

## Lunar Laser Ranging

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Lunar laser ranging was made possible by the placement of an array of 100 retro-reflectors on the lunar surface by Apollo 11 astronauts on July 20, 1969. The Apollo program—a source of pride for all Americans—was “launched” eight years prior to this first Apollo landing by President John F. Kennedy in a speech he gave to Congress on May 25, 1961 in which he said that the U. S. should commit to “sending an American safely to the Moon before the turn of the century.” Somewhat over a year after the Apollo 11 landing (in November 1970), a French-made retro-reflector array located on Lunokhod 1 was carried to the Moon by the Soviet spacecraft Luna 17. The next two lunar retro-reflector arrays were placed on the Moon by Apollo 14 and Apollo 15 astronauts. The Apollo 14 array (deployed February 5, 1971) is similar to the Apollo 11 array. The Apollo 15 array (deployed July 31, 1971), however, is larger and contains 300 corner reflectors. Finally, a fifth array, mounted on Lunokhod 2, was carried to the Moon by Luna 21 that landed on January 15, 1973. These five “placements” transformed our Moon into a “satellite” that could be used for Earth, Moon, and Earth-Moon science and, at the same time, made possible “the near-complete relativistic gravity experiment.”

The resulting lunar ranging experiment, a real and still ongoing triumph of the Apollo program, was called at that time “NASA’s most cost effective experiment.” This experiment is an outstanding example of the fact that evolving technologies together with technological progress (i.e., our being able to go to the Moon or, as is the case with the two Russian arrays, being able to send things to the Moon) have implemented and driven most of our scientific advances. In this paper, I will discuss the early ideas of using satellites to test gravitational theories, the origin of the idea for lunar laser ranging, the concerns that drove the design of the three Apollo retro-reflector arrays, and the events that led up to, and resulted in, the first detection of retro-reflected laser pulses from the Apollo 11 array. Finally, I will say a few words about how this still-ongoing experiment is evolving and where, now 46 years later, it stands today.

For more than 2000 years the Moon has been used to test human theories of the universe. In the third century B.C., Aristarchus of Samos inferred from lunar eclipses that the distance to the Moon is roughly 10 times the diameter of the Earth by estimating the diameter of the Earth’s shadow on the Moon during a lunar eclipse. And although he realized that the cone-shaped shadows cast by the Sun taper down with an angle of about half a degree (and he corrected for this), he estimated (incorrectly) the apparent diameter of the Moon’s disk to arrive at his (three times too small) value for the Earth-Moon distance. A century later Hipparchus, using a more

accurate value for the Moon's diameter, computed the distance of the Moon as being 59 Earth radii. [The true mean distance is 60.3 Earth radii, or some 380,000 kilometers, which makes the round trip travel time, for a pulse of light, a bit over 2.5 seconds.]

Except for minor improvements in some of the measurements, there was no fundamental advance in knowledge of the lunar motion until the revolution that swept astronomy in the 16<sup>th</sup> and 17<sup>th</sup> centuries. The climactic achievement of this period was Newton's theory of gravitation, in which the Moon figured prominently. "[I] compared," Newton wrote, "the force requisite to keep the Moon in her orb with the force of gravity at the surface of the Earth, and found them answer pretty nearly."

In the next two and a half centuries astronomers used measurements of optical parallax and simultaneous observations of stellar occultations to reduce the uncertainty in the Earth-Moon distance to about 2 miles. Beginning in 1957, conventional radar techniques were used to determine the Moon's distance from the Earth to within 0.7 mile.

In the late 1950s, as a graduate student in Professor R. H. Dicke's research group at Princeton, I was learning about (and using) rotation-insensitive retro-reflectors (Figure 1)

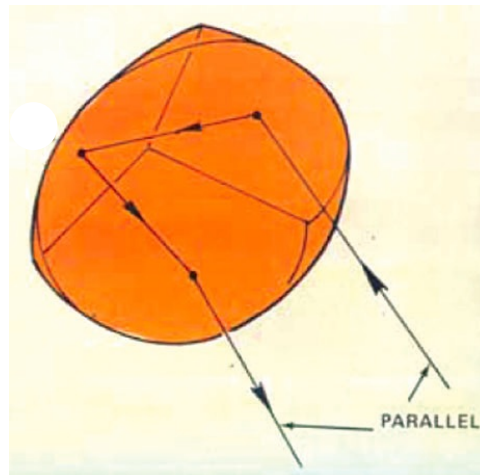


Figure 1. Retro reflector ray path

as "mirrors" in free-falling optical systems to measure, interferometrically, little  $g$ . One of the early triumphs of my rather long graduate career was that on suggesting to Bob Dicke that he hold evening meetings once a week in which each of his graduate students and postdocs would talk about their work, he agreed to do this. In these meetings, people talked not only about what they were presently working on but also what was slowing their work down and/or stifling its progress. Dicke was always there as was Martin Schwarzschild from Princeton's astronomy department. With both students and postdocs taking their turn at the blackboard at each of these meetings questions, ideas, and some answers spewed forth well into the late hours of the night. Simply put, it was during these meetings that I "learned" how to think about, as well as how to do, physics.

