How High the Moon: A Decade of Laser Ranging

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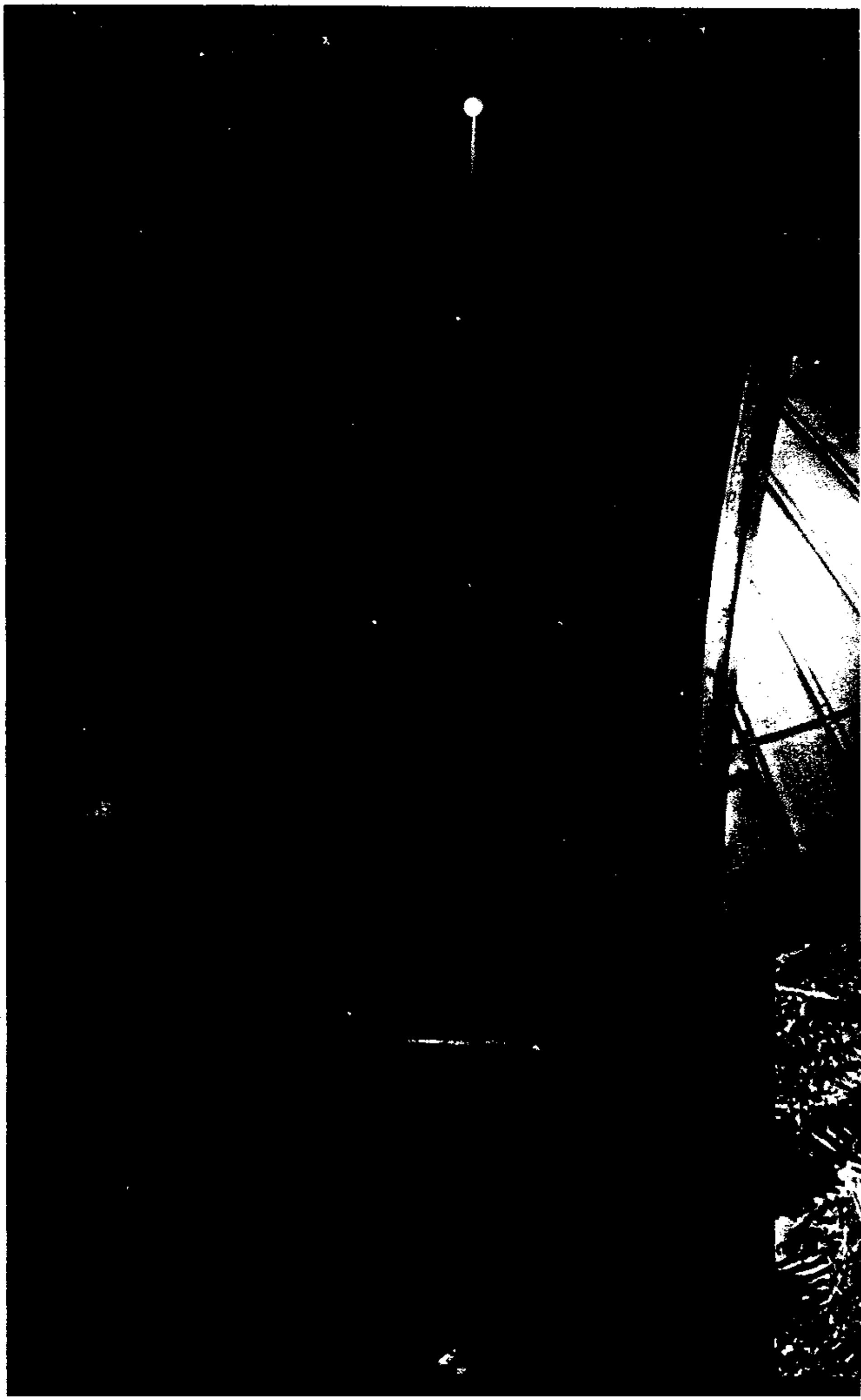
IT WAS MONDAY, July 21, 1969. The television screen was filled with a view of a lunar plain sprinkled with a few craters. Every few seconds, the center of the screen was illuminated by a flash of light, broken into a strange pattern around a central spot. Walter Cronkite assured us that we were seeing something called the "lunar laser experiment" in action. The light, he said, was reflected from a tray of mirrors that astronaut Neil Armstrong had set down on the lunar surface that very day. The scene then switched to a studio, where a distinguished scientist explained why the light was broken into a diffraction pattern.

It was all very impressive. Too bad it wan't true. An overly eager reporter had filmed the flashes off a monitor in the lobby of the dome for Lick Observatory's 3-meter telescope. Having got the shot, he sped down the Mount Hamilton road (allegedly in 25 minutes!) to the San Jose airport, where he packed his film off to New York, without having asked the questions that would have slowed him down. He had filmed flashes not from the moon, but from a calibration reflector mounted on the Lick telescope.

The first *real* laser observations from the Apollo 11 reflectors came 11 days later. And there wasn't any diffraction pattern either, because the signals consisted of only one or two photons per "flash." Moreover, the reflection was invisible to the eye and had to be detected by a very sensitive photomultiplier system.

