

EM Sources at Europa. The synodic rotation of Jupiter's magnetic field creates a "kinematic" time-varying signal that is the largest induction source. Additional signals are at the orbital period and the harmonics of the synodic period [10]. We show below that these low frequencies (~10^{-6}Hz), while well-suited to investigating the subsurface ocean, cannot resolve structure within the ice shell. Higher frequencies are required, which can be exploited from magnetospheric waves [e.g. 11-13]. Now the MT method must be applied because the source amplitude amplitude and phase are not independently known from the induction response near the body. Elimination of plasma effects is actually more straightforward, because the inductive parts of B and E must satisfy certain dispersion relations [14] and responses to strong conductors like briny water layers have distinct forms (Fig. 1).

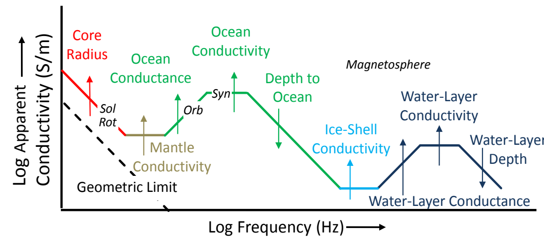


Fig. 1. Schematic broadband EM sounding for Europa. Apparent conductivity is the conductivity of a halfspace having the measured EM response at the specified frequency. All segments can be imagined extending over the whole bandwidth so vertical shifts with varying layer thicknesses and conductivities determine which are visible and which are obscured. Relevant EM sources are indicated but have effects beyond their marked locations.

Europa Response. We calculate a suite of induction models for a radially symmetric Europa [7]. The reference model is water-layer depth, thickness, and conductivity 3 km, 2 km, and 1 S/m, respectively; ice-shell thickness and conductivity 10 km and 10^{-4} S/m, respectively; ocean thickness and conductivity 100 km and 1 S/m, respectively, and mantle conductivity 10^{-3} S/m. We confirm that ocean thickness and conductivity both strongly affect σ_a at the kinematic frequencies (Fig. 2), and that the spread in frequency is useful in separating the "equivalence" in these two quantities. There is no response to these parameters at magnetospheric frequencies, as these signals negligibly penetrate the ocean. Both the kinematic and magnetosphere signals have some sensitivity to ice-shell thickness, with opposite, complementary, dependencies.

In contrast, the kinematic frequencies have no sensitivity to the depth or thickness of a water layer in the ice shell at nominal conductivity and only begin to respond when conductivity is very high. However, clear responses are evident in the magnetospheric band for all of these properties; in fact, diagnostic responses are mostly bounded between 0.01 and 100 Hz. Depth and conductivity are well-determined; resolution o fthickness improves for shallower, thinner, and less conductive water layers, or a thicker ice shell.

In Situ Measurement. A fluxgate magnetometer is already specified for a Europa lander [5], so a complete MT sounder only requires adjustment of sam-

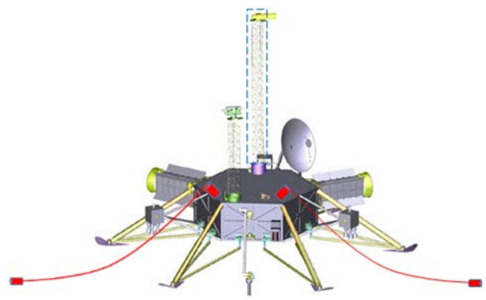
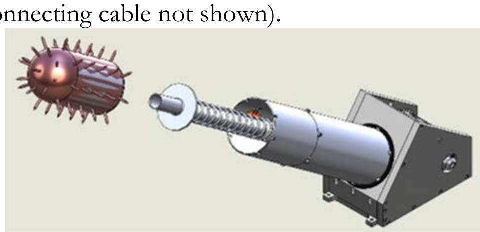


Figure 2. Top: Europa Magnetotelluric Sounder (EMS) sensors comprise magnetometer on vertical boom (dashed blue box; specified by ref. 5) and two remote electrodes (red cylinders on ground) that have been deployed by spring launchers (red cylinders on lander) to ~20 m distance (not to scale). Bottom: Drawing of electrode and spring launcher (connecting cable not shown).



