Olhoeft, G. R., 1998, Ground penetrating radar on Mars: in Proc. of GPR'98, Seventh Int'l. Conf. on Ground Penetrating Radar, May 27-30, 1998, The University of Kansas, Lawrence, KS, USA, p. 387-392.

GROUND PENETRATING RADAR ON MARS

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ABSTRACT

In the past decade and in the next decade, several ground penetrating radar systems have been or will be launched toward Mars. GPR systems have been built or proposed for study of Mars and the Martian satellite, Phobos, from orbit, balloons, and rovers. The scientific problems include those of finding evidence of past or present life on Mars, unraveling the history of climate change, locating water and other volatiles, and mapping geohydrologic stratigraphy in polar caps, sedimentary deposits, and volcanoes. The two problems of most interest are the search for life, and the use of polar ice stratigraphy on Mars with similar information from the Earth to separate and understand the solar function of climate change on both planets. Environmental constraints on a radar system include low operating temperatures and atmospheric pressures, high radiation and g-forces, and wind driven electrostatic and magnetostatic dust. Hardware constraints are small size, low weight, and low power, especially in antenna design. Software constraints are low data transfer rates and long time delays in communication. Material properties are, in general, favorable to ground penetrating radar (low temperatures and low water contents giving low electrical losses) with depths of penetration and antenna coupling controlled mostly by the relatively high iron content of the soil, possible clay minerals, clathrate hydrates, and electromagnetic scattering from heterogeneities.

Key words: Mars, magnetic, clay, scattering, losses

INTRODUCTION

"Mars has been a subject of wonder since earliest recorded time." (Kieffer et al., 1992a) and this wonder continues today after the success of the Mars Pathfinder mission (Golombek et al., 1997) and its rover, Sojourner. Much of the fascination with Mars arises as it appears to be so much like the Earth, with active geology and hydrology, and the possibility that it may have once harbored life (McKay et al., 1996).

However, for all the success of the Viking (see detailed reviews in Kieffer et al., 1992b) and Pathfinder space missions, there is still very little known about the subsurface of Mars. Outstanding scientific problems include those of finding evidence of past or present life on Mars (Klein et al., 1992; McKay et al., 1992, 1996), unraveling the history of climate change (Fanale et al., 1992; Kieffer and Zent, 1992), locating water and other volatiles (Carr, 1996; Jakosky and Jones, 1997; Mellon et al., 1997), and mapping geohydrologic stratigraphy in polar caps (Thomas et al., 1992; Legrand and Mayewski, 1997), sedimentary deposits (Greeley et al., 1992; Tanaka et al., 1992), and volcanoes (Mouginis-Mark et al., 1992). Ground penetrating radar is a possible tool to address several of these problems (Olhoeft and Strangway, 1974; Grant et al., 1995; Ori and Ogliani, 1996).

HARDWARE AND SOFTWARE CONSTRAINTS

The hardware constraints for ground penetrating radar on Mars are those encountered by any space mission. These include severe constraints on size, weight (a few payload kilograms) and power consumption (a few watts) as well as extremes of temperature, shock (up to 40 g), and radiation hardness to survive launch, cruise and arrival at Mars. These constraints are well documented in the literature (Snyder and Moroz, 1992) and by NASA Announcements of Opportunity, plus added constraints caused by limited funding. As an example, for $150 million, the Mars Pathfinder mission delivered a 25 kg payload to Mars, consisting of the scientific instruments, Sojourner rover, and rover support equipment in a 275 kg lander (Golombek, 1997). The rover can carry only a 1.5 kg payload. One of the biggest problems in all of these is the size and weight of the antenna system to operate at low ground penetrating radar frequencies.

The software constraints include ability to run on the limited numbers of computer hardware that are radiation hardened for space travel, the limited data transfer rates (a few hundred bytes per second) at interplanetary distances, the limited amount of on board storage, the long communication delays (tens of minutes), and the competition for resources from other imaging instruments (Golombek, 1997). These all result in requirements for considerable on board processing of data and compression of the final results before transmission back to Earth.

