

**COMPARISON OF GROUND-PENETRATING RADAR AND LOW-FREQUENCY ELECTROMAGNETIC SOUNDING FOR DETECTION AND CHARACTERIZATION OF GROUNDWATER ON MARS.** R.E. Grimm<sup>1,2</sup>, <sup>1</sup>Blackhawk Geoservices, 301 B Commercial Rd., Golden CO 80403, [grimm@blackhawkgeo.com](mailto:grimm@blackhawkgeo.com), <sup>2</sup>Univ. Colorado LASP, Boulder, CO.

**Summary:** Two orbital, ground-penetrating radars, MARSIS and SHARAD, are scheduled for Mars flight, with detection of groundwater a high priority. While these radars will doubtlessly provide significant new information on the subsurface of Mars, thin films of adsorbed water in the cryosphere will strongly attenuate radar signals and prevent characterization of any true aquifers, if present. Scattering from 10-m scale layering or wavelength-size regolith heterogeneities will also degrade radar performance. Dielectric contrasts are sufficiently small for low-porosity, deep aquifers that groundwater cannot be reliably identified. In contrast, low-frequency (mHz-kHz) soundings are ideally suited to groundwater detection due to their great depths of penetration and the high electrical conductivity (compared to cold, dry rock) of groundwater. A variety of low-frequency methods span likely ranges of mass, volume, and power resources, but all require acquisition at or near the planetary surface. Therefore the current generation of orbital radars will provide useful global reconnaissance for subsequent targeted exploration at low frequency.

**Introduction:** Electromagnetic (EM) methods are fundamentally divided between high- and low-frequency regimes. Energy transport at high frequency is propagative (wave-like) and is controlled by the electrical permittivity and the magnetic permeability. This is the radar regime. At low frequency, energy transport is by diffusion and is controlled by the magnetic permeability and the electrical conductivity. This is the inductive regime. The division between the two formally occurs where the loss tangent is unity; for typical terrestrial near-surface electromagnetic properties, the transition is at ~10 MHz. Unmineralized, anhydrous portions of the martian crust will be very resistive, lowering the transition between diffusion and propagation to ~1 kHz [1].

The principal advantages of ground-penetrating radar (GPR) for subsurface exploration are the ability to operate from orbit, signal-to-noise improvements made possible by controllability of the transmitted waveform, and high resolution. The principal disadvantages are potential strong losses due to absorption, scattering, and multiple reflection, contrasts in permittivity that are small compared to those in conductivity, and limited depth of penetration in conductive materials. Because the case for GPR utility, especially for detection of groundwater, has been de-

scribed elsewhere [2-6], this paper will highlight the potential limitations.

Low-frequency EM methods have dominated terrestrial geophysical exploration for groundwater [7]. Active methods use a transmitter and share with radar some of the signal-to-noise improvements of a repeated, controllable waveform, but typically require significantly more mass and power than GPR. Passive methods use natural EM sources; they can be compact and low-power but depend on the nature and strength of ambient EM energy. I have previously forward-modeled low-frequency EM sounding for groundwater on Mars [1]; here some preliminary aspects of the inverse problem are considered, particularly to compare the penetration depth and resolution with radar.

**Radar Scattering Losses:** Published simulations of the potential radar response of the uppermost crust of Mars have used mean layer thicknesses of 50-4800 m [2-5]. Models for depths of investigation < 1 km have used smaller layer thicknesses, but those including deep investigations (to several km or more) have not propagated this complexity to depth, using fewer, thicker layers. The MGS MOC has revealed ubiquitous layering with thicknesses of meters to tens of meters to depths of ten kilometers [8]. Each interface can generate a radar reflection that removes energy from continued, downward propagation, and each interface again causes a downward reflection that attenuates the upward-propagating return signal. For a reflection coefficient  $R$  and transmission coefficient  $T$ , the returned signal amplitude is  $RT^{2n}$ , where  $n$  is the number of layers. Best and worst cases are shown in Figure 1; the selected dielectric contrasts are smaller than mean contrasts of 1.5-2.9 used by others [2-5] and therefore the calculation is conservative with respect to these choices. Predicted losses of many tens of dB may be tractable for investigations to depths of 1 km (SHARAD), but hundreds of dB in scattering losses due to layering may defeat attempts to sound to several kilometers depth (MARSIS).

