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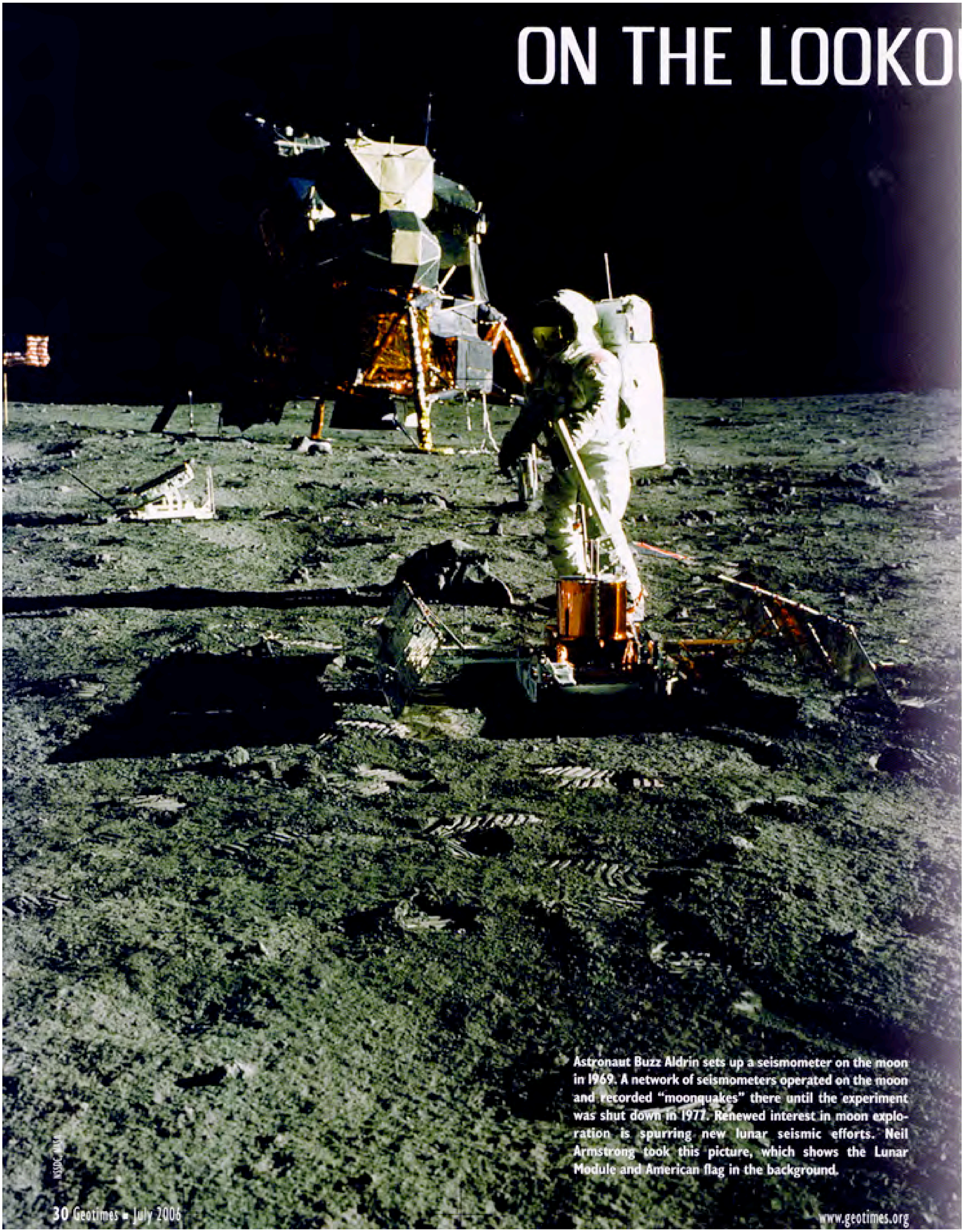


NSSDC/NASA

Astronaut Buzz Aldrin sets up a seismometer on the moon in 1969. A network of seismometers operated on the moon and recorded "moonquakes" there until the experiment was shut down in 1977. Renewed interest in moon exploration is spurring new lunar seismic efforts. Neil Armstrong took this picture, which shows the Lunar Module and American flag in the background.

