# THE DESIGN AND IMPLEMENTATION OF INSTRUMENTS FOR LOW-FREQUENCY ELECTROMAGNETIC SOUNDING OF THE MARTIAN SUBSURFACE.

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**Introduction:** Low-frequency electromagnetic (EM) soundings of the subsurface can identify liquid water at depths ranging from hundreds of meters to ~10 km in an environment such as Mars [1]. Among the tools necessary to perform these soundings are low-frequency electric and magnetic field sensors capable of being deployed from a lander or rover such that horizontal and vertical components of the fields can be measured free of structural or electrical interference. Under a NASA Planetary Instrument Definition and Development Program (PIDDP), we are currently engaged in the prototype stages of low-frequency sensor implementations that will enable this technique to be performed autonomously within the constraints of a lander platform. Once developed, this technique will represent both a complementary and alternative method to orbital radar sounding investigations, as the latter may not be able to identify subsurface water without significant ambiguities [2,3]. Low frequency EM methods can play a crucial role as a ground truth measurement, performing deep soundings at sites identified as high priority areas by orbital radars. Alternatively, 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.

**Searching for Water:** The ability to detect and characterize extraterrestrial water and ice has important implications for the understanding of planetary geological and climate histories, past or extant life, and for the planning of future robotic and human exploration of the solar system. The characterization of past or present water on Mars remains a core goal of the Mars Exploration Program (MEP), representing a cross-cutting theme that ties together investigations relevant to life, climate, geology, and the identification of sites relevant for future exploratory landed missions. There is a significant amount of geologic evidence that water on Mars was abundant at some point in the past, forming valley networks, outflow channels and possibly ocean basins [4,5,6]. Assuming that the Martian water inventory was not lost to space, it may be contained within the frozen upper portions of the crust in the cryosphere. Liquid water may exist due to heterogeneous thermal properties or if the amount of water exceeds the storage capacity of the cryosphere. Depths to the base of the cryosphere vary between 2-6 km [7] 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 [8]. Alternatively, the gullies may be due to basal snowmelt without the need for groundwater [9].

**Low-Frequency EM Soundings:** EM waves used in low-frequency soundings are in the diffusive regime, in which the dominant parameter controlling the emissions is the finite conductivity of the subsurface. A passive sounding method includes the magnetotelluric 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. Active methods include both spectral and time domain measurements of the fields in response to artificially generated waves. In the time domain, the decay of secondary magnetic fields generated from subsurface currents in response to an artificially produced EM pulse are recorded to estimate subsurface conductivity. For all low-frequency sounding methods, it is the electrical conductivity as a function of depth into the subsurface that is determined. 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 detected subsurface impedance. Using this methodology, both the depth and thickness of multiple aquifers can be determined depending on the availability of naturally or artificially 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 thus becomes difficult to detect, unless massively segregated [1].

**Sources of Low Frequency EM on Mars:** On Earth, the deepest soundings are obtained by monitoring a myriad of naturally generated electromagnetic wave sources. These include ULF emissions produced by Solar Wind-Magnetosphere interactions (0.001-1 Hz), and lightning-related sources (Schumann resonances and ELF emissions, 1 Hz-2 kHz). With the presence of magnetic anomalies, an ionosphere, and windblown dust there is every reason to believe that Mars will also possess a rich and dynamic electromagnetic environment. ULF perturbations have been witnessed near Mars on both MGS and the Phobos missions [10,11]. The triboelectric charging of dust within the ubiquitous dust devils and larger scale dust storms may produce discharges that can form an ELF continuum of EM emissions when guided by the ionosphere-surface cavity [12]. Similarly, Schumann resonances may exist on Mars at frequencies close to their Terrestrial counterparts [13]. Additional potential sources of low frequency emissions include Solar-Quiet ($S_q$) variations, resulting from couplings between the lower ionosphere and atmospheric thermal tides. The relatively fast response of the Martian atmosphere to radiative heating [14] may produce strong $S_q$ signatures on Mars. All of these signals represent potential sources for deep EM soundings of the subsurface on Mars.

