

Induced-Polarization Mapping of Subsurface Ice on the Moon

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Summary. Geoelectrical methods have been used for nearly a century to explore for minerals and groundwater and to characterize subsurface geology. They most commonly employ arrays of electrodes at the planetary surface to inject current into the ground and measure the voltage and phase response. Ice has a characteristic electrical signature (an "induced polarization," or IP) at low frequency that allows it to be distinguished from regolith at $\sim 1\%$ volumetric accuracy. Depth of investigation scales with electrode separation: electrodes mounted on lander footpads or rover wheels would sense to depths of a few tens of centimeters, whereas a ballistically deployed electrode string could probe ten meters or more into the subsurface. A string of electrodes has the additional advantage of being able to form a true cross-section

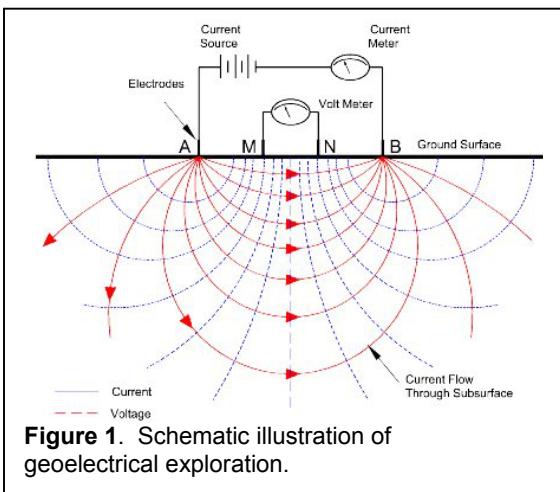
due to the numerous current-potential geometries. Conversely, continuous measurements of depth-averaged ice abundance could be made from a rover. The Huygens probe and Rosetta lander both carried electrical-properties experiments closely related to the methods described here. There are several organizations, both domestic and foreign, who could credibly propose an IP instrument to map subsurface ice for the RLEP-2 mission. Resource requirements are modest for configurations using lander footpads and/or rover wheels (< 1 kg, 1 W, average data rate < 10 bps), with mass increasing to several kg for ballistic electrode-string deployment. Induced polarization offers a simple and proven approach to subsurface investigation that can be used alone or in conjunction with other experiments.

Background. Geoelectrical methods use natural or artificial ground currents to image subsurface structure (see Ward, 1990; Telford et al., 1990, for reviews, and Grimm et al., 2005 for a state-of-the-art application). Induced polarization (IP) is the geophysical term for joint measurements of the conductive and capacitive properties of earth materials. This method has seen broad application in many disciplines: it is also known as complex resistivity at low frequency and as the complex dielectric response at radiofrequencies, as impedance spectroscopy in electrochemistry, and as dielectric spectroscopy in biophysics. The Mutual Impedance (MI) sensor of the

Permittivity, Wave, and Altimetry Analyzer (PWA) on Huygens and the Permittivity Probe (PP) on the Rosetta Lander operate on similar principles.

A classic geoelectrical survey (Fig. 1) transfers current I in the subsurface between two electrodes (AB) and measures the potential V between two other electrodes (MN). The magnitude of V/I is of course a resistance; when multiplied by a geometric factor ($2\pi \times$ distance MN for the geometry of Fig. 1), the geophysical property resistivity is recovered. Conductivity is the reciprocal of resistivity. For a sinusoidal signal, the phase ϕ is related to the capacitance of the ground (for convenience, the negative sign for voltage lagging current is discarded). The geophysical properties of resistivity and phase can be alternatively expressed as imaginary and real dielectric constant, respectively.

Capacitance is a manifestation of the separation of bound charges under an applied electric field. The induced polarization (IP) is formally the resulting induced dipole moment per unit volume. Charge separation occurs at finite speed, however, which results in frequency dispersion or "relaxation" of the dielectric constant. The optimum frequency for charge motion results in maximum energy loss. Therefore a relaxation is characterized by a decrease in real permittivity with frequency and a maximum in imaginary permittivity near this optimum, or alternatively, a drop in the resistivity with frequency and an associated phase peak.



Charge separation can be caused by orientational, faradaic, or membrane (electrolytic) polarization. Water displays an orientational polarization and high dielectric constant due to its dipolar structure. In ice, polarization is due to the migration of charge defects. This property can be exploited to map the abundance of ice in the lunar subsurface using an extension of classical induced-polarization techniques.

Ice Response. The dielectric relaxation or peak induced-polarization response for ice at temperatures characteristic of the shallow subsurface of permanently shadowed lunar craters lies between 1 mHz and 1 kHz depending on the nature of contaminating charge carriers in associated regolith. Additional laboratory studies of the IP response of putative lunar polar materials would be helpful, but an in situ frequency sweep would nonetheless be used to accurately determine the relaxation properties.

A simple calculation illustrates the capability of IP to measure the depth to ice and its abundance (Fig. 2). The colinear, equispaced electrode geometry of Figure 1 is used. Using the relaxation time constant of ice after Kawada (1978), dry regolith resistivity $10^{12} \Omega\text{-m}$ after Carrier et al. (1991), and a test frequency 1 mHz, ice contents of $\sim 1\%$ can be distinguished at depths of tens of cm.

Instrumentation. At the high resistivities of planetary environments lacking any moisture, galvanic current injection is impossible; therefore currents must be coupled capacitively. Impedance increases with decreasing frequency and robust ice detection at the cold temperatures of the shadowed lunar poles could require lower frequencies than implemented in any previous terrestrial or planetary IP/dielectric sensor. Maximum input impedances of $\sim 10 \text{ T}\Omega$ and minimum capacitance 1-10 pF are nonetheless well within present capabilities (e.g., INA 116). Buffering, shielding, and guarding will be necessary to couple currents at the desired electrode locations and to mitigate stray currents.

