THE LUNAR LASER REFLECTOR

A reflector array placed on the moon by its first visitors returns pulses of light emitted by lasers on the earth. The round-trip travel time yields the distance to the moon with an accuracy of six inches

by James E. Faller and E. Joseph Wampler

In July of last year the astronauts of *Apollo 11* placed on the surface of the moon an array of prismlike reflectors that has made it possible to measure the distance between the earth and the moon with an accuracy approaching six inches. The distance is determined by aiming the intense light beam from a laser at the reflecting array and measuring the time required for a brief pulse of light to travel to the moon and back.

The important quantity, however, is not the absolute distance between the earth and the moon at some particular instant but the variations in distance measured with six-inch precision or better over a period of months and years. Such variations can be studied to answer a number of important scientific questions. These include the determination of how the mass inside the moon is distributed, the rate at which the continents on the earth are drifting toward (or away from) one another and changes in the location of the earth's North Pole (which shifts in response to unknown forces). A more fundamental question than any of these, which may be answered by long-term observations of the earth-moon distance, is whether the gravitational constant is indeed constant or whether it may slowly be weakening with the passage of time.

For more than 2,000 years the moon has been a testing ground for man's 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. He based his estimate on the observation that the diameter of the earth's shadow on the moon during an eclipse is about two and a half times the diameter of the moon. If the sun were a point source of light at infinity, the earth's shadow would be exactly as wide as the earth itself. In that case the diameter of the moon would be 40 percent of the diameter of the earth. Aristarchus realized, however, that cone-shaped shadows cast by the sun taper down with an angle of about half a degree. Allowing for this, and estimating (incorrectly) the apparent diameter of the moon's disk, he arrived at his value for the distance.

Aristarchus' estimate would have been much better if he had not badly misjudged the apparent size of the moon. His estimate was two degrees of arc, or four times the actual value, with the result that he thought the moon was much closer than it actually is. A century later Hipparchus used a more accurate value for the apparent diameter and computed the distance of the moon as being 59 earth radii. (The true mean distance is 60.3 earth radii, or some 239,000 miles.) Hipparchus also discovered the eccentricity of the moon's orbit, the inclination of the moon's orbit to the plane of the earth's orbit, the motion of the nodes (the points where the moon's orbit intersects the plane of the earth's orbit) and the motion of the apsides (the moon's minimum and maximum distance from the earth).

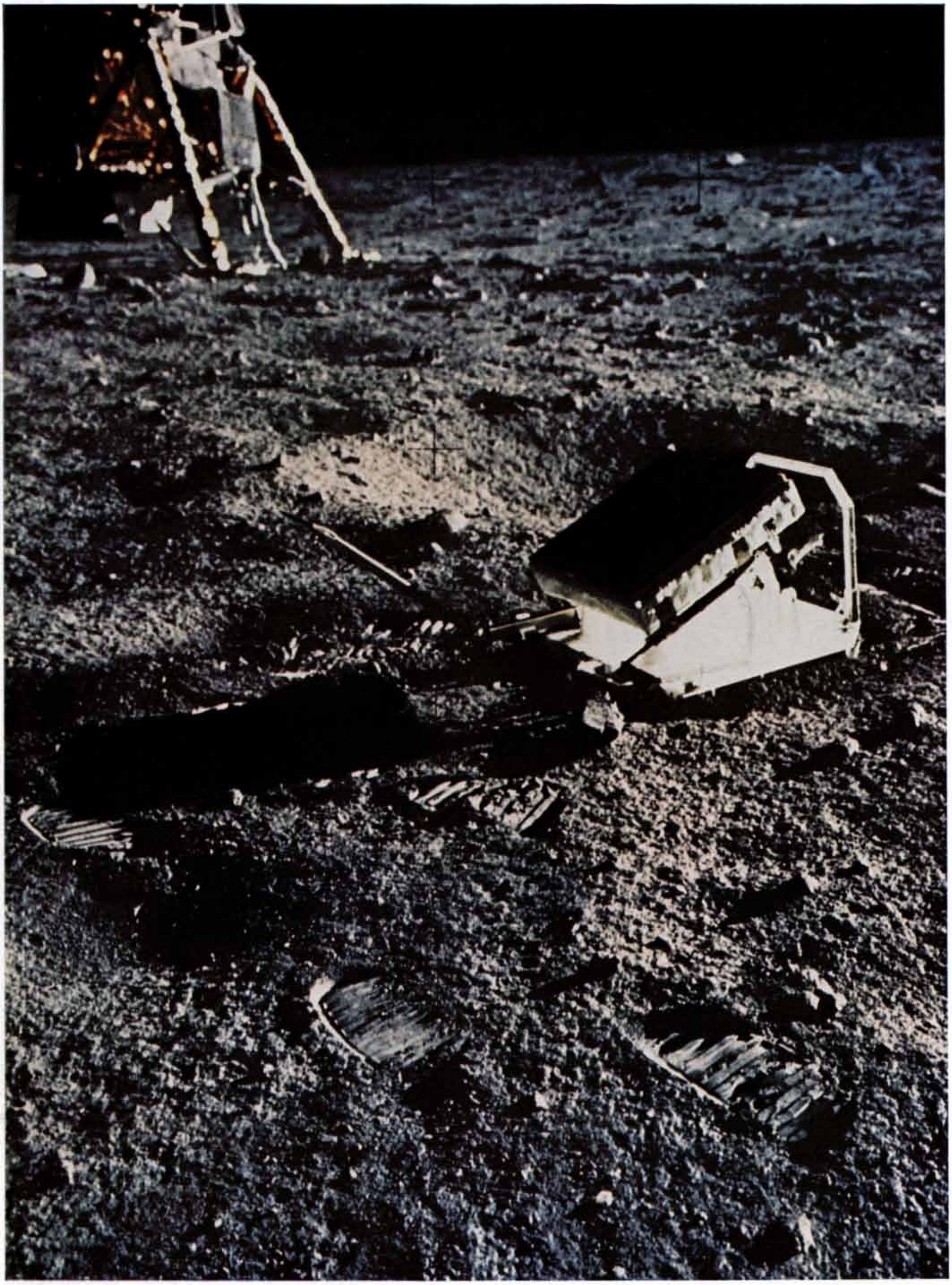
Except for minor improvements in some of the measurements there was no fundamental advance in knowledge of the lunar motion until the revolution that swept astronomy in the 16th and 17th centuries. The climactic achievement of this period was Newton's theory of gravitation, in which the moon figured 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 ±2 miles. Since 1957 conventional radar techniques have also been used to study the moon. In addition to determining the moon's distance to ±.7 mile, radar studies have provided information concerning the small-scale roughness of the moon's surface and even some electrical properties of the surface material.