UT FOR QUAKES ON THE MOON

Scientists are working to create a seismic network for the moon, in preparation for an eventual permanent lunar station.

Clive R. Neal

Many people think of the moon as a dead planetary body, both in terms of volcanic and seismic activity. The Apollo missions in the 1970s, however, proved otherwise.

A half-illuminated Earth hangs over the horizon, as the Apollo II Lunar Module *Eagle* returns from the surface of the moon to dock with the Command Module *Columbia*. The moon, like Earth, has seismic events, but they differ in their causes and nature.

NSSDC, NASA

The Apollo Passive Seismic Experiment (APSE), a network of four seismometers that was completed in April 1972, recorded seismicity on the moon until the network was shut down because of cost-cutting measures on Sept. 30, 1977. While the network was operational, it clearly demonstrated that the moon is seismically active, albeit on a smaller scale than Earth. The moon is less active because it is a "one plate planet" and does not, therefore, contain plate boundaries, the sites of large seismic events here on Earth. But plate boundaries aside, the moon exhibits seismic activity on a similar scale to that of intraplate settings on Earth.

With the advent of a new era of lunar exploration, the importance of the Apollo seismic database has greatly increased, highlighting the many unanswered questions about so-called moonquakes, the lunar equivalent of earthquakes. Understanding moonquakes is especially important to any future plans for a permanent lunar base, currently called for in President Bush's space exploration plan. Having a long-term human presence on Earth's only moon requires a full evaluation of the seismic risk.

MOONQUAKES

Over the last three decades, many researchers, most notably perhaps Yosio Nakamura of the University of Texas in Austin, have mined the Apollo seismic database and identified four different types of lunar seismic events. These are thermal moonquakes, deep moonquakes, meteoroid impacts and shallow moonquakes.

Thermal moonquakes are small and were recorded in several locations by the Apollo seismometers. These are the result of daily temperature changes that produce stress and strain of lunar rocks in young craters, eventually causing them to crack or "slump," as evidenced by the repetition of signals with nearly identical waveforms at the same time during each lunar day. Seismic activity begins abruptly two days after lunar sunrise and rapidly deteriorates after lunar sunset. Of the four types of moonquakes, these events emit the lowest energy.

Deep moonquakes are also low in energy but are the most abundant type, with more than 7,000 events recorded during the eight years of monitoring. These small-magnitude events (generally less than magnitude 2) occur approximately halfway between the surface and the center of the moon (700 to 1,200 kilometers deep), at highly regular monthly intervals, indicating a strong association with the tidal pull of Earth. Deep moonquakes originate from specific locations, or "nests," that produce a quake of unique waveform. To date, researchers have identified 318 nests from the Apollo dataset.

Meteoroid impacts also register as seismic events. While most of the energy of an impact is expended in excavating a crater, some is converted to seismic energy. Between 1969 and 1977, the APSE network recorded more than 1,700 events representing meteoroid masses between 0.1 and 1,000 kilograms. Events generated by smaller impacts were too numerous to be counted.

The strongest type of lunar seismic event is the shallow moonquake. These quakes were originally referred to as "high frequency teleseismic events," and seven of the 28 events that the APSE network recorded were greater than magnitude 5. The depths at which these moonquakes originate are "shallow," likely between 50 and 200 kilometers, although the exact depths are unknown because all recorded events were outside the perimeter of the APSE network. These events are relatively rare and not correlated with tides. While they appear to be associated with boundaries between dissimilar surface features, the exact origin of these events is still unclear. A recent development by Nakamura and colleagues suggests shallow moonquakes may originate from interaction of the moon with nuggets of high energy particles ("strange quark matter") originating from a fixed source outside the solar system.

