Electromagnetic Induction Sounder for Subsurface Mapping of Resistivity and Magnetic Susceptibility on Mars

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Abstract

This paper describes the Electromagnetic Induction Sounder (EMIS), a proposed electromagnetic geophysical instrument for mapping the near-subsurface of Mars. The EMIS transmitter generates a primary EM field which induces eddy currents in subsurface electrical conductors – the prime target, in this case, being brine pockets above a thick permafrost layer. The conductors, in turn, generate a "secondary" EM field which is sensed, together with the primary field, by the EMIS receiver antenna(s). The amplitude of the secondary field component out-of-phase with the primary field is a direct measure of subsurface conductivity. In addition, the in-phase signal can be used to estimate magnetic susceptibility.

The EMIS will be mounted on the Skimmer Martian exploration vehicle which will also carry a drill capable of investigating to a depth of 1 m. The depth of exploration of the EMIS is in excess of 10 m, depending on the operating frequency and electromagnetic properties. It can be used to perform lateral and vertical soundings. Zones of relatively high conductivity are of key interest and could be selected as drilling sites.

1. Introduction

Although the Martian atmosphere contains many of the elements necessary for life, its mean surface pressure is about 8 hPa, and the mean temperature is -60°C. The pressure is close to the triple point pressure of water, which is the minimum pressure at which a liquid state can exist. The low pressures and low temperatures make it such that liquid water is rare and transient if it occurs at all (Ingersoll, 1970; Lobitz et al., 2001; Haberle et al., 2001; Hecht, 2002; Kuznetz and Gan, 2002; Sears and Chittenden, 2005). In the rare locations at low elevation where the pressure and temperature are sufficient to support liquid water (Haberle et al., 2001; Lobitz et al. 2001) the surface is desiccated. Due to seasonal transport, available water is trapped as ice in the polar regions. Even eutectic brine solutions cannot exist in equilibrium with the atmosphere near the equator (Haberle et al., 2001). The absence of liquid water on the surface of Mars is probably the most serious argument against the presence of life anywhere at the surface of the planet today.

As such, given that Mars is apparently unable to support liquid water and possible life on its surface, it is prudent to look elsewhere, such as in the subsurface of the planet for pockets of water. In November 2005, radar mapping by the Mars Express Orbiter over Chryse Planitia, a mid-latitude lowland region of Mars, revealed liquid-phase water apparently pooling 1.5-2.5 km beneath the surface (Picardi et al., 2005). The liquid-phase water was found in a 250-km wide buried impact crater filled with volcanic ash, soil and, probably, a large proportion of water ice. Its radar signature was a strong, linear reflection near parallel to the planet's surface. These encouraging results continue to foster interest in mapping the subsurface of Mars, especially in the search for liquid-phase water. Detection, characterization and mapping of liquid-phase water is of critical importance for geological and astrobiological studies and, eventually, for human life support.

Salty Mars

The geological evidence of aqueous alteration at both the Meridiani Planum and Gusev Crater Mars Exploration Rover (MER) landing sites implies the presence of intermittent liquid water at the Martian surface, and generally wetter conditions on the planet than is apparent today (Squyres et al. 2004a; Haskin et al., 2005). At Meridiani Planum, the sedimentary, mineralogical and geochemical evidence for an ancient aqueous environment has been described from the finely laminated sulfate-rich sedimentary rock record of the Eagle Crater outcrop (Squyres et al., 2004b). Cross-laminations and high abundances of sulfate salts (jarosite, and magnesium and calcium sulfates) in the outcrops were interpreted as recording periods of shallow and episodic surface water inundation of the investigated area, followed by evaporation and desiccation (Squyres et al., 2004b). Furthermore, the discovery of uniformly distributed hematitic spherules and crystal-mold vugs in the Eagle crater rock exposures gave insights into the complex diagenetic history of the area. The concretions likely grew by precipitation from groundwater, while the vugs were likely the product of chemical dissolution of post-depositional sulfate mineral growths (Herkenhoff et al., 2004; Squyres et al. 2004a, b).

As Mars lost its ancient atmosphere and subsequently froze, it is possible that briny surface waters which would have already been incorporated into the megaregolith, underwent eutectic freezing to produce a mixture of H_2O ice, $NaCl \bullet 2H_2O$ and $CaCl \bullet 6H_2O$ salts, and highly concentrated brine in the subsurface (Knauth et al., 2001). In the Martian subsurface, eutectic brines are a more likely possibility than freshwater, as highly saline waters can have exceptionally low freezing points. These highly concentrated brines could be possible points of refuge for extant Martian psychrophilic halophiles. The brines should also carry a significantly greater electrical conductivity than that of pure water, and be easier to detect in the subsurface using geophysical techniques (Knauth et al., 2001).