ENVIRONMENTAL CONSTRAINTS

Environmental constraints begin with surviving the g-forces of launch (20 g), the temperature and radiation (especially from solar activity) environment of cruise, and the g-forces of landing (40 g). However once on Mars, the environment still has a strong influence on performance. Temperatures vary roughly from 140 to 300 K, depending upon location (elevation and latitude), time of day and season of the year (Kieffer et al., 1992a; Zurek et al., 1992). Similarly, atmospheric pressures vary from a few hundred to a thousand Pa (Zurek et al., 1992).

The atmospheric dynamics result in high speed winds and large quantities of dust in the atmosphere (Zurek et al., 1992; Kahn et al., 1992). Such wind blown dust can create electrostatic and magnetostatic problems for mechanical and electrical devices as well as simply coating optical and solar panel surfaces (Olhoeft, 1991; Kolecki, 1997; Rover Team, 1997a). One unknown is the level of electromagnetic noise created by electrostatic charging of wind blown sand and subsequent discharge as lightning during sand storms, or from charging and discharge of objects on the surface of Mars (such as rovers, Kolecki, 1997).

The ionosphere and the solar wind interaction (Barth et al., 1992; Luhmann et al., 1992) also provide sources of electromagnetic noise that have not been completely characterized. The ionosphere has energy absorption below 700 kHz at night, to 3 MHz in daylight, especially limiting to low frequency sounding from orbit (from radio-occultation measurements, summarized in Luhmann et al., 1992).

MATERIAL CONSTRAINTS

Mars has been studied with earth based, orbital spacecraft, and lander or rover infrared spectroscopy (Soderblom, 1992; Erard and Calvin, 1997), in situ alpha proton X-ray spectrometry (Rieder et al., 1997), radar (Simpson et al., 1992; Harmon, 1997; Haldemann et al., 1997) and other techniques to determine the composition and abundance of surficial materials (Banin et al., 1992; Gooding et al., 1992; Christensen and Moore, 1992; Rover Team, 1997b). Most of the materials found should have low losses and be favorable towards ground penetrating radar (Olhoeft and Strangway, 1974). Some regions of Mars are so unusual as to be characterized as "stealth" regions (Muhleman et al., 1991; Edgett et al., 1997) because they return no radar echo above the noise.

However, there is roughly 18 weight percent iron oxide magnetic materials found at both Viking landing sites (Banin et al., 1992) and at the Pathfinder landing site (Rieder et al., 1997). The exact composition of these iron bearing minerals is not known, but direct measurement has shown them to be highly magnetic at both Viking landing sites (Hargraves et al., 1977) and at the Pathfinder landing site (Hviid et al., 1997). Arguments from the combination of magnetic and chemical composition measurements suggest the iron bearing phase in the soil to be maghemite (γ-Fe_2O_3), or a mixture of ferric oxides, ferric oxyhydroxides and smectite clay minerals, or titanomagnetites occurring in palagonites derived from basalts (Hviid et al., 1997; Erard and Calvin, 1997).

Magnetic materials can have a strong influence on the propagation of ground penetrating radar signals (Olhoeft and Capron, 1994) and such effects have been seen in terrestrial soils (Olhoeft and Capron, 1993). The amount of magnetic loss is controlled by the amount and magnetic polarizability of the minerals. The frequency dependence of the magnetic loss is modeled by the Cole-Cole equation (Olhoeft and Capron, 1994)

$$\mu' - i\mu'' = \mu_\infty + \frac{\mu_S - \mu_\infty}{1 + (i\omega\tau)^\alpha}$$

where μ' = real part of magnetic permeability
μ'' = imaginary part of permeability
i = $\sqrt{-1}$
μ_S = low frequency limit of permeability
μ_∞ = high frequency limit of permeability
ω = radian frequency = $2\pi f$
α = distribution parameter, describing the breadth of the time constant distribution (α=1 for a single relaxation) and actually determined by the magnetic grain size distribution. The time constant of relaxation, τ, may be given by the Neel model (model choice and details depend upon single domain versus multidomain grains and other factors, see Dunlop and Ozdemir, 1997):

$$\tau = \frac{\tau_o}{2} e^{\frac{\mu_o v H_c J_s}{2kT}}$$

where τ = time constant of relaxation
$\tau_o \sim 10^{-9}$ s = atomic reorganization time or interval between successive thermal excitations
μ_o = magnetic permeability of free space
v = magnetic grain volume
H_c = coercivity
J_s = saturation remnance
k = Boltzmann's constant
T = temperature.