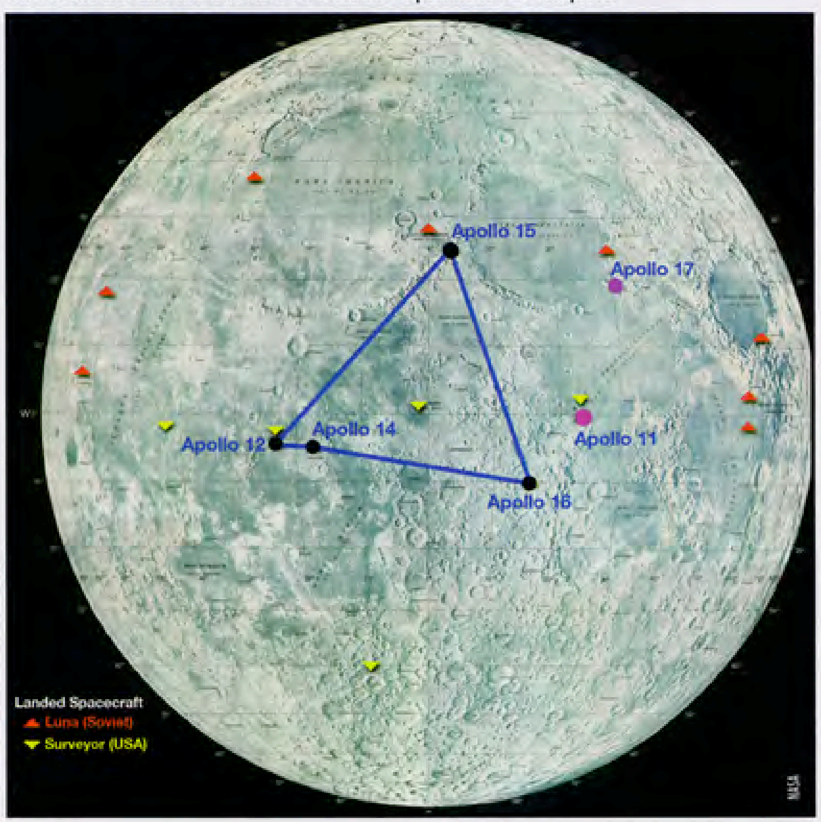
The shallow moonquakes and those caused by meteoroid impacts pose potential (and very real) hazards to establishing a long-term habitable facility on the moon. Still, it is important to note that the seismicity generated by meteoroids is unlikely to pose a significant threat to any structure, unless the impactor's mass is on the order of tons and the impact is close to the site of the moon base. Shallow moonquakes, however, contain more energy at high frequencies than quakes on Earth of similar magnitudes.

EVALUATING RISK

Of critical importance to a lunar base is the amount of ground motion associated with shallow moonquakes. As already noted, seven of the 28 shallow seismic events recorded by the APSE network had magnitudes of 5 or more. On Earth, such quakes can cause structural damage around the epicenter, often manifested by the propagation of cracks through and along walls. In a lunar setting, a magnitude-5 or greater quake could breach the seal of a moon base, resulting in a catastrophic loss of oxygen, which would devastate the habitat.

Currently, we do not know the cause or exact locations (especially the depths) of these strong, shallow moonquakes, but they are in many respects comparable to infrequent, highly destructive intraplate earthquakes. As a first order approach, researchers have modeled ground motion and acceleration using equations derived for terrestrial quakes (there are no such equations as yet for the lunar scenario). Applying such terrestrial models to the lunar environment is, at present, the best estimate we can make. However, there are distinct differences in terms of seismic wave transmission between the moon and Earth that could render the above estimates totally inadequate.

The Apollo Passive Seismic Experiment involved deployment of a network of seismometers (outlined in the large triangle) on the nearside of the moon. The seismometer at Apollo 11's landing site failed after 21 days. The Apollo 17 seismometer was intended to determine the shallow structure of the site and was switched off once the experiment was complete.



For example, researchers have observed the maximum signal from a shallow moonquake to last up to 10 minutes with a slow tailing off that can continue for hours in total duration, demonstrating that signals dampen less while traveling through the moon than they do traveling through Earth. This effect suggests the mechanical properties of lunar rocks are distinct.

Studies have demonstrated the dramatic damping effect that water has on seismic energy. Thus, seismic energy is more efficiently propagated through the moon, which is incredibly dry. Significantly, moonquakes tend to produce seismic waves of higher frequency than earthquakes. This consideration is important for wave transmission through the lunar interior as well as interaction with the near surface.