Electromagnetic Geophysical Methods

This contribution describes the Electromagnetic Induction Sounder (EMIS), a proposed electromagnetic (EM) geophysical survey system for mapping the near-subsurface of Mars in search for brine. Brine pockets in the Martian near-subsurface could be identified using geophysical electromagnetic sounding on the basis of their high electrical conductivity and be accessible for direct sampling through shallow drilling.

EM geophysical survey systems have been successfully operated worldwide for over 50 years (Fountain, 1998) in a variety of applications ranging from mineral and hydrocarbon exploration, to hydrogeology and environmental studies. From the inception of this technology, Canada has been the world leader in the design and commercialization of EM geophysical survey systems.

In EM sounding, a time-varying "primary" EM field is generated by a transmitter antenna. The primary signal can be one or several superposed continuous waveforms, typically sinusoidal (frequency-domain system) or a waveform switched on and off periodically (time-domain system). This primary field induces eddy currents in subsurface electrical conductors according to Faraday's Law of induction. The eddy currents, in turn, generate a "secondary" EM field which is sensed, together with the primary field, by a receiver antenna (Grant and West, 1965).

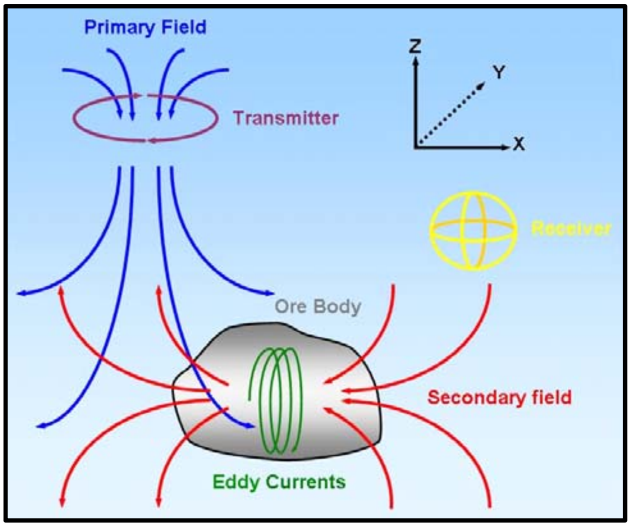

Figure 1. Principle of EM sounding (modified from Grant and West (1965))

The induction process in the subsurface can be modeled as a simple circuit with a resistance *R* and an inductance *L* in series. The secondary response is a complex quantity which is a function of the induction number $\omega L/R$ where ω is the operating frequency. The secondary response can be decomposed into a component in-phase with the primary field (the "in-phase" component) and a component 180° out-of-phase with the primary field (the "quadrature" component). At low induction numbers, the secondary response is typically small and in quadrature with the primary field. Above a certain value, however, the response becomes larger and in-phase with the primary field. Selecting the system operating frequency is an optimization problem where the need for strong responses must be balanced with conductivity resolution and practical transmitter-receiver separations. For EM geophysical survey systems, the primary signal is typically in the audio frequency (kHz) range.

EM geophysical data recorded in the field are inverted to obtain models of the subsurface which often reproduce the observations with a high degree of fidelity. The "quadrature" amplitude component of the secondary field for systems that are physically small and operating over relatively resistive subsurface materials is useful because it is a direct measure of subsurface electrical conductivity and is not influenced by the magnetic susceptibility of the subsurface. The amplitude of the "in-phase" component of the secondary field, under the same conditions, is primarily sensitive to susceptibility, especially in areas of low conductivity.

2. The Electromagnetic Induction Sounder (EMIS)

System Description

The proposed EMIS for Mars exploration is based on instruments currently commercialized by Dualem Inc. of Milton, Ontario (www.dualem.com). Their sensor package has been developed by Geosensors Inc. of Toronto, Ontario (www.geosensors.com).

A simplified schematic of one type of EMIS, a Dualem-1S™, is presented in Figure 2. In its most basic configuration, the instrument consists of a transmitter loop antenna and a receiver loop antenna both lying in a plane parallel to the ground surface (Z-orientation). The addition of a vertical (X-orientation) receiver loop antenna allows probing of the subsurface at a second depth simultaneously. The two loop antennas are housed at both ends of a cylindrical tube to achieve maximum transmitter-receiver separation. The system electronics are located in the middle of the tube.