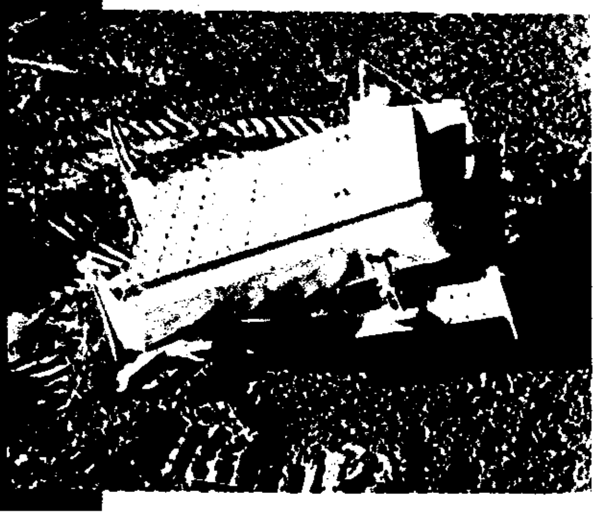
Today the lunar laser ranging (LLR) program is the only one that regularly uses an experimental device left by Apollo astronauts. This is possible because the reflectors deposited on the moon during three Apollo landings (and by two Soviet Lunakhod rovers as well) are entirely passive; they just sit there. The only requirement for their successful use is for Earthlings to do all of the right things down here. This is a tough but realizable condition.

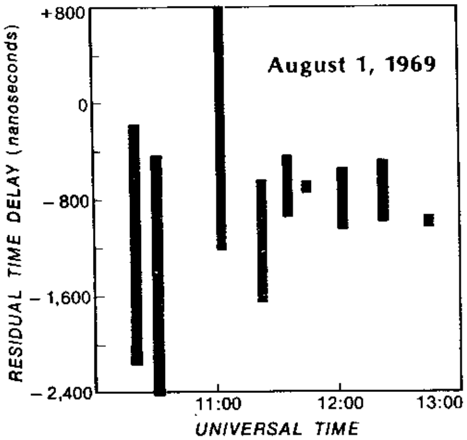
The LLR program is no longer considered an experiment. More than a decade of successful ranging has contributed to significant scientific advances in several areas, such as lunar dynamics,



Left: The moon, seen here during an eclipse last year, is little more than a one-second trip away for this laser pulse, fired from Lure Observatory on Maui, Hawaii. Paul Ely photograph.

Below: The target is a bank of high-efficiency reflectors like the one set up here by Apollo 14 astronauts. Photo courtesy Brown University.





The first laser-ranging test with the Apollo 11 retroreflector array. Times along the vertical axis indicate deviations from the expected round-trip travel time. The last value, −900 nanoseconds, indicates the moon was 135 meters closer than predicted.

relativity theory, and geophysics. Because lunar ranging provides a vital link between geodetic artificial satellites and the inertial celestial reference frame, it has been incorporated into a global program for studying the relative motions of the earth's crust, such as continental drift and polar wander.

HOW DOES IT WORK?

The technique of laser ranging is conceptually quite simple. In brief, light is transmitted through a telescope pointed at the target, a panel of retroreflectors. These are mirrors designed on the principle that a perfect reflection from three right-angle planes will send the light back exactly in the direction from which it came. Thus, these "cube-corners" send the laser light that strikes them back to the transmitting telescope, where it can be detected. The measured quantity is the time delay, or the length of time that the light takes to make its round-trip journey.

This can be considered a precise distance measurement, although that is not quite true, due to the motions of the earth and moon while the light is en route. The scientific value comes from the accuracy with which the time delay can be measured. In 1969 the best accuracy was equivalent to 40 cm; today the *typical* accuracy is about a quarter of that. Stations now under development may achieve two to three cm.

The technique is also no longer experimental in the sense that one station, at McDonald Observatory, has maintained routine, near-daily operation over long periods. Still, LLR depends on systems that are yet on the leading edge of technology. Because the atmosphere defocuses the outgoing beam of light, causing most of the photons to miss the reflector, it is necessary to send out a pulse containing a billion billion photons for every one that comes back to the telescope. At the same time, the accuracy is inversely proportional to the length of the light pulse. Current systems produce pulses only a few billionths of a second in duration; the newest generation of lasers flash for one or two ten-billionths of a second. For the brief time of the flash, the laser beam packs enormous power, on the order of a billion watts. Only special (and costly) materials can withstand such a wallop, and the laser systems must be regulated carefully to avoid breakage.

The detection problem is no less difficult, although not so physically delicate. Since the overall loss of photons is enormous, it is necessary to recapture as many of them as possible. Thus, LLR systems try to detect individual photons that enter the telescope. One photon isn't much light; even on the darkest night the eye receives many of them each second. To "see" the light coming back from the retroreflectors requires both high-efficiency photomultipliers and sophisticated electronics to monitor them. Even so, most of the reflected photons go undetected.

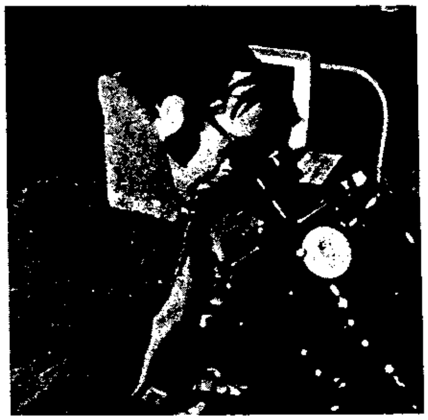
Of course, the photomultiplier can't tell where a photon comes from, and there are a lot of them around that don't come from the laser. This problem is partially resolved by making each photon pass a series of tests before it can get to the detector. First, the light is passed through a diaphragm, typically only a few arc seconds in diameter, to assure that it came from the right direction. Since the laser produces monochromatic light of a known wavelength, the incoming beam is then passed through a narrow spectral filter to insure that it is the right color; at McDonald, this filter has a bandpass of only 1.2 angstroms.