In 1959 three members of that group wrote a paper, “Precision Optical Tracking of Artificial Satellites” [Ref.1] that reviewed the problem of making precise optical position measurements of artificial satellites. The paper discussed three methods of illuminating a satellite in order to obtain range information: direct sunlight, a pulsing light aboard the satellite, or an optical corner reflector (retro-reflector) aboard the satellite to return pulsed beams from an Earth-based searchlight. [This paper, I believe, led to the early experiments by Henry H. Plotkin and his satellite-tracking group at the Goddard Space Flight Center.]

In May of 1960, the first laser (a pulsed ruby laser) was invented by Theodore Maiman, and in December of 1960 the first He-Ne (continuous) gas laser was built by Ali Javan. It was in May of 1962 that a group from MIT reported a weak photon echo from a pulsed laser that was fired at the Moon—which they published with the clever title: “Project Lunar See.” [Ref. 2] Finally, three years later in 1965, a Russian group used a 104-inch (2.6-meter) telescope to transmit and detect pulses of 50-nanosecond duration produced by a Q-switched (short pulse) ruby laser. This experiment achieved enough accuracy to improve our knowledge of the Earth-Moon distance to about 180 m. At this accuracy, lunar topology was beginning to spread in time the reflected pulse.

During one of the interviews associated with my giving talks in late 1961 and early 1962 (in part, job hunting), I mentioned the scientific merits of putting a corner-cube on the Moon. As a result I was given a corner cube that one of my host institutions had left over from the Second World War. [Ref. 3 (i.e., Note 1)] I used this corner cube, in combination with a 25-cent rubber ball from Woolworths, silicon rubber to hold the cube in place, and a wire-frame “cube guard”, to make a model of my proposed “lunar retro-reflector package” (see Fig. 2).

On March 25, 1962, two months before the first photon echo from the lunar surface was seen, and having thought for some time about “ranging to the Moon,” I wrote up a note (“proto-paper”) entitled “A Proposed Lunar Package (A Corner Reflector on the Moon)” the first paragraph of which read as follows:

**“This note describes what is felt to be both a useful and at the same practical (i.e., feasible) lunar package [Fig. 2]. The total weight involved would be only 2–3 pounds, and it would be constructed to withstand a rather hard landing. Once on the Moon, the only**

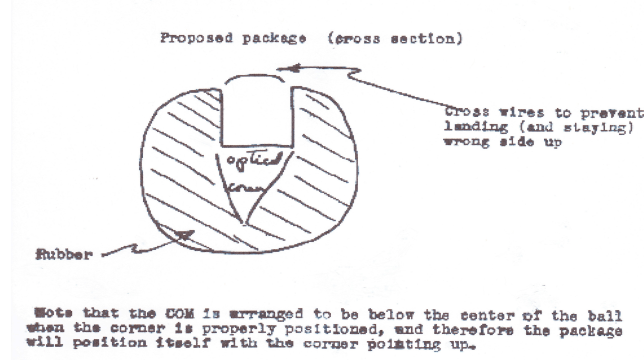


Figure 2. (Original Drawing)

requirement for it to function is that the landing leaves it free to bounce and roll until it comes naturally to rest. This lunar package, containing an optical corner, has been built.” (Fig. 3)

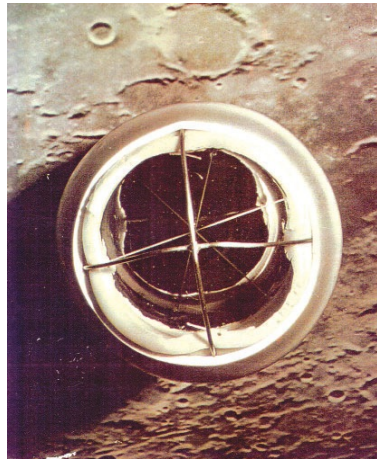


Figure 3

The idea was to have one of the Surveyor missions roll a retro-reflector mounted in a spherical container onto the lunar surface, with this package’s center of mass positioned so that the cube corner would come to rest pointing up (more or less directed back at the Earth). A ground telescope (see Fig. 4) then sends up a pulse of (laser) light and this same telescope would be used to “see” (i.e., detect) the returning retro reflected light—thus making possible Earth-to-Moon (i.e., telescope-to-retro-reflector package) ranging.