**Radar Dielectric Contrasts:** The radiofrequency relative permittivity or dielectric constant of 87 of liquid water is supposed to be diagnostic of that substance when compared to typical dielectric constants of 5-7 for solid-earth materials. However, the composite dielectric constant of a water-rock mix may not provide sufficient contrast under all conditions for robust identification of water. The Hashin-

Shtrickman formulae [9] provide upper and lower bounds to material properties of mixtures without specific geometrical assumptions. A mean dielectric constant of 5 for dry martian materials [2-5] is lower than typical terrestrial rock values of 7-8 [10] but is conservative for this calculation. Assuming that inferred dielectric constants  $>10$  are indicative of liquid water, porosity must exceed at least 8% and perhaps 20%. Such porosity is likely to be found only in the top few km of a compaction-limited crust [11], favoring both MARSIS and SHARAD in this regime but rendering MARSIS attempts to distinguish deeper groundwater strongly ambiguous.

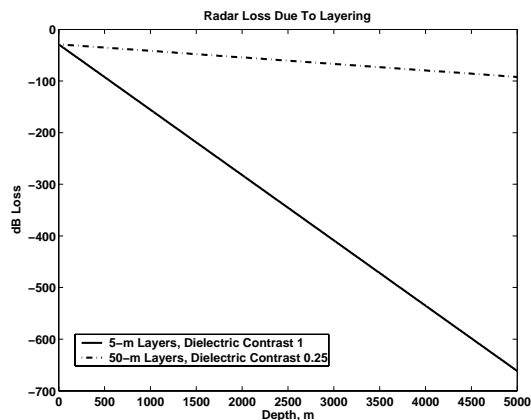


Figure 1. Observed thicknesses of layering on Mars will lead to strong radar-reflection losses.

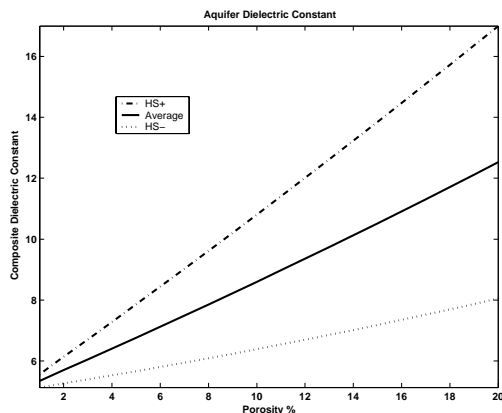


Figure 2. Hashin-Shtrickman bounds for dielectric constant of water+rock mixture. At low porosity, contrast is too small to distinguish from rock alone.

**Radar Absorption Losses:** Published models of the martian subsurface focusing on electrical conductivity [1] are very different from those focusing on dielectric constant [2-5]. The latter have used loss tangents typical of terrestrial rocks, whose conductivities are almost completely controlled by moisture