As the coercivity and the saturation remnance also depend upon the grain size distribution (Hunt et al., 1995; Dunlop and Ozdemir, 1997), the time constant is most strongly determined by the magnetic grain size (the volume affected by domain wall displacement) distribution and temperature.

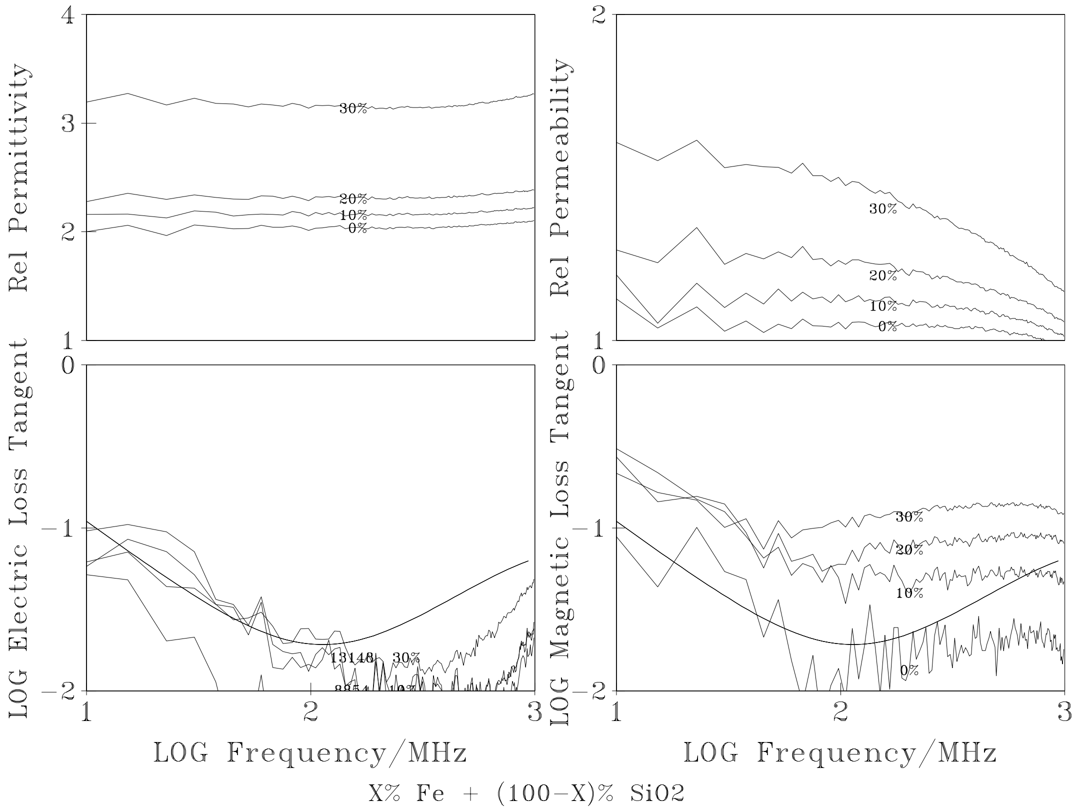

Figure 1. The relative dielectric permittivity and magnetic permeability, and the electric and magnetic loss tangents for 400 mesh iron particles mixed by weight percent, X, into clean quartz sand and measured at 295 K (derived from Olhoeft and Capron, 1994). The smooth solid line passing through the loss tangent plots is the loss measurement limit of the instrumentation. Note the higher magnetic than electric losses, and that permeability multiplies times permittivity in Maxwell's Equations and in determining the propagation velocity.