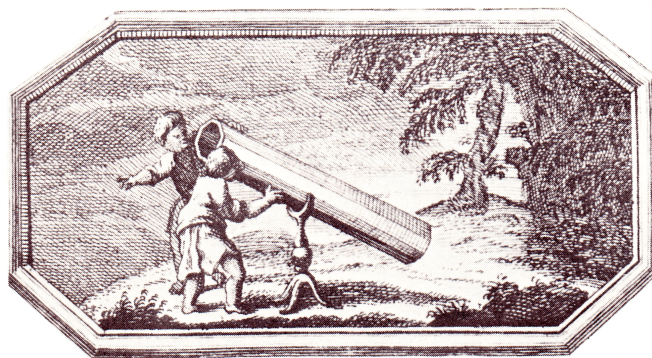


Figure 4, “Lunar Laser Ranging: The Idea.” The woodcut is from Henry Pemberton’s book “*A View of Sir Isaac Newton’s Philosophy*” printed by S. Palmer, in 1728 in London. One of these small boys has a stopwatch in his hand.

I gave a copy of my write-up to Dicke with the following note (in the upper right-hand corner), “Professor Dicke, Would you see if this makes any sense. Jim Faller.” His response (written in the upper left-hand corner) was, “Perhaps we could discuss this. Bob Dicke.” [In Bob’s defense for not suggesting that I be somewhat aggressive in pursuing this idea, my thesis dragged out for

seven years (it was a difficult experimental thesis, and I was slow but thorough). I suspect his thinking at the time was, “leave this until later, and, for now, get on with your thesis!” Later, however, at the celebration of his 60<sup>th</sup> birthday (in May 1976), I was asked to give the talk on Lunar Laser Ranging.] At any rate, being rather naïve about the ways of the world, and also the world of physics, I did not write up and publish this idea at that time—which may have been a (personal) mistake.

I reproduce here Bob Dicke’s “Lunar Laser Ranging Reminiscences” that he wrote, but did not date. Based on his Jadwin Hall address (this new physics building was completed in 1969 and dedicated in 1970), he must have written these reminiscences sometime between August, 1969 and 1997—the year he died. Peter Bender (a JILA colleague who comes up later in this paper) found a copy of these reminiscences in a file “that is in quite good temporal order, between things dated April, 1996 and April, 1997.” Since Bob died March 4, 1997, this would indicate that he probably wrote these Lunar Laser Ranging Reminiscences during the last year of his life. These “reminiscences” to my knowledge, have not been widely disseminated, and I am not certain how Bob intended to have them used; but they provide a useful “prelude” to the rest of this paper. [The bracketed inserted portions are my commentaries.]

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**LUNAR LASER RANGING  
REMINISCENCES**

**“While on leave at Harvard in 1954-55, I considered the experimental basis of general relativity, Einstein’s theory of gravitation. I concluded that the observational basis was thin and that much more was needed, particularly a modern high precision version of the Eotvos experiment. This experiment was started at Princeton in 1955. Problems were encountered and many students, post docs and faculty contributed to their solutions.**

**Among the interests of our research group was Dirac’s Cosmology and its implication of a decreasing gravitational constant. Mach’s principle and the scalar-tensor theory [were] developed in collaboration with Carl Brans.**

**The gravitational research group would meet in the evening once a week to discuss research ideas, some wild and some not so wild. One night testing for a decreasing gravitational constant was proposed using a zero drag satellite orbiting the Earth and reflecting a light pulse from a corner reflector carried on the satellite. The laser had not yet been developed and we had in mind using a flash lamp for illumination. With the development of the laser it became feasible to eliminate the artificial satellite and use the Moon instead. Jim Faller first suggested this and I remember that he brought a corner reflector mounted in a rubber ball to one of the evening meetings to show how the experiment might be done. The ball could be dropped from a**

**lunar lander [at that time the Surveyor program] and the ball would roll to point the reflector upward.**

**Some years later, after several members of the group had left Princeton, a number of us met at a Physical Society meeting to discuss the possibility of proposing such an experiment to NASA. We decided that some one person should take the responsibility of proposing the experiment and Carroll Alley was urged to do this. [At that meeting, the rationale for having Carroll do this was ‘since he was at the University of Maryland, and therefore close to NASA headquarters, he would be in a better position to coordinate and interface the group’s efforts with NASA.’] Alley was successful. Later an advisory committee was established with members from both inside and outside the Princeton group. [The LURE (Lunar Ranging Experiment) Team initially consisted of (in alphabetical order): Carroll O. Alley, Jr., University of Maryland; Peter L. Bender, National Bureau of Standards; D.G. Currie, University of Maryland; R. H. Dicke, Princeton University; James E. Faller, Wesleyan University; Henry H. Plotkin, Goddard Space Flight Center; David T. Wilkinson, Princeton University; J. D. Mulholland, Jet Propulsion Laboratory; William M. Kaula, University of California, Los Angeles; and Gordon J. F. MacDonald, University of California, Santa Barbara]**

