Electromagnetic Sounding of Solid Planets and Satellites

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1. Introduction

Electromagnetic (EM) sounding encompasses a wide variety of methods used to sense subsurface structure from less than a few meters to a thousand kilometers or more. EM sounding is distinct from surface-penetrating radar in being inductive rather than wavelike; the diffusive transfer of energy is akin to that in heat flow, groundwater, and electrical circuits. This transition to induction occurs at low frequency where the loss tangent exceeds unity, in the kilohertz to megahertz range depending on ground electrical conductivity. A vast underworld of the EM spectrum, from below one microhertz to perhaps one megahertz, is therefore the continuous realm of EM sounding. Recent work aimed at large-scale terrestrial geodynamics spans the hydration state of the upper mantle (*1,2*), melting on the 410-km discontinuity (*3*), heterogeneity in lithospheric structure across Europe (*4*), and the nature of accreted crust in Canada (*5,6*). EM methods have been used for decades in mining exploration (*7,8*) and have recently seen a major surge in oil and gas exploration (*9*). Yet EM exploration can be simple enough to be widely used in environmental and engineering applications (*10*).

There have been only two campaigns of EM sounding in the history of planetary exploration: use of landed and orbital measurements to determine the general interior properties of the Moon, particularly to constrain the size of a conductive core (e.g., *11-14*), and the discovery of the highly conductive internal oceans of the icy jovian satellites (*15*) with the Galileo spacecraft. Yet potential applications abound, over a comparable or greater range of depths than the Earth: buried ice on Mercury, Mars, and the Moon; groundwater on Mars, ice-shell thicknesses and brine contents of icy satellites, lithospheric thicknesses on Mercury, Venus, and the Moon, and by inference, geothermal gradients; and impurity content of silicate mantles, particularly water.

The purpose of this White Paper is to provide some background and guidance on the applicability and requirements of EM methods for investigating the interiors of many solid bodies in the Solar System. A large number of general endorsements was not sought; rather, the signatories largely reflect a cross-section of experienced geophysicists and space physicists, particularly those in low-frequency electromagnetics. Although this document can be considered reference material for White Papers on landed networks for Mars (*16*) and the Moon (*17*), specific missions are not advocated here. Rather, it is intended to inform panel deliberations that might be considering interior investigations about what can done with EM sounding and what measurements are necessary.

2. Principles of EM Sounding

Useful summaries of EM geophysics abound (e.g., *7,8,18*); this paper focuses on the essential elements relevant to planetary exploration.

2.1 Material Properties. The complex dielectric permittivity ε^* and complex permeability μ^* are the constitutive parameters of all electromagnetics. The latter rarely differs from its free-space value and will be neglected hereafter. The real part of ε^*, when normalized by the free-space value, is the dielectric constant, which in turn is the square of the real refractive index. It measures storage of electrical energy. The imaginary part of ε^* depends on the conductivity σ and measures loss of electrical energy. A complex conductivity contains the same information as complex permittivity with the storage and loss in the imaginary and real parts, respectively. The complex permittivity is frequency dependent in the vicinity of dielectric relaxations. Such behavior is important in rocks containing certain minerals (*8,19*) or H_2O (as liquid, solid, or hydrate; (*8*,*20*-*23*) but in truly dry rock—lacking even surface-adsorbed water—the frequency dependence is weak (e.g., *20*,*24*).

Electrical conduction in the familiar sphere of Earth's upper crust is largely electrolytic, i.e., by movement of ions in water—conductivity increases with porosity and solute content, as in the classic Archie's Law (*8,10*). In subeutectic frozen H_2O systems, conduction through ice and hydrates is protonic, through charge defects resulting from lattice substitutions of salts, acids, and bases (*21*-*22*). Analogous substitutions by iron, aluminum, oxygen, and hydrogen in silicates result in electronic semiconduction, both from electrons and holes (*25*). Conductivity is also strongly temperature dependent, with Ahrennius activation energies in the eV range.

Table 1 gives some representative conductivities for planning purposes. The most striking feature is that the outer portions of all other silicate or icy bodies in the Solar System are likely to be much more resistive than the Earth, for the simple reason that free water is lacking. This opens up these regions to EM sounding at higher frequencies (see below), which in turn provides better measurements and more convenient signal integration.