For the known Martian temperature range, the time constant of relaxation will change by many orders of magnitude over a typical Martian day in the near surface materials (roughly tens of centimeters depth), but stabilize at the mean annual subsurface temperature at greater depths (210 K at the surface, but unknown at depth as heat flow is unknown and likely variable). Exactly how this will happen depends upon the magnetic mineralogy, but the magnetic properties of many of the proposed Martian materials are unknown. For the fine grained soils (Kahn et al., 1992) of the surface of Mars, this can put significant magnetic losses in the tens to hundreds of megaHertz frequency range. Typical Cole-Cole parameter values for 400 mesh, 20 weight percent iron mixed into quartz sand (Olhoeft and Capron, 1994) and measured at 295 K (Figure 1) are:

$$\mu_S = 1.31 \qquad \mu_\infty = 1.03$$

$$\tau = 5.x10^{-10}\ \text{s} \qquad \alpha = 0.72.$$

Clay minerals also can be troublesome to ground penetrating radar (Olhoeft, 1987). Engineering size fraction clays (rock flour) are not a problem as they do not have the high surface area, active clay-water electrochemistry of the cation exchange process to absorb radiofrequency radar energy. Well below the freezing point of water and below the lowest temperatures on Mars, at temperatures of 140 K or less, montmorillonite clays will retain some unfrozen water and have significant dielectric losses (Forslind and Jacobsson, 1975; Olhoeft, 1977).

Under Martian environmental conditions, water can only remain a liquid when saturated with salt brine (Brass, 1980) or when in the immediate vicinity of mineralogical clay. In both cases, the electrical forces of the salt ion in solution or of the clay mineral interface with water cause significant freezing point depression. Pressure-temperature-composition phase diagrams for a variety of gases mixed with water also indicate the possible existence of clathrate hydrates. The salt brines and clay minerals could produce significant conduction losses through the unfrozen water, and the wet clay minerals could produce significant electrochemical relaxation losses at frequencies up to a hundred megaHertz. The dielectric relaxations in water ice and clathrate hydrates could produce additional losses at frequencies from the kiloHertz to tens of megaHertz (Davidson, 1973; Prensky, 1995).

Scattering losses are the result of interactions between the material spatial heterogeneity on a scale comparable to the electromagnetic wavelength in the material. Such scattering can occur at interfaces (surface scattering) or within the bulk material (volume scattering). Such scattering has been found to limit the depth of ground penetrating radar investigation in terrestrial glacier ice studies (Watts and England, 1976) as well as earth based studies of Mars and other solar system bodies (Hagfors et al., 1997).

The details of such scattering losses (and changes in polarization) depend upon the distribution of surface roughness (Rover Team, 1997b) and structure of the Martian regolith (Simpson et al., 1992; Christensen and Moore, 1992; Greeley et al., 1992). There exist observations and measurements about the surface roughness (Harmon, 1997; Haldeman et al., 1997; Golombek and Rapp, 1997) already indicating considerable rough surface scattering, but there are no comparable observations for the subsurface volume scattering.

DISCUSSION

Earth-based radar has been used to study the surface properties of Mars since 1963 (see review in Simpson et al., 1992). Some early studies (Olhoeft and Strangway, 1974) based on material arguments and the Apollo experience on the moon (Carrier et al., 1991) suggested Mars would be transparent to radiowaves and a good target for investigation with ground penetrating radar. However, more recent models which include the material property losses caused by magnetic materials, partially frozen clay minerals, concentrated salt brines, clathrate hydrate dielectric relaxation, and surface or volume scattering suggest ground penetrating radar needs to be carefully applied to problems on Mars. Like the Earth, it is likely that Mars will have places with material properties very favorable towards problem solution with ground penetrating radar. However, other locations will not be conducive to good investigation with ground penetrating radar from high losses that limit the depth of investigation.

Such variations in radar performance with location as a function of clay presence, water content, and scatterer size distributions are not unusual on the Earth. However, the large variation in frequency dependence for the magnetic losses will also mean that they will move in and out of any given radar frequency range of measurement over the normal temperature variation of a Martian day. This means a given ground penetrating radar system might experience considerable variations in performance over the course of a Martian day, and that the time of best performance could vary with location on Mars as magnetic mineralogy and season change. Depending upon the regolith depth range influenced by the temperature change and the distribution and type of magnetic minerals, the impact on the radar system could range from relatively minor antenna coupling changes to limitations on depth of investigation. Given that magnetic materials exist on Mars (Hviid et al., 1997), it is likely that a ground penetrating radar system should also measure both electric and magnetic fields, instead of just the conventional electric field only measurement.