**A high point in my memory of the Lunar Laser Ranging program is the night that reflected optical pulses were first observed. After the first set of corner reflectors had been left on the Moon at the time of the first lunar landing, attempts were made at two different observatories to observe light pulses from the reflectors, using large telescopes, especially instrumented for the job. One of these efforts, directed by Jim Faller [and Joe Wampler of Lick] used the large telescope of the Lick observatory on Mt. Hamilton. The other directed by Carroll Alley, used a large telescope of the University of Texas.**

**For several days neither team was successful. The situation was desperate for the allotted time at the Lick observatory was nearly exhausted. I had not been involved with either group but happened to be spending a month at the Lick observatory on the Santa Cruz campus. On our last night, I visited the telescope. Jim showed me the instrument details and he convinced me that everything was well tested and working. [This “convincing” was accomplished during an intensive two to three hours of my showing Bob *every* aspect of what we had done and answering *all* of his many questions.] I spent the rest of the night in the control room looking for photon counts above the noise in the range channels. I like to believe that, in some small way, my good luck contributed to the success of that night’s observation.” [As did also the thought and energy that Bob put into the nightly group meetings that taught a generation of Princeton physicists how to do experiments.]**

In late December of 1962, when I had finished my thesis work but was still in the process of writing it up, I moved to JILA in Boulder, Colorado as a NRC postdoc to work with Peter Bender (and also to finish writing my thesis). Not long after arriving in JILA (then the Joint

Institute for Laboratory Astrophysics), I met with Jan Hall and Peter in Peter's office; and they asked me, "What sort of ideas have you been thinking about?" I told them my idea regarding the feasibility and usefulness of putting a retro-reflector on the Moon. The two of them were a most attentive audience, nevertheless, the "what to do" was not talked about. I had plenty of other things to think about...in addition to finishing the writing of my thesis.

[At that time, stabilized He-Ne lasers had just appeared on the scene (e.g., the Spectra Physics 119 Lamb-dip stabilized laser) and I was thinking about constructing a laser-based—as opposed to a white-light-fringe-based—free-fall instrument to determine of the absolute value of little  $g$ . A corner cube was to be dropped in an optical interferometer. This 5-parts-in- $10^8$  (as it turned out to be) method of determining little  $g$  could be thought of as a "laboratory version" of lunar ranging (one sends photons to a corner cube from which they are reflected back...however in the case of determining little  $g$ , the "detection system" is a little different and the "ranging" is over a considerably shorter distance.)]

A little over a year later (June 1, 1964), a paper by Mahlon Hunt (who was at the Air Force Cambridge Research Laboratories in Bedford, Massachusetts) appeared in the *Journal of Geophysical Research* entitled "A Prototype Lunar Transponder." [Ref. 4] The paper described a "prototype microwave transponder" (an active device) that could be hard-landed on the Moon and used for continuous-wave lunar ranging. [Not unlike the method one uses to determine little  $g$  interferometrically.] Peter had read this article, and told me about it with the comment that "we should probably look again at your idea and publish it." He suggested that I begin by thinking about how one would design a corner cube array that would best perform in the lunar environment.

The problems that arise, from placing optical corners on the Moon, stem from the fact that one must meet, and simultaneously satisfy, many different and sometimes conflicting requirements. In an ideal environment, the choice is relatively simple since, for a given allowed weight (payload), one maximizes the return signal by making a single diffraction-limited retro-reflector as large as weight restrictions and fabrication techniques will permit. However, velocity aberration (which displaces the center of the returned diffraction pattern between 1.5 and 2.0 km) limits the diameter of a diffraction-limited retro-reflector to about 12 cm unless one employs two telescopes spatially separated from one another. If one rules out this two-separated telescopes scenario as more complicated, then it turns out that the optical efficiency is essentially the same, for a fixed payload weight, for corner sizes ranging from 4 cm to roughly 12 cm. [The smaller cubes spread the returning beam more with the result that a single transmitting and receiving telescope is located higher up in intensity on the returning diffraction pattern.] Noting this, an array of cube corners of 3.8 cm (1.5 inches) in diameter was the obvious choice as the smaller size reduces solar-radiation-induced cube distortion that occurs because the index of refraction for fused silica has a substantial temperature dependence. Fused-silica cubes do not physically expand, but they do optically "distort" when subjected to an input of solar energy. And although the result is almost intuitively obvious, a "spherical cube" model of a cube corner was constructed and analyzed (with help from Peter Bender) to study how the thermal performance of a corner-cube depends on its size. This analysis revealed that *small is better*; an array of 3.8-cm (1.5-inch) diameter *uncoated* cubes would perform better thermally than an array of the same weight consisting of one or more larger cubes.

