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Radar backscatter. The surface and subsurface scattering properties of the Moon can be analyzed using radar backscatter imaging. The radiation is both transmitted and received by Earth-based radar antennae. Two-dimensional backscatter images are derived using a delay-doppler technique developed in the 1960s and 1970s. The returned signal is directly related to the geometry of the measurements, the number of scatterers encountered on the scale of the wavelength, and the dielectric properties of surface materials. Surfaces that are smooth on the scale of the wavelength reflect the radiation in a specular manner. Surfaces containing abundant scattering elements on the scale of the wavelength return a higher signal. Since the lunar surface is anhydrous, subsurface block population can also be detected with longer wavelengths.

As summarized in Table 2, radar measurements of the Moon have also had a long history with several important milestones. First was simply the detection of the Moon with Earth-based instruments. As technology advanced during the 1960s and 1970s, the techniques for measurement of radar backscatter of the Moon were perfected and two-dimensional images of the radar backscatter properties were produced at relatively low spatial resolution. Analyses of dual-polarization radar data confirmed the sensitivity to block population on the surface. The last several years have seen dramatic improvement of radar measurements possible. These include an improvement in both sensitivity and, more important for lunar measurements, an improvement in the spatial resolution that can be obtained with Earth-based telescopes.

Current technical capabilities indicate that a spatial resolution of 30–300 m is possible for lunar nearside targets (optical telescopes can achieve 1-km resolution; Lunar Orbiter IV obtained ~100-m resolution for the lunar nearside from orbit). Several tests of these new radar capabilities have already been made. In order to achieve the desired resolution and science analysis return, a modest upgrade to current radar telescopes is required to allow dual polarization at three wavelengths and more extensive data analyses (information extraction) capabilities need to be developed for lunar specific applications.

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LUNAR SURFACE ROVERS.

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Despite the Ranger, Lunar Orbiter, Surveyor, Apollo, Luna, and Lunokhod programs, many questions of lunar science remain unanswered because of a lack of specific data. With the potential for returning humans to the Moon and establishing a long-term presence there, a new realm of exploration is possible. Numerous plans have been outlined for orbital and surface missions. Here we describe the capabilities and objectives of a small class of rovers to be deployed on the lunar surface. The objective of these small rovers is to collect detailed in *situ* information about the composition and distribution of materials on the lunar surface. Those data, in turn, would be applied to a variety of lunar geoscience questions and form a basis for planning human activities on the lunar surface.

The initial rover design has been scoped for a small Artemis lander payload (about 60 kg). It consists of a four- or six-wheeled, solar-powered rover with a mass of 28 kg. Two rovers would be deployed from a single Artemis lander. Rover lifetime would be at least 3 lunar days and hopefully 7–10; at least tens of kilometers of range are possible (depending upon the amount of time devoted to moving vs. sampling and analysis). During the lunar night, the rover would hibernate. About 11 kg of the total 28 kg is available for science payload and sampling equipment, which allows for a variety of capabilities that capitalize on microtechnology. Rover speed would be 0.5–1.0 km/hr depending upon the terrain. Power (60–200 W) is provided by solar panels (0.3 m^2) that also serve to shield the rover from high thermal loads during the day. 120 Whr of AgZn batteries provide capability for short-period, high-load demands; these batteries are capable of withstanding the lunar night. Nominal data rate would be about 30 kbps at 20 W RF; rates as high as 150 kbps would be possible for limited periods. Control of the rover mobility would be in two modes: behavioral control driving and teleoperation driving. In the behavior control mode, a series of way points would be selected and the rover would navigate along the predetermined path to a site, invoking autonomous obstacle avoidance if necessary. In the teleoperation driving mode, mobility would be controlled in a real-time sense from the Earth using slow-scan video for viewing. Sampling and deployment would all be done autonomously once a specific action and position had been selected from the ground. The system would not make autonomous decisions about measurement or sampling.

Two types of payloads are envisioned for such a small rover: a geoscience payload and a physical properties payload. The nominal geoscience payload is aimed at addressing the chemical and mineralogic properties of the regolith and rocks, the composition of absorbed and adsorbed gases in the regolith, and the morphology of the surface to millimeter scale. The payload includes stereo imaging, field lens camera, infrared imaging spectrometer, evolved gas analysis, and alpha/proton/X-ray fluorescence instruments, as well as a scoop and an auger drill to obtain samples of the upper meter of regolith. Using these data, several questions can be addressed: geochemical and petrological processes; regolith stratigraphy and development; history of the solar-wind-implanted gases; lunar resources; small-scale surface morphology; and site evaluation.

Stereo imaging is achieved through two mast-mounted CCD framing cameras (800 × 1000 pixels) with a separation of about 25 cm. Mast mounting allows 360° horizontal viewing and 120° of vertical viewing. The field lens camera is the same type of camera but mounted on the rover body with optics that allow imaging at a resolution of a few millimeters in the near field. The infrared imaging spectrometer covers the spectral range of 0.7 to 2.5 μm and focuses on the portion of the spectrum sensitive to pyroxenes, olivines, FeO content, and soil composition. A spatial resolution of <2 mm at 30 cm is possible. The alpha/proton/X-ray fluorescence instrument is aimed at obtaining elemental composition. The alpha/proton mode measures low Z elements, whereas the X-ray fluorescence mode is sensitive to higher Z elements. Curium-244 is used as the source for the alpha particles; ^{109}Cd or ^{244}Cm would be used for the X-ray excitation. The evolved gas analysis system would be used to heat the samples to drive off gases that would then be analyzed by a mass spectrometer or other system. Target gases include H_2, ^{3}He, SO_2, CO, CO_2, H_2S, H_2O, and N_2. Two types of sample acquistion equipment are planned: a scoop and a drill. The scoop is a clamshell mounted on a 4 degree-of-freedom arm and would collect samples for analysis to depths of a few centimeters with a sample volume of a few cubic centimeters; it could also be used for shallow trenching. This same arm would also deploy the alpha/proton/X-ray device to the surface. The drill is an auger drill mounted to the rover body that could penetrate to depths of about 1 m. Sample volume of a few cubic centimeters from depth intervals of a few centimeters would be obtained. The auger would be housed in a tube such that samples from a given depth remain isolated from regolith material at other depths.

A physical properties payload would be intended to study the geotechnical properties of the surface and subsurface. Those data would be aimed primarily at engineering objectives but would also be applicable to geoscience problems. Parameters of interest include particle size and shape, density and porosity, compressibility, shear strength, bearing capacity, trafficability, electrical conductivity, and charging/discharging of the surface. The complete payload is under study and has not yet been determined. However, it is anticipated that an electron-magnetic sounding system would be used to determine the thickness, stratigraphy, and boulder content of the regolith. This system would be mounted on the rover body such that long distance or areally extensive traverses could be obtained.

Later Artemis landers have a larger payload capability, about 200 kg or larger. Additional studies are underway that consider the possibility of building larger rovers that have more capability, particularly with respect to lifetime, range, and drilling. Alternatively, the larger payload capacity could be used to deploy more of the small rovers outlined above.

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COMBINED GAMMA RAY/NEUTRON SPECTROSCOPY FOR MAPPING LUNAR RESOURCES.

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Some elements in the Moon can be resources, such as hydrogen and oxygen. Other elements, like Ti or the minerals in which they occur, such as ilmenite, could be used in processing lunar materials. Certain elements can also be used as tracers for other elements or lunar processes, such as hydrogen for mature regoliths with other solar-wind-implanted elements like helium, carbon, and nitrogen. A complete knowledge of the elemental composition of a lunar region is desirable both in identifying lunar resources and in lunar geochemical studies, which also helps in identifying and using lunar resources. Discussed here is the use of gamma ray and neutron spectroscopy together to determine abundances of many elements in the top few tens of centimeters of the lunar surface. To date, very few discussions of elemental mapping of planetary surfaces considered measurements of both gamma rays and the full range of neutron energies.

The concepts of using gamma rays or neutrons escaping from the Moon to determine lunar elemental composition date back over 30 years (e.g., [1]). In 1971 and 1972, gamma ray spectrometers (GRS) on Apollos 15 and 16 mapped $\approx$22% of the lunar surface but only could determine the abundances of several elements (Th, Fe, Ti, K, and Mg) because of the use of low-resolution NaI(Tl) scintillator detectors and the short durations of the missions. A high-resolution germanium GRS is on the Mars Observer scheduled to be launched in late September 1992 [2]. Such a spectrometer is much more sensitive for determining lunar elemental abundances and for identifying surface components than was the Apollo GRS [3]. Neutron spectroscopy of another planet has not been done yet, although the Mars Observer GRS is capable of detecting thermal and epithermal neutrons [2]. A germanium GRS can also detect neutrons $\geq$0.6 MeV by triangular-shaped peaks in the spectrum made by neutron-induced inelastic-scattering reactions in the detector [4]. The inclusion of a detector specifically designed to measure fast ($E_n \sim$ 0.1–10 MeV) neutrons improves the sensitivity of detecting hydrogen in the lunar surface [5]. Spectrometers to measure the fluxes of gamma rays and neutrons escaping from the Moon are discussed elsewhere in this volume [6]. A gamma ray spectrometer can also be used to detect thermal and epithermal neutrons using coatings of thermal-neutron-absorbing materials [3], although not with the sensitivity of detectors designed specifically for such neutrons. The theories for gamma ray and neutron spectroscopy of the Moon and calculations of leakage fluxes are presented here with emphasis on why combined gamma ray/neutron spectroscopy is much more powerful than measuring either radiation alone.

Sources of Neutrons and Gamma Rays: Most gamma ray lines made by the decay of excited states in nuclei are produced by several types of nuclear reactions, mainly neutron nonelastic scattering and neutron capture [7–9]. The main exceptions are the gamma rays made by the decay of the naturally radioactive elements (K, Th, and U). The neutrons are made by the interaction of the energetic particles in the galactic cosmic rays (GCR) with the lunar surface [10]. Neutrons are produced mainly with energies of ~0.1–10 MeV, with some made with higher energies. The rates for the production of these fast neutrons depends on the intensity of the GCR particles, which can vary by a factor of $\approx$3 over an 11-year solar cycle [11], and is slightly (~5%) dependent on the surface composition [12]. The transport and interactions of these fast neutrons are also dependent on the surface composition. Neutrons in the Moon can be slowed by scattering reactions to epithermal ($E_n \sim 0.5$–10^3 eV) and thermal ($E_n \sim$ 0.01–0.5 eV) energies. The flux of epithermal neutrons is mainly dependent on the hydrogen content of the surface, while the flux of thermal neutrons depends both on the amounts of neutron moderators like H and of thermal-neutron absorbers like Fe, Ti, Sm, and Gd [1,5,12,13]. Many neutrons escape from the lunar surface and can be detected in orbit. The gravitational field of the Moon affects slightly the flux at orbit of the lowest-energy neutrons [14].

The reaction of these neutrons with atomic nuclei in the lunar surface produces most of the gamma rays used for elemental mapping. Fast neutrons make gamma rays by a large variety of nonelastic-scattering reactions. Many elements (e.g., O, Mg, Si, and Fe) are mapped by neutron inelastic-scattering reactions making excited states in the target nucleus, such as ^{24}Mg(n,n γ)^{24}Mg exciting the 1.369-MeV state of ^{24}Mg (which almost immediately, $\lesssim$1 ps, decays to the ground state). Neutrons with energies of ~0.5–10 MeV make most of these inelastic-scattering gamma rays. Neutrons with higher energies can induce many types of reactions, such as the ^{28}Si(n,n α γ)^{24}Mg reaction, which also can make the 1.369-MeV gamma ray. Many thermal and some epithermal neutrons produce gamma rays by neutron-capture reactions, such as the ^{28}Si(n,γ)^{29}Si reaction, which makes a cascade of gamma rays. The cross sections for neutron-capture reactions vary by orders of magnitude, and the elements mapped by gamma rays made by such reactions (e.g., Ti, Fe, and possibly Cl, Sm, and Gd) are those with high cross sections for (n,γ) reactions and that emit one or more gamma ray with a high yield per captured neutron.

Calculations of Neutron and Gamma Ray Fluxes: The ultimate sources of lunar neutrons and most lunar gamma rays are from interactions of the high-energy ($E \sim$ 0.1–10 GeV) particles in the galactic cosmic rays. The Los Alamos high-energy transport