REFERENCES

Barth, C. A., Stewart, A. I. F., Bugher, S. W., Hunten, D. M., Bauer, S. J., and Nagy, A. F., 1992, Aeronomy of the current Martian atmosphere: in Kieffer et al. (1992b), p. 1054-1089.

Banin, A., Clark, B. C., and Wanke, H., 1992, Surface chemistry and mineralogy: in Kieffer et al. (1992b), p. 594-625.

Brass, G. W., 1980, Stability of brines on Mars: *Icarus*, v. 42, p. 20-28.

Carr, M. H., 1996, *Water on Mars*: Oxford University Press, Oxford, 229p.

Carrier III, W. D., Olhoeft, G. R., and Mendell, W., 1991, Physical properties of the lunar surface: in *Lunar Sourcebook*, Heiken, G., Vaniman, D., and French, B.M., eds.: Cambridge Univ. Press, p. 475-594.

Christensen, P. R. and Moore, H. J., 1992, The Martian surface layer: in Kieffer et al. (1992b), p. 686-729.

Davidson, D. W., 1973, Clathrate hydrates: in *Water a comprehensive treatise, v. 2, water in crystalline hydrates, aqueous solutions of simple nonelectrolytes*, F. Franks, ed., Plenum Press, NY, p. 115-234.

Dunlop, D. J. and Ozdemir, O., 1997, *Rock magnetism, fundamentals and frontiers*: Cambridge Univ. Press, 573p.

Edgett, K. S., Butler, B. J., Zimbelman, J. R., and Hamilton, V. E., 1997, Geologic context of the Mars radar “stealth” region in southwest Tharsis: *J. Geophys. Res.*, v. 102, p. 21545-21567.

Erard, S. and Calvin, W., 1997, New composite spectra of Mars, 0.4-5.7 μm: *Icarus*, v. 130, p. 449-460.

Fanale, F. P., Postawko, S. E., Pollack, J. B., Carr, M. H., and Pepin, R. O., 1992, Mars: epochal climate change and volatile history: in Kieffer et al. (1992b), p. 1135-1179.

Forslund, E. and Jacobsson, A., 1975, Clay-water systems: in *Water a comprehensive treatise, v. 5, water in* *disperse systems*, F. Franks, ed., Plenum Press, NY, p. 173-248.

Golombek, M. P., 1997, The Mars Pathfinder Mission: *J. Geophys. Res.*, v. 102, p. 3953-3965.

Golombek, M. P. and Rapp, D., 1997, Size-frequency distributions of rocks on Mars and Earth analog sites: implications for future landed missions: *J. Geophys. Res.*, v. 102, p. 4117-4129.

Golombek, M. P., Cook, R. A., Economou, T., Folkner, W. M., Haldemann, A. F. C., Kallemeyn, P. H., Knudsen, J. M., Manning, R. M., Moore, H. J., Parker, T. J., Rieder, R., Schofield, J. T., Smith, P. H., and Vaughan, R. M., 1997, Overview of the Mars Pathfinder mission and assessment of landing site predictions: *Science*, v. 278, p. 1743-1748.

Gooding, J. L., Arvidson, R. E., and Zolotov, M. Yu., 1992, Physical and chemical weathering: in Kieffer et al. (1992b), p. 626-651.

Grant, J. A., Schultz, P. H., and Collins, W. K., 1995, Effectiveness of ground penetrating radar in Argentine loess: implications for future Mars surface radar sounders: in *Lunar and Planetary Sci. XXVI*, Lunar & Planetary Institute, Houston, p. 497-498.

Greeley, R., Lancaster, N., Lee, S., and Thomas, P., 1992, Martian aeolian processes, sediments, and features: in Kieffer et al. (1992b), p. 730-766.

Hagfors, T., Dahlstrom, I., Gold, T., Hamram, S.-E., and Hansen, R., 1997, Refraction scattering in the anomalous reflections from icy surfaces: *Icarus*, v. 130, p. 313-322.