and clay content [e.g., 7]. Models that compute electrical properties as temperature- and frequency-dependent functions of the relative proportions of rock, ice, and water with specified dissolved solids [1] show that conductivity can be almost negligible in the cold, dry cryosphere but is higher than used in radar models in areas where liquid water is present, particularly if saline. Furthermore, adsorbed water below freezing [12] is electrically conductive and can strongly influence EM signals. Consider a model (Figure 3) of electrical properties of the crust [1], with the following modifications: freezing temperature 252 K, 5 g/l dissolved solids, heat flow 20 mW/m<sup>2</sup> [13]. The melting point is appropriate to brine [11] but the actual dissolved solids are taken to be those of sea ice; this leads to a best case for radar performance as the cryosphere is thin but not too salty. The formal base of the cryosphere is 4.1 km in this model; again note that there is no significant change in dielectric constant (Figure 3; the variations in the cryosphere are due to the dielectric relaxation of ice). The presence of thin films of unfrozen water in the cryosphere, comprising a few percent by volume, introduce significant electrical conductivity below 2.1 km. The skin depth, computed from the complex wavenumber, is effectively infinite at all frequencies in the cryosphere and in the underlying saturated zone below 1 Hz, but decreases with frequency such that penetration depths (a few skin depths) are  $< 100$  m at 1 MHz. Therefore radar will be sharply attenuated upon reaching temperatures within some tens of degrees of the freezing point and will not be able to penetrate to any “true” subsurface aquifer on Mars. The variation in skin depth between 0.1Hz and 1 kHz forms the basis for resolving this conductivity structure with low-frequency EM sounding.

**Penetration and Resolution of Low-Frequency EM:** Formal parametric inversion of apparent resistivity data for conductivity (or resistivity) structure with depth is a key analysis goal. Consider here a proof-of-principle using asymptotic inversions that assume ground currents decouple to form a one-to-one mapping between frequency and depth [14]. Results for three models show the significant variations in resistivity with depth as a function of the distribution of subsurface water (Figure 4). Differences in the thickness of the subcryospheric aquifer and an overlying vadose zone can also be discriminated [Ref. 1, Figures 7, 11]. Note that the specific range of frequencies that resolves the water-relevant structure in this example is in the spheric band; the most likely natural source would be lightning. At higher salinity, skin depth decrease and the appropri-

ate frequencies are lower, centering near 100 mHz for briny groundwater [1]. Crustal-magnetospheric and ionospheric sources are appropriate for this lower frequency band.

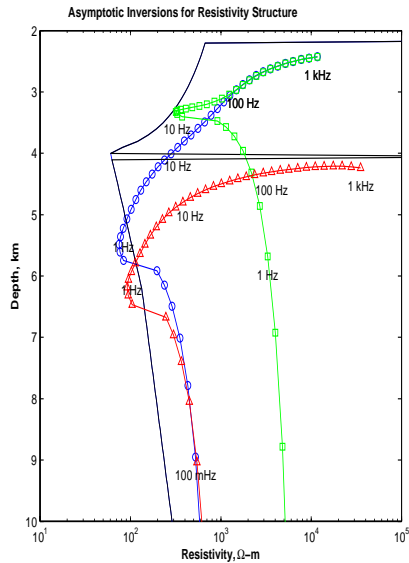


Figure 4. Asymptotic inversions for (1) thin films in cryosphere + subcryospheric aquifer, blue circles; (2) thin films in cryosphere only, green squares; (3) subcryospheric aquifer only, red diamonds. True resistivity structures shown as solid black lines. Dry models are off-scale to right.

**Concluding Discussion:** The limitations of GPR performance due to scattering, absorption, and dielectric contrast will not likely affect detection of groundwater at depths of several hundred meters with SHARAD. However, the lure of shallow groundwater [15] has been considerably diminished by alternative models of gully formation [16-18], and there is no guarantee such groundwater is extant anyway. Deep, stable groundwater is more likely even given recent downward revisions of heat flow [13], but detection with MARSIS is unlikely. Abrupt attenuation of the MARSIS return should not be taken as a direct indicator of an aquifer but instead will likely be due to adsorbed water in the cryosphere. Such indications may be sufficient to constrain the geotherm and point to where groundwater might occur, but true detection and characterization of groundwater must await aerial or landed assets performing low-frequency EM.