The coverage and resolution of the subsurface depends on the number and spatial distribution of electrodes, and recovery of the relaxation signature of ice depends similarly on the spectral coverage and resolution. A straightforward approach is ballistic deployment of a string of electrodes ($N=16-64$) to a maximum distance of 100 m or more. Grouping the electrodes (Fig 3) will allow local high vertical resolution of the shallow subsurface as well as low-resolution deep imaging. Multiple electrode strings will increase the mass of the investigation, but will allow cross-line transmit-receive, providing 3D coverage. A rover can optimize coverage and resolution by working in concert with an electrode string, or it can operate independently. The fixed electrode geometry of rover footpads or rover wheels does not permit as much depth discrimination as with an electrode string, but the rover mobility can be used to produce a continuous profile of average ice abundance to depths of tens of centimeters. Induced Polarization is a robust, simple approach to wide-area lunar ice detection.

References Cited. Carrier, W.D., et al., in *Lunar Sourcebook*, Cambridge Univ. Press, p. 475, 1991. Grimm, R.E., et al., *J. Env. Eng. Geophys.*, Dec. 2005. Kawada, S., *J. Phys. Soc. Jpn.*, 44, 1881, 1978. Telford, W.M., et al., *Applied Geophysics*, Cambridge Univ. Pres., 1990. Ward, S.H., in *Geotechnical and Environmental Geophysics, Vol 1*, Soc. Explor. Geophys., p. 147, 1990.

Note that IP is also useful to infer the density of regolith, which has implications for properties of landing systems, vehicle trafficability, and rippability for construction and resource exploitation. The density and dielectric constant for dry lunar regolith are related as $\epsilon = 1.871$ (Carrier et al., 1991): this prediction has an RMS error on the density of $\sim 0.2 \text{ g/cm}^3$.

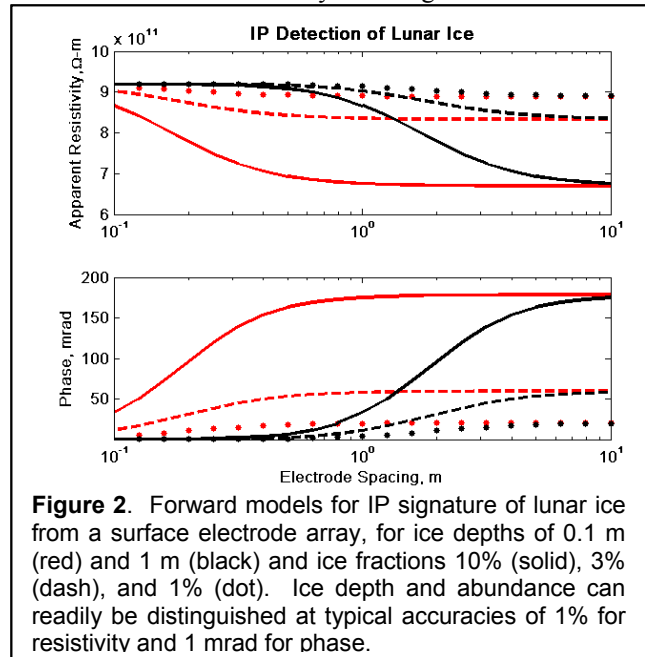


Figure 2. Forward models for IP signature of lunar ice from a surface electrode array, for ice depths of 0.1 m (red) and 1 m (black) and ice fractions 10% (solid), 3% (dash), and 1% (dot). Ice depth and abundance can readily be distinguished at typical accuracies of 1% for resistivity and 1 mrad for phase.

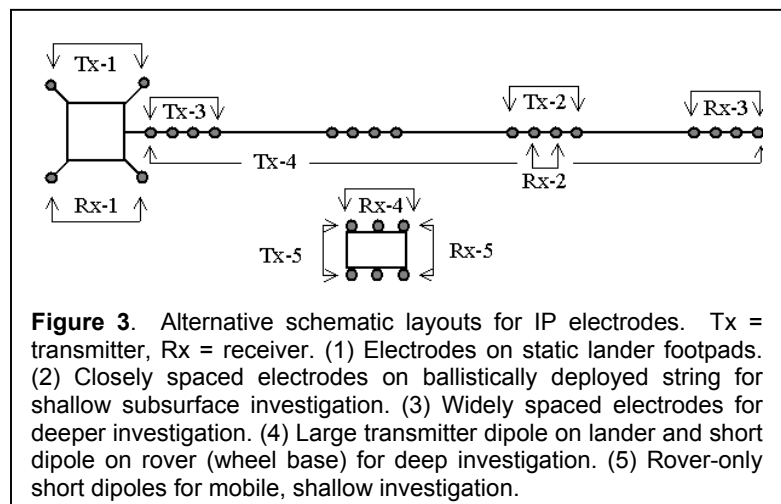


Figure 3. Alternative schematic layouts for IP electrodes. Tx = transmitter, Rx = receiver. (1) Electrodes on static lander footpads. (2) Closely spaced electrodes on ballistically deployed string for shallow subsurface investigation. (3) Widely spaced electrodes for deeper investigation. (4) Large transmitter dipole on lander and short dipole on rover (wheel base) for deep investigation. (5) Rover-only short dipoles for mobile, shallow investigation.