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GARRY C. HENDERSON
Applied Research Laboratory
General Dynamics Corp.
Fort Worth, Tex.

Lunar Exploration for Water Deposits by Electrical Methods

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Several electrical techniques employed in terrestrial exploration geophysics appear to show considerable promise for lunar-surface applications, particularly in the search for water in the upper 100 meters of the surface. All of these methods rely primarily on the degree and extent of contrasts in the electrical properties of materials which lend themselves quantitatively to the interpretation process. The choice of scientific methods depends largely on the properties suspected to exist; the choice of operational methods influences the choice of scientific methods by limitations imposed by mission constraints. The selection of frequency (or frequency spectrum) in orbital or surface electromagnetic methods requires considerably different analyses than do the LF-DC (low frequency-direct current) resistivity techniques.

Since there may be subsurface water as well as ice in some cases, the various kinds of ice, impurities (such as minerals, debris, and chemical contaminants), and multiphase systems and the effects on the conductivities of these water deposits are investigated primarily from the familiar resistivity viewpoint.

INTRODUCTION

Numerous geophysical techniques have been suggested in the exploration for lunar water deposits, be they liquid, ice, or in the form of hydrated rocks. Seismic and electrical techniques have logically received the most serious attention, although magnetic and even gravity methods have been proposed. (See, e.g., the work of Speed (ref. 1) and Westhusing and Crowe (ref. 2).) Obviously, the parameters on which the interpretation of gravimetric, magnetic, and, to an extent, seismic data depend do not readily lend themselves to such purposes on early missions.

Variations in the magnitude and extent of density contrasts are the basis for gravimetric exploration; besides the stringent survey requirements for meaningful exploration by gravimetry (ref. 3), the number of models relating density contrasts to water deposits is infinite. Even if a very sizable body of ice were present, the inherent ambiguity of gravity data necessitates reliance on other types of information in the process of interpretation. Essentially the same can be said for magnetic prospecting, except for the possibility of locating likely zones of volcanics (which may stand out even in the weak magnetic field of the Moon), thereby allowing one to suspect a greater likelihood of water association in that particular locale. Seismic methods, one of the most powerful tools in exploration geophysics, may be a rewarding means to determine the presence of bulk ice (or water) in early missions (ref. 4), but again the nature of velocity discontinuities, related parameters, and environmental conditions may limit the early utility of these methods for this purpose. A good knowledge of the lunar subsurface is necessary to the choice of: method(s) (refraction and/or reflection); the technique(s) (profiling, fan shooting, etc.); instrumentation (seismic energy source, filters, amplifiers, telemetry, etc.); and, of course, interpretation (ref. 5).

The principal method of geophysical prospecting for water on Earth, the electrical method, appears to be as potentially useful, if not more so, on the Moon, providing the pertinent parametric factors relating to such experiments are ascertained. Mathematical treatments and case histories of electrical methods are amply described in the literature and so are not presented here. A brief bibliography is included with this paper to give the reader a fair sampling of available literature on the subject.

LUNAR WATER SOURCES

It is probably incorrect to assume that much, if any, water beneath the Moon's surface is in the liquid state. Such a case would require an impervious interface to prevent migration of liquid or vapor to the surface and, of course, a temperature sufficiently high to prevent solidification. However, in heated zones, electrolytic action might feasibly result from "ground water" in the presence of certain minerals (sulfides, for example); this might create a self-potential field in the vicinity of contact. It appears, for early missions, that the possibility of useful water resources is probably limited to subsurface ice in the maria.

If the original source of the ice is accepted to be of volcanic origin, that is, condensates of vent or fumarole vapor trapped in ground fissures, veins, or porous material, it can also be assumed that the ice is contaminated to a degree and is more conductive than if it were pure. At standard atmospheric pressure, conductivities range from about 2.3×10^{-8} (ohm-cm)$^{-1}$ for pure water at 10° C to 5×10^{-10} (ohm-cm)$^{-1}$ for certain pure ices at low temperatures (−70° C or so). A method of determining the direct-current values is described by Bradley (ref. 6). For near-surface (about 1 meter) temperatures of −23° to −53° C (ref. 7), the vapor pressure of ice ranges from about 7.5×10^{-1} torr to approximately 4×10^{-2} torr (ref. 8); therefore, the base of the surface layer must be impervious if it contains the ice or water for any appreciable period of time.

