Conclusions: We thus see that the adaptation of this well logging technique is entirely consistent with most of the needs for a robotic lunar mission (e.g., low power, small size, rugged instrumentation) and could provide a broad range of elemental data for the shallow lunar subsurface. With the neutron generator turned off, the detector would provide natural and solar-flare-produced activity data, which are likely to be proposed by other investigators; by also using the neutron generator one can obtain much more detailed composition data. One can envision dragging the generator and detector package behind a rover for mobile measurements, i.e., getting the source of radiation away from other experiments. One could also design the whole package so that it could be inserted into a shallow borehole for near-surface measurements.

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GEOPHYSICAL METHODS—AN OVERVIEW.

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Geophysics is expected to have a major role in lunar resource assessment when manned systems return to the Moon (ca. 1995). Geophysical measurements made from a lunar rover will contribute to a number of key studies: estimating regolith thickness, detection of possible large-diameter lava tubes within maria basalts, detection of possible subsurface ice in polar regions, detection of conductive minerals that formed directly from a melt (orthomagmatic sulfides of Cu, Ni, Co), and mapping lunar geology beneath the regolith.

The techniques that can be used are dictated both by objectives and by our abilities to adapt current technology to lunar conditions. Instrument size, weight, power requirements, and freedom from orientation errors are factors we have considered in this paper. Among the geophysical methods we believe to be appropriate for a lunar resource assessment are magnetics, including gradiometry, time-domain magnetic induction, ground-penetrating radar, seismic reflection, and gravimetry.

Depending on weight limitations, all or some of these instruments, together with their power supplies and data acquisition/telemetry, would probably be mounted on a small rover and on a towed nonmagnetic, nonconductive trailer. Rover and trailer might be controlled remotely. To reduce power and data storage requirements, the data would probably be taken at discrete locations, rather than continuously. We envision that the rover would also be equipped with a lunar version of a GPS receiver to display and record position and elevation.

Magnetics: Two- or even three-component flux-gate magnetometers could be attached via short booms to the trailer to measure the total (scalar) magnetic field plus its horizontal and vertical gradients. These small, low-power devices are commonly used in many applications, including some of the past Apollo missions. They have a useful sensitivity of 0.1 nT, which is perfectly adequate for resource evaluation and for the mapping of lunar rock types.

Because the Moon presently has negligible, if any, internal dipole field due to a metallic core, the small magnetic fields at the surface are due to permanent magnetization, possibly TRM, of the lunar rocks. There is also a small time-varying field of external origin due to fields carried in the solar wind and the fields associated with the Earth's magnetotail. Magnetic field variations over the Moon's surface due to changes in rock magnetization may amount to ±2000 nT. A major unresolved question concerns the nature and origin of localized strong magnetic anomalies detected from orbit.

Time-Domain Magnetic Induction: The absence of water and conductive minerals gives the lunar surface environment an extremely low, and presumably uniform, electrical conductivity (less than 10^{14} S/m) to considerable depths. Solar heating of the surface will raise the conductivity several orders of magnitude within a thin layer, but this does not alter the very resistive nature of the Moon. Thus, conductivity measurements, such as the shallow-probing time-domain EM measurements done on Earth to search for conductive features like groundwater, might not be a candidate for lunar geophysics were it not for the fact that the lunar regolith and crust contain micrometer-sized particles of elemental iron and FeS. These single-domain magnetic particles are superparamagnetic, which results in a frequency-dependent magnetic relaxation loss phenomenon when rocks and soils are subjected to an alternating magnetic field [1]. This property can be exploited to determine the vertical distribution of superparamagnetic particles, information that could be used as a guide to regolith thickness and age.

The magnetic induction system might consist of a pair of coplanar, colinear coils on the trailer (Fig. 1). A transmitter coil, about 1 m in diameter, surrounds a small-diameter, multiturn detector coil. The transmitter is energized by a series of square-wave current pulses with sharp rise and decay times. During the brief time current flows through the transmitter loop, a primary magnetic field is created. At the instant the loop current goes to zero, the only remaining magnetic field is a rapidly decaying secondary magnetic field caused by a magnetic polarization current

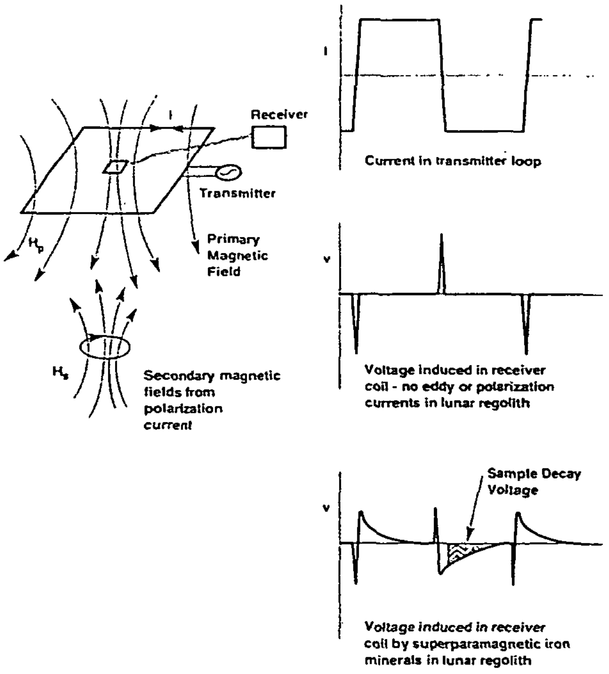

Fig. 1. Principle of a time-domain magnetic induction system.

in the lunar material. The decay current is measured in terms of a voltage induced into the detector coil. The voltage decay curve is recorded within microseconds after current in the loop goes to zero, and one can, in principle, determine from its shape and magnitude the vertical distribution of polarizable material. If one were to measure the change in magnetic field in the center of the during the current on-time, relative to its free space value, one could also obtain an estimate of the magnetic susceptibility of the lunar soil.

