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Applications of Planetary Electromagnetic Sounding: Microhertz to Gigahertz

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Abstract

EM sounding formally encompasses both propagative (high-frequency) and inductive (low-frequency) methods. Orbital, surface-penetrating radars have been shown to be effective to depths of kilometers on the Moon and in icy parts of Mars, but have been ineffective over the most of Mars' silicate surface. Fixed, surface-based radars will likely improve penetration to no more than several hundred meters. The optimum future application of surface-penetrating radar on Mars is to provide subsurface geological context for rovers. Deep sounding can be accomplished using natural-source induction, and has been used to probe the Moon and Galilean satellites. Applications include Mars groundwater, Venus geodynamics, and the interior of the Moon from crust to core. Magnetotellurics has the advantage of performing a complete sounding from a single station.

1. Surface-Penetrating Radar

SPR operates propagatively where the loss tangent (tanδ) << 1, typically above kHz-MHz [e.g., 1]. The upper limit near 1 GHz is where scattering prevents significant subsurface penetration. Flown orbital SPRs comprise A17 Lunar Sounder, MARSIS, and SHARAD. Effectively dry lunar rocks have tanδ (loss tangent) ~10^{-2} at several MHz (attenuation α ~ 6 dB/km) [2], so absorption losses are negligible and sounder imaging to a few km depth [3] was dominated by scattering and the instrument's limited dynamic range. SHARAD reflections from the subsurface of Mars are absent-to-rare in all except ice-rich and young volcanic units [4], from which losses 0.065-0.27 dB/m for the radar-opaque units could be derived. Such attenuation is more Earth-like than Moon-like, and points to the ubiquitous presence of a few monolayers of adsorbed water. A future Mars orbiter would have to improve dynamic range by up to 50 dB to image to ~100 m depth at 20 MHz.

The Netlander [5], now Netstation [6], mission would use fixed SPR, with the stated investigation depth "in excess of 1-2 km." This performance relies on optimistic estimates of system dynamic range, large dielectric contrast of targets, and extreme signal integration (Table 1). In particular, signal averaging is limited in practice due to coherent, nonrandom effects such as electronic offsets and drifts [e.g., 7]. I too have been guilty of sanguine signal integration in predicting instrument performance [8]. Using more realistic parameters, I find maximum investigation depths for 2-20 MHz SPRs of hundreds of meters. The local 3D imaging capability of this instrument is innovative, but SPR cannot address goals of large-scale properties as can seismology, heat flow, and inductive EM, as was done for the Moon by Apollo.

Rover-based Mars SPR has been under study for some time [e.g., 9] and will fly on ExoMars [10]. Subsurface context for surface investigations is the greatest benefit, but some information on material properties also follows, especially with broadband systems. If materials with a strong temperature dependence such as hematite are present [11], subsurface temperatures can also be estimated.

2. Natural-Source Induction

Induction operates where tanδ >> 1. Ambient EM energy useful for sounding is widespread and derives from the solar wind, magnetospheres, ionospheres, and lightning [e.g., 12]. Skin depths increase with decreasing frequency. The lowest frequencies in terrestrial induction comprise periods up to 100 days. In general, two quantities must be measured at each frequency to determine the impedance. During Apollo, the magnetic field was measured on the surface and in distant lunar orbit. Two or more surface magnetometers separated by a skin depth can establish the impedance, as can co-measurement of the electric and magnetic fields at a single location—the magnetotelluric method.

Saline groundwater on Mars is near-ideal induction target [1], responding even in partial saturation to depths of many kilometers over a wide bandwidth (mHz-kHz). Thus groundwater may be detected whether the source is solar-wind/ionosphere or lightning. The lower crust and upper mantle can be probed using diurnal variations in the ionosphere: because the wavelength is known to be the planetary circumference, only a single-station magnetometer is necessary.

Next-generation sounding of the Moon [13] can improve upon Apollo by (1) assessing the electrical structure of the outermost 500 km and its lateral variability, specifically to understand the extent of upper-mantle discontinuities and the structure of the PKT; (2) determining the thermal structure of the lower mantle and its lateral variability; and (3) tightly constraining core size.

Lightning on Venus causes global Schumann resonances, which have penetration depths up to 100 km if the lithosphere is dry. Furthermore, these TEM waves can be measured from a balloon. Using a long traverse, the mean thermal gradient can be recovered to within 25% [14].

3. References

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Table 1: Radar Range Calcs. for Mars SPR[1]

Freq, MHz	Eff. Dyn. Range, dB	Atten, dB/m	Dielectric Constants ε_1, ε_2	Investi-gation Depth, m
2	134 [2]	0.02 [5]	3,13 [9]	2000
2	134	0.013 [8]	5,8 [10]	2500
2	134	0.05 [8]	5,8	790
2	80 [4]	0.013	5,8	900
2	80	0.05	5,8	360
20	134	0.065 [6]	5,8	440
20	134	0.27 [7]	5,8	130
20	105 [3]	0.065	5,8	270
20	105	0.27	5,8	90

[1]512 effective coherent sums, reflectivity limited to first Fresnel zone.[2]Ref [5], from Tx power and theoretical noise floor only.[3]Median value Pulse EKKO GPR at 25 MHz, including antenna pattern and coupling.[4]Extrapolated from PulseEKKO freq. range.[5]Assumed [5] from ice soundings. [6]Typical value and [7] upper limit value inferred from SHARAD [4]. [8]Freq dependence determined by lab meas. [9]Ice-rock contrast implicit in source cited by [5], when corrected for reflection from Fresnel zone only. [10]Typical in-ground contrast [4].