PROSPECTING FOR SUBSURFACE LIQUID WATER USING MAGNETOTELLURICS ON MARS. G. T. Delory[1], R. E. Grimm[2], T. Nielsen[3], and W. M. Farrell[4], [1]Space Sciences Laboratory, University of California, Berkeley CA 94720 gdelory@ssl.berkeley.edu, [2]Southwest Research Institute, 1050 Walnut St., Suite 400, Boulder CO 80403, [3]QUASAR Federal Systems, 5764 Pacific Center Blvd., Suite 203 San Diego, CA 92121, NASA Goddard Space Flight Center, Mail Code 695, Greenbelt, MD 20771.

Introduction: Detection of liquid water on Mars remains a key exploration objective, but geophysical methods currently in use or under consideration for subsurface exploration (radar and seismic, respectively) are not optimal for water detection. Electromagnetic (EM) sounding is sensitive to water with even modest dissolved solids, and brines are a near-ideal EM target. The magnetotelluric technique is a passive, low-frequency EM sounding method that can be compactly implemented and is capable of the characterization of groundwater from depths ranging from 100m to 10 km on Mars [1]. With support from NASA planetary and Mars instrument development programs, we have developed an autonomous magnetotelluric sensor platform and demonstrated it at several field-test sites in Idaho's eastern Snake River Plain, the terrestrial type location for planetary plains-style basaltic volcanism. Soundings over 1 km deep detected the contact between aqueously altered tuff and relatively unaltered basalt, a proxy for the water table on Mars. Here we discuss passive EM methodologies, our instrument development effort and field-test results, and the use of low-mass, passive instrumentation to enable deep subsurface exploration on future Mars scout or network class missions.

Science Background & Objectives: The ability to detect and characterize extraterrestrial water and ice has important implications for the understanding of planetary geological and climate histories, extinct or extant life, and for the planning of future robotic and human exploration of the solar system. There is a significant amount of geologic and geomorphic evidence that water on Mars was abundant at some point in the past, forming valley networks, outflow channels and possibly ocean basins [2-4]. The Mars Exploration Rovers have provided additional insights into the history of water on Mars, including indications of abundant groundwater in Meridiani Planum [5], while rocks and soils in the Columbia Hills region appear to have undergone significant aqueous alteration [6]. While it is clear that Mars once had significant amounts of liquid water both in the crust and on the surface, the state, distribution, and overall inventory of present-day water continues to be heavily debated. While significant quantities of water may have been lost to space through impacts or solar wind erosion [7], it may also have become trapped in the frozen upper portion of the crust, thus creating a cryosphere [8]. Depths to the base of the cryosphere vary between 2-6 km [9] depending on latitude; the discovery of the gullies [4] indicates that the cryosphere may only be hundreds of meters thick in some regions, enabling the emergence of liquid water within relatively recent timescales depending on the geothermal gradients present [10]. Alternatively, the gullies may be due to basal snowmelt without the need for groundwater [11], or result from dry flows of Aeolian material [12]. There is direct evidence for water-ice in the near subsurface, detected within the first meter by the neutron/gamma-ray spectrometer on Mars Odyssey [13], and concentrated poleward of 60° latitudes [14], while initial results from the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) indicate the presence of relatively pure ices to km depths, particularly in the northern polar layered deposits [15]. While measurements of recent changes in the gully features may hint at active subsurface processes on Mars [16], direct detection of liquid water remains an elusive goal. Orbital radar sounding investigations may not be able to identify subsurface water without significant ambiguities [17, 18]. Where radar methods are successful, follow-up ground truth measurements will need to be performed in order to corroborate these results.

Low frequency EM methods can play a crucial role in the search for subsurface water on Mars, both as a primary means of detection or as a ground truth measurement [1]. Where radar methods are successful, low-frequency EM methods can perform deep soundings at high priority sites. More likely, the penetration depth and conductivity discrimination of low-frequency methods may enable detection of subsurface water in areas that render radar methods ineffective. In either case, the sensitivity and depth of penetration inherent in low-frequency EM exploration makes this tool a compelling candidate method to identify subsurface liquid water from a landed platform on Mars or other targets of interest. Electromagnetics is also superior to seismic methods for water detection. Seismic velocities are not as sensitive to low saturation as EM and furthermore these velocity variations are confined to pressures corresponding to depths less than a few kilometers on Mars.