Haldemann, A. F. C., Mitchell, D. L., Jurgens, R. F., Slade, A. M., and Muhleman, D. O., 1997, Mars Pathfinder landing site assessment with Goldstone delay-Doppler and CW radar experiments: *J. Geophys. Res.*, v. 102, p. 4097-4106.

Hargraves, R. B., Collinson, D. W., Arvidson, R. E., and Spitzer, C. R., 1977, The Viking magnetic properties experiment: primary mission results: *J. Geophys. Res.*, v. 82, p. 4547-4558.

Harmon, J. K., 1997, A radar study of the Chryse region, Mars; *J. Geophys. Res.*, v. 102, p. 4081-4095.

Hunt, C. P., Moskowitz, B. M., and Banerjee, S. K., 1995, Magnetic properties of rocks and minerals: in *Rock physics and phase relations*, T. J. Ahrens, ed., Am. Geophys. Union, Wash. DC, p. 189-204.

Hviid, S. F., Madsen, M. B., Gunnlaugsson, H. P., Goetz, W., Knudsen, J. M., Hargraves, R. B., Smith, P., Britt, D., Dineson, A. R., Mogensen, C. T., Olsen, M., Pedersen, C. T., and Vistisen, L., 1997, Magnetic properties experiments on Mars Pathfinder lander: preliminary results: *Science*, v. 278, p. 1768-1770.

Jakosky, B. M. and Jones, J. H., 1997, The history of Martian volatiles: *Rev. of Geophysics*, v. 35, p. 1-16.

Kahn, R. A., Martin, T. Z., Zurek, R. W., and Lee, S. W., 1992, The Martian dust cycle: in Kieffer et al. (1992b), p. 1017-1053.

Kieffer, H. H., Jakosky, B. M. and Snyder, C. W., 1992a, The planet Mars: from antiquity to the present: in Kieffer et al. (1992b), p. 1-33.

Kieffer, H. H., Jakosky, B. M., Snyder, C. W. and Mathews, M. S., eds., 1992b, *Mars*: The Univ. of Arizona Press, Tucson, 1498p.

Kieffer, H. H. and Zent, A. P., 1992, Quasi-periodic climate change on Mars: in Kieffer et al. (1992b), p. 1180-1218.

Klein, H. P., Horowitz, N. H., and Biemann, K., 1992, The search for extant life on Mars: in Kieffer et al. (1992b), p. 1221-1233.

Kolecki, J. C., 1997, Electrostatic charging of the Mars Pathfinder rover: *http://powerweb.lerc.nasa.gov/DOC/pathfinder/rec.html*, 2p.+figures.

Legrand, M. and Mayewski, P., 1997, Glaciochemistry of polar ice cores: a review: *Rev. of Geophysics*, v. 35, p. 219-243.

Luhmann, J. G., Russell, C. T., Brace, L. H. and Vaisberg, O. L., 1992, The intrinsic magnetic field and solar-wind interaction of Mars: in Kieffer et al. (1992b), p. 1090-1134.

McKay Jr., C. P., Mancinelli, R. L., Stoker, C. R., and Wharton Jr., R. A., 1992, The possibility of life on Mars during a water-rich past: in Kieffer et al. (1992b), p. 1234-1245.

McKay, D. S., Gibson, E., Thomas-Keprta, K., Hogatollah, V., Romanek, C., Clement, S., Chiller, S., Maechling, C., and Zare, R., 1996, Search for past life on Mars: possible relic biogenic activity in Martian meteorite ALH84001: *Science*, v. 273, p. 924-930.

Mellon, M. T., Jakosky, B. M., and Postawko, S. E., 1997, The persistance of equatorial ground ice on Mars: *J. Geophys. Res.*, v. 102, p. 10357-19369.

Mouginis-Mark, P. J., Wilson, L., and Zuber, M. T., 1992, The physical volcanology of Mars: in Kieffer et al. (1992b), p. 424-452.

Muhleman, D. O., Butler, B. J., Grossman, A. W., and Slade, M. A., 1991, Radar images of Mars: *Science*, v. 53, p. 1508-1513.

Olhoeft, G. R., and Strangway, D. W., 1974, Electrical properties of the surface layers of Mars: *Geophysical Research Letters*, v. 1, p. 141-143.