However after my lunar-array analysis was completed, but before a paper on lunar ranging had been prepared, an invitation was received from Dave Wilkinson at Princeton for both Peter and myself to be participants in writing up a paper describing the prospects for lunar ranging that would (also) be submitted to *JGR*. [I suspect that Dave had not been told about my “suggestion” from three years earlier which was, nonetheless, referred to in various subsequent LURE Team papers.] At any rate, a paper was written which appeared in *JGR* in 1965 [Ref. 5] in which—it was somehow decided that—the authors’ names would appear in alphabetical order. Although, at the time, this seemed a harmless thing to do (we were all professional “friends”), in retrospect, this ordering has facilitated some “claims of credit” for the idea that are simply inaccurate.

This early analysis that I did at JILA served me well when I was asked to write a chapter (for proposing this experiment to NASA) that discussed the problems presented by the lunar environment. [Around this time I left JILA and moved to Wesleyan University in Middletown, Connecticut.] I recommended using an array of small, solid, fused-silica, corners. I had also looked at an alternative approach (involving what then was referred to as a *slight* extension of demonstrated fabrication techniques) that would make use of a few somewhat larger open corners (triple mirrors). In the end, however, because of already-demonstrated fabrication techniques, their inherent ruggedness, and their greater insensitivity to thermal problems, it was suggested that an array of small corner cubes be used for the lunar package. Additionally, it was recommended that some sacrifice in returned signal (because of polarization “spreading”) be accepted by using total internal reflection (uncoated cubes) in order to increase their lifetime and to prevent additional thermal distortion.

The veracity of this recommendation was confirmed by detailed thermal calculations by Arthur D. Little (at the time one of the largest companies in the world that offered consulting on science and engineering problems), as well as by a group at the University of Maryland led by Doug Currie that studied, in particular, the polarization (return-beam-spreading) effects that would come into play if one used total internal reflection rather than an evaporated metal coating on the cube’s back surfaces.

Thermal testing of fused-silica corner cubes under simulated solar illumination was performed by Arthur D. Little and by the Goddard Space Flight Center. One hundred 3.8-cm diameter cubes were used in both the Apollo 11 and the Apollo 14 arrays. In order to increase the returned signal strength (which is at best only a few photons per laser pulse) the Apollo 15 array contained 300 cube corners. [Our experiment’s weight allowance had been increased.]

Perhaps, as a harbinger of things to come (see my antepenultimate and penultimate paragraphs), in addition to spending a lot of time at the Arthur D. Little company (array optical thermal testing) and Bendix Aerospace (ALSEP interface), I spent quite a few afternoons with men in suits at NASA Headquarters who were worrying about keeping the array from being covered with Kapton shreds and lunar “sand” (dust) during the Eagle’s (the name given to the Lunar Excursion Module, or LEM, on Apollo 11) lift-off from the Moon. [At that time, the lunar surface, although dry, was thought to have somewhat the consistency of wet sand. Note the astronaut’s footprints seen in the photograph of the Apollo 11 array that appears later in this paper.] Solutions to protect the array such as time-release window-shade-like covers, arrays that flipped from looking down to looking up, etc., were all ultimately rejected by this headquarters



group as “single point failure modes” [as I would have also described the array’s surface being covered with LEM ejecta and contaminants kicked-up from the lunar-surface ...but this scenario was (for some reason) judged to be a less likely mode of failure.]

Even though the prospects for the lunar ranging experiment and a retro-reflector array being taken to the Moon were still in doubt in fall of 1968, work continued on this project. The possibility of retro-reflectors being carried on an unmanned NASA mission had disappeared with the close of the Surveyor program. The Apollo Lunar Surface Experiments Package (ALSEP) for each of the early Apollo lunar landing missions was under construction, and space for a retro-reflector panel could not be made available without dropping (or delaying to a later mission) scheduled experiments. It was thus with great excitement that we learned on September 6, 1968 that the astronaut work load for the first manned lunar landing by Apollo 11 in July of 1969 might be too heavy (demanding of too much astronaut time outside on the lunar surface) to permit deployment of the planned ALSEP. A proposal to develop a Lunar Ranging Retro-Reflector (LR<sup>3</sup>) package so that Lunar Laser Ranging could become a contingency experiment for Apollo 11 was quickly prepared.

Three factors ultimately led to the decision to make Lunar Laser Ranging one of the experiments carried on Apollo 11: first, the importance of the scientific objectives that could be achieved; second, the reliability inherent in the completely passive nature of the retro-reflector array; and third (and probably the winning factor), the time needed for astronaut deployment of the array on the lunar surface was very short. [The experiment was quite literally saved by the clock!] Nevertheless, and independent of the reasons for which it was finally selected, the LR<sup>3</sup> was an experiment that Irwin Shapiro described (at that time) as “NASA’s most cost effective experiment” and an experiment that Ken Nordtvedt called “the near-complete relativistic gravity experiment.”