The material, or "regolith," on the lunar surface has formed through micro- to macro-sized meteoroid impacts. This incredibly dry unconsolidated material tends to scatter seismic waves. Modeling of this scattering using frequency-dependent diffusion appears to allow a statistical approach to quantifying the data recorded by the APSE network. Using this model, earlier researchers highlighted the fact that there is very low attenuation of waves in the surface zone.

KNOWN LIMITS

While the APSE network has defined two potential hazards for any permanent habitation on the moon, accurate risk assessment is difficult to formulate because of the limitations of the current lunar seismic database. By integrating the existing seismic data with strategically acquired new data, researchers can not only better understand potential hazards, but also can better refine scientific models about the moon's interior structure and formation.

The small area covered by the APSE network has resulted in difficulty in estimating epicenter locations for seismic events. While attempts have been made to locate the origins of both deep and shallow moonquakes, exact locations require knowledge of the composition of the lunar mantle. The small areal extent of the APSE network has resulted in reduced resolution of seismic information from deep in the moon's interior, limiting interpretation.

For example, seismic data have been interpreted to indicate the presence of garnet in the lunar mantle. However, the same seismic data were also interpreted to represent an increased proportion of magnesium-rich olivine, representing conflicting views. The presence of garnet in the lunar mantle is also supported by the trace element ratios of some lunar volcanic glasses. Resolving these differences to evaluate the moon's composition is important to any seismic risk evaluation, as it affects how seismic waves travel through the body. More seismic data are necessary to better understand the composition.

Likewise, very little seismic information is available regarding the nature of the lunar core, as the APSE network was located on the nearside of the moon. A large meteoroid impact on the farside of the moon produced a seismic wave that was significantly delayed in reaching one of the Apollo seismic stations. This event suggested the presence of a molten core approximately 720 kilometers in diameter, but no additional data were collected to confirm this.

Geochemical and magnetic data also suggest that the moon does indeed have a small core with a diameter estimated to range from approximately 500 to more than 800 kilometers. However, the composition of this core has been reported to be anything from iron to iron sulfide to ilmenite (which also contains iron). These compositions have important implications for the thermal history of the moon. For example, if the core is predominantly iron, it would be solid, but if it is iron sulfide, it could still be (partially) liquid. Appropriate seismic data could rigorously test the nature and composition of the lunar core.

The location of the APSE also did not provide much information regarding deep seismic activity on the lunar farside. Early research reported 109 distinct nests of deep moonquakes, but only one of these was located on the farside. A reevaluation of the APSE database found two more indisputable farside nests with several other nests having epicenter locations on the nearside, but uncertainty remains. These farside nests seem to produce seismic waves that stop while traveling through the moon's interior, suggesting there is a "plas-

CHALK OR CHEESE?

Thirty-seven years after humans first set foot on the moon, we now know it is made of the same elements as Earth, has bright sunlight-reflecting mountains and dark, lava-filled craters, and possibly hidden pockets of frozen water (though direct evidence of that water has proven elusive). But early astronomers, lacking high-tech instruments and moon rock samples, formed their own hypotheses about the moon's makeup. Here are some highlights of nearly 2,500 years' worth of speculation about the substances that compose our only natural satellite:

450 B.C.: Greek philosopher Anaxagoras asserts that the moon is a giant spherical rock, not a deity. He is arrested and exiled from Athens.

384-322 B.C.: Greek philosopher Aristotle postulates that the moon is a perfect sphere made of celestial, not earthly, matter.

A.D. 46-120: Greek writer Plutarch suggests that the moon's dark regions are the shadows of rivers or chasms, and the light spots are land. He also ponders whether life exists there.

1546: In *Proverbes*, English poet John Heywood writes (probably not literally), "the moone is made of a greene cheese."

1609: Galileo Galilei observes mountains and craters on the moon's surface. Instead of Aristotle's perfect sphere, he says, it is "rough and uneven, and just like the surface of the Earth itself."