Even after this, the "noise rate" (the flux of unwanted photons) will typically be many thousands per second. Happily, we have a pretty good estimate of when to expect the laser reflection, and the last test uses this information. The detection apparatus is programmed to accept only those photons that arrive during a brief "window" around the expected time; it may be 0.3 to several microseconds long, depending on the situation. Yet even after all of this, most of the detections are still noise, and statistical processing is required to determine which ones are really signals from the moon.

It may seem like a minor miracle that this procedure works, but actually the laser signals are determined with greater than 99-percent reliability when the observing system operates properly. It works so well that the single-photon counting technique has been adopted for some of the newest artificial satellite observing facilities, where the technical problems are somewhat different. Yet this success is severely tempered by the experience of other groups. Success in working at the limits of technical possibility requires a critical combination of skills, personal dedication, institutional commitment, and funding. Experience shows that an insufficient supply of any one of these will hamper or prevent the achievement of regular lunar laser success.

A SURVEY OF LUNAR LASER OBSERVATORIES

The idea of astrometric laser ranging began in 1962, when L. D. Smullen and G. Fiocco at Massachusetts Institute of Technology succeeded in detecting a laser illumination of the lunar surface. A Soviet team repeated this feat in 1964; that year a NASA group also obtained the first ob-



ERIC SILVERBERG: McDONALD'S SECRET INGREDIENT

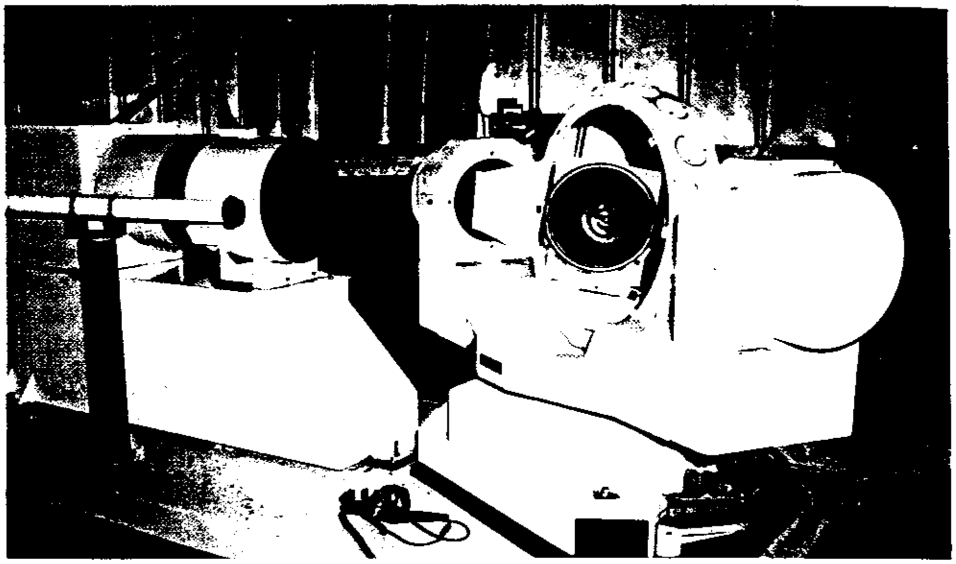
Emerson urged "Do your own thing" — realize the potential for uniqueness. Most of us don't, even in astronomy, where there is much opportunity. One who has done so is Eric Silverberg, responsible for operating the lunar laser station at McDonald Observatory since 1970. Those familiar with lunar ranging are convinced that this station, which sets a standard not approached elsewhere in the world, works so well due largely to Silverberg's direction.

Coming to the University of Texas directly after his doctoral research (laser studies of the upper atmosphere), he soon established himself as an independent and gifted observing team leader. Routine success began roughly coincidentally with his arrival, and his absences during the early years are discernible in the success-rate statistics. His knowledge and skills concerning the atmosphere, laser physics, celestial mechanics, and advanced instrumentation have earned him a just position as a principal consultant to other nascent LLR stations and to NASA, as well as NASA's Distinguished Service Award. Today he directs not only the McDonald LLR operations, but also a highly-mobile laser station for artificial satellites and the construction of the replacement LLR station for McDonald.

servations of Explorer 22, a reflector-equipped artificial satellite. The following year, a large group associated with Princeton University's Robert Dicke argued that laser reflectors on the moon would give new information on a wide range of problems in dynamics, and other lunar-ranging teams were organized in France and the Soviet Union.

After much urging, NASA added the first LLR reflector array to the Apollo 11 payload at nearly the last moment, mainly because the first Apollo Lunar Surface Experiment Package (ALSEP) was too far behind schedule. Armstrong set it on lunar soil, oriented it properly, and laser ranging became an astrometric reality.

During the first decade of LLR operations, signals from one or more of the five lunar reflectors have been detected at nine observatories in five countries. Some of these observing stations are no longer active, some have not yet achieved regular operation, and two new ones have not yet fired at the moon.



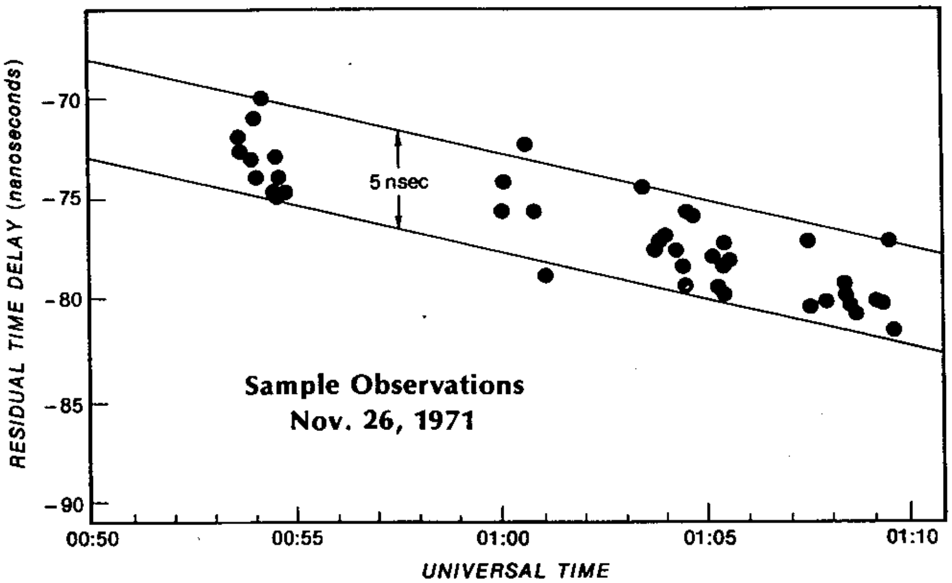
From a powerful laser in a room below, the light beam of the "lunastat" transmitter on Haleakala is turned horizontally at left and then reflected moonward by the mirror of the coelostat at right. This and the picture opposite are *Sky and Telescope* photographs by Leif J. Robinson.

Lick Observatory provided temporary use of its 3-m telescope for a pair of NASA-sponsored teams for two months after the Apollo 11 landing. As mentioned, the first successful observation was made on August 1, 1969.

McDonald Observatory was, and is, the principal LLR station in the United States. Success was attained shortly after Lick's, and the observations have continued without interruption since, providing more than 90 percent of the worldwide total of LLR data. Next year, a 76-cm dedicated lunar and artificial satellite laser station should replace the current system on the 2.7-m reflector.

Pic du Midi, in the French Pyrenees, contributed its 105-cm reflector to the first French station. Construction was begun on a giant "fly's-eye" light collector, but this was abandoned because the high-transmission fiber optics on which it depended were unavailable. After some successes, the laser system was dismantled and transferred to Centre d'Etudes et de Recherches Géodynamiques et Astronomiques (CERGA), due to excessive cloudiness at the Pic.

Catalina Mountain, above Tucson, was the site of another of the several novel but abortive experiments. A specially designed laser telescope there used a 1.5-m metal mirror, but it never performed adequately. The primary was eventually replaced with one of Cer-Vit material. Only a few detections were made before this system was dismantled and sent in 1972 to Australia. It reached successful operation late in 1978 and is now the only regularly active facility other than McDonald. Current efforts are directed at improved accuracy.



Here dots represent the "capture" of individual pulses. The downward slope of the bracketed returns suggests that the moon's motion was differing increasingly from predicted values, at a rate of about 4½ meters per hour.

The Soviets use the 2.6-m reflector of the Crimean Astrophysical Observatory, near Simeis. Operations have continued since 1969 but only for about 20 days per year. This is simply not enough to be useful scientifically or to give the observers enough experience. A special laser facility is said to be under construction.

Astronomers at Tokyo Observatory's Dodaira Station have been trying since 1969 to refine a system that uses a 50-cm off-axis transmitter and a separate receiver with a 2.7-m metal primary. A few photons have been detected, but the entire transmitter is now being redesigned.

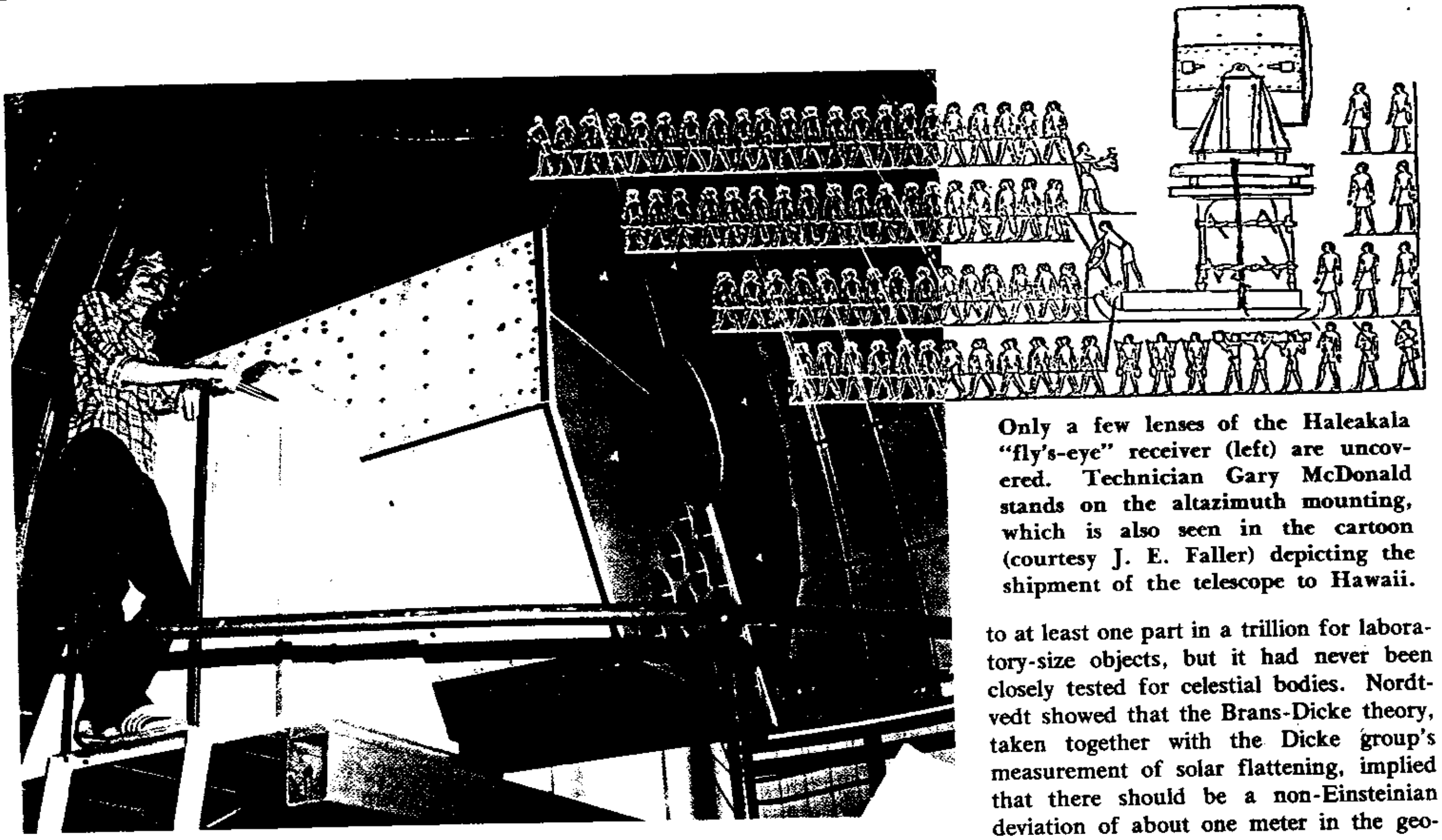
In 1971 NASA authorized the construction of a laser observatory on the peak of Haleakala in Hawaii, using another unique design. Transmission is accomplished by a 40-cm "lunastat," while the receiver is a large fly's-eye. A few successes have been obtained, but lunar operations have been temporarily halted for conversion to accommodate both LLR and the Lageos satellite (described in SKY AND TELESCOPE for March, 1978, page 198).

In 1972, Harvard's Agassiz Station was the scene of a successful but brief demonstration of a transportable LLR station built by the Smithsonian Astrophysical Observatory. It has not operated since.

A new 1.5-m lunar laser telescope has been erected at the CERGA observatory on the southern edge of the French Alps, using the laser from Pic du Midi. It has been successfully tested on terrestrial targets but has not yet tracked lunar sites.

The artificial satellite laser station at Wettzell, West Germany, is now being converted to lunar capability and is expected to begin operations within a year.

One thing seems clear from this survey. The basic technique is so delicate that radical innovation carries an extreme risk



Only a few lenses of the Haleakala "fly's-eye" receiver (left) are uncovered. Technician Gary McDonald stands on the altazimuth mounting, which is also seen in the cartoon (courtesy J. E. Faller) depicting the shipment of the telescope to Hawaii.

of failure. The only novelty that has worked successfully thus far is the coelostat used at Haleakala. On the other hand, advances in lasers and detectors have reduced the need for large collecting areas, the problem that the fly's-eyes were intended to address. For example, Eric Silverberg, director of the McDonald system, estimates that the average detected signal from the 76-cm telescope will exceed that of the present 2.7-m facility that it will replace.

SCIENTIFIC RESULTS

Laser ranging requires technical wizardry, but it doesn't produce spectacular, headline-grabbing results. There is nothing to see that rivals "Star Wars," there are no breathtaking photos, and even in the mind's eye there is no majestic spacecraft soaring out into the beyond. There are only a few pieces of aluminum and silica sitting on our nearest celestial neighbor, surrounded by the abandoned litter of lunar exploration. Here on Earth, a few people try to find them with complicated flashlights.

Despite the lack of glamour, however, 10 years of lunar ranging have produced some solid and impressive science.* Since the observations can be used to study essentially anything affecting the motions of either the earth or moon, these advances have been distributed between solar system physics, relativity, and geodesy. A summary of the achievements is given in the table below. Only the most striking results will be discussed in detail.

Einstein wins again. Since the time of Isaac Newton, the moon has been the most demanding test-bed of gravitational theories. The original motivation for the Apollo reflectors was to test Einstein's theory of general relativity. Numerous modifications have been proposed during the six decades since its formulation, and none of them has seemed more plausible than that advanced by C. Brans and Dicke (and also discovered independently by P. Jordan). In 1968, Kenneth Nordtvedt noticed that one of the implications of the Brans-Dicke theory is that a large self-gravitating body such as the moon or a planet would show a difference between its inertial mass (the m in $f = ma$) and its gravitational mass (which determines its effect on other bodies).

This would be a violation of the "equivalence principle" of general relativity. Equivalence had already been shown valid to at least one part in a trillion for laboratory-size objects, but it had never been closely tested for celestial bodies. Nordtvedt showed that the Brans-Dicke theory, taken together with the Dicke group's measurement of solar flattening, implied that there should be a non-Einsteinian deviation of about one meter in the geocentric motion of the moon.

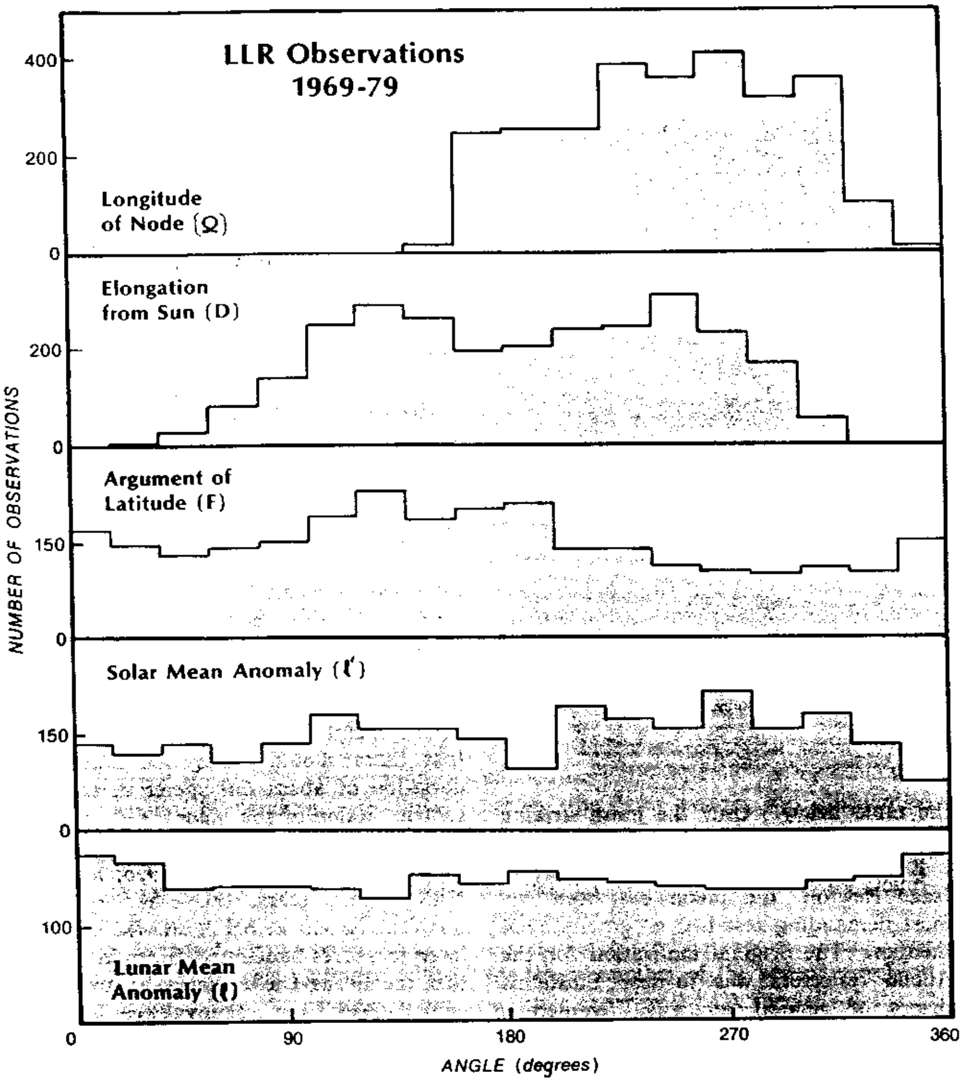
This is well within LLR capabilities, and two independent studies in 1976, one by a NASA-Apollo team, the other by Irwin Shapiro's group at MIT, showed that the laser measures confirmed Einstein so well that the Brans-Dicke theory became basically a dead issue. Equivalence was confirmed for massive bodies to nearly the same level as for small ones. Another round goes to Einstein.

There is a tide in the affairs of moon. Dicke's original interest in lunar ranging was not equivalence, but the idea that the gravitational constant might be changing with time. This is a prediction of nearly all non-Einsteinian relativity theories, beginning with P. A. M. Dirac in 1938. If this were so, it would show up as an unexplained acceleration in the apparent angular motion of the moon. The Brans-Dicke theory and several others predict deviations from Einstein that should, in principle, be observable with just a few

MAJOR RESULTS FROM LUNAR LASER RANGING

Lunar orbit and rotation	Improved two orders of magnitude
Mass of Earth + Moon	1/328,900.5 solar mass
Lunar tidal acceleration	24″ per century^2; consistent with Spencer-Jones
Nordtvedt effect	Confirms Einstein, destroys Brans-Dicke
Time variation of gravity	Smaller than 3×10^{-11} part of G per year
Lunar moments of inertia	Evidence of a dense core
Lunar gravity field	Tri-axial model no longer adequate for calculating librations
Free libration	Suggests recent large impact
Earth rotation	Annual and longer-period terms detected
Terrestrial chords (straight-line)	
McDonald-Crimea	9,453.4 km
McDonald-Orroral	11,039.46 km
Crimea-Orroral	11,577.4 km

*A comprehensive technical treatment has been given by the author in "Scientific Achievements from Ten Years of Lunar Laser Rang-



These graphs chronicle a decade of experimentation with lunar laser ranging (LLR), giving the spread of observations for five different cycles that help describe lunar motion. Ω is the angle between the vernal equinox and the point in the moon's orbit where it climbs above the ecliptic, measured eastward in the ecliptic plane; this point migrates slowly around the ecliptic every 18.6 years, hence the restricted range in angle. *D* is the moon-Earth-sun angle, measured eastward along the lunar orbit from the point of new moon; note that lunar ranging is very difficult (and rarely attempted) near new moon. *F* is related to the moon's latitude above or below the ecliptic, as seen from Earth. Our planet does not move at a constant speed around the sun, but if it did the solar mean anomaly, *l′*, would be the angle swept out by the earth at any given time since its last perihelion passage. Similarly, the lunar mean anomaly, *l*, is the angle covered by a hypothetical, constant-velocity moon since its last passage through perigee. Diagrams are from the author.

years of LLR data. But there is a skeleton in the closet of the lunar motion. It's called tidal friction.

Nearly a century ago, it was realized that tides on the earth must involve friction, meaning that the earth must continually lose energy. This raised the question of where the energy goes, since it cannot be destroyed. Tides also produce a bulge in the earth's shape, which by the pull of gravity must affect the moon's orbit. It seemed plausible that the energy lost by the earth was transferred to the lunar orbit — but how much? This "tidal acceleration" of the moon is proportional to the friction, but there is neither a direct nor an adequate theory to predict it.

For a long time the problem was simply inverted — if there were an unexplained lunar acceleration, it would be ascribed to tidal friction for want of a better explanation. We aren't really much better off now, except that there is a second candidate to confuse the issue, which arises from relativistic arguments. Dicke knew of this problem and hoped that the tidal part could be understood well enough to discern the relativistic effect. Unfortunately for him, just as the lunar laser program started, disagreements among various studies rendered the value of the tidal effect uncertain by a factor of two. It be-

ty, if any, was not going to be easily detected even with lunar ranging.

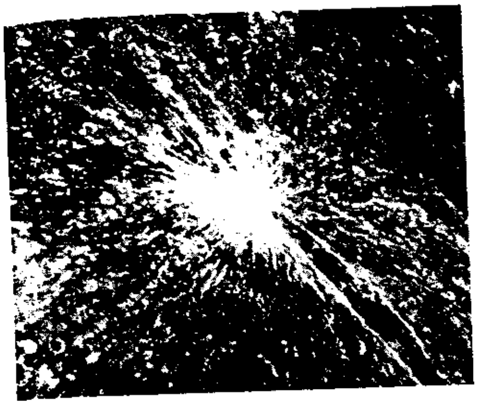
The problem should eventually be solved, however, since the two effects act differently on the lunar distance. But even now there exists no cogent determination of a gravity variation by any means. On the other hand, LLR data have shown that the 1938 determination of the tidal acceleration by H. Spencer-Jones was pretty good. He found 22 arc seconds per century per century; LLR gives about 24.

Tugging and ringing the moon. To a casual observer, the moon always presents the same face to us. This means that, on the average, it completes one rotation on its axis per orbital revolution. But while the Man-in-the-Moon is never seen in profile, he does nod back and forth. This is due to three effects, although only one is discernible without precise measurements. That one, called the optical libration, is simply a geometric parallax effect caused by the 5.5-percent ellipticity of the lunar orbit, which carries the moon toward and away from the earth over the course of a month. The other causes of libration, though less obvious, are more interesting. They are due to the moon's shape and to meteorite impacts.

The physical libration, whose amplitude is about one kilometer along the lunar surface, is an actual rocking of the moon due to the earth's gravity pulling on the lumps in its shape. Precise measurements of the lunar rotation can be used to determine the shape of the moon's gravity field, and thus the homogeneity of its internal structure. Over the past decade, the theory of physical libration has been improved by a factor of perhaps a hundred, largely due to the LLR program. Back in 1969, for example, some astronomers thought that the lunar crust was much denser than the center, but the laser data have consistently shown the opposite to be true. Recent studies at the Jet Propulsion Laboratory, using LLR and Lunar Orbiter tracking data, support the idea that, in fact, the moon has a sizable metallic core.

Countless meteorites — and lots of big ones — have struck our moon; most lunar craters are remnants of these collisions. Such impacts destroy the smaller body, while the larger one responds like a bell struck with a hammer. The vibrations induce rotational effects that disappear only gradually. For the moon, these are called free librations. Their size is governed only by the history of meteorite impacts and internal friction, so there is no theory to predict them.

The first visual observations of free librations were claimed by Karol Koziel in 1967; the amplitude was about 150 meters on the surface, or 1/12 arc second as seen from Earth. Frankly, neither the lunar orbit nor the libration theory that he used (and maybe not the observations!) were re-



Was this bright rayed crater on the moon's far side, Giordano Bruno, formed only eight centuries ago? Photograph courtesy National Space Science Data Center.

the LLR observations to show clearly that the true amplitude cannot be more than about 15 meters. Even this requires a major impact event in the astronomically recent past. Geologist Jack Hartung has suggested, based on the annals of Canterbury Cathedral, that the spectacular crater Giordano Bruno was formed in A.D. 1178. This, of course, remains speculation, but it is consistent with the LLR results.