Bernett and others (ref. 9) noted that pulverized olivine basalt, material apparently analogous to the lunar-surface covering, has a thermal conductivity about 2 orders of magnitude less in a vacuum of 5×10^{-6} torr than at 1 atmosphere. Moreover, they observed that the variation of the particle sizes tested had more effect on the thermal conductivity in a vacuum than in air and that compaction markedly increased these values.

The various forms of ice (see Dorsey, ref. 8) may affect the interpretation of electrical exploration data because of the crystalline structure system associated with the circumstances under which it formed and the nature of the present environment. For example, the intercrystalline material existing between the surfaces of crystals becomes more concentrated by repeated fractional freezing, with the result that the ice itself becomes more pure and is composed of larger grains, perhaps in a different crystallographic system. For bulk ice (essentially homogeneous as a body compared with that filling pore spaces in rock), effective interstitial material may eventually migrate to the outer periphery of the mass, thereby emphasizing the conductivity contrast. The more rapidly the transition from vapor (if any) to water to ice occurs, the more likely it is that conducting and/or resistive materials are entrapped in the body of ice.

Dorsey (ref. 8) proposes that no type other than ice-I exists at pressures less than 2000 atmospheres unless the temperature is very low; he also states that both ice-II and ice-III types proceed very slowly to ice-I. All known varieties of ice, except ice-I, are denser than water under identical conditions of temperature and pressure; however, to the writer's knowledge, this has not been verified for a vacuum and low-temperature environment such as that found on the Moon.

Under the action of an induced electric field, a space charge will be acquired by the ice unless it is extremely pure. A sort of polarization will result from a direct-current field, and an alternating-current field will cause a varying concentration of the field, the end result being a reasonable probability of misinterpretation unless proof of the existence of the ice is established by other means (visible exposure or coring). The relationship of field frequency to the measured variation of the dielectric constant of ice is given in figure 1(*a*); the thermal variations of the dielectric constant of ice are shown in figure 1(*b*). A compilation of observed laboratory data on the apparent resistivity of ice at various frequencies is shown in figure 2. The primary point to be made here is that some preknowledge of the temperatures of the ice and the overlying material greatly reduces the probability of misinterpreting the data from electrical methods.

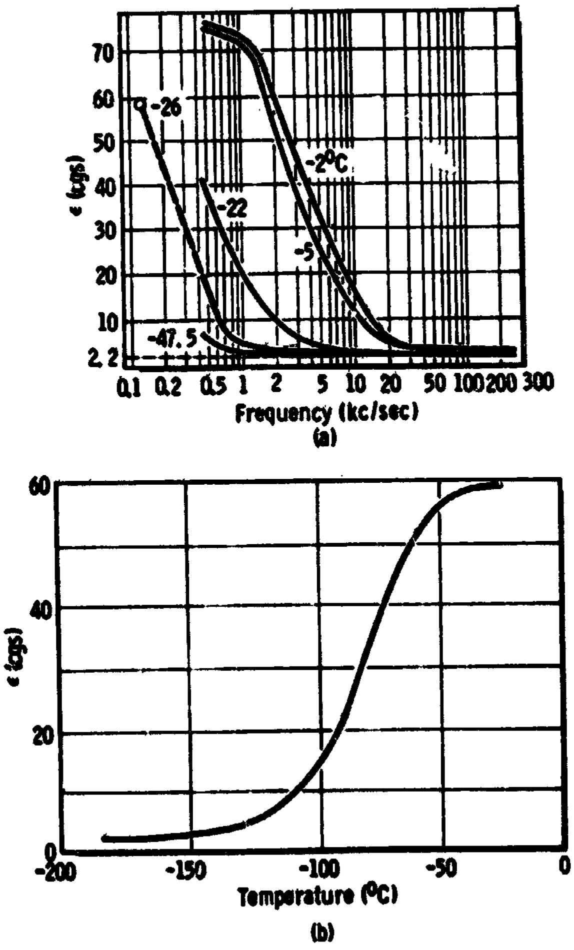

FIGURE 1.—Dielectric constant of ice against frequency and temperature. Data taken from reference 8, pp. 502 and 503. (*a*) Field frequency versus the dielectric constant of ice. (*b*) Temperature versus the dielectric constant of ice at 120 charges and discharges per second.

