Clockwise from right: McDonald Observatory's 107-inch telescope fires a laser at the Moon; a laser lights up the Apache Point 3.5-meter telescope; part of the Apollo 15 retroreflector; Earth rises above the Moon as seen from Apollo 11.

CLOCKWISE FROM LEFT: McDONALD OBSERVATORY; TOM MURPHY/APACHE POINT OBSERVATORY; NASA (2)

MOONSHOTS

40 years after the first astronauts walked on the Moon, Apollo's last experiment is still probing the Moon, Earth, and much more

By Damond Benningfield

Tom Murphy scrambles up a narrow ladder into a concrete vestibule beneath the 3.5-meter telescope at the Apache Point Observatory in southern New Mexico. A blue metallic cone punctures the center of the tiny room, part of the support structure for the 45-ton telescope. But Murphy is there to check on a boxy electronics cabinet in the corner. A new addition to the room, it measures the up-and-down flex of the 9,200-foot mountain peak below the telescope in response to changes in air pressure, tides in Earth's crust, and even the crash of storm-driven waves on shores thousands of miles away. "If the site moves up or down by half a millimeter, we can sense that," says Murphy, an associate physics professor at the University of California-San Diego.

Such a tiny distance is critical because Murphy is making some of the most precise astronomical measurements ever attempted. He is using the telescope as a giant laser pointer, bouncing its light off of special reflectors left on the Moon by three Apollo missions and a robotic Soviet rover to measure the Earth-Moon distance to within one millimeter — about the thickness of a paperclip.

Murphy's observations could add one more "giant step" to Apollo's accomplishments by showing that Albert Einstein's theory of gravity is wrong. Such a result could explain dark energy, provide the first support for string theory, and unify two fundamental fields of physics — general relativity and quantum mechanics.

"It sticks in the craw that the two pillars of physics don't get along," Murphy says. "When you try to merge them, it simply doesn't work. You get pathologies in that marriage that make physicists scratch their heads."

Testing general relativity was one of the original goals of the laser experiment, which has operated continuously since just days after Apollo 11 touched down on the Moon on July 20, 1969 — the only Apollo experiment that is still in operation. Scientists also hoped it would help plot any wobbles in the rotation of the Moon or Earth, reveal details about the Moon's interior, and determine whether the Moon is moving away from us. And over the decades, the experiment has accomplished all that and more.

How Far?

First McDonald Laser Detection

August 19, 1969

Roundtrip Laser Travel Time

2.49596311 seconds

Calculated Distance to the Moon

374,135,457.91211219 meters

232,476 miles, 5,246 feet, 5.485 inches

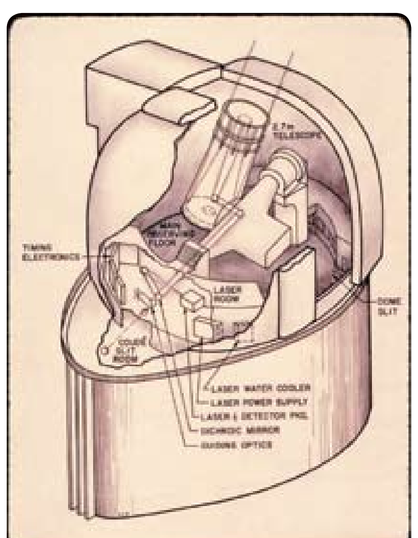
Estimated Error

±.000000003 seconds
4.5 meters
14 feet, 9 inches

Total McDonald Lunar Ranges

(April 2009)
Approximately 6,560

(each 'range' incorporates the results from many individual laser shots)



Schematic shows the McDonald 107-inch telescope and the arrangement of the laser components.

"All the goals we identified have been realized," says Carroll Alley, lead scientist for the Apollo 11 laser experiment and a research professor in physics at the University of Maryland-College Park. "The fact that it's lasted for 40 years has greatly increased the precision of the measurements. The longer the experiment lasts, the more we can say about our original questions."