**Instrument Development Effort:** The penetration depth and detection threshold for subsurface water using EM methods hinges on the availability of electric and magnetic sensors with sufficient sensitivity at low frequencies to detect naturally occurring EM waves. Of the two measurements, the electric field detection is by far the more challenging endeavor in this regime. The term “low-frequency” in the context of EM soundings denotes the division between propagative (wave like) and diffusive behavior of the EM fields; below this division, the electric field diffuses into the subsurface media with a skin depth and initial amplitude dependent on the subsurface conductivity. On Mars, waves become diffusive around ~1 kHz [1], while a desire to probe deep within the cryosphere requires a low frequency limit in the milli-Hertz (0.001 Hz) or lower frequency regimes. Terrestrial applications have utilized fully grounded (buried) electrical dipoles with separation distances of 100s of meters or more to detect long-period, low-amplitude signals. These dipoles make direct resistive contact with the subsurface using an electrolyte medium for long-term signal stabilization, and necessitate a process of manual installation and subsequent settling time.

While such techniques have detected water and other natural resources to depths of hundreds of meters or more in Terrestrial settings [15], a simpler, non-contacting and autonomously deployable system must be developed in order to use this method in planetary exploration. Our efforts have thus far focused on the development of low-frequency, low-noise electric field sensors capable of measurements near or on the surface without the need for direct, galvanic contact with the subsurface itself. One of the more crucial measurements for effective soundings is the component of the electric field parallel with the surface, since this amplitude directly indicates the subsurface resistivity structure when combined with simultaneous magnetic field measurements. Measurement of this component of the ambient electric field is also the most challenging, since amplitudes can be less than 1 uV/m depending on subsurface properties.

Strategies to measure these low-frequency electric fields include the use of short dipole probes that make direct resistive contact with the atmosphere of Mars. This is enabled through the use of ultra-high input impedance op-amps ($R_{in}$ ~$10^{14}$ ohms or greater) and spherical or cylindrical electrodes that draw a current from the atmosphere directly. With a Martian pressure of ~6-8 mBar, the atmospheric conductivity is roughly $10^{-11}$ S/m [16]; under these conditions, a probe with a surface area of ~200 $cm^2$ will have a coupling impedance of ~ 2 x $10^{11}$ ohms. The feasibility of this method has already been proven in the terrestrial stratosphere, where the atmospheric conductivity is nearly identical with the value on the surface of Mars [17]. In this regime, stratospheric balloons have measured low-amplitude DC electric fields from ionospheric ULF waves for decades [18], a particularly useful wave for deep magnetotelluric soundings. Similar direct resistive contact of electric field probes in the Martian atmosphere may enable the measurement of ULF or

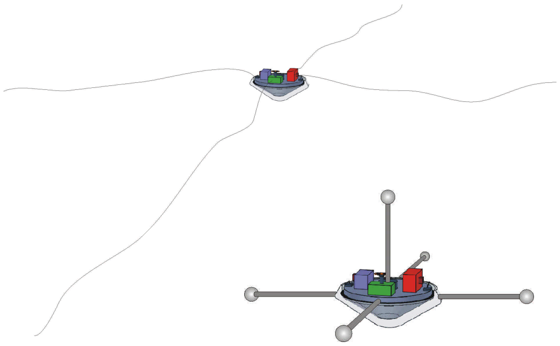

**Figure 1** Antenna and probe deployment schemes to measure parallel and horizontal electric fields on the surface of Mars. When combined with magnetic field measurements, the ratio of E/H can be used to derive the subsurface conductivity structure.

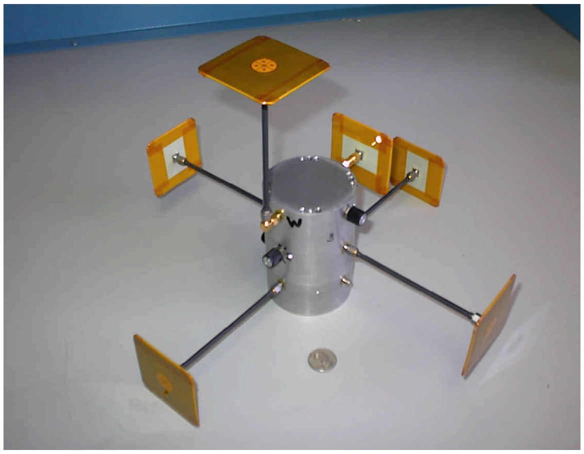

**Figure 2** Miniature 3-axis electric field receiver under development at Quasar, Inc. in support of PIDDP field test activities.

similar waves on Mars for purposes of deep (~km) soundings. Complicating factors on the surface of Mars include the presence of airborne dust which can deposit static charge on the surface of the probes, creating a succession of high-frequency transients that as an ensemble can cause a continuum of increased low-frequency noise. A second possible issue relates to the fact that while stratospheric balloon payloads rotate, lander platforms are stationary, reducing the capability to reject spurious signals resulting from payload charging and effectively increasing the $1/f$ noise of the system.