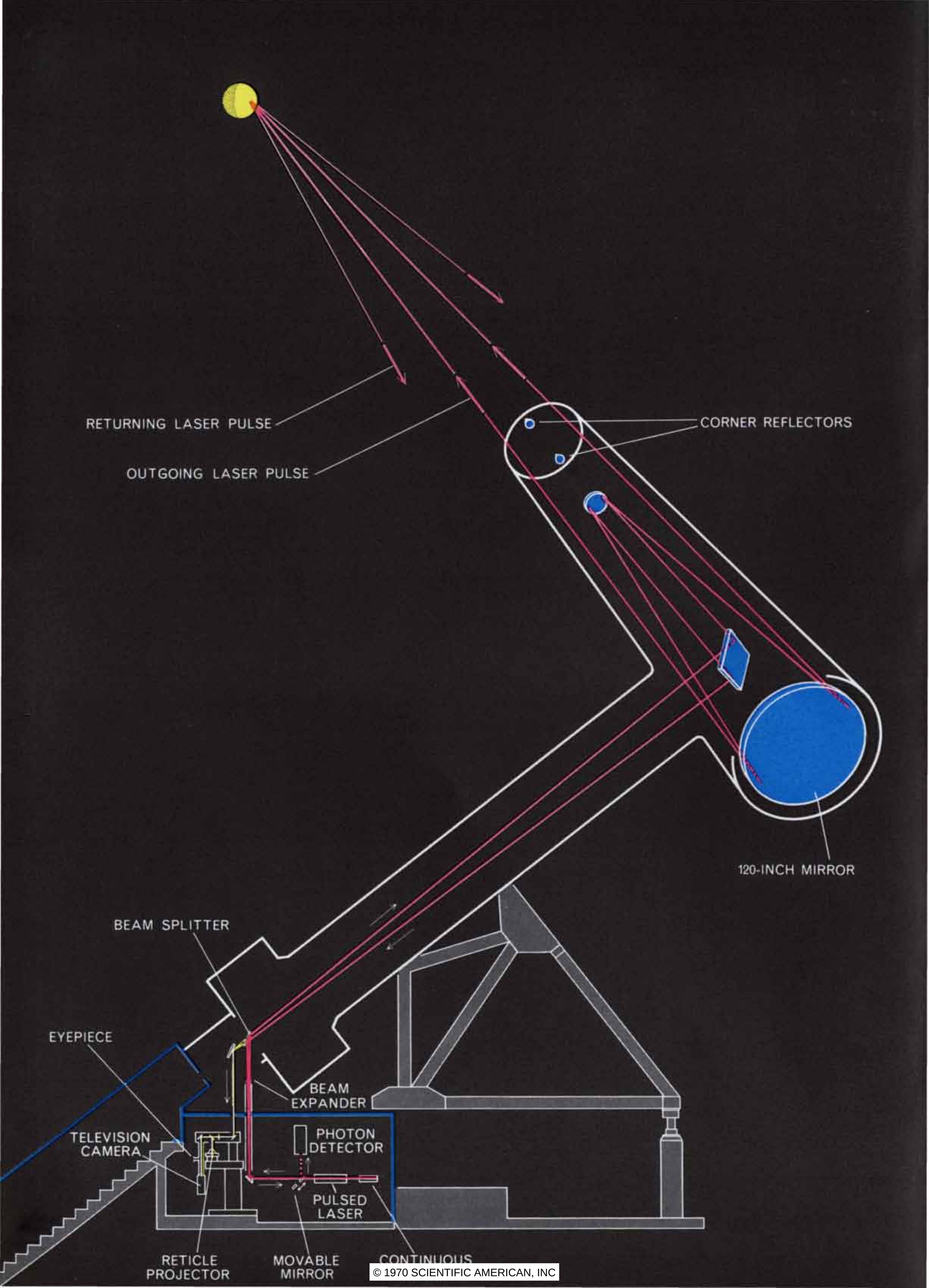
More recently light from ruby lasers has been directed at the moon and the weak signal reflected back has been detected. The first detection of ruby laser