Many of those questions were born in the days after the Soviet Union launched the first artificial satellite, Sputnik 1, in late 1957, when Alley was a member of a research group at Princeton. Group leader Robert Dicke suggested that shining giant searchlights on satellites studded with special reflectors could yield new insights into the physics of gravity.

The idea gained momentum with two developments in the early 1960s: the invention of the laser and plans to send both machines and people to the Moon. The Moon would provide a bigger and more stable platform for studying tiny effects of gravity, while lasers would provide a stronger signal than conventional light sources with a smaller investment of energy.

Alley and his colleagues developed the concept of lunar laser ranging, in which a spacecraft lands an array of "retroreflectors" on the Moon and an astronomical telescope fires a laser beam at it and measures the reflection. Precise timing of the beam's round trip reveals the distance between Earth and the Moon far more accurately than any other technique.

A retroreflector looks like the inside of a cube that's been cut in half from corner to corner. "You take three mirrors and arrange them so they're at right angles to each other, and that forms a corner," explains Jerry Wiant, assistant manager for laser ranging at McDonald Observatory, which has been firing lasers at the Moon since 1969. "Any light that comes in bounces off those surfaces and comes back out toward the source. It's a beautiful concept." Retroreflectors are used on cars, bicycles, and highways to reflect a car's headlights, allowing drivers to see obstacles more easily.

NASA turned down a proposal to attach a reflector to the last of a series of unmanned missions to explore the lunar surface. The craft's television camera did detect laser beams fired from Earth, though, giving NASA enough confidence in the experiment to schedule a reflector for the first manned landing, in 1969.

Alley's group designed an array of 100 retroreflectors, each 1.5 inches wide, housed in a metal frame. The tray was as big as an attache case and its 10-by-10 array of reflectors, which were recessed to protect them from direct sunlight, looked like an egg carton. The experiment required no power, communication, or moving parts, making it easy to set up and operate.

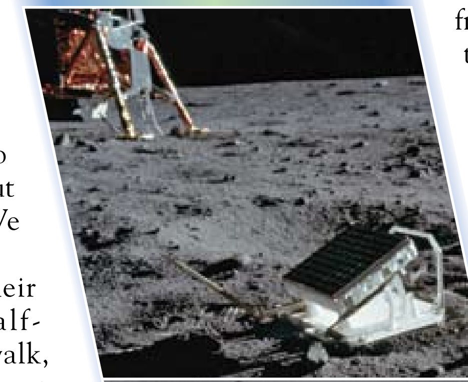
While the scientists prepared the lunar end of the experiment, Alley also looked for the terrestrial end: an astronomical observatory. Several rebuffed his overtures because their telescopes were too busy or because they feared that the high-power laser could damage a telescope's reflective coating. The University of Michigan agreed to host the experiment on a new telescope under construction in Hawaii, while Lick Observatory signed up for a few weeks of work on its 120-inch (3-meter) telescope, then the world's second largest.

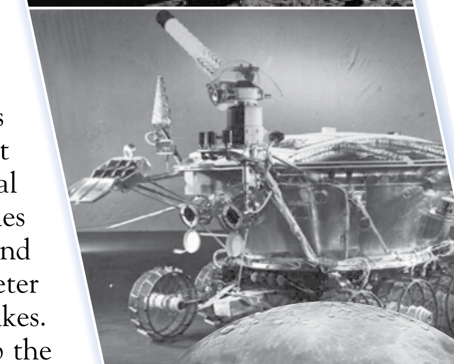
In early 1969, though, Michigan backed out of the deal, leaving Alley with no long-term home for the lunar laser ranging experiment.