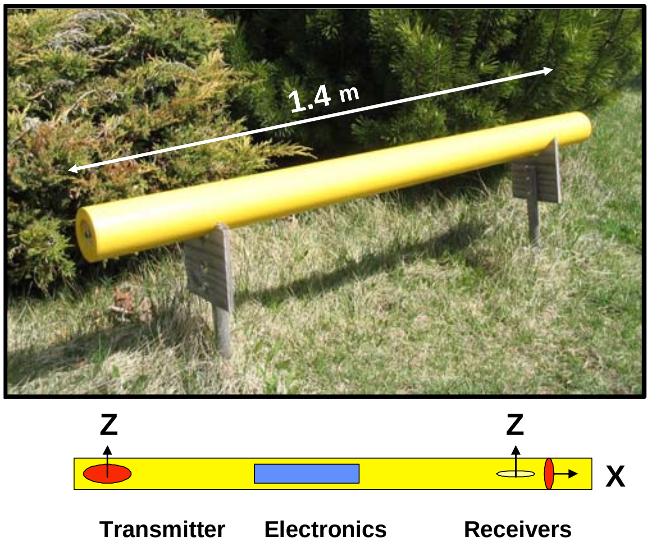

Figure 2. Dualem-1S ™

Figure 3.IcePic ™ mounted on a Canadian Coast Guard helicopter

Small EMIS instruments can be deployed on the ground or from a helicopter (Figure 3). This technology has been demonstrated for applications ranging from ice thickness mapping in the Canadian Arctic to the characterization of agricultural soils and environmental monitoring (see Taylor (1999) for a concise review).

EMIS and the Skimmer Martian Exploration Vehicle

We propose an EMIS as a payload on the Skimmer, a proposed unmanned Martian exploration vehicle (Draisey et al., 2006). In its current design, the Skimmer is a saucer-like platform of 1 m in diameter, raised above the ground by three legs 20 cm in height. The major innovative feature of the Skimmer is its propulsion concept based on the compression of CO_2 from the Martian atmosphere overnight, providing propellant for mobility in the morning. The skimmer would move on the surface of Mars in a series of "hops". The maximum vertical jump is on the order of 15 m during which the vehicle would stay above 10 m for approximately 3 seconds. The maximum lateral leap is also 15 m, with an elapsed time of 5.6 to 7.5 seconds, depending on flight path profile. The ability to make short, pre-planned "hops" offers the potential to traverse slopes (slope angle $< 40^o$) and difficult soil conditions.

The Skimmer design is partially driven by reducing the number of moving metal components and vibration, in order to minimize electromagnetic contamination and to maximize the EMIS signal to noise ratio. The EMIS transmitter and receiver(s) are mounted underneath the solar panel shield. The maximum receiver-transmitter separation is 66 cm, and is dictated by the diameter of the Skimmer. Both the transmitter and the Z-oriented receiver are in a plane parallel to the planet surface; the optional X-oriented receiver is immediately to the side of the Z-oriented receiver, closer to the center point of the vehicle (Figure 4). The transmitter and receiver loop antennas will fit around two spherical CO_2 tanks. Because the diameter of the loop antennas (20 cm) is smaller than that of the tanks (25 cm), the antennas will sit below the hemispheric plane. The antennas will be firmly attached to the vehicle structural chords by composite harnesses, rather than to the tanks, which will experience minute levels of dilatation between empty and full conditions. The vehicle will also carry a drill capable of investigating to a depth of 1 m.