Table 1. Representative Solar-System DC Electrical Conductivities (*1,3,8,10,11,22,26*)

Material	**σ, S/m**	**Material**	**σ, S/m**
Typical Earth Crust	10^{-2}	Mars dry crust	$<10^{-6}$?
Moist silt and clay	0.1	Mars wet crust	$>10^{-2}$?
Massive rock	10^{-4}	Cold ice (<188 K) in nonconvecting shell	$<10^{-13}$
"Pure" quartz	10^{-12}	Warm, briny ice (250 K) in convecting shell	10^{-6}
Earth upper mantle	0.1-1	Ice with 1% seawater-filled cracks	$\sim10^{-4}$
Lunar lower mantle	10^{-4} to 10^{-2}	Seawater, 293 K (internal ocean?)	5
Lunar upper mantle/crust	$<10^{-8}$ to $<10^{-4}$		

2.2 Investigation Depth. The EM skin depth (m) is $\delta = 500/\sqrt{\sigma f}$, where σ is the conductivity (S/m) and f is the frequency (Hz). However, the effective exploration depth is commonly taken to be $350/\sqrt{\sigma f}$ (*10*). Table 2 gives a convenient summary of EM exploration depths as functions of frequency and conductivity. It can also be interpreted as what frequencies are necessary to probe to a specified depth at a particular average conductivity. For example, terrestrial exploration geophysics seeking targets at several tens meters to several kilometers depth spans ~10 mHz to 10 kHz, but mantle studies require 10 μHz or less. Conversely, the lunar lower mantle was previously adequately sounded in the mHz range, but better characterization of the more resistive upper mantle and crust will require frequencies up to 1 Hz or more. Combinations of high frequency and/or low conductivity transition to the propagative regime where surface-penetrating radar is the appropriate tool (this calculation only treats absorption losses and not scattering; e.g., *27*). Note that a low-frequency signal can propagate through a resistive medium and still inductively penetrate an underlying conductor (e.g., Mars cryosphere over aquifer).

Table 2. EM Exploration Depths in km

Freq., Hz	Conductivity, S/m							
	10^{-1}	**10^{-2}**	**10^{-3}**	**10^{-4}**	**10^{-5}**	**10^{-6}**	**10^{-7}**	**10^{-8}**
10^{5}	3.5 m	10 m	35 m	Transition	Transition	Radar	Radar	Radar
10^{3}	35 m	0.1	0.35	1	3.5	Transition	Transition	Radar
10^{1}	0.35	1	3.5	10	35	100	350	Transition
10^{-1}	3.5	10	35	100	350	1000	3500	
10^{-3}	35	100	350	1000	3500			
10^{-5}	350	1000	3500					

Radar = loss tangent <0.1, propagative signal. Transition = loss tangent 0.1-10

2.3 Active vs. Passive Methods. Within the low-frequency branch of diffusive EM, the primary division is between those that use an artificial source (a transmitter) and those that rely on natural sources. The former enjoy considerable flexibility and high signal-to-noise but require significant additional resources. Terrestrial exploration depths using multi-kilometer setups and massive generators and typically have been limited to several kilometers. The higher resistivities of other silicate and icy bodies (Table 1) would, however, enable active seeking of conductive targets (e.g., water) at depths of a few kilometers using more modest resources (*28*). However, the best use of an active system is to perform a geometrically controlled sounding (see below) to determine the complex conductivity in the very shallow subsurface, say ice in the top several meters of the Mars or the lunar poles (*29*). Otherwise, soundings from <100 m to >1000 km can be performed with minimal resources using natural sources. On Earth, abundant energy exists <1 Hz from magnetospheric pulsations and the interaction of the magnetosphere with diurnal heating of the ionosphere (*30*). Above 1 Hz, the ground-ionosphere waveguide allows lightning energy to be recorded globally as the low-frequency Schumann resonances and regionally at higher frequencies as TEM/TM waves (*30*). These signals are collectively known as spherics. These sources of energy for EM sounding will likely be present on other bodies with magnetospheres, ionospheres, and chargeable atmospheres. (Table 3). In interplanetary space, temporal variations in the plasma density of the solar wind provide signals that have already been exploited for lunar sounding. Finally, special circumstances around specific planets can provide unique sources; in particular, the inclination of satellite orbits with respect to the static magnetic field of Jupiter yields an apparent time variation at the orbital period (*15*). Overall, some kind of ambient energy is likely present at most bodies that would enable EM sounding.