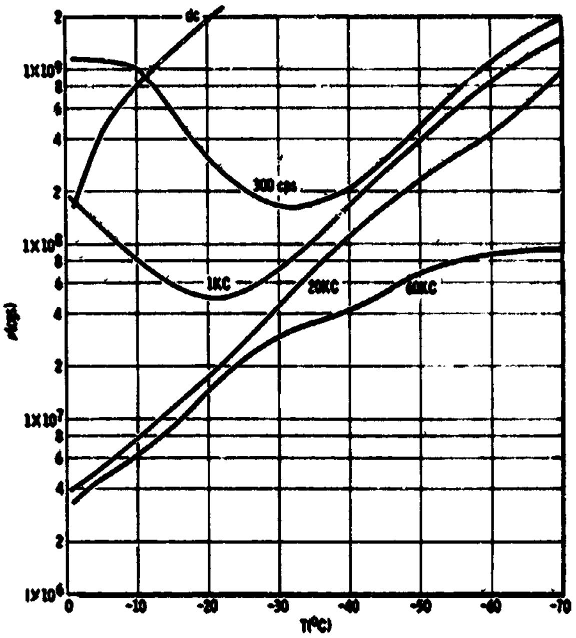

FIGURE 2.—A compilation of observed apparent conductivities of ice versus temperature at various frequencies (frequency data from ref. 8, p. 506; direct current data from ref. 6).

Various factors are related to the wide range of resistivities encountered in Earth materials. Some of these may be more pronounced for water exploration on the Moon. Not necessarily in order of importance, these are—

(1) Temperature of the ice and thermal gradients of the surrounding materials

(2) Inhomogeneity of the ice and the surrounding materials

(3) Degree and type of hydration of the surrounding materials

(4) Particle size and degree of compaction of unconsolidated materials surrounding a body of ice

(5) Choice of electrical method, configuration, and frequency

(6) Degree of polarization in connection with associated fluids or ionized gases (if any)

(7) Magnitude of lithostatic pressure

(8) Lunar-surface state and topography

It would appear that a real requirement exists, regardless of the intended method of geophysical exploration, that one acquire some borehole data before one attempts a surface reconnaissance for bulk water deposits. Although the probability of drilling into ice or water-bearing strata by chance cannot be determined at this time, it seems that it would be very low. A useful accumulation of subsurface data would act as a guide for planning surface exploration.

GENERAL ELECTRICAL METHODS

Electrical methods in exploration geophysics may be broadly categorized as self-potential (SP), induced potential (IP), magnetotelluric (and telluric), electromagnetic (EM), resistivity, and borehole logging, which may involve any one or a combination of these methods. Interpretation processes of the SP and IP methods are dependent on polarization phenomena associated with electrochemical reactions between the different subsurface constituents. Although such phenomena may occur on the Moon, the likelihood seems sufficiently small to the author to exclude these methods from this discussion. Magnetotellurics is not discussed here because the probability of locating recoverable deposits of ice by this method in early missions seems unlikely.

One of the most attractive aspects of electromagnetic exploration is that of being amenable to remote (orbital altitude) or surface (roving vehicle or contact) operations. In the preceding discussion of lunar water, it was noted that the effects of material temperature and sensing frequency lead to possibilities of misinterpretation. Ward and others (ref. 10) report a study on electromagnetic reflections in the 10^{-4}- to 10^{8}-hertz range in which they describe a method of the "possibility of uniquely determining the presence of water, in solid or pore liquid form, from electromagnetic soundings made on or above the lunar surface." They detail the distribution and sequential variations of electrical parameters of several models to determine responses for each range and combination they selected.

Because of the promise of remote sensing, considerable emphasis has been placed on electromagnetic methods. This is particularly true in terrestrial applications, as evidenced by the numerous applications and investigations on the subject. Since the primary purpose here is to discuss electrical resistivity techniques of water exploration, let it suffice to refer the reader to publications listed in the bibliography at the end of this paper.