1651: Italian astronomers Giovanni Battista Riccioli and Francesco Maria Grimaldi map the visible, nearside of the moon and name its craters. Referring to ancient beliefs, they call the dark patches *maria*, or seas, and the white patches *terrae*, for land.

1957-1975: The Cold War space race heats up between the United States and the Soviet Union. By the end of the era, Soviet robotic spacecraft have taken the first pictures of the farside of the moon, the Americans have mapped 99 percent of its surface, U.S. astronaut Neil Armstrong has taken a lunar walk, and Apollo astronauts have brought back 382 kilograms of moon rocks.

Jan. 7, 1998-July 31, 1999: NASA's Lunar Prospector mission makes the first "direct" chemical measurements of the entire lunar surface, detecting significant amounts of hydrogen in lunar craters at the poles — possibly a sign of water ice.

March 5, 1998: NASA announces that images from its 1994 Clementine mission suggest that enough water is frozen in the moon's polar craters to support a human colony and a rocket fueling station.

Now, scientists and nations are again feeling the moon's pull, and a new era of lunar exploration has begun. In early 2004, U.S. President George W. Bush called for manned lunar missions by 2020. Japan, India and the People's Republic of China have each announced their own moon exploration plans. Meanwhile, the European Space Agency's unmanned SMART1 has begun its mission to inventory the moon's chemical makeup and investigate the collision theory of its origin.

tic," or partially molten, zone located somewhere in the deep lunar interior. Two major questions remain: 1) Are there other nests on the lunar farside that were not detected by the APSE? 2) What is the nature and extent of the purported plastic zone?

More seismic data will not only help resolve these questions about the moon's interior, but also could inform hypotheses about the moon's formation. The lunar magma ocean model has become the cornerstone of our understanding of moon evolution. This model postulates that immediately after formation, the moon underwent a global melting event that affected approximately the outer 500 kilometers of the moon or even all of it.

The APSE data have been interpreted to indicate the presence of a seismic discontinuity at approximately 400 to 600 kilometers beneath the equatorial moon that could represent the base of the lunar magma ocean, but it is unclear whether it extends around the whole moon. If it does, then there is evidence for the global melting event, although it may indicate that only the outer "skin" of the moon melted. If it does not, then a rethinking of the magma ocean model is required. Again, more seismic data are necessary.

UNEARTHING THE MOON'S BIRTH

Impacts are the key players in the moon's and Earth's early histories. A leading hypothesis for the moon's formation focuses on the idea of a Mars-sized planet striking Earth shortly after the solar system formed, and then ejecting debris that ultimately became the moon. The energy from the impact caused the forming moon to melt, creating a lunar magma ocean, which may have encompassed the entire moon.

Evidence supporting this "giant-impact hypothesis" from early Apollo missions includes lunar rocks with an oxygen isotopic composition nearly identical to Earth's mantle. Such a composition is consistent with the moon forming mostly from Earth's mantle and partly from the mantle of the impacting body.

The giant-impact hypothesis, however, has come under fire in recent years. Orange pyroclastic glass returned from the Apollo 17 mission — the last manned American mission to the moon — contains a greater abundance of volatile gases than other volcanic products on the moon. But the energy from the giant impact would have resulted in the moon's interior being more depleted in volatile elements. The primordial imprint found in the glass would have been vastly altered in a giant impact (and subsequent melting in the magma ocean), necessitating an alternative explanation for how the moon formed.

Some researchers have suggested that instead of the giant impact, Earth captured the moon from another orbit, and that all planets initially formed with cool primordial cores. Subsequent impacts could have then created sufficient energy to create the lunar magma ocean.

Sorting through these hypotheses to understand how the moon formed addresses just one of many scientific questions that further moon exploration can answer. A global, long-lived, lunar seismic network will tell scientists more about the composition of the moon's interior, including the size of the core and potentially the depth of any magma ocean, and in turn, inform discussions about its origins. ○

THE NEXT GENERATION

Predicting where shallow moonquakes will occur is of prime importance for the next phase of lunar exploration. Current data make this difficult because only 28 such events were recorded before the APSE was shut down.