Low Frequency EM Sounding: EM waves used in low-frequency soundings are in the diffusive regime, in which the dominant parameter controlling signal behavior is the finite conductivity of the subsurface. A passive sounding method includes the magnetotelluric (MT) technique, in which the electric and magnetic amplitudes of long-period waves from natural planetary EM sources are monitored near the surface in order to determine the subsurface electrical impedance as a function of wave skin depth [19]. Since the conductivity of even mildly saline liquid water is several or more orders of magnitude greater than the surrounding medium, its presence significantly modifies the subsurface resistivity. Using this methodology, both the depth and thickness of multiple aquifers can be determined depending on the availability of naturally produced low frequency EM waves and the conductivity contrast between the liquid water and the surrounding media. The response of ice to low-frequency EM waves is essentially the same as radar and becomes difficult to detect, unless massively segregated [1]. Thus low-frequency methods may be ideal for the detection of liquid water in permafrost-rich mediums such as the Martian cryosphere.

The focus of our instrument development effort has been to demonstrate a system capable of performing the MT technique on Mars, in which the horizontal components of naturally occurring electromagnetic

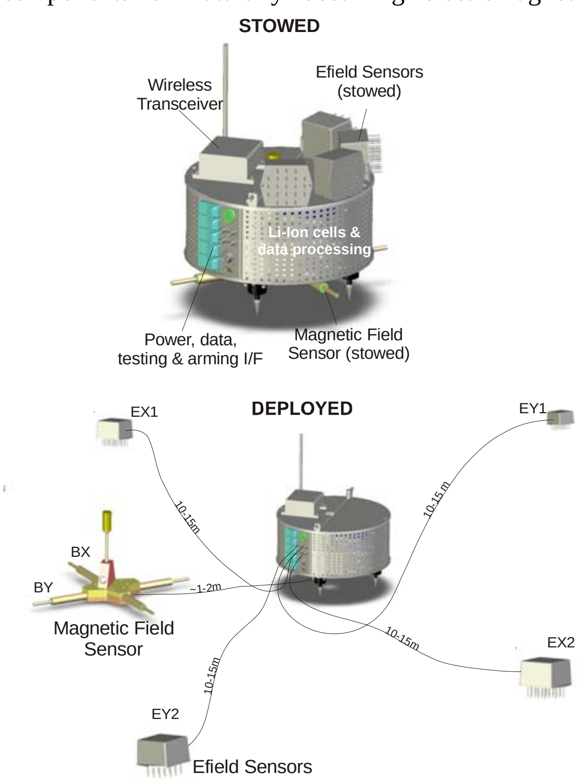

Figure 1 *Deployable EM sounder system design. Central station is ~30 cm wide and < 8 kg.*

signals are recorded as an indicator of subsurface conductivity. On Earth, some of the deepest non-invasive soundings have been obtained by monitoring the myriad of naturally generated EM wave sources present throughout the terrestrial environment. These include ULF emissions produced by Solar wind-magnetosphere interactions above the ionosphere, and lightning-related sources within the terrestrial atmosphere. Together these sources provide a near continuum (with occasional nulls) in the 0.001 Hz – 20 kHz band that can be used as a source for MT soundings.

The essential physics behind the MT technique relies on the fact that the surface and subsurface are not perfect conductors, and will generally possess a finite electrical resistivity depending on composition, temperature, and water content of subsurface materials (typically between ~1 to 1000s of ohm-m in value.) In MT soundings the central quantity of interest is the apparent impedance, given by:

$$\rho = \frac{1}{5f}\frac{E_x^2}{B_y^2} \qquad (1)$$

where f is the wave frequency (Hz), E_x is the magnitude of the horizontal component of the electric field (in μV/m), and B_y (in nT) is the magnitude of the horizontal magnetic field perpendicular to E_x, each measured at the surface [19]. The quantity ρ, given in ohm-m, represents the apparent electrical resistivity of the subsurface at a given frequency f. The dissipation represented by ρ, caused by the flow of direct currents through the resistive media of the subsurface, has a frequency dependent penetration distance given by the wave skin depth:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \sim 500\sqrt{\frac{\rho}{f}}\ \mathrm{m} \qquad (2)$$

Because the depth of penetration of EM waves is frequency dependent, the quantity ρ can then also be estimated as a function of depth. The result of the sounding is then a depth-conductivity profile, yielding the depth and thickness of subsurface conductors.