SURFACE RESISTIVITY METHODS

The classical resistivity methods of measuring irregularities in the conductivity of subsurface materials depend on the determination of the magnitude and extent of the potential gradient on the surface caused by the asymmetric flow of current introduced into the subsurface. The measurements made on the surface result in quantitative values of the apparent resistivity caused by conductivity contrasts in the subsurface.

Various electrode configurations exist for resistivity surveying along the surface; these are used to determine the approximate depth, shape, and anomalous resistivity of discrete bodies or features. A simple illustration of the concept, using the common Wenner configuration, is shown in figure 3. Since potential lines are by definition perpendicular to current flow lines, any distortion of the current lines by material of anomalous conductivity is expressed on the surface by a distortion of the potential field. In practice, two general field techniques are employed: (1) maintaining fixed electrode separation and moving the array along a profile line, then plotting resistivity values at the midpoint of the array, that is, resistivity profiling at a given electrode separation a approximately equivalent to the maximum depth of effective penetration; or (2) systematically varying a for successively greater depths of effective penetration and repeating this process at points along a line, that is, resistivity sounding. Often both techniques are used in the same area and parallel profiles must be employed to ascertain the lateral extent of an anomalous body.

Theoretical studies of the mathematical modeling of various resistivity systems have been pursued for many decades and are for the most part very straightforward; however, the quantitative interpretation of these data seems to be as much an art as a science because of several complicating factors. For example, Earth ground water and moisture in the weathered zone cause some difficulties, pri-

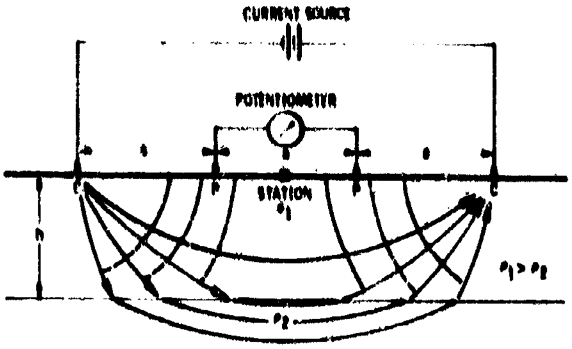

FIGURE 3.—The Wenner electrode configuration.

marily because of a wide range of mineral content affecting conductivity, as well as gross irregularities in their extent. In some areal surveys, fences, railroad tracks, underground cables, etc., cause distortions in the potential field. Coupling of the electrodes to the surface layer is often inconsistent as a result of several factors (variability of surface materials, variability of the degree and type of surface moisture, improper implacement and/or care of the electrodes, etc.). The Moon may be 2 or 3 orders of magnitude more amenable to such surveys than are terrestrial sites because of the obvious lack of some of these troublesome features. A few of the more subtle implications presently suspected may enhance the attractiveness of resistivity techniques. For instance, if discrete layering of near-surface materials is prevalent in the maria, we approach the ideal case and thereby may rely more on scientific than on "analogy-type" interpretations.

Several model studies of geophysical methods for lunar water exploration have been reported by Westhusing and Crowe (see, in particular, pp. 278–279 and 348–351 of ref. 2). In most cases reported by them, apparent resistivity measurements yield significant responses for the resistivity contrasts they considered (assuming, of course, that high resistivities may be measured with the lunar system). Their conclusions are summarized in reference 2 in tables, all of which are worthy of the reader's review. (Methods in orbital mode, pp. 337–339; instrumentation in orbital mode, p. 340; methods in surface mode, pp. 343–346; and instrumentation in surface mode, pp. 355–357.)

Preliminary tests with resistivity models in a vacuum chamber have been initiated using olivine basalt. Temperature ranges of 150° to 100° C have been employed in a vacuum of 4 to 8×10^{9} torr with two parallel Wenner electrode configurations. A thermally and electrically isolated ceramic container is used to house the model. (See fig. 4.) Preliminary studies were performed with a mechanical-diffusion pump system, the results of which were inconclusive; the suspected cause was oil contamination of the sample material. Sorbent roughing pumps and ion pumps have been installed on the chamber, and models are currently being prepared to conduct a more complete series of measurements. Materials with electrical properties similar to those of ice are placed in various subsurface positions in the model. To date, samples of granite, rock salt, limestone, Bakelite 140, and marble (for high resistivity) have been studied as model substitutes for ice. The two electrode arrangements are alternately activated at given model temperatures for a certain electrode separation *a*. Then the process is repeated for different values of *a*. Results obtained with the new system are not presently available; however, it is reasonable to say at this time that the method appears promising.