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**References:** [1] Grimm, R.E., *JGR* 107, 2001JE001504, 2002. [2] Heggy, E. et al., *JGR* 108, 2002JE001871 (2003). [3] Leuschen, C. et al., *JGR* 108, 2002JE001875, 2003. [4] Shchuko O.B. et al., *JGR* 108, 2002JE001879 (2003). [5] Ciarletti, V. et al., *JGR* 108, 2002JE001867, 2003. [6] Bertelier, J.J. et al., *JGR* 108, 2002JE001866, 2003. [7] McNeill J.D., in *Geotech. and Environ. Geophys.*, Soc Explor Geophys., vol. 1., pp. 191-218, 1990. [8] Malin M.S. and Edgett K.S., *JGR* 106, 23429, 2001. [9] Hashin Z. and Shtrikman S., *J. App. Phys.* 33, 3125, 1962. [10] Keller G.V., in *EM Methods in Appl. Geophys.*, Soc. Explor Geophys., vol. 1., pp 13-52, 1988. [11] Clifford, S.M., *JGR* 98, 10973, 1993. [12] Anderson D.M. and Tice A.R., *Hwy Resour. Res.*, 373, 12, 1972. [13] McGovern P.J. et al., *JGR* 107, 2002JE001854, 2002. [14] Schmucker, U., *PAGEOPH* 125, 341, 1987. [15] Malin M.S. and Edgett K.S., *Science* 288, 2330, 2000. [16] Costard F. et al., *Science* 295, 110, 2002. [17] Christensen P.R. *Nature*, 10.1038/nature01436, 2003. [18] Treiman A.H. *JGR* 108, 2002JE001900, 2003. [19] Delory, this volume.

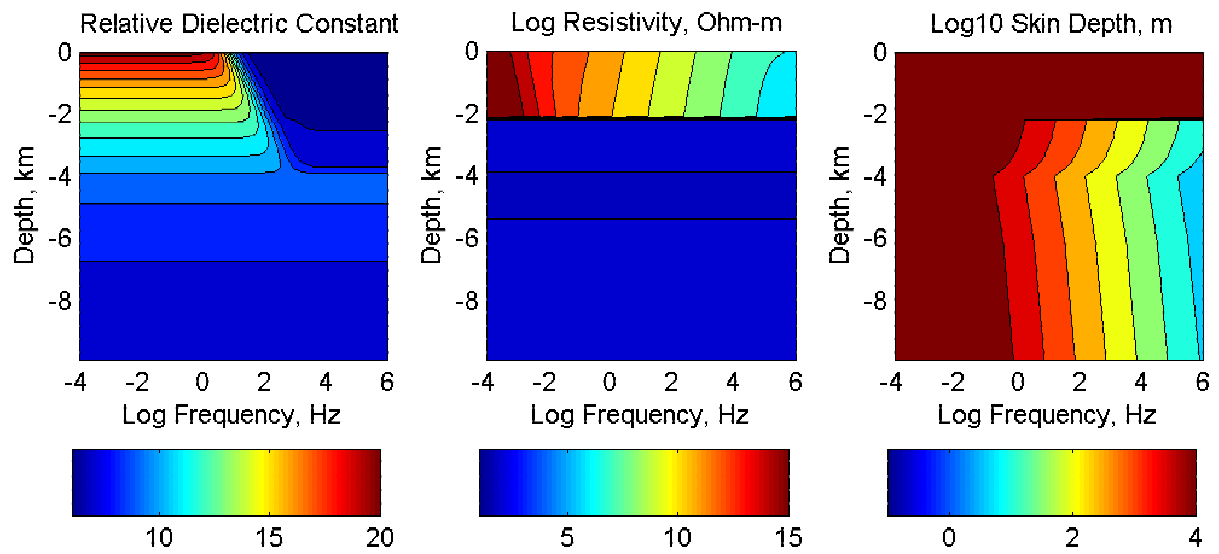


Figure 3. EM properties for nominal crustal structure (see text). Formal base of cryosphere is 4.1 km depth but thin films of unfrozen, adsorbed water introduce significant electrical conductivity below 2.1 km. MHz (GPR) frequencies and above are strongly absorbed. Variations in skin depth between 0.1 and 100 Hz form basis for inversion of conductivity structure using low-frequency sounding.