Now that this experiment was a “go”, in order to optimize the chance for “seeing” the array while the astronauts were still on the Moon (before the Eagle (LEM) blast off possibly kicked up array-covering contaminants), NASA asked for permission to use the Lick Observatory 120-inch (3.05-meter) telescope as an additional, albeit temporary, ranging station. The 108-inch (2.74-meter) McDonald Observatory telescope was not only supposed to provide initial ranging, but was also to serve as the permanent (long-term) ranging telescope. [There was one LURE team voice that wanted the Lick ranging station to be run (i.e., supervised) by one member of the McDonald ranging team. However, when the Lick director, Bob Kraft, told NASA that if they wanted to “borrow” his telescope, it would only happen if Joe Wampler and I were given total and unfettered authority for the ranging effort at Lick, NASA quickly acceded to that condition.]

In the weeks and months leading up to the Apollo 11 launch, I met several times at the Lick Observatory with Joe Wampler (a very clever, hands-on Lick astronomer); and we made plans for transforming Lick’s 120-inch (3.05-meter) telescope into a viable ranging station. Joe worried about the telescope, and its guiding on a lunar target, together with laser-telescope interface issues. I worried about lasers and electronics together with assembling ranging teams. Since Lick’s ranging successes have been described in easily-accessible literature [Refs. 6 and 7], and because I was told by those organizing these proceedings that I could not have fifty pages for this paper, let me simply discuss a few important matters as well as a few interesting things.

In order to eliminate one possible failure mode, I arranged for Lick Observatory to have two different lasers and two separate ranging systems. [What is a car without tires, and what is a lunar ranging station without a working laser system.] I wrote to Henry Plotkin at NASA Goddard and asked if it would be possible for NASA Goddard to provide a laser ranging system and a knowledgeable crew to operate it—which they agreed to do. As a result, Lick had two completely independent laser systems that could be used for ranging. Each system had its own high-power ruby laser, detection electronics, and operating crew. Both ranging systems were used successfully, though there were some initial difficulties with one of the lasers (a water leak and also a power supply failure). These problems were, however, quickly resolved. One of the laser systems (the one from Goddard) could fire 20 times per minute. The other, which the group from Wesleyan had purchased from Korad, could be fired only twice a minute but it had both a higher pulse energy and a lower beam divergence.

The first night we attempted ranging was on the same night as the lunar landing, July 20, 1969. Unfortunately, because of LEM landing problems (the Apollo 11's LEM landing came close to being aborted; fuel was running very low and only at the last moment did the astronauts find a suitable landing site), the range and position data of the array were not known with very much accuracy. Moreover, since the Moon was so low on the horizon, we had only about an hour to conduct a somewhat random search in both position and range (time) for the retro-reflected returns before the Moon disappeared. The search failed.

The following days were equally frustrating. The Moon was drifting south in its orbit, so that it appeared lower in the sky each night; as a consequence turbulence in the atmosphere produced an increasingly poor image and additionally the Moon was waxing, and this resulted in an increase in the background moonlight picked up by the detectors. So, four days after landing, having detected no return signals and with the Moon now unfavorably low in the sky, we decided not to range for the next five days, and instead used the time to work on the equipment and recheck every detail.

On August 1, the night of our initial success, the (lower repetition rate) laser was fired a total of 162 times in the course of 9 runs before any returns from the lunar array were recognized. A final series of 120 shots, after various adjustments were made, yielded 100 returns that exceeded the background. Thus more than 80 percent of that final series of shots resulted in a detectable return. On two of the runs we achieved (by good luck, the range distance straddled two timing bins) a timing precision of 0.1 microseconds, which meant we had established the distance to the Moon with a single shot accuracy of approximately 8 meters. On August 3, the Goddard laser system was operated successfully for nearly two hours and achieved a range accuracy of 6 meters.

Two additional retro-reflector panels—in addition to the three arrays placed by Apollo astronauts—have been placed on the lunar surface. The first was a French-built package of 14 glass corner reflectors, each one 11 cm on an edge, that was carried to the Moon by the Soviet spacecraft Luna 17 in November 1970 (a year and four months after the Apollo 11 landing), but before the Apollo 14 and 15 landings). This package was mounted on the eight-wheeled lunar exploration vehicle Lunokhod 1. A second French-built package, similar to that carried by Luna

17, was mounted on Lunokhod 2 and landed on the Moon on January 15, 1973 following the Apollo 14 (deployed February 5, 1971) and Apollo 15 (deployed July 31, 1971) landings.

Interestingly, there was also a Lunokhod “0” whose attempted launch (it blew up on the launch pad) on February 19, 1969 took place before the Apollo 11 mission. I have often wondered whether Lunokhod “0,” as did the other two, carried a retro-reflector package; for, had this been the case and had the launch and the lunar-landing all been successful, it would have provided even more “grist for the mill” of those who question the need for *manned* landings. I’ve asked all of the Russians who I’ve met that I thought might know whether this might have been the case, and have always gotten the reply, “only the (Russian) military knows.”