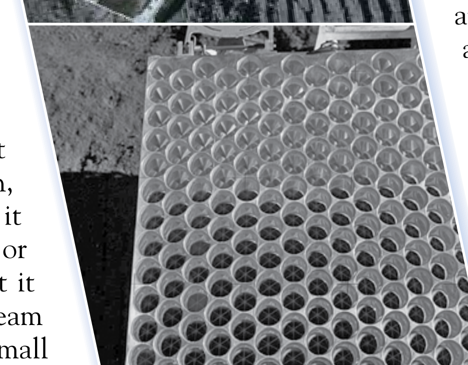
"A colleague here at Maryland told me that there was a new telescope coming on line at the McDonald Observatory," Alley says. "The 107-inch was then the third-largest telescope in the world. I got in touch with the director, Harlan Smith, and his response was very positive. He even provided a plane to meet us in El Paso and fly us to McDonald." NASA had funded the telescope, which was dedicated in late 1968, to support its ambitious program of solar system exploration.

By the time Maryland and Texas worked out the details, though, time was running short. It was spring, and Apollo 11 was scheduled for launch in mid-July. Alley dispatched a team of scientists, engineers, and technicians to install and test the laser and its instrumentation on the telescope, which itself was still in shake-down mode.

"There was no alternative — you *would* be ready when they landed," recalls Eric Silverberg, a member of the Maryland team who later oversaw the McDonald laser effort. "About all I remember of that first few weeks is that you worked until you couldn't stay awake any longer, then you went to bed, and you got up and went back to work again. But we made it. We had it ready."







From top: Apollo 11 laser reflector, Lunokhod before launch, the four working retroreflectors pinpointed on an Apollo image of the Moon, Apollo 14 reflector, and Apollo 15 reflector.

During their two-and-a-half-hour moonwalk, Apollo 11 astronauts Neil Armstrong and Edwin Aldrin gathered about 50 pounds of rocks and soil, set up a sheet of metal foil to gather particles of the solar wind, and deployed a seismometer to listen for moonquakes. Armstrong also set up the Lunar Ranging Retro Reflector (LR³), NASA-speak for the laser experiment, about 70 feet away from the lunar lander, Eagle.

McDonald and Lick both took aim at Tranquility Base within minutes, but without success. Scientists weren't sure just where Eagle had landed, they had little experience at aiming a telescope at such a rapidly moving target, and the distance to the Moon was known only within a half-mile or so.

Scientists needed precise three-dimensional coordinates because of the way the laser worked.

At McDonald, the Korad laser shined its red beam on the telescope's primary mirror, which reflected the light into space. Each shot consisted of a single pulse just three billionths of a second long. That created a "pancake" of laser light that was 107 inches wide and a few feet thick as it left the telescope. As it traveled through the atmosphere, though, the pancake spread out. By the time it reached the Moon, the beam was a mile or two across, but any targeting error meant it could miss the LR³. And even if the beam did hit its target, only an infinitesimally small fraction of the laser light actually struck the LR³. The process was repeated as this trickle of light reflected off the instrument and returned to Earth.

So while each laser pulse consisted of trillions of particles of light, known as photons, it took several shots to get a single photon to return to the telescope. Instead, the telescope was filled with background light from the Moon and other sources. So scientists needed to know just when to look so they could filter out the stray light and identify the laser photons. "If you didn't know the range, the background light was horrific," says Silverberg.

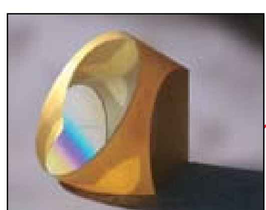
Lick Observatory recorded the first successful return, on August 1. McDonald didn't see its reflection until August 19.

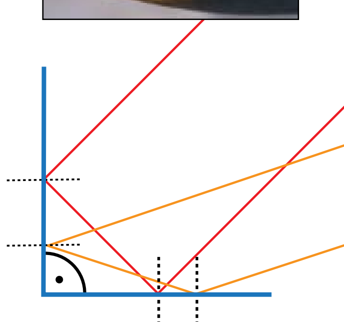
Lick dropped out a few weeks later, leaving the field to McDonald. The scientific team refined its techniques and began regular ranging experiments in early 1970. "All of a sudden, we knew how to do it," says Silverberg, who became project manager when McDonald took over the NASA contract from the University of Maryland.