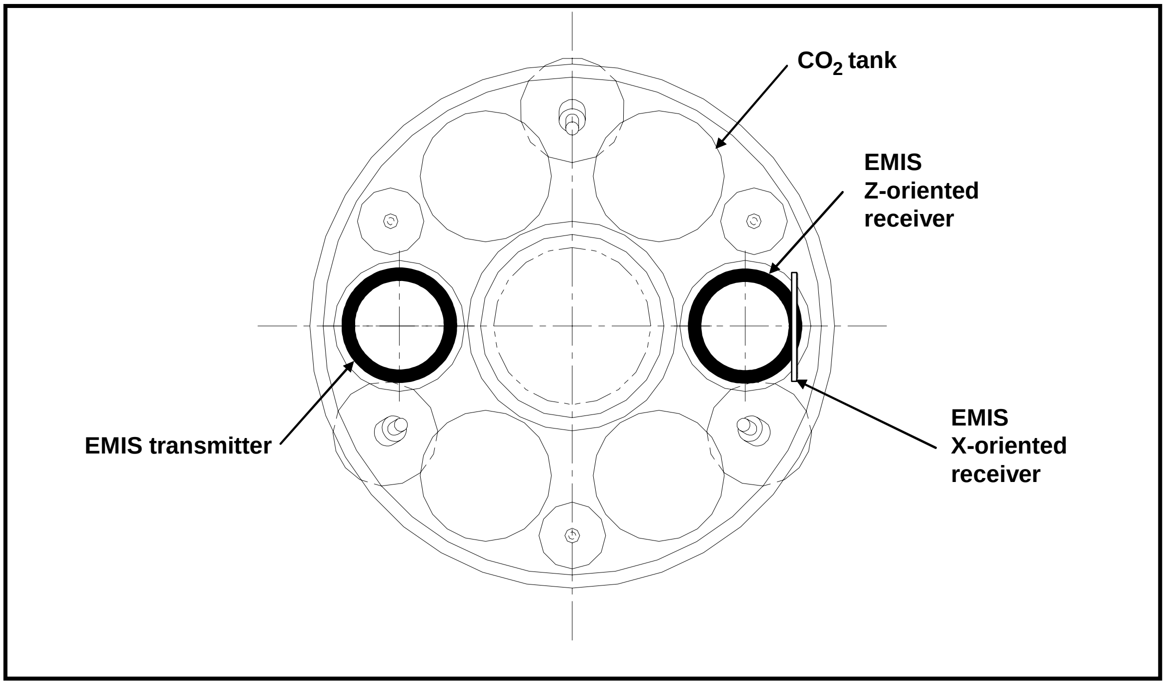

Figure 4. Detailed technical drawing (top view) showing the EMIS transmitter and receivers mounted within the Skimmer (diameter ≈ 1m).

3. Mars Exploration Scenarios

Depth of exploration

As a general rule, the depth of detailed exploration of the EMIS for poorly conducting soils (conductivity $\sigma \leq 0.001$ S/m) is approximately 1.5 times the distance between the transmitter and the Z-oriented receiver, and equal to the distance between the transmitter and the X-oriented receiver. To determine the depth of exploration of the EMIS for the geological environment expected on Mars, more specific simulations have been performed. The near-subsurface of Mars is hypothesized to consist of a conductive layer of moist, brine-bearing regolith sandwiched between resistive dry surficial regolith and permafrost, as depicted in Figure 5. For modeling purposes, the near-subsurface has therefore been represented as a sequence of 2 horizontal layers above a half-space whose properties are listed in Table 1.

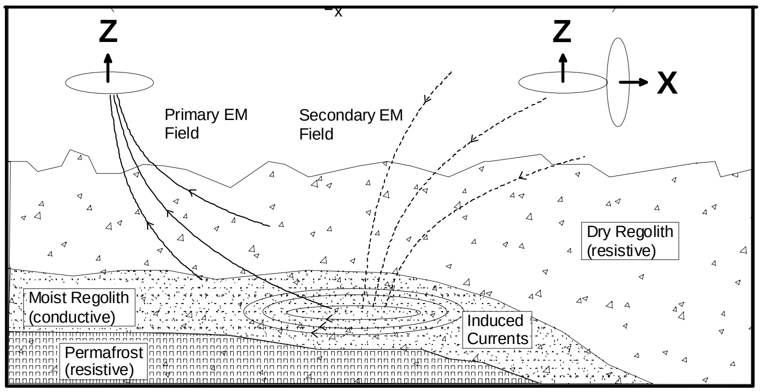

Figure 5. EM induction in the Martian near-subsurface

Table 1. Geophysical model of the Martian near-subsurface

	Geological description	Thickness [m]	Conductivity [S/m]
Layer 1	Dry regolith	0 - 20	0.001
Layer 2	Moist regolith	2	1.0 (Model A)
			0.1 (Model B)
Half-space	Permafrost	Infinite	0.001