Instrument Development Effort: Among the tools necessary to perform MT soundings are low-frequency electric and magnetic field sensors capable of being deployed from a lander or rover such that horizontal components of the fields can be measured free of structural or electrical interference. Under Planetary Instrument Definition and Development Program (PIDDP) funding, we developed small electric field sensors capable of measuring horizontal fields with light contact on a variety of surfaces. This work was extended into the Mars Instrument Development Program (MIDP), where these sensors were combined

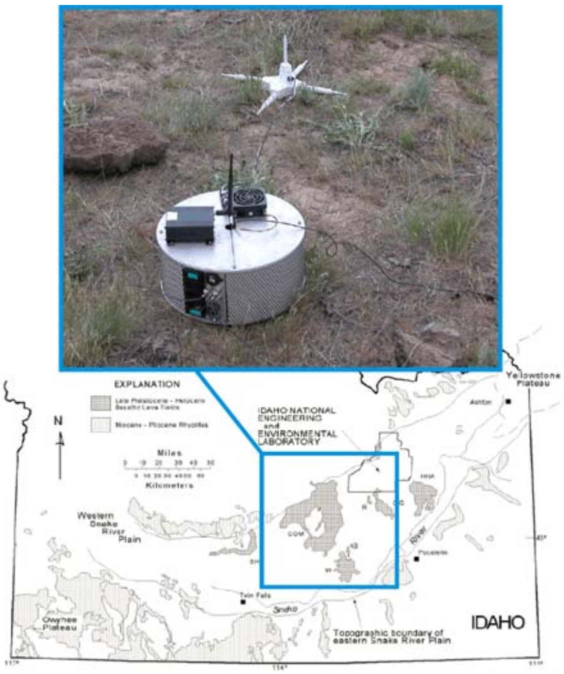

Figure 2 *EM Sounding system prototype (top) and field-test site in the eastern Snake River Plain, Idaho (bottom.)*

with magnetic field sensors and an integrated, autonomous EM sounder system was developed (Figure 1).

Electric and magnetic field sensors. The horizontal electric field is determined using pairs of probes that determine the potential difference between two points on the surface. The electric field is then derived by dividing the measured potential by the distance between the probes. Each electric potential sensor couples to the surface using a spiked copper plate, enabling both galvanic and capacitive coupling to the surface, including in the dry, highly resistive media we would expect to find on Mars. Effective signal coupling can be achieved with the sensors simply resting on the surface, with very little insertion force needed in most environments.

The magnetic field sensors used for the EM sounder consist of a unique design developed by members of our team under various NSF and DARPA programs in addition to MIDP. The design is based on a typical wire-wound induction coil, and uses a high-permeability core material with a unique construction geometry. This approach achieves unparalleled noise and sensitivity using coils only 18” across. The performance of the magnetometer coils is similar to a commercial BF-6 series (Schlumberger Inc.) but at $1/3^{rd}$ the size and mass. Sensor noise levels are ~1 pT at 1 Hz, becoming 30 fT at 100 Hz.

The overall frequency response of both the electric and magnetic field sensors is ~1 Hz to ~100 kHz with typical upper sample rates of ~50 kHz used in practice. The depth penetration of this system varies between 1-4 km depending on the subsurface properties.

Deployable EM sounding station. A central support package was developed to perform data acquisition and processing tasks, provide power, and a wireless telemetry system (Figure 1 and Figure 2). The station structure provides areas to stow the electric and magnetic field sensors in order to be transported in a compact form. During measurements, high resolution, 24-bit ADC converters continuously digitized low-frequency EM signals, while a higher speed 16-bit system performed discrete captures of transient EM events (such as lightning). An RF transceiver using an Ethernet protocol enables the system to be configured and operated remotely using a laptop.

Field test results: The goal of our field tests was to obtain geophysically meaningful data in a Mars-relevant subsurface environment; for this purpose, several sites were selected in the eastern snake river plain (ESRP) region of Idaho shown in Figure 2. The resistive overburden of relatively young, unaltered Quaternary (Qb) basalt with conductive targets such as groundwater and older basalt/tuff materials provides a useful analogy to the subsurface of Mars, where an electrically resistive, frozen cryosphere is likely to exist with more conducting liquid groundwater at depth. Extensive surveys conducted at ESRP prior to our tests enabled independent verification of our field test results.