The relatively small number of events and the error in locating epicenters has limited the statistical significance of relating these shallow seismic events to tectonic features or a possible extra-solar-system origin. Thus, the causes and locations of shallow moonquakes are not known with any high degree of confidence. However, the existing data indicate that one magnitude-5 or greater event occurs each year. Because the shallow quakes are potentially the most destructive, such knowledge must be obtained in the near, if not immediate, future.

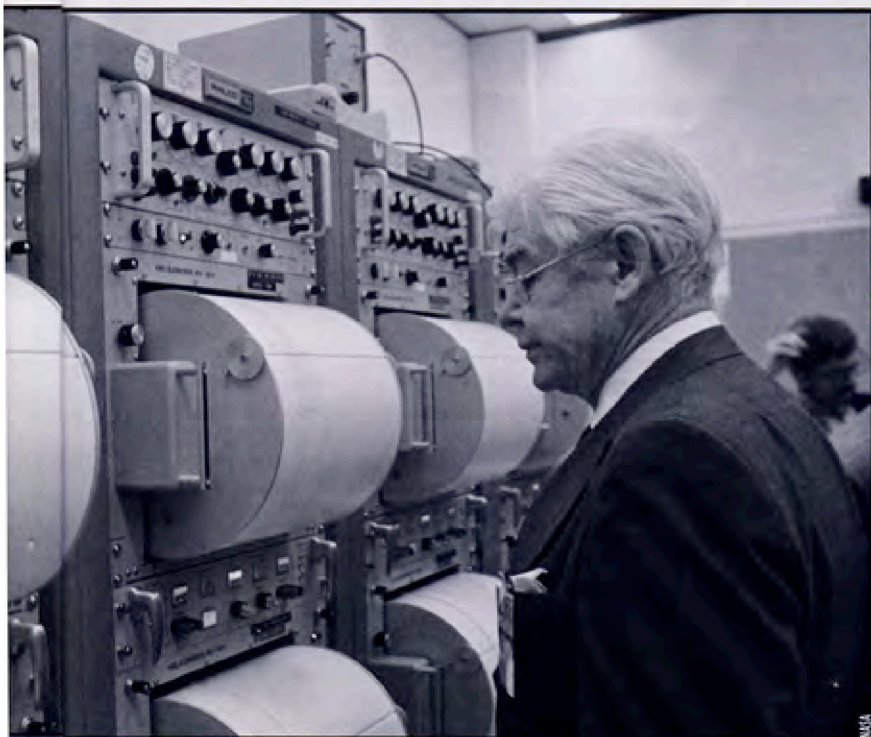
Thus, an urgent need exists for a long-lived global seismic network to be established on the moon. Over the last three years, without the help of astronauts, an international team has been investigating the intricacies of remotely deploying the Lunar Seismic Network (the "LuSeN mission").

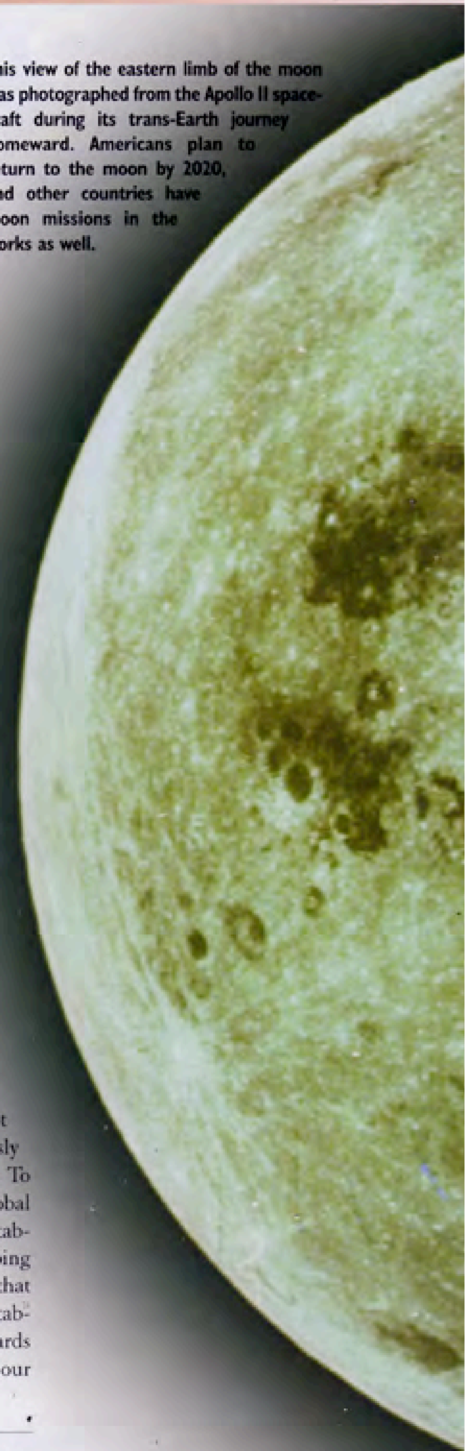
The seismometer that was chosen for this investigation was the Centre National d'Etudes Spatiales' "very broadband seismometer" that was developed for deployment on Mars, and is more sensitive than those used in the APSE. However, the outcomes of this investigation highlighted major technology gaps in the remote deployment of seismic networks on airless bodies. The major issues include developing long-lived power supplies (with a six-year minimum lifespan) that can survive the long lunar night and planning for a hard versus soft landing deployment of the sensors.