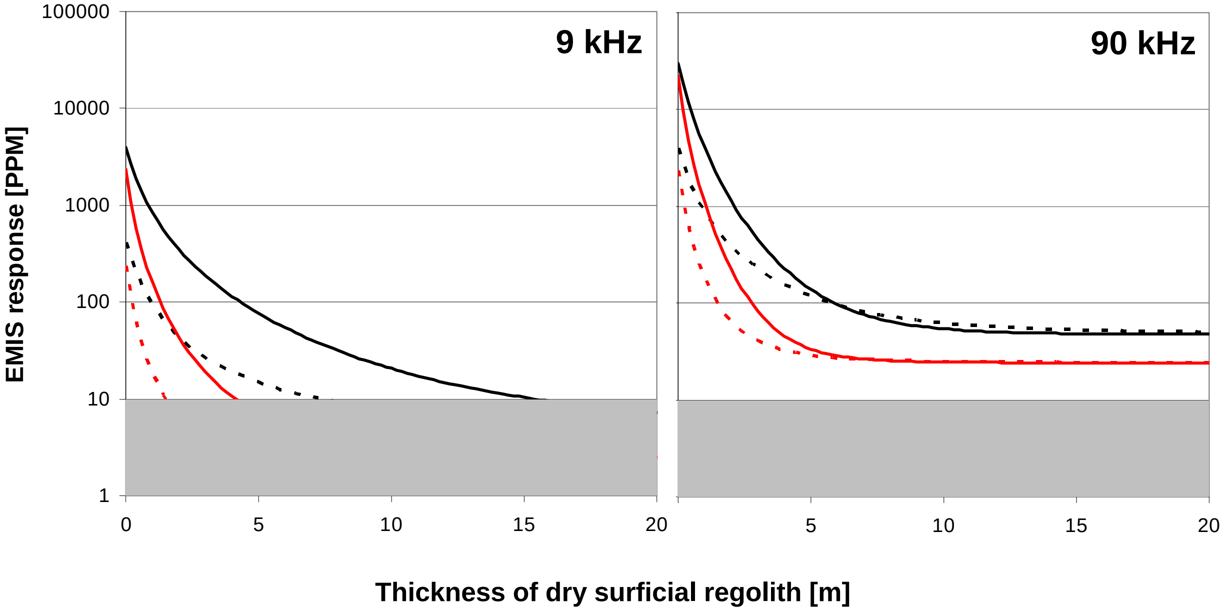

Figure 6. Synthetic quadrature EMIS responses for Models A (solid lines) and B (dotted lines) of the Martian near-subsurface. The transmitter-receiver separation is 60 cm. Black: Z-oriented receiver. Red: X-oriented receiver. Responses above 10 PPM (unshaded area) are considered most reliable.

Synthetic EMIS responses have been computed for a transmitter-receiver separation of 60 cm, typical of what can be achieved with the Skimmer, and two different operating frequencies (Figure 6). At these frequencies and for the range of expected conductivities, the induction number is low and the quadrature response is typically much stronger than the in-phase component (Holladay et al., 2005). The noise level has been fixed at a conservative 10 PPM (parts per million).

As seen in Figure 6, the EMIS quadrature responses decrease as the thickness of the dry surficial regolith (layer 1) increases. The responses are stronger for Model A, where the conductivity of layer 2 is 1.0 S/m, than for the more challenging Model B, where the conductivity of layer 2 is one order of magnitude less. At 9 kHz, the typical operating frequency used in terrestrial surveys, the responses of the Z- and X-oriented receivers stay above noise down to depths of 15 m and 4 m, respectively. For Model B, the responses for the Z- and X-oriented receivers are still above the noise down to depths of 7 m and 2 m, respectively. At an operating frequency of 90 kHz, the responses are stronger than at 9 kHz, and stay above the 10 PPM noise threshold. Their rate of decay versus depth, however, is very rapid over the few first metres (depth ≤ 7 m) of surficial regolith. Below that depth, the responses reach a plateau and the system becomes insensitive to conductivity variations. The results presented in Figure 6 indicate that the EMIS mounted on the Skimmer has a maximum depth of exploration of approximately 15 m, for an operating frequency of 9 kHz. Choosing the operating frequency for Martian exploration will be a complex optimization task taking into account parameters like desired depth of exploration, expected regolith properties, EM induction in the Skimmer structure and coil specifications.

Magnetic susceptibility is a material property reflecting the degree to which a body can be magnetized in the presence of an external magnetic field. For geological material, susceptibility is influenced primarily by the percentage of magnetite (Fe_3O_4) and, to a lesser degree, of ilmenite ($FeTiO_3$) and pyrrhotite ($Fe_{0.83-1}S$) (Telford et al., 1990). In exploration geophysics, magnetic maps are used extensively to unravel geological structure. In the context of Mars exploration, magnetic susceptibility measurements could help to characterize different regoliths, identify parent materials and weathering processes. Mars does not currently have an internal magnetic field so most of the measured magnetic susceptibility will be remnant features in the crust.

Since the EMIS responses are primarily sensitive to changes in magnetic susceptibility in areas of low subsurface conductivity, they have been calculated for Model B with a highly-susceptible (1000 PPM RMKS volume susceptibility) surficial regolith (layer 1, Figure 7). As predicted by theory, the in-phase responses dominate in these circumstances. As seen in Figure 7, the in-phase responses of the Z- and X-oriented receivers approach their limiting values for layer 1 thicknesses of 2.0 and 1.6 m, respectively. The response of the Z-oriented receiver is weaker. Thus, in terms of its response to variations in subsurface susceptibility, the EMIS in its present configuration is most sensitive to susceptibility changes in the upper metre of the subsurface.