Today the lunar arrays continue to be ranged to for ever-improving studies of gravity as well as the Earth and Moon system. This ranging is to all of the Apollo arrays (though the Apollo 15 array is the preferred target because its returned signal is approximately three times larger) as well as to both of the Lunokhod arrays. Interestingly, for some 40 years, Lunokhod 1 was “lost” and assumed to be tipped over and/or “covered with sand.” However, it was recently found (using lunar ranging) at a location other than the one to which scientists thought it had been moved.

Given the importance of the science that has been, and is still generated by the lunar laser ranging program, Lick’s “seeing” returns from the Apollo 11 retro-reflector array *after* the LEM’s liftoff was critically important. It provided two all important pieces of information: (1) the array was working and working well—at least for a while the “sand” (dust-covering) issue was not a problem—and, most importantly, (2) Lick was able to tell other observatories, McDonald and an Air Force observatory near Tucson, Arizona, exactly where the array was located with respect to features on the lunar surface and also its precise range from Lick.

In spite of having received this implementing information, it was not until August 19<sup>th</sup> that the McDonald team successfully saw returns. Weather was certainly one contributing factor; but also, and in spite of its apparent simplicity, lunar ranging (in contrast with satellite ranging where the number of returning photons are many...not just one or two at best as is the case in Lunar ranging) has a *zero* margin for error. There are quite a number of critical, as well as subtle, experimental details that must all be exactly right for lunar ranging to succeed. So, without Lick’s contributions (where to look, what’s the range; and, incidentally, “it’s working”) I wonder how long it would have taken the group at McDonald—or any other group—to find it. At Lick we were extremely methodical; but also, I suspect, we were lucky. I cannot help but wonder how long NASA would have allowed McDonald to continue searching for the array before deciding to decommission this experiment “because” the array was almost certainly covered with Kapton and lunar soil...i.e., suffering from the other single-point failure mode.

As can be seen from Figure 5, the members of the team that first ranged successfully to the Apollo 11 retro-reflector array on the lunar surface were not the “mature” scientists that one might have expected. Rather they were a group of undergraduate students from Wesleyan University in Connecticut who joined Joe, myself, and others from Lick and Goddard in bringing enthusiasm and the necessary skills to the exciting and important task of detecting the first

returns from the Apollo 11 retro-reflector array. [Coincidentally, today each of the young men in the photo has a Ph.D. in physics, engineering, or oceanography.]

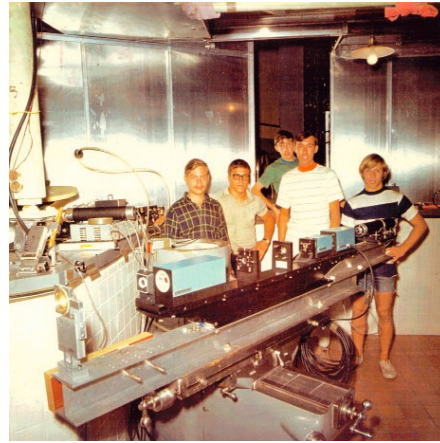


Figure 5. The team that first successfully ranged to the Apollo 11 reflector on the Moon. From left to right are Steve Moody, Robin “Tuck” Stebbins, Tom Giuffrida, Barry Turnrose, and Dick Plumb (lab photo).

The Lunar Laser Ranging Experiment which began with the July 20<sup>th</sup> placing of the array of optical corner cubes on the surface of the Moon (Fig. 6) by the Apollo 11 astronauts has made possible a dramatic change in our ability to measure the distance between the Earth and its moon—initially, with an accuracy of some tens of centimeters; and today, four additional retro-reflector packages and 40 years later, with an accuracy of millimeters!

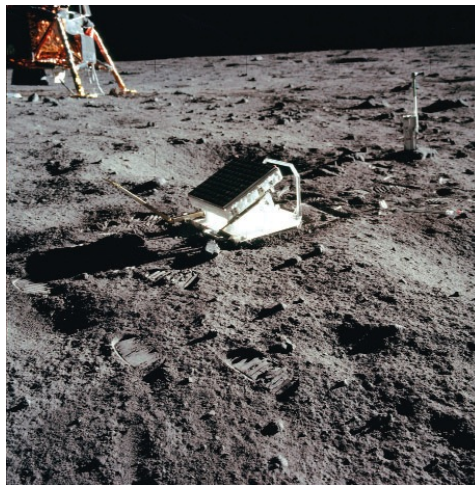


Figure 6. The Apollo 11 array seen on the lunar surface.

In lunar laser ranging, the Earth-Moon distance is determined by aiming an intense pulse of laser light at one of the reflector arrays on the Moon, and measuring the time required for this pulse of light to travel to the Moon and back. The important quantity is not, however, the absolute distance between the Earth and the Moon at some particular instant. Rather it is the variations in this distance measured over periods of months and years that are important. These variations have been, and are continuing today, to be analyzed in order to answer a number of important

scientific questions relating to the Earth, the Moon, and the Earth-Moon system. [Refs. 8, 9, 10, and 11] In this year in which we are celebrating the 100<sup>th</sup> anniversary of Einstein's General Theory, let me just provide a bit more detail regarding one of lunar laser ranging's many important contributions...namely that it provided a new test of Einstein's theory.