Alternative methods include purely capacitively coupled, flexible antennas ballistically deployed from a lander platform to lengths of 20m or more. In the capacitively coupled regime, no atmospheric currents are measured; instead, the conductors in the wires couple capacitively to the surface to which they are parallel, measuring the parallel component of the electric fields which should be continuous across the surface-subsurface boundary. Advantages in this approach include larger intrinsic signal gain due to the longer baseline for the potential measurement, and lower noise due to the large antenna capacitance relative to sensor input capacitance. The low-frequency response of this system is governed by op-amp stability and the effective *RC* time constant formed between the antenna capacitance and the internal sensor input impedance, typically in the 0.1-1 Hz range. A hybrid system composed of flexible antennas with galvanically coupled probes on the ends is also possible, enabling sensitive AC measurements via the long antennas and DC measurements from the end probes. Fundamental engineering concepts for the deployment of long flexible antennas from a Mars lander are already well-established as part of the proposed NetLander payload [19].

Once successful measurements of the electric field parallel ($E_x$) to the subsurface are obtained, they can be combined with simultaneously measured magnetic fields in the orthogonal direction ($H_y$) to derive the subsurface impedance using the Magnetotelluric technique:

$$Z = \frac{|E_x|^2}{|H_y|^2} \approx \frac{|E_y|^2}{|H_x|^2} \rightarrow r = \frac{1}{5f}\left|\frac{E_x}{H_y}\right|^2$$

where $Z$ is the subsurface impedance, $r$ the resistivity (in ohm-m) and $f$ the wave frequency. When measured as a function of frequency, the result is an apparent conductivity vs. depth profile. Inversion methods to determine depth to conductive features depend on a description of the subsurface as a series of resistive half-spaces, forming a layered model whose response to vertical plane waves is calculated through a recursive procedure [1]. Similar information about the subsurface conductivity can be obtained via the wave-tilt method using the ratio of $E_z/E_x$. Onboard spectral processing using FFTs or cascade decimation can produce spectra of each field component and form the ratio of $E/H$ directly. This data along with snapshots of time series measurements can then be transmitted back to Earth for analysis and interpretation of both signal source quality and subsurface electrical properties.

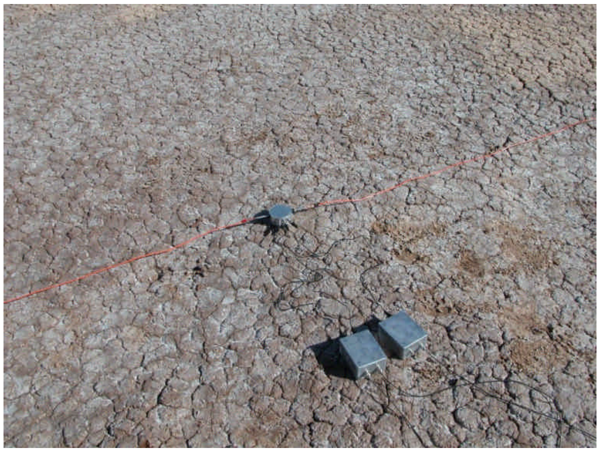

**Figure 3** Field tests conducted in the Mojave desert (March 2003) studied the capabilities of various antennas geometries to sense low-frequency parallel electric fields.

**Field Test Experiments:** Terrestrial field tests of non-grounded probes and antennas for sensing low-frequency electrical fields near the surface are ongoing under NAG5-11781 (PIDDP). In this approach several classes of recently available high-input impedance, low noise electrometers and op-amps are being mated to various antenna coupling strategies in order to derive a system with maximum sensitivity and minimum noise. Measurements of the vertical component of Schumann resonances have been obtained with small, lightweight sensors such as the example shown in Figure 2. Measurements of the electric fields parallel to the surface are far more challenging and may require longer baseline measurements and larger antenna form factors. Figure 3 shows a test of this concept in the Lavic Lake region of the Mojave desert. Initial results of these tests indicates that naturally occurring low frequency electric fields with amplitudes ~0.01-.1 uV/m parallel to the surface may be detectable using deployable antennas as shown. Goals for the next year of the program include a full magnetotelluric sounding using our low-frequency electric field sensor prototypes in combination with widely available magnetic sensors. Once developed, such a system could be easily deployed from a fixed lander platform to perform EM soundings using either active or passive EM sources depending on the mass and power available for the instrument.

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