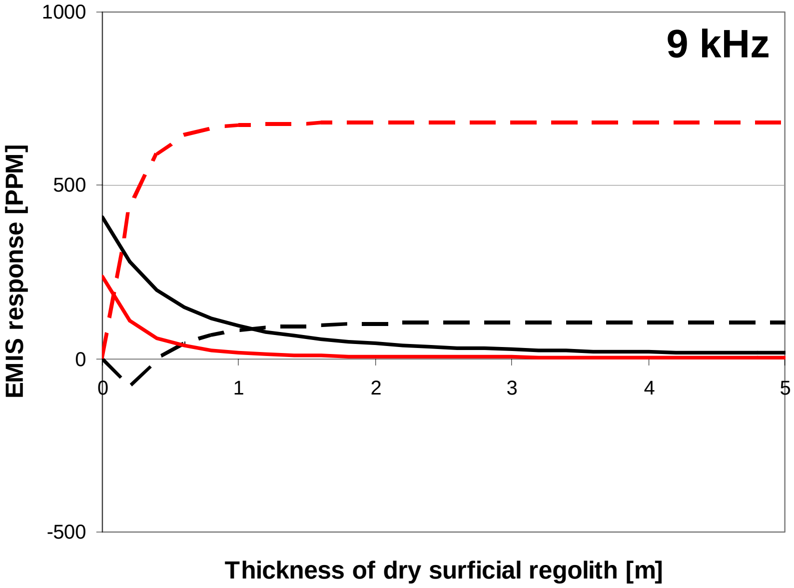

Figure 7. Synthetic in-phase EMIS responses for Model B of the Martian near-subsurface and a highly-susceptible surficial regolith (1000 PPM RMKS volume susceptibility). The transmitter-receiver separation is 60 cm, and the operating frequency is 9 kHz. Solid lines: quadrature responses; Dashed lines: negative in-phase responses. Black: Z-oriented receiver. Red: X-oriented receiver.

Lateral sounding

During its Mars exploration campaign, the EMIS will perform lateral and vertical soundings.

When performing a lateral sounding, the EMIS is measuring the induction response at two depths, using its Z- and X-oriented receivers. Measurements are taken at each "hop" of the Skimmer, that is, at a spatial resolution of a few metres. After several days of operations, a baseline is established that represent the average response of the near-subsurface. The detection of anomalous zones where the response differs from the baseline is particularly interesting. They can be zones where the dry surficial regolith varies in thickness or pinches out (Holladay et al., 2005), or zones of enhanced electrical conductivity and/or magnetic susceptibility. Zones of high conductivity are of key interest in the search for brine and might be selected as drilling sites.

Vertical sounding

The ability of the Skimmer to "hop" vertically a few metres above Mars' surface opens interesting surveying possibilities. EMIS measurements could be made while the Skimmer is ascending and descending to yield a vertical sounding for a given site. These data can be inverted to yield estimates of electrical conductivity and magnetic susceptibility as a function of depth.

Figure 8 shows EMIS responses computed for heights ranging from 0.25 to 12 m over the model of the near-subsurface described in Table 2. To simulate survey conditions, noise was added to the responses. The data were then inverted to recover the model of the subsurface. An example of these inversion results are listed in Table 2 and shown in Figure 9.

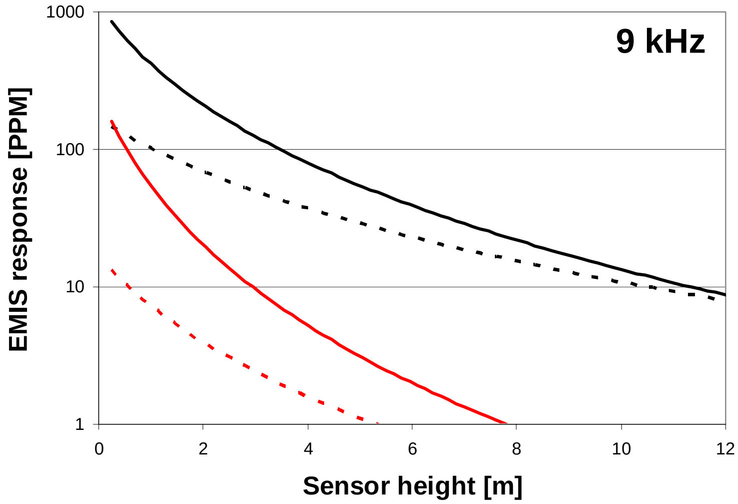

Figure 8. Synthetic EMIS responses for a vertical sounding over Model A of the Martian near-subsurface. The transmitter-receiver separation is 60 cm, and the operating frequency is 9 kHz. Solid lines: quadrature responses; Dotted lines: in-phase responses. Black: Z-oriented receiver. Red: X-oriented receiver.