Specifically, the lunar laser ranging experiment has provided an answer to the, heretofore, unanswerable question: Does gravitational self-energy fall at the same rate as does matter and other forms of energy? By using lunar laser ranging data to observe the "free fall" of our Earth and its Moon towards the Sun [both massive bodies which therefore contain a substantial amount of gravitational (self) energy], one has been able to verify, for the first time, that gravitational energy falls at the same rate as does ordinary matter and other forms of energy—with a tested precision of 0.01%. Einstein, were he alive today, would be pleased but not, I think, surprised.

Finally, unless you were at this meeting, you might wonder, what is the situation today as regards the future of lunar ranging? McDonald is still ranging, but now only occasionally. However a new group, headed by Tom Murphy, at the Apache Point Observatory, has picked up the lunar-ranging baton; and using that observatory's 3.5-meter (138-inch) telescope, they have moved lunar laser ranging from the centimeter level to the millimeter level of accuracy. [Ref. 12] (See also Tom's articles in these proceedings.) And this stunning improvement has been achieved in spite of the fact that the various arrays are now showing "wear" after some 40 years of sitting exposed on the lunar surface. A partial dust covering of the individual cubes' front surfaces is thought to be causing the observed reduction, of roughly a factor of 10, in the arrays' retro-reflecting efficiencies.

An indirect confirmation of this suspected "partial dust covering" is that the arrays' efficiencies are now correlated with the times when their faces are exposed to direct sunlight. During the short design phase of the lunar laser ranging experiment the decision was made *not* to evaporate a metal coating on the backsides of the cubes. This was done to avoid the cubes' backsides being heated by the sunlight that transits the cube and that would be partially absorbed were there a metal coating. The resultant heating would create a thermal gradient in the cube that would give rise to a refractive-index-related optical distortion. However, there is little that could be done to prevent a slow obscuration of the cube faces because of dust migrating from the lunar surface. Furthermore, whenever a cube's dust-covered face is exposed to direct sunlight, the warmed dust heats the cube and creates a temperature gradient within the cube that further degrades (by roughly another factor of 10) its optical performance. [Being partially covered with dust—something that was thought might happen as a result of the LEM's ascent—*will* degrade the performance of the lunar arrays. On the other hand, it is a bit of good luck (and this experiment has benefitted from many such "bits") that the timescale over which this occurs is decadal and not shorter.] [I was quite amused to read in *Physics Today's* "The week in physics 2–6 February" that dust (also) seems to be a problem for other experiments: namely it appears to be the actual cause of the microwave polarizations (that generated so much—perhaps even Nobel prize-related—excitement about cosmological inflation) that provided last year's "evidence" for primordial gravitational waves.]

While today's lunar ranging experiment is beginning to suffer from the burden of time spent in the lunar environment, you might find it interesting that our capability to measure the Moon's

distance has increased in accuracy over the past 2000 years by a factor of  $10^{11}$ —a remarkable improvement!

In conclusion, I would like to thank the organizers of this conference, which celebrated fifty years of satellite ranging, for inviting me to attend and to speak. Although he is no longer with us, I would like to acknowledge the wisdom and skill of Col. Art Strickland of NASA Headquarters for his masterful oversight of the LURE Team and its activities, particularly, for pushing through the funding of a one-page proposal for \$100.7 K to buy a laser, etc. in support of Wesleyan's efforts, in less than two weeks! I would also like to thank him for supporting, separately, but in the same remarkable turn-a-round time, Lick's efforts. Art also helped the LURE Team effect a beneficial leadership change prior to the Apollo 14 and 15 missions.

Also my thanks to NASA Goddard for their generous help in making available a proven ranging system and a team to operate it for the Apollo 11 array ranging effort at Lick. Everyone's efforts, as well as the associated financial and instrumental support, were critical not only to the Lick team's ranging successes, but also for today's continuing scientific "returns" from this, the only still-operating, Apollo experiment. I would also like to thank my thesis advisor, Bob Dicke, a designer of experiments...not an observer, for contributing his "good luck." Finally, I would like to thank JILA's Gwen Dickinson for her much needed assistance and greatly appreciated support in the creation of this manuscript.

Einstein once said, "I have little patience with scientists who take a board of wood, look for its thinnest part, and drill a great number of holes where drilling is easy." [Ref. 13] While listening to the various talks and the ensuing discussions at this conference, I was constantly reminded that satellite ranging—be it to the Moon or to artificial satellites—is a *thick* board...as well as an important and fascinating area of science.

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