Olhoeft, G. R., 1977, Electrical properties of natural clay permafrost: *Canadian Journal of Earth Science*, v. 14, p. 16-24.

Olhoeft, G. R., 1987, Electrical properties from 10^{-3} to 10^{+9} Hz -- physics and chemistry: in *Physics and Chemistry of Porous Media II*, American Institute of Physics Conf. Proc. 154, Ridgefield, CT, 1986, J.R. Banavar, J. Koplik, and K.W. Winkler, eds., NY, AIP, p. 281-298.

Olhoeft, G. R., 1991, Magnetic and electrical properties of Martian particles: in *Sand and Dust on Mars*, R. Greeley and R. M. Haberle, eds., NASA Conf. Publ. 10074, p. 44-46.

Olhoeft, G. R., and Capron , D. E., 1993, Laboratory measurements of the radiofrequency electrical and magnetic properties of soils from near Yuma, Arizona: *U.S. Geological Survey Open-File Report 93-701*, 214 p.

Olhoeft, G. R. and Capron, D. E., 1994, Petrophysical causes of electromagnetic dispersion: in *Proc. of the Fifth Int'l. Conf. on Ground Penetrating Radar*, Kitchener, Ontario, 12-16 June 1994, p. 145-152.

Ori, G. G. and Ogliani, F., 1996, Potentiality of ground penetrating radar for the analysis of the stratigraphy and sedimentology of Mars: *Planet. Space Sci.*, v. 44, p. 1303-1315.

Prensky, S., 1995, Physical Properties of Hydrates and Ice: *International Society of Offshore and Polar Engineering*, Golden Colorado, vol. 1, p. 674-683.

Rieder, R., Economou, T., Wanke, H., Turkevich, A., Crisp, J., Bruckner, J., Dreibus, G., and McSween Jr., H. Y., 1997, The chemical composition of Martian soil and rocks returned by the mobile alpha proton X-ray spectrometer: preliminary results from the X-ray mode: *Science*, v. 278, p. 1771-1774.

Rover Team (49 authors), 1997a, The Pathfinder microrover: *J. Geophys. Res.*, v. 102, p. 3989-4001.

Rover Team (31 authors), 1997b, Characterization of the Martian surface deposits by the Mars Pathfinder rover, Sojourner: *Science*, v. 278, p. 1765-1767.

Simpson, R. A., Harmon, J. K., Zisk, S. H., Thompson, T. W. and Muhleman, D. O., 1992, Radar determination of Mars surface properties: in Kieffer et al. (1992b), p. 652-685.

Soderblom, L. A., 1992, The composition and mineralogy of the Martian surface from spectroscopic observations 0.3 μm to 50 μm: in Kieffer et al. (1992b), p. 557-593.

Snyder, C. W. and Moroz, V. I., 1992, Spacecraft exploration of Mars: in Kieffer et al. (1992b), p. 71-119.

Squyres, S. W., Clifford, S M., Kuzmin, R. O., Zimbelman, J. R., and Costard, F. M., 1992, Ice in the Martian regolith: in Kieffer et al. (1992b), p. 523-554.

Tanaka, K. L., Scott, D. H., and Greeley, R., 1992, Global stratigraphy: in Kieffer et al. (1992b), p. 345-382.

Thomas, P., Squyres, S., Herkenhoff, K., Howard, A., and Murray, B., 1992, Polar deposits of Mars: in Kieffer et al. (1992b), p. 767-795.

Watts, R. D. and England, A. W., 1976, Radio-echo sounding of temperate glaciers: ice properties and sounder design: *J. Glaciol.*, v. 17, p. 39-48.

Zurek, R. W., Barnes, J. R., Haberle, R. M., Pollack, J. B., Tillman, J. E., and Leovy, C. B., 1992, Dynamics of the atmosphere of Mars: in Kieffer et al. (1992b), p. 835-933.

Olhoeft, G. R., 1998, Ground penetrating radar on Mars: in Proc. of GPR'98, Seventh Int'l. Conf. on Ground Penetrating Radar, May 27-30, 1998, The University of Kansas, Lawrence, KS, USA, p. 387-392.