Table 2. Inversion results

		Layer 1 Dry regolith		Layer 2 Moist regolith		Half-space Permafrost	
		Thickness [m]	Conductivity [S/m]	Thickness [m]	Conductivity [S/m]	Thickness [m]	Conductivity [S/m]
Modelled subsurface		1	0.001	2	1	Infinite	0.001
Inversion	Initial model	1.5	0.0001	1	0.001	Infinite	0.1
	Final model	0.848	0.0001	1.35	0.872		0.113

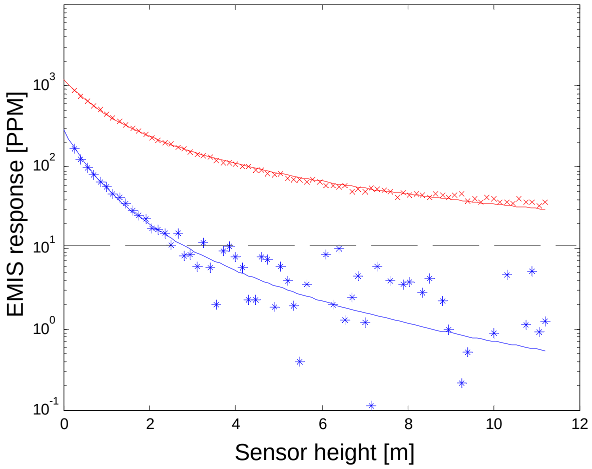

Figure 9. Inversion of the quadrature data shown in Figure 8 for thickness and conductivity, using the initial model described in Table 2 as starting point for inversion. Random noise with 3 PPM was added to synthetic before inversion. Red: Z-oriented receiver. Blue: X-oriented receiver.

The preliminary inversion results are encouraging as can be seen by comparing the "modeled subsurface" and the "final model" properties listed in Table 2. The inversion is not very sensitive to the first layer conductivity, since the sensor starts the sounding at over 40% of the transmitter-receiver separation. In future numerical simulations, both quadrature and in-phase responses will be inverted for resistivity and susceptibility. Parameters like data acquisition rate and sensor height will be optimized.

Site selection

The surface of Mars, like most other known extraterrestrial bodies, is harsh and lacks liquid water and is therefore probably barren of life at the present time. However, conditions below the surface may be quite different. At any depth, the subsurface will be protected from potentially sterilizing radiation found at the surface. Furthermore, because of geothermal heating, there will inevitably be some depth below the surface where temperature and pressure conditions allow liquid water (e.g. Carr, 1996), though this depth may be as great as a few kilometers. Clifford (1993) has proposed extensive subsurface aquifer systems on Mars where circulation is driven by geothermal convection cells. There is extensive evidence of outflows on Mars, and some, such as those in Athabasca Vallis, appear to be recent and probably represent ground water interactions with volcanic sources (Burr et al., 2002; Berman and Hartman, 2002; Plescia, 2003; Keszthelyi et al., 2000). The gully features observed by Malin and Edgett (2000) suggest the presence of liquid water in very recent times — perhaps as recent as the last few million years. Christensen (2003) has proposed that these gullies form by the action of melting snowpacks. Heldmann et al. (2005) have proposed that the gullies are formed by outflow from briny subsurface aquifers. In this case the aquifers would be located, on average, only 200 m below the surface.

Subsurface brines on Mars could become trapped between permafrost above and salts beneath, forming what Burt and Knauth (2003) refer to as a "brine sandwhich". Thawing and seepage of these salty fluid layers could be one of many explanations for the formation of young gully systems on Mars (Heldmann et al., 2005). As such, searching for subsurface brines near these outflow points maybe strategically profitable. Regions displaying volcanic features are particularly prospective sites to search for subsurface brines on Mars. Through their work on perennial springs on Axel Heiberg Island, Nunavut, Canada, Andersen et al. (2002) have proposed that thick aquitards of permafrost may help prevent discharge and freezing of briny groundwaters in areas without any volcanic heat sources. This possibility may eliminate some limitations on exploration site selection for these subsurface waters.