Results from ESRP Site 3 (N43 21.875' W113 08.389') are shown in Figure 3, where the electrical resistivity was determined to a depth of about ~1.8 km. Depths between ~10 and <200m correspond to dry, resistive basalt that is common throughout the region, with maximum resistivities of ~2000 ohm-m. A conductor at ~200 m is likely the top of water-saturated basalt, i.e., the water table. Underlying resistivity changes correlate with the estimated transition from younger to older basalt. The sudden increase in resistivity below ~1.6 km is somewhat ambiguous, resulting from the finite bandwidth available as the low frequency limit of the receivers is approached. The increase in conductivity is probably real (sedimentary bedrock), but likely occurs at deeper levels than we resolve here.

Our results correlate well with previous survey data in the region. The thickness of the Qb basalt is believed to be between 770-920m at our test location, corresponding to the broad resistive layer we see to about ~900m. Previous DC electrical resistivity surveys [20] detected an upper layer of extremely resistive, 1000-3000 ohm-m young dry basalt above more conductive basalt saturated with water, followed by

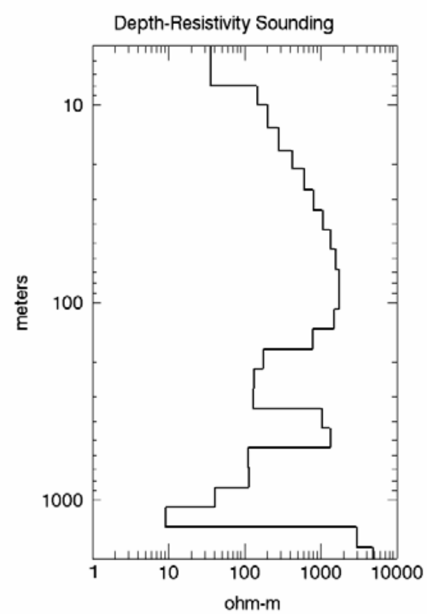

Figure 3 *Inversion of the apparent resistivity data Quaternary basalt provides a resistive layer (~2000 ohm-m) followed by groundwater at ~200-300m.*

increasingly conductive materials such as basalt flows and clay combinations (100-200 ohm-m). Pliocene and younger basalt rock aquifers permeate much of the region; local surveys indicate the depth to the water table at our site to be between 215-500 m beneath the surface. In our results we detect both the highly resistive materials up to ~2000 ohm-m, followed by what is likely the water saturated zone at a depth of about 200m.

Mission Implementation: Since Magnetotellurics is a passive technique, the approach is inherently low in power consumption and is consistent with what can be provided by reasonably-sized solar arrays. Onboard data compression and selection brings data rates to well within what can be accomplished with a local link to a rover or via UHF relay to an orbiting satellite. An important issue is the deployment of the electric field sensors, each of which requires ~10 meters separation from the central EM sounder package. The size (500 cc), mass (<150 g), and required insertion force of these sensors is easily within the capabilities of rover manipulators. Once deployed, our field test experience indicates that useful soundings can be acquired in 30 minutes or less. Deeper soundings (~10 km), together with system commissioning, checkout, and data validation are easily accomplished within a nominal 30 days of operation.

Our system was tested and deployed using the K-9 rover prototype in the NASA Ames Mars yard to demonstrate compatibility with future Mars rover missions that may carry such instrument packages to Mars, such as the Astrobiological Field Laboratory (AFL) rover. The system we have developed may also apply to a long-lived network mission. In this case, deployment of the magnetometer and electric field sensors would have to occur autonomously. Many of these issues were studied and prototyped in the development of the NetLander mission prior to its cancellation in late Phase B, and would also apply here.

A final question relates to the nature of the EM environment on Mars, since a certain level of natural EM noise is required for successful MT. Mars possesses many of the ingredients necessary for the generation of natural EM noise, including an ionosphere immersed in a solar wind, magnetic anomalies, and the triboelectric charging and subsequent discharging of dust within the atmosphere. Given our current level of knowledge, the dependence of MT surveys on natural EM sources is similar to assumptions made regarding the availability of seismic signals for seismometer instruments, and is thus a justifiable candidate as a tool for subsurface exploration on future Mars Scout, network, or rover missions.

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