Apollo 14 left a second reflector on the Moon in early 1971, and Apollo 15 added a third that was three times bigger than the others. The Soviet Union attached reflectors to the Lunokhod 1

Debunking the Debunkers

The lunar laser ranging experiment not only tells us about the Moon's orbit, rotation, and interior, it also proves that astronauts really did walk on the Moon, says Tom Murphy. "If the lunar landing business was a hoax, I'd know they were lying, because we wouldn't get any reflection," he says. So the 10 or so photons that Murphy gets from each "moonshot" confirms that the reflectors are sitting on the lunar surface — placed there by moonwalkers.





Top: A corner retroreflector like those in the laser arrays on the Moon. Above: Diagram shows how the corner reflectors always reflect a light beam in the direction from which it came.

and 2 rovers, although the Earth-bound drivers parked Lunokhod 1 in the wrong direction, so only Lunokhod 2 has provided any ranging data.

Teams in Hawaii, Arizona, Australia, and Germany also tried laser ranging, but with limited success. France got into the game, too, and although its laser system has been out of operation for several years, it has amassed more moonshots than any group other than McDonald.

Texas astronomers "ranged" three times a day: when the Moon was halfway across the sky and three hours before and after. "It was a gruesome schedule," says Silverberg. But "somehow, it just worked," adds Peter Shelus, who has directed the McDonald laser project since the late 1970s.

By 1985, though, NASA could no longer afford to fund the experiment on the 107-inch telescope, and other astronomers were eager to get rid of the interruptions to their own projects. So McDonald donated the original laser to the Smithsonian and built a permanent laser-ranging station with a 30-inch telescope one mountaintop away, and it's still operating today.

The new McDonald Laser Ranging Station, which fires shorter but more frequent pulses of a blue-green laser, not only keeps tabs on the Moon, it also shoots artificial satellites in low orbit, just as Robert Dicke had envisioned after Sputnik. Among other applications, the satellite ranging provides information on Earth's rotation and the motions of its tectonic plates.

Artificial satellites don't answer questions about the Moon, though, or about gravity. That still requires observations of Earth's only natural satellite.

Those observations have helped planetary scientists piece together many details about the Moon and its interactions with Earth.

"At the start, we were just learning about the orbit of the Moon," says James Williams, a senior research scientist at NASA's Jet Propulsion Laboratory who has studied laser-ranging results since 1971. "That's not very exciting, but you need it to do other science."

One of the first things scientists learned is that the Moon is moving away from Earth at a rate of about 1.5 inches (3.8 cm) per year as a result of the gravitational interaction between the two. As Earth and the Moon circle each other, their gravity acts as a brake, slowing the other's rotation. This has locked the Moon so that it rotates at the same rate at which it spins on its axis, so the Moon always presents the same face to Earth.

The Moon is trying to do the same thing to Earth through the tides. As Earth slows down, some of the energy of its rotation is transferred to the Moon, which moves farther away from Earth.

Laser ranging also has plotted wobbles in the Moon's rotation that are caused by the gravitational tug of Earth, the Sun, and other astronomical bodies on the Moon's lumpy surface. The wobbles have helped scientists plot the Moon's shape, and have even revealed secrets about its core.

"One of the fun surprises is that we saw something funny in the Moon's rotation — a rather strange dissipation in its energy," Williams says. "It took 20 years to lock it down, but it's telling us that the Moon has a fluid core about 350 to 390 kilometers in diameter." There is evidence that the liquid core surrounds a solid inner core, although the observations are inconclusive.

The Moon's interior could become clearer, though, with new data from Tom Murphy's project in New Mexico: the Apache Point Observatory Lunar Laser-ranging Operation (APOLLO).

Thanks to its bigger telescope, more powerful laser, and more sensitive detectors, APOLLO is providing far more laser-ranging data than any previous effort. The system gathers 100 to 1,000 times more photons than the McDonald station. Combined with more precise measurements of the laser's position on Earth's surface, that is allowing Murphy and other project members to plot the Moon's orbit about 10 times more precisely, he says.