Probably the greatest operational disadvan-

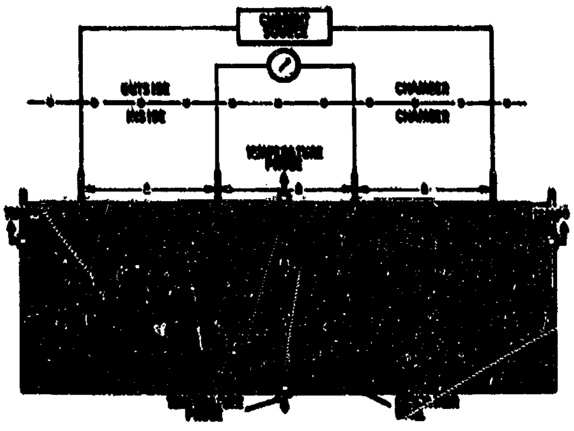

FIGURE 4.—Schematic of the model arrangement of the resistivity tests in the vacuum chamber. A, B, C, and D are test materials.

tages to resistivity methods are (1) the time-consuming, cumbersome handling of the electric cables; and (2) the power required for high-resistivity measurements and widespread electrodes. On Earth, vegetation, creeks, large rocks, hills, etc., aggravate the problem, but in the lunar maria, and considering the early, limited profiles, the resistivity method may be comparatively quite rapid. Of course the restrictions on the astronauts' dexterity and mobility caused by their space suits will be a handicap and must be considered in planning experiments of this type.

SUBSURFACE ELECTRICAL METHODS

Early lunar missions preclude any *in situ* subsurface techniques other than borehole logging, unless tunnels or accessible fissures are found and explored. The more advanced missions may employ tunnel and shaft applications of electrical methods.

Borehole logging by electrical methods consists essentially of recording the resistivities and potentials of subsurface formations by down-hole instruments applied throughout the depth of the borehole. Discussion of potential measurements is excluded in this section because of the assumed lack of fluids in the lunar subsurface.

Common electric logging techniques are designated as standard, or conventional (lateral, normal, induction, micro, etc.). However, these are usually employed in the fluid medium of the water or oil well; therefore, there are necessary modifications to terrestrial practices in electric logging for lunar applications. (See, e.g., the work of Tixier, ref. 11.; Stratton and Ford, ref. 12; Dieter and Paterson, ref. 13; and Guyod, ref. 14.)

Several resistivity-measuring systems exist for logging purposes, but the most adaptable for lunar logging appear to be the multielectrode normal techniques. Logging electrode configurations are basically those used in surface methods. With contact electrodes rather than insertion electrodes, continuous recording is possible by pulling the sonde from the bottom to the top of the hole.

Induction logging measures formation resistivity by electromagnetic means. Where conductivity contrasts exist, induction logging yields a sharper delineation of interfaces than do conventional means and may be more feasible in lunar logging than are conventional resistivity logs, since no contact with the hole wall is necessary. Definition of thin beds is better with induction logs. One reason for this difference is that eddy currents induced in the formation tend to circulate through the less resistive formations, and thereby sharpen the record response.

Lateral logging forces current to flow radially through beds as a "sheet" of predetermined thickness by placing electrode contacts in such a way as to allow continuous adjustment of potential differences between them. However, fluid is required for this otherwise desirable method.

Combination logging tools are in use and are worthy of consideration in early lunar missions in prospecting for water. They have advantages in terms of simplicity, ease of adaptation for lunar missions, and low power/size/weight specifications; however, logging tools are characteristically cumbersome and, in the case of lunar work, may require severe operational modifications to alleviate excessive astronaut participation.

Where lunar boreholes are not widely separated, resistivity measurements between holes may be performed in addition to standard logging. Equipotential points may be mapped locally when identical logging tools are used simultaneously. It is sufficient to say that the subject should have much more study.

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