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. James D. Blacic, Los Alamos National Laboratory, D462, Los Alamos NM 87545, USA.

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 structures. The LIBS pulses may impart sufficient energy into the ground to also serve as seismic sources. The following table summarizes the estimated instrument gross specifications.

TABLE 1. Instrument summary.

	LIBS	XRF/XRD	MS	Geophys	Total
Mass (kg)	30	10	20	20	80
Average regulated power (W)	7	10	35	20	72
Data rate (bits/s)	1 M	10 k	40 k	50 k	1.1 M

The TOPLEX operates in a mobile, exploration-and-sample acquisition mode during the lunar day and in a stationary, sample-analysis mode during the lunar night. The rover vehicle that carries the instruments is estimated to mass 100 kg and require 25 W of average power. Vehicle requirements/specifications include the following: Range – 200 km; maximum speed – 500 m/hr; communications – high-gain antenna and data rate consistent with teleoperation; endurance – 4 to 6 months; and must be self-deploying from the lunar lander. In addition, the rover will have stereoscopic vision with zoom and selectable band filtering, and a robotic arm for sample acquisition, preparation (i.e., powdering), and conveyance to appropriate instruments.

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DRILLING AND DIGGING TECHNIQUES FOR THE EARLY LUNAR OUTPOST. Walter W. Boles, Department of Civil Engineering, Texas A&M University, College Station TX 77843-3136, USA.

Introduction: The theme of this workshop is lunar resource assessment. Topics include identification, quantification, and location of useful elements on and below the lunar surface. The objective of this paper is to look at another side of the issue—how to remove soil from the stiff lunar-soil matrix once useful deposits are located.

The author has been involved with the study of digging and excavating on the Moon for several years. During that time he has overheard some disturbing comments such as the following:

"We know what works best here [on the Earth]. Just make the systems such as power and thermal control work in the lunar environment and the machine will work well on the Moon."

"Just send something up there that looks like a front-end loader with a back hoe. It will work. Don't worry about it."

Comments such as these are disquieting, to say the least, because even if a machine's subsystems are designed to operate well in the lunar environment, it may still perform its tasks poorly. Also, one cannot assume that the operational characteristics of terrestrial machines, based upon terrestrial heuristics, will be similar to machines operating on the Moon. Finally, due to the suspect accuracy of terrestrial soil-tool interaction theories, one cannot justifiably argue that these theories can be used along with terrestrial heuristics to make accurate predictions of the performance of various excavating methods on the Moon. The need is great, therefore, for quantitative and verifiable evidence of the performance of various digging methods. This evidence is necessary for the confident selection of appropriate methods for further research and development.

The goal of this paper is to challenge comments such as those mentioned above and to cause those who think that digging or excavating on the Moon is a trivial problem to rethink the reasons for their opinions. Another goal is to encourage them to view total reliance upon terrestrial heuristics with suspicion. This paper will focus primarily upon digging since another paper will focus primarily upon drilling.

Lunar Soil: Much is known about the lunar soil. The characteristics of interest here, however, are those that tend to make the soil difficult to excavate. The soil is composed of very angular, abrasive, fine-grained particles that have re-entrant corners. As a result, they tend to cling to each other. The soil matrix is very loose (low density) at the surface and is very hard (high density) at relatively shallow depth. It is believed that the soil approaches 90% to 100% relative density at a depth of approximately 0.7 m. Additionally, it is reasonable to assume that rocks and boulders will be encountered in any digging activities. The regolith has been described as a dense, interlocking soil matrix [1].

The lunar soil, therefore, will be very difficult to penetrate below about 0.5 m. Penetration of blades, scoops, and cutters will require crushing and shearing of many soil particles since the soil nears 100% relative density at shallow depth. This crushing and shearing action requires high forces. Encounters with rocks and boulders will serve to make a difficult situation worse. Expected performance of traditional terrestrial methods, therefore, is low.

Lunar Experience: During the Apollo missions, hollow stems were augered into the lunar soil. The first attempts were only able to drill to about 1.5 m. This was due to discontinuous auger flights at splice locations on the stem. It is assumed that the soil particles seized the stem at the joint and caused the stem to fail. On later missions the stem was redesigned with continuous auger flights and depths of approximately 3 m were reached. The rate of penetration, however, had to be kept low since the stem would tend to screw itself into the soil and was difficult to remove [1].

There are two major problems regarding drilling. The first one is the removal of cuttings. The second one is cooling of the drill bit. Both these problems are usually solved on the Earth with fluids. The use of fluid to remove cuttings and cool the bit is obviously a problem on the Moon.

Shoveling on the Moon was relatively easy in the top 10 to 15 cm. Below this depth the shoveling became very difficult. Also, hammer tubes were driven to a depth of approximately 0.7 m before the resistance became too great [1]. It is interesting that this depth corresponds well with the depth at which the regolith is assumed to approach 90% to 100% relative density. In summary, these limited data tend to verify data in the previous section. It also tends to confirm that digging in the lunar regolith will be very difficult.

Excavation Methods: Typical terrestrial excavation methods include bulldozers, hoes, shovels, scrapers, draglines, bucket-wheel excavators, and continuous miners with rotating cutting heads. All these methods depend heavily upon gravity to generate downward and horizontal forces. These forces are necessary for the machines to perform well. With the gravity of the Moon approximately one-sixth that of the Earth's, one can expect a corresponding decrease of the machines' performance. For example, the maximum productivity of a 15,000-lb bulldozer on Earth, over a 100-ft haul distance, is approximately 100 yd^3/h. On the Moon,