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.

By Damond Benningfield

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.


How Far?
First McDonald Laser Detection
August 19, 1969

Roundtrip Laser Travel Time
2.49563310 seconds

Calculated Distance to the Moon
374,135,457.91211219 meters

Estimated Error
±0.0000003 seconds
4.5 meters
14 feet, 9 inches

Total McDonald Lunar Ranges
(April 2009)
Approximately 6,560
(inch ‘range’ incorporates the results from many individual laser shots)

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

“Almost the goal 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 so many years has greatly increased the precision of the measurements. The longer the experiment lasts, the more we can say about our original questions.”

While the scientists prepared the lunar end of the experiment, Alley also looked for the terrestrial end: an astronomical observatory. Several rebuilt his entire property 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,” says Alley. “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. That was our attitude, and we made it. We had it ready.”

During their twoto-three-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 Retroreflector (LR1), NASA—speak for the laser experiment, about 70 feet away from the lunar lander.

McDonald and Lick both took aim at Transquity 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 billions of a second long. That created a “pancake” of laser light that was 107 inches wide and an inch 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 LR1. And even if the beam did hit its target, only an infinitesimally small fraction of the laser light actually struck the LR1. 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, when the beams met again in the sky, it converted into an electron. The trickles of light were then sent to Earth, where they were collected and recorded. 

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 placed retroreflectors to the Lunakhod 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 entire debunking business was a hoax, I’d know they were lying, because we wouldn’t get any reflection,” he says. So the 10 or so photos that Murphy gets from each “moonshot” confirms that the reflectors are sitting on the lunar surface — placed there by moonwalkers.

Artificial satellites don’t answer questions about the Moon, though, about gravity. That still requires observations of Earth’s only natural satellite. Those observations have helped planetary scientists piece out the Moon’s gravity, and thus the Moon’s interior. At the start, we were just learning about 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 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 causes a braking effect slowing the other’s rotation. This has locked the Moon’s rotation 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 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 orbit. These wobbles are caused by the gravitational tug of Earth, the Sun, and other astronomical bodies on the Moon’s lumpy surface. These 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 now it’s telling us that the Moon has a fluid core about 150 to 390 kilometers in diameter.” There is evidence that the Moon was once warmer than it is now. “Murphy says, “It’s at the very heart of general relativity.”

Lunar laser ranging also 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 bent 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 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. 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 10 billion. 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. Dragon Benningfield is executive editor of StarDate.