As the world turns . . . Today, all of the easy gains from lunar ranging have been harvested. Nearly every aspect of the physical theory has been improved upon since Armstrong and Edwin Aldrin, Jr., walked on the the moon over a decade ago. Currently, the main scientific effort concerns our own capricious Earth. The various things that go on in its interior are so poorly known and understood that relevant theories — for Earth's rotation, tectonic drift, and seismic activity — just don't exist. Stuck up here on the surface, the most obvious thing that we see is that our Earth rotates on its axis in an unpredictable way (see SKY AND TELESCOPE for August, 1976, page 99). Oh sure, it goes around roughly once every 24 hours, and for most people that's enough. But the little unpredictable wobbles are important in positional astronomy, in high-speed navigation, and as clues to understanding geophysical dynamics.

Laser ranging, both to the moon and to artificial satellites, is one of the new high-precision ways to study the earth's rotation. As it turns out, artificial satellites such as Lageos are very effective for finding the direction of the pole in space but cannot give the rotation around that pole very well. This parameter, Universal time, is determined readily by lunar ranging, so the two techniques are complementary. (That is why several LLR and satellite facilities are now being converted to have both capabilities.) Astronomy and its turn-of-the-century offspring geophysics are rejoining forces, as it becomes neces- ... the skies to learn more

NEWS NOTES

ASTEROID OCCULTATION ALERT

Observers in northwestern states and western Canada may have a chance to determine the size, shape, and possible binary nature of the asteroid 216 Kleopatra. On October 10th, this minor planet will occult the 8.8-magnitude star SAO 128066 (David Dunham's prediction can be found in the January, 1980, issue of SKY AND TELESCOPE, page 38; updated information and a finder chart appear in the current *Occultation Newsletter*.)

David Tholen (SKY AND TELESCOPE, September, 1980, page 203) reported the unusually large amplitude in the rotational light curve of Kleopatra, suggesting a highly irregular shape. But S. J. Weidenschilling of the Planetary Science Institute in Tucson believes that the light curve could be explained by a binary asteroid in contact. If it were a single body, according to Weidenschilling, Kleopatra would have to be three times longer than it is wide, but with its 5.4-hour rotation, it would not be stable.

The occultation this month could resolve the issue. Weidenschilling advises that observers look for possible multiple events and also that they station themselves at pairs of locations relatively close together for confirmation.

FIRST INDIAN LAUNCH

On July 18th, India joined an elite circle of nations by using a launch vehicle of its own design and construction to boost a satellite into orbit. The 35-kg payload, called Rohini, carried radio equipment to assist tracking stations. Soviet boosters were used for two previous Indian satellites.

July's test, conducted from Sriharikota Island, north of Madras, employed a four-stage vehicle powered by solid fuel. Officials hope to construct other versions capable of lofting payloads weighing 500-600 kg. India becomes the eighth nation or organization to launch a satellite.

HIATUS AHEAD

Interested in erecting a 400-inch telescope? Or sending a probe to Pluto or a manned voyage to Mars, or building a space colony or satellite power station? We are coming into an unfavorable time for starting such projects, according to experts who recently gathered at the Massachusetts Institute of Technology and in Toronto.

The MIT conference, appropriately called "Macroengineering," was an intensive four-day seminar consisting of an all-star faculty that presented case studies and experiences in undertaking large engineering projects.

The Apollo program is probably the The Apollo decision led to some of the most exciting scientific dividends ever experienced by humanity. Many of the results reported in these pages owe a debt to Apollo. The culmination of these efforts will be this November's Voyager 1 encounter with Saturn. But in the absence of another Apollo, we can expect to see a hiatus in space research. Funding for even modest new space initiatives has largely dried up, although the coming years will be occasionally punctuated by the Space Telescope, the Galileo mission to Jupiter, and possibly a Halley's comet probe.

Participants in the June, 1980, MIT seminar, which was co-sponsored by the Sloan School of Management and the Center for Advanced Engineering Study, arrived at no clear consensus about the best techniques for launching megaprojects. Each case is unique.

Robert Seamans, MIT dean of engineering and former deputy administrator of NASA, pointed out that Apollo was triggered by cold war events and a forward-looking administration. Money was no object.

The Supersonic Transport, on the other hand, died because the project managers lacked sensitivity to environmental concerns. The Space Shuttle, which is scheduled for its first orbital flight next spring, hangs at the edge of extinction because of tight design, budgeting, and scheduling constraints.

Some common threads to macroengineering projects are that very few burst forth spontaneously from a new idea (Jules Verne thought of the lunar landing a century ago), and all projects need careful planning and management lest their costs overrun or they arouse public resistance because of environmental impacts. Some of the conferees pointed out that we live in an era of political and corporate unwillingness to attack mankind's fundamental long-term problems.

Pessimistic predictions also pervaded the First Global Conference on the Future, held July 20th to 24th in Toronto. The nearly 5,000 delegates were continually reminded that our small planet is running out of energy, food, and raw materials, that the Third World would like a larger share of their benefits, and that international tensions are bound to increase as a result.

A panel discussion on Space Industrialization presented the technical and economic case for using the abundant resources and energy available to us in space to relieve the limits to growth on Earth. But as Georgetown political scientist Charles Chafer pointed out, these dreams are having difficulty turning to reality.

"The political climate nowadays," said Chafer, "is very different than that of the