5. Conclusion

The EMIS is a promising instrument for Mars exploration based on the well-established geophysical technique of electromagnetic induction. The EMIS will be mounted on the Skimmer, a vehicle with good mobility potential, and therefore could be deployed in a number of prospective geological settings. The EMIS would delineate areas of the near-subsurface of Mars which are anomalous in terms of electrical conductivity and magnetic susceptibility. It would particularly excel at the detection of conductive liquid-phase brine. Conductivity or susceptibility anomalies could be further investigated by drilling as is commonly done in terrestrial mineral exploration.

6. References

Andersen, D. T. et al. 2002. Cold springs in permafrost on Earth and Mars. J. Geophys. Res. 107: 1-7.

Berman and Hartman. 2002. Icarus 159: 1-17.

Burr D.M. et al. 2002. Icarus 159: 53-73.

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

Christensen, P.R. 2003. Formation of recent Martian gullies through melting of extensive water-rich snow deposits, Nature 422: 45-48.

Clifford, S.M. 1993. A model for the hydrologica and climatic behavior of water on Mars. J. Geophys. Res. 98: 10973-11016.

Draisey, S., Mullins, M., Samson, C., Holladay, J.S., and Lim, D. 2006. Martian unmanned science skimmer – Simulation. Proceedings of the 13th Canadian Astronautics Conference, Paper 37.

Fountain, D. 1998. Airborne electromagnetic systems – 50 years of development. Exploration Geophysics 29: 1-11.

Grant, F.S., and West, G.F. 1965. Interpretation theory in applied geophysics. McGraw-Hill, 584 p.

Haberle, R.M., McKay, C.P., Schaeffer, J., Cabrol, N.A., Grin, E.A., Zent, A.P. and Quinn, R. 2001. On the possibility of liquid wateron present-day Mars J. Geophys. Res. 106: 23317-23326.

Haskin, L. A. et al. 2005. Water alteration of rocks and soils on Mars at the Spirit rover site in Gusev crater. Nature, 436: 66-69.

Hecht, M.H. 2002. Metastability of liquid water on Mars. Icarus 156: 373-386.

Heldmann, J.L., McKay, C.P., Pollard, W.H., Andersen, D.T., and Toon, O.B. 2005. Annual development cycle of an icing deposit and associated perennial spring activity on Axel Heiberg Island, Canadian High Arctic. Arctic, Antarctic, and Alpine Res. 37: 127-135.

Herkenhoff, K. E. et al. 2004. Evidence from Opportunity's Microscopic Imager for water on Meridiani Planum. Science, 306: 1727-1730.

Holladay, J.S., Lee, J., Samson, C., Draisey, S., and Lim, D. 2005. Electromagnetic induction sounder for the detection of near-surface liquid-phase water on Mars. 5th Canadian Space Exploration Workshop.

Ingersoll, A.P. 1970. Mars: Occurrence of liquid water. Science 168: 972-973.

Keszthelyi et al. 2000. J. Geophys. Res. 105: 15027- 15050.

Knauth, L.P., Burt, D.M. and Tyburczy J.A. 2001. Highly conductive eutectic brines rather than water expected in the Martian subsurface. Conference on the Geophysical Detection of Subsurface Water on Mars.

Kuznetz, L.H. and Gan, D.C., 2002. On the existence and stability of liquid water on the surface of Mars today. Astrobiology 2: 183-195.

Lobitz, B., Wood, B.L., Averner, M.A., and McKay, C.P. 2001. Use of spacecraft data to derive regions on Mars where liquid water would be stable. Proceed. Nat. Acad. Sci., 98: 2132-2137.

Malin, M. C. and Edgett, K.S. 2000. Evidence for recent groundwater seepage and surface runoff on Mars. Science 288: 2330- 2335.

Picardi, G. et al. 2005. Radar soundings of the subsurface of Mars. Science 310: 1925-1928.

Plescia, J.B. 2003. Cerberus Fossae, Elysium, Mars: A source for lava and water. Icarus, 164: 79-95.

Sears, D.W.G., and Chittenden, J.D. 2005. On laboratory simulation and the temperature dependence of the evaporation rate of brine on Mars. Geophys. Res. Lett. 32 (3), L23203.

Squyres et al. 2004a. The Opportunity Rover's Athena science investigation at Meridiani Planum, Mars. Science, 306: 1698-1702.

Squyres et al. 2004b. In situ evidence for an ancient aqueous environment at Meridiani Planum, Mars. Science, 306: 1709-1714.

Taylor, R.S. 1999. Development and applications of geometric sounding electromagnetic (EM) systems. 69th Annual Meeting of the Society of Exploration Geophysicists, Expanded Abstract.

Telford, W.M., Geldart, L.P., and Sheriff, R.E. 1990. Applied geophysics. 2nd Edition. Cambridge University Press, 770 p.