Maurice Ewing looks at data being downloaded from the Apollo Passive Seismic Experiment in the 1970s. Some researchers are now reexamining the old Apollo data to learn more about the nature of seismicity on the moon as well as about the moon's interior.

The seismometers that formed the APSE network were powered by RTGs (Radioisotope Thermoelectric Generators) with a design output of 73 watts. The LuSeN team has estimated that the maximum power required for the very broadband seismometer, integrated with computerized recording and transmission components, is between 2 and 4 watts. It is unclear whether electrical power in this range can be maintained for a minimum of six years using conventional solar-battery technology. An Apollo-sized RTG for each seismometer package, however, would be overkill.

What is required is the development of so-called "mini-RPS" (Radioisotope Power System) units that supply between 0.1 and 10 watts of power. While this concept has been explored by NASA, actual fabrication and testing of such units is not





This view of the eastern limb of the moon was photographed from the Apollo II spacecraft during its trans-Earth journey homeward. Americans plan to return to the moon by 2020, and other countries have moon missions in the works as well.

occurring, nor is it planned to occur in the near future. However, the concepts presented by researchers at NASA's Jet Propulsion Laboratory in Pasadena, Calif., in 2004 are tantalizing for the LuSeN mission and any mission that attempts to deploy a global seismic network on an airless body. For example, the mass of the RPS unit would be between 3 and 6 kilograms, resulting in a total mass for each seismometer package of less than 8 kilograms — much lighter than using conventional solar-battery-power supplies, which cause the packages to weigh much more than 10 kilograms each.

In general, mass is a critical limiting factor. If the mission calls for a "hard landing," each seismometer package will need cushioning material to protect the delicate instrumentation as it drops from a low-altitude orbiter. But if a "soft landing" deployment is planned, each package will need its own individual "retro-rocket assembly" to slow its landing. Either option adds more mass to each package, and, especially if conventional solar-battery-power technology is used, a network cannot be established with a single launch. At least two launches will be required to establish a minimum network of eight seismometers. The mission will, therefore, be cost-prohibitive using the current mission programs available through NASA.

Hopefully, the LuSeN team will continue to try to meet the goals laid out in January 2004 by President Bush "of living and working [on the moon] for increasingly extended periods of time" and ultimately establishing an extended human presence on the moon. Obtaining a better understanding of lunar seismic activity is crucial for achieving the president's vision.

At this time, it is suspected, but not known, that seismic events could seriously compromise a permanent lunar habitat. To fully evaluate this risk, a long-lived, global lunar seismic network needs to be established. Now is the time to start developing the new power-generation systems so that the lunar seismic network can be established to monitor and locate seismic hazards before we humans can make the moon our home.

Neal is an associate professor at the University of Notre Dame in Indiana and has been conducting lunar research for 20 years. He would like to thank to Yosio Nakamura, whose patience and encyclopedic knowledge of lunar seismicity greatly improved this story.