Table 3. Natural Sources of Energy for EM Sounding

	Solar Wind	Magnetosphere	Ionosphere	Spherics	Other
	10^{-4} to 100 Hz	10^{-4} to 0.1 Hz	10^{-6} to 10^{-5} Hz	10 to $>10^{4}$ Hz	
Mercury	√	√			
Venus			√	√	
Earth		√	√	√	Ring Current
Moon	√	√			
Mars		√ (crustal)	√	√	
Interplanetary	√				
Jupiter		√			Inclined Static Field
Saturn		√	√ (Titan)	√ (Titan)	

2.4 Parametric vs. Geometric Methods. The second main division in low-frequency EM is whether the source is horizontally separated from the receiver by greater than or less than a skin depth. The former case of large induction number corresponds to natural-source soundings as well as large-offset artificial-source methods. Here exploration depth varies parametrically, i.e., with frequency, soundings are performed by inverting impedance as a function of frequency for conductivity as a function of depth (see below). Conductivity is assumed to be real and independent of frequency. Where the receiver is within a skin depth of the transmitter (small induction number), exploration depth increases with transmitter-receiver offset, and geometric soundings are performed by inverting impedance as a function of offset to conductivity as a function of depth. While sharply limited in investigation depth to about 1/3 of the maximum transmitter-receiver separation, geometric soundings have the advantage of being able to solve for the frequency dependence of complex conductivity.

2.5 Measurements. The fundamental quantity that must be derived in any sounding is the frequency-dependent EM impedance *Z*, and it is the variety of approaches to *Z* that lead to more individual techniques in EM than in any other geophysical method (*31*). The impedance is related to the apparent resistivity ρ_a—the most commonly used parameter because of its dimensional analog to true resistivity—as $\rho_a = Z^2/\mu\omega$, where μ is the permeability and ω is the angular frequency. Alternative EM response parameters such as the admittance or the transfer function can also be related to *Z* (*32,33*).

Two known quantities are necessary to determine the impedance, e.g., Ohm's Law $Z = V/I$ (see Table 4). One of those quantities is nearly always the magnetic field B near the target, i.e., the sum of source + induced magnetic fields. Note that this first platform need not be on the surface, but can be a spacecraft within about one skin depth at the highest frequency of interest. In a variety of Transfer-Function (XF) methods, the second known quantity is the source magnetic field. This is straightforward for an artificial transmitter, or, in passive measurements, the source is measured by a second, distant spacecraft, as was done for Apollo-era lunar soundings (*11,12,14*). In a few special cases of accurately characterized natural signals—the Earth's ring current (*34*) or the time variation introduced by the motion of the Galilean satellites in Jupiter's main field (*15*)—the source can be specified a priori, so a single platform is sufficient. Single-magnetometer characterization can also be performed where the target can be approximated as a perfect conductor, like the Moon's core (e.g., *13*).

Geomagnetic Depth Sounding (GDS) uses surface arrays of magnetometers to determine impedance from the ratio of vertical *B* to the magnitude of the horizontal gradient of *B* (*35*). Because the wavelength in the ground $\lambda = 2\pi\delta$, GDS requires array spacing comparable to the skin depth in order to resolve the relevant horizontal wave structure. This calls for dense arrays to resolve the outer tens to hundreds of kilometers of planetary bodies. However, the wavelength can be specified when diurnal signals and their low-order harmonics are detected, such as daily variations of the ionosphere. As with the other special cases discussed above, this approach can provide single-station soundings over a limited frequency range. On the other hand, the *electric* field E can supply the required second piece of information, and enable complete EM soundings from a single station.

Table 4. Approaches to Natural-Source EM Sounding

Method	Measurements	Num. of Stations	Comments
Transfer Function (XF)	Magnetic Field B	2	Determine source field by distant 2nd stn. unaffected by target
Transfer Function-1 (XF-1)	B	1	Special case using prior know-ledge of source-field strength OR target is "perfect" conductor
Geomagnetic Depth Sounding (GDS)	B	3 or more	Compute impedance from vertical field and horizontal gradients
Geomagnetic Depth Sounding (GDS-1)	B	1	Special case where horizontal gradient can be computed using diurnal periods and harmonics.
Magnetotellurics (MT)	B + Electric field	1	General single-station method
Wave Tilt (WT)	Electric field	1	General single-station method

The magnetotelluric method (MT) uses orthogonal horizontal E and B to form a plane-wave impedance, which applies not only locally but can be transformed to spherical geometry, i.e., to planetary scale (*36,37*). The wave-tilt method (WT) is preferred for aerial surveys because the quadrature horizontal E (containing most of the inductive signal) can be readily determined by comparison to the vertical E (*38*). Only B-field methods have been used heretofore in planetary exploration because of their simplicity; E-field measurements are more challenging at low frequencies and noninductive contributions to E must be identified. Nonetheless, those methods using E have the significant advantage of complete soundings from a single vehicle that do not require a priori knowledge or special conditions.

5. Interpretation

In a parametric sounding, the impedance as a function of frequency is inverted to determine the conductivity as a function of depth. Inverse methods are highly developed and robust (*39,40*). Resolution is geometric and is typically several percent of the depth. Overall, the thickness of a relatively resistive unit overlying a relatively conductive unit is well determined, whereas the thickness-conductivity product of a conductor overlying a resistor is recovered. Deep soundings usually fall in the former category, because increasing temperatures with depth dominate conductivity (e.g., Fig. 1). Saline water (Mars or icy satellites) is a near-ideal target.

These vertical profiles can be interpreted directly, especially where major discontinuities are evident (e.g., *4-6*). Advanced approaches use laboratory measurements of electrical conductivity to convert inverted quantities to subsurface temperature and/or composition (e.g., *1-3*). Although the shallow subsurface can be very heterogeneous, there are a limited number of factors that can affect deep conductivity (see above). The increasing sophistication of interpretation leads to data products that fit NASA definitions (Table 5).

Table 5. EM Data Products

Level 1A	Raw time series or spectra
Level 1C	Impedance vs. Frequency
Level 2	Conductivity vs. Depth
Level 3	Temperature/Composition vs. Depth

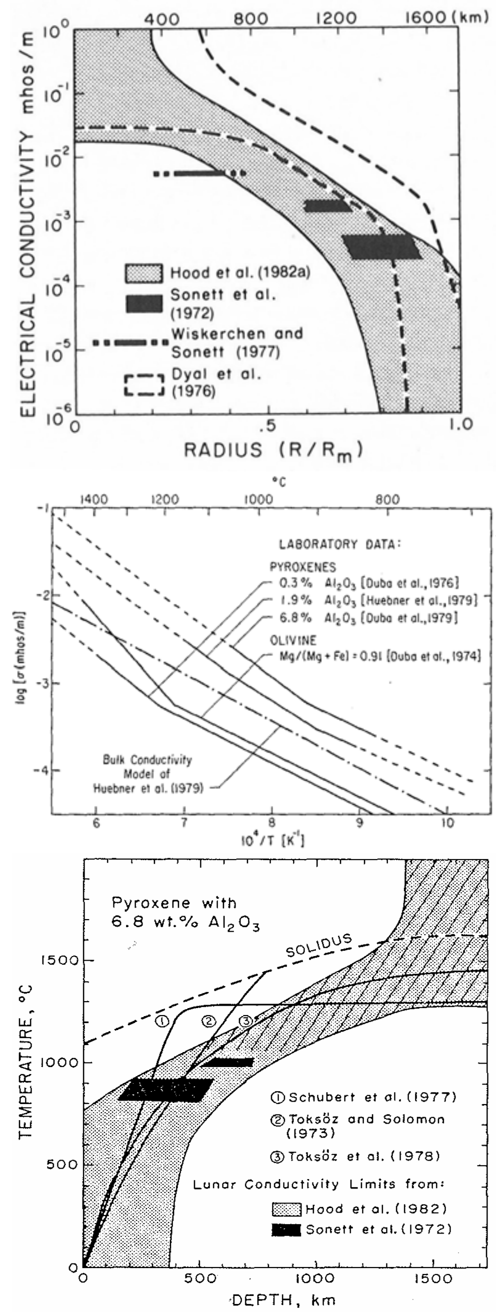

Figure 1. Lunar EM sounding interpreted using laboratory data (*14*). *Top panel*: Estimated limits on electrical conductivity vs. radius from magnetic transfer-function data. *Middle panel*: Laboratory temperature-conductivity data for pyroxenes, olivines, and a bulk model for the lunar interior below several hundred km. *Bottom panel*: Derived lunar temperature-depth profile. Shaded area represents range of temperature profiles based on electrical conductivity limits. Trace quantities of H_2O in the lunar mantle can also meet temperature constraints without invoking high alumina (*41*).

6. Planetary Applications

6.1 Mercury. A significant magnetosphere makes Mercury the most Earth-like in terms of classical natural EM sources, yet frequent reconnection events (*42*) define an even more dynamic environment. It is not known if the XF method can be applied within a heterogeneous magnetosphere; MT from the surface or low orbit is complete from one spacecraft. Core size can be estimated from the static magnetic field, but as an excellent conductor the core will also be a prime EM target. The conductivity profile in the mantle may determine whether it is convecting or whether the lithosphere takes up the entire mantle. The crustal thickness may be measured, although this conductor-over-resistor case is less precisely determined. Level 3 data may constrain the temperature profile in the mantle, and hence the geothermal gradient. Iron content of the mantle may also be recovered.