Such precision will allow them to better address the laser ranging experiment's original goal: testing Albert Einstein's theory of gravity, known as general relativity.

So far, Einstein's version of relatively has withstood every test. Yet general relativity cannot accurately describe the behavior of the universe at the smallest scales — the realm of quantum mechanics — so scientists have a gut feeling that if they keep testing, eventually it will fail.

"It doesn't make sense that we'd get gravity right on just the second try," says Murphy. "Newton tried it in the 1600s, but it wasn't quite right. It doesn't make sense that Einstein would come along and get it right the second time around. Nature is more complex than that."

Lunar laser ranging tests one of the basic tenets of general relativity, known as the equivalence principle. In Einstein's theory, every object is gravitationally the same regardless of its composition. In other words, if you drop a hammer and a feather on the airless Moon, as astronaut David Scott did in 1971, then the Moon's gravity should pull them down to the surface at the same rate. (It did.)

"If that's the case, then you can formulate gravity as a property of space-time itself — gravity is a geometric concept," Murphy says. "It's at the very heart of general relativity."

Lunar laser ranging allows physicists to test the concept on a large scale.

"Because the Earth and Moon are each in orbit around the Sun, each is being accelerated toward the Sun" by solar gravity, Murphy says. If general relativity is correct, then the Sun will pull equally on both of them. If other theories of gravity are correct, then the Sun will pull on them differently, so the Moon's path will be shifted toward the Sun by a tiny amount — no more than 13 meters (40 feet).

Earlier laser ranging studies, which plotted the Moon's position with an accuracy of about one centimeter (0.4 inch), show that the Moon is just where general relativity says it should be. But by improving the precision of the measurements to one millimeter (0.04 inch), APOLLO will test general relativity 10 times more precisely. "Is that enough? Nobody knows," Murphy says. "There's a scientific paradigm that expects a violation at any time now. But there's no guarantee that another order of magnitude will put the theorists out of work."

If the equivalence principle fails, then so does general relativity. That might explain dark energy — a discovery that the universe is expanding at a faster rate as it ages. It could be a mysterious form of energy that is pushing outward on space itself, or it could simply be a flaw in our understanding of gravity, which is based on general relativity.

A flaw in general relativity would also provide the first experimental support for string theory — a view of the universe in which all forms of matter and energy consist of tiny, vibrating strings. And it would open the way to a new theory of gravity that would play nicely with quantum mechanics.

"You can never anticipate what new, fundamental insights into the world will provide," Murphy adds. "General relativity is a part of everybody's lives. It's used in the GPS system, for example. If we didn't understand general relativity, the entire system would fall apart in an hour.

"General relativity departs from Newton's theory of gravity by about one part in 100 million. That's irrelevant for most applications — too many other things get in the way. But what if the next breakthrough is at one part in 100 million of general relativity? We don't know what might come from that."

But it would be quite a legacy for the last working experiment of our first trips beyond Earth.

Damond Benningfield is executive editor of StarDate.

McDONALD OBSERVATORY

Left: The McDonald laser station 'shoots' the Moon, which is overexposed in this image.

RESOURCES

Web

McDonald Observatory
mcdonaldobservatory.org

McDonald Laser Ranging Station
www.csr.utexas.edu/mlrs

Apache Point Laser Experiment
www.physics.ucsd.edu/~tmurphy/apollo/apollo.html

Apollo Project Sites
www.apolloarchive.com

www.nasa.gov/mission_pages/apollo/index.html

Apollo 11 Experiments
history.nasa.gov/alsj/a11/a11EASEP.pdf

Radio

StarDate
Series on Apollo 11 Mission
July 16: Apollo 11
July 17: Shooting the Moon
July 18: Lunar Dust
July 19: Lunar Artifacts
July 20: Lunar Landing
July 21: A Giant Leap
July 22: Moonbugs
July 23: Testing Moonrocks
July 24: Return to the Moon
stardate.org/radio