Ground-Penetrating Radar (GPR): During the last decade, GPR has become a staple method in shallow investigations. GPR systems working in the 100-MHz to 1-GHz range are routinely used to probe the Earth to depths of up to tens of meters. The depth of investigation is limited by a number of system and subsurface parameters, e.g., radiated power, frequency, and attenuation by wave spreading, conductive losses, and scattering, to name a few. Because lunar surface rocks have very low conductivity and low dielectric constant, radar waves penetrate more deeply into the Moon than into the Earth; radar frequency penetration may be hundreds of meters. Spatially coherent reflections, if they are detected at all from shallow sources, would provide exciting new information on the Moon's internal structure and possible presence of either conductive mineral concentrations or an ice horizon, which some scientists believe exists beneath the polar regions.

No new technology would have to be developed to add GPR to a lunar rover. Antenna design would have to be optimized for a lunar mission, antenna size dictating the lowest frequencies. Small, highly directional horn antennas could be used at frequencies over 1 GHz for high-resolution shallow soundings; 1-m electric dipoles could be used at frequencies of around 300 MHz. Currently, Sensors and Software Corp., Mississauga, Ontario, is planning to space harden and lighten a commercial GPR system for a possible French-led Mars mission in the 1998–2000 time period.

Seismic Reflection: Seismic reflection may be the most difficult geophysical technique to adapt to a lunar rover because the system must be lightweight and remotely controlled, and the technique requires physical coupling of sources and detectors to the Moon's surface.

Several source types used on Earth might be adaptable to a rover, e.g., a hammer or an accelerated weight drop onto a plate, a shotgun slug fired into the ground, or a mechanical vibrator [2]. Of these, a mechanical vibrator with sufficient moment to be useful is probably the least attractive candidate source because of its size, complexity, and power requirements. However, it should not be excluded from consideration at this time because new technology could make piezoelectric devices, such as bimetallic "benders," a candidate source if a good way were to be found to couple energy into the Moon. The accelerated weight drop produces the highest energy of all the small commercial sources, but significant redesign and weight reduction of the Bison Elastic Wave Generator is needed for a lunar source.

The seismic system would probably have only a few detectors and corresponding data channels. Detectors might be embedded into the wheels of the rover-trailer vehicle; a pressure-activated switch in the wheel would relay a signal to the driver that the detector(s) is (are) positioned for a measurement.

Gravimetry: Gravity measurements will provide the basic information for determining the Moon's internal density distribution, and thus will be an important method for discerning subsurface structures and rock-type variations. Gravity measurements are among the most tedious and time-consuming geophysical measurements to make because the meter must be very precisely leveled and elevation, terrain, and tidal correction factors must be calculated and applied before the meter readings become useful data. For example, we would need to know station elevation relative to a datum surface to much better than 1-m accuracy, the local topography to 1-m accuracy out to a radial distance of at least 10 km, and the lunar tide effect. The latter requires a nearby monitoring station.

At present there is no gravity meter that meets the specifications for a lunar resource assessment. The meter must be self-leveling to 10 arcsec or better, provide digital readings under the direction of system control, work in a low absolute gravity environment, have a precision of 0.1 mGal or better, and have an operating range of perhaps 2000 mGal. Scintrex Corp., Concord, Ontario, has redesigned its CG-3 Automated Gravity Meter for the Canadian Space Agency for possible use in the French-led Mars mission. The design calls for a smaller and lighter meter than the 10-kg CG-3, one that would be autoleveling to better than 200 arcsec, more precise leveling to be achieved by means of a numerical correction.

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TOPLEX: TELEOPERATED LUNAR EXPLORER—INSTRUMENTS AND OPERATIONAL CONCEPTS FOR AN UNMANNED LUNAR ROVER.

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We propose a Teleoperated Lunar Explorer, or TOPLEX, consisting of a lunar lander payload in which a small, instrument-carrying lunar surface rover is robotically landed and teleoperated from Earth to perform extended lunar geoscience and resource evaluation traverses. The rover vehicle would mass about 100 kg and carry ~100 kg of analytic instruments. Four instruments are envisioned: (1) a Laser-Induced Breakdown Spectrometer (LIBS) for geochemical analysis at ranges up to 100 m, capable of operating in three different modes [1]; (2) a combined X-ray fluorescence and X-ray diffraction (XRF/XRD) instrument for elemental and mineralogic analysis of acquired samples [2]; (3) a mass spectrometer system for stepwise heating analysis of gases released from acquired samples [3]; and (4) a geophysical instrument package for subsurface mapping of structures such as lava tubes [4].

The LIBS (30 kg, 7 W) uses plasma atomic emission and (optionally) mass spectrometry for elemental analysis of unreachable locations such as cliff faces. Mineralogic information is obtained by using the optical portion of the LIBS as a UV/VIS/near-IR reflectance spectrometer. The XRF/XRD instrument (10 kg, 10 W) requires powdering of scoop-and-screened or other acquired samples. Mineral structures are determined by Rietvelt analysis of powder diffraction data combined with elemental analysis by XRF. The mass spectrometer system (20 kg, 35 W) will be used to measure isotope ratios of light-element gases released from step-heated samples, and will include an evaluation of lunar H and ^{3}He resources. The geophysical instrument package (20 kg, 20 W) uses a combination of high-frequency seismic and electromagnetic sensors to measure subsurface physical properties and map struc-