6.2 Venus. With a shielding ionosphere and no defined external sources, EM soundings of Venus must be performed from the surface or atmosphere, using spherics (*43*) or ionospheric disturbances. Although measurements could be made in the hour or so lifetime of a lander on the hot surface, aerial vehicles in the benign middle atmosphere can remotely sense the subsurface using MT or WT. A platform at 55 km altitude is sensitive to skin depths that significantly penetrate the lithosphere and hence can determine not only its thickness, but lateral variations over the ground track. This measurement is pivotal to understanding the geodynamic history of Venus. Indeed, by correlating variations in EM penetration depth to topography, lithospheric thickness can be determined using Level 2 data, i.e., without reference to laboratory measurements (*44*). Dry-rock conductivities $<10^{-5}$ S/m allow frequencies ~10 Hz to achieve the necessary exploration depth, i.e., using the global Schumann resonances. Upper-mantle water content may be inferred from Level 3 data.

6.3 Moon. Apollo-era lunar soundings (Fig. 1, Ref. *14*) allowed significant uncertainty at both extrema in radius. The core appears as a perfect conductor at the longest periods tested so far. It may be possible to distinguish a molten silicate core from an iron core at longer periods (hundreds of hours), complementing inferences from a global seismic network (*17,45*). Conversely, the crust and upper mantle have been poorly resolved because very low conductivities in the cold outer portions of the Moon are still associated with large skin depths even at the highest useful frequency in the current data sets (~10 mHz). The frequency band must be extended well above this limit in order to accurately probe the outermost few hundred kilometers of the Moon. This region is important for the record it may contain about the depth of the magma ocean and the nature of lateral contrasts in crustal and lithospheric thicknesses between the Moon's principal geological provinces (*45,46*). As frequency is increased, however, spatial aliasing may limit the classical XF method, requiring MT. The latter can be performed from a landed network or orbits with periapses of order 100 km or less.

Geometric sounding/profiling can uniquely determine ice, ilmenite, and iron content in the top several meters (*23,29*), complementing a surface-penetrating radar and neutron spectroscopy.

6.4 Mars. In a likely diverse EM environment (Table 3), broadband investigations can probe Mars to a variety of depths. Detection of subcryospheric aquifers would not only validate extant groundwater on Mars, it would provide a ready estimate of geothermal gradient. Because of the strong resistor/conductor contrast, aquifers would be evident across the mHz-kHz range and would be optimally sensed using landed or aerial MT or WT (*26*). Deeper exploration using lower frequencies is complemented with GDS (*47*); the Mars sol is short enough to perform single-station soundings using diurnal variations of the ionosphere and its harmonics. Crustal and lithospheric thicknesses and upper-mantle properties can be assessed. As with lunar investigations, deep parametric EM can complement global objectives of seismology and heat flow and/or provide shallow geometric EM to assess ice content and other properties of the regolith.

6.5 Asteroids and Comets. Small anhydrous bodies are likely sufficiently resistive that, barring heavy scattering, surface-penetrating radar would be able to probe globally. The presence of hydrated minerals and salt hydrates in aqueously altered objects, or higher temperatures in larger objects, may produce higher conductivities amenable to EM sounding. These solar-wind obstacles can be sounded with XF, MT, WT, and GDS methods, the last perhaps due to short diurnal periods. Time variations in the dielectric constant of subsurface ice, measured by geometric soundings, can map the diffusion of heat into the interior, either diurnally or as a comet approaches the sun.

6.6 Giant-Planet Satellites. The extremely low-frequency time variations developed at the satellites of Jupiter by their inclined orbits with respect to the main field (*15*) will also be present at Uranus and Neptune. This will enable single-magnetometer global XF soundings for close flybys of satellites of the ice giants. Harmonics of these fundamental periods may also be present and their strengths determined a priori from the multipole expansion of the main field. Saturn's satellites have negligible inclination with respect to the main field. For all the giant planets, however, the diversity of magnetospheric phenomena may provide a rich spectrum of EM signals; at higher frequencies, ice-shell thicknesses of kilometers to tens of kilometers, and the presence of brine intrusions into the shell, may be assessed. XF soundings may be appropriate if it can be demonstrated that fields will not be spatially aliased; otherewise landed or low-altitude MT can be used. Titan is of course different because of its atmosphere; like Venus, MT or WT measurements from landed or aerial assets could detect ionospheric disturbances or spherics. Long-period (16-day) signals also may be evident from diurnal ionospheric changes.

7. Conclusion. Electromagnetic sounding incorporates a range of mature techniques used at all spatial scales in terrestrial subsurface exploration. Pioneering EM soundings of the Moon and icy satellites of Jupiter have demonstrated the potential of these methods for planetary science.

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