pling rates and addition of an appropriate electric-field measurement (Fig. 3). The fluxgate can be reconfigured to sample up to a few hundred sps in order to measure magnetospheric waves up to 100 Hz. The electrometer needs a long baseline (up to a few tens of meters) between the electrodes or voltage probes in order to achieve the necessary voltage SNR from the ambient electric field ($\Delta V = E \Delta x$). To attain this separation, the electrode can be spring launched and ballistically deployed (Fig. 3); our prototype-deployments to several meters translate to >20 m on Europa. Resources for a Europa Magnetotelluric Sounder (EMS) are modest, ~3 kg ~4 W CBE, and the system is readily adapted to the low temperature (70 K) and high radiation (500 krad) environment of Europa.

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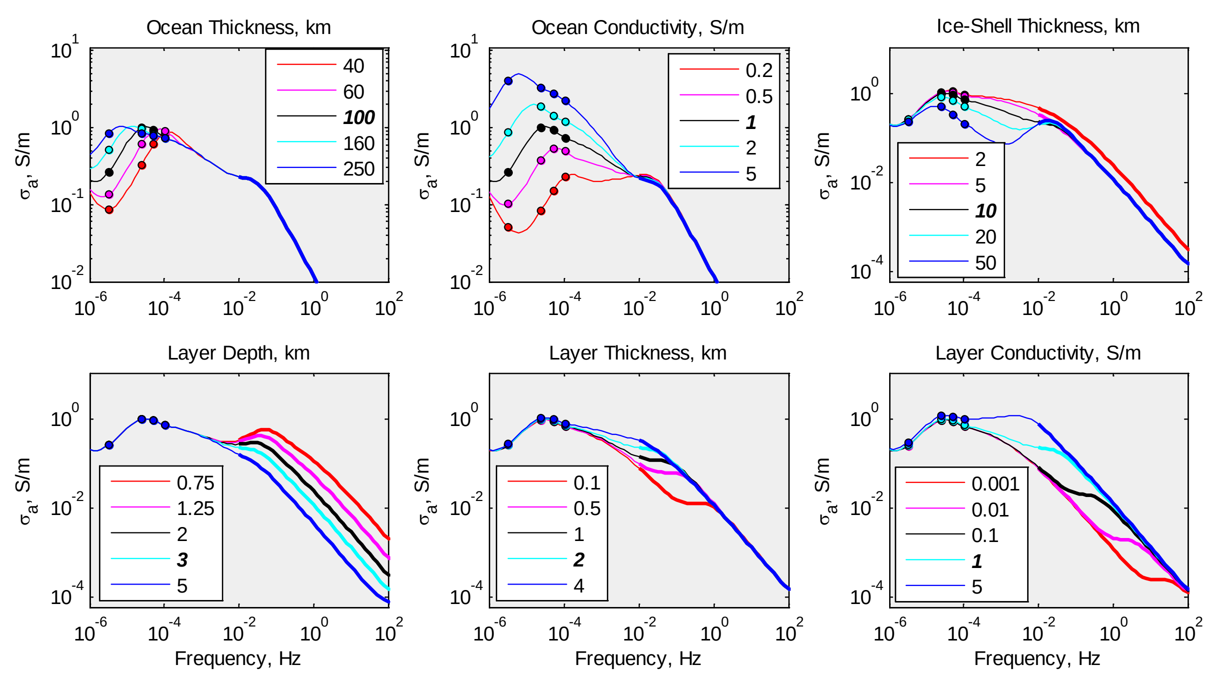

Fig. 2: Broadband EM sounding of Europa expressed as apparent conductivity σ_a. Reference value for each parameter (i.e., that used in other panels) is labeled in bold italic. Symbols are discrete kinematic frequencies; heavy lines specify instrument range to measure broadband magnetospheric phenomena. Kinematic frequencies can determine ocean properties and shell thickness, but magnetospheric frequencies are necessary to resolve water-layer properties