EDITOR'S NOTE

The Lunar Laser Ranging Experiment is the responsibility of the LURE group, which consists of 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 at Los Angeles, and Gordon J. F. MacDonald, University of California at Santa Barbara. The success of the experiment owes much to a number of other workers at these member institutions as well as to the scientific staffs of both the Lick and the McDonald observatories.



RETROREFLECTOR ARRAY was placed on the lunar surface last July 20 by Neil A. Armstrong and Edwin E. Aldrin, Jr., the first men to walk on the moon. The array contains 100 corner reflectors, prismlike devices that will reflect a beam of light back to its source. The individual reflector sockets are not visible because the face of the array is in deep shadow. The device is tilted so that its face is perpendicular to light rays originating from the earth. *Eagle*, the landing module of *Apollo 11*, can be seen in the background.


RETURNING LASER PULSE
OUTGOING LASER PULSE
CORNER REFLECTORS
120-INCH MIRROR
BEAM SPLITTER
EYEPIECE
BEAM EXPANDER
TELEVISION CAMERA
PHOTON DETECTOR
PULSED LASER
RETICLE PROJECTOR
MOVABLE MIRROR
CONTINUOUS

light reflected from the lunar surface was accomplished eight years ago by a group at the Massachusetts Institute of Technology. Laser pulses of one-millisecond duration were transmitted through a 12-inch telescope. With a 48-inch telescope as the receiver, many shots were required to define a detectable return signal. A similar reflection experiment was carried out in 1964 by Russian astronomers, who used a 104-inch telescope for both transmitting and receiving.

The first experiment with enough accuracy to be of scientific value was conducted by the same Russian group in the fall of 1965, when they used the 104-inch telescope to transmit and detect pulses of 50-nanosecond duration produced by a "Q-switched" (short-pulse) ruby laser. The experiment established the earth-moon distance to an accuracy of about 600 feet. A fundamental limitation on the precision that can be obtained by bouncing a light beam directly off the lunar surface arises from the curvature and the irregularity of the surface, which spread out the arrival time of the returning signal.

Eight months ago, some 2,000 years after the first measurement, the method of determining the earth-moon distance was dramatically changed. During their brief sojourn on the moon Edwin E. Aldrin, Jr., and Neil A. Armstrong set up an array of "retroreflectors" that can return a laser signal with an intensity between 10 and 100 times greater than that produced by reflection from the natural surface. Equally important, the array eliminates the stretching out in time that results from light pulses' being reflected back from different parts of the lunar surface.

The laser-ranging experiment had its origin some 10 years earlier at Princeton University in a gravitational research group headed by R. H. Dicke. In 1959 three members of that group wrote a paper reviewing the problem of making precise optical position measurements of artificial satellites. The paper discussed three methods of illuminating a satellite to obtain range information: direct sunlight, a pulsing light aboard the satellite or an optical "corner" reflector, or retroreflector, aboard the satellite to return pulsed beams from an earth-based searchlight. The paper led to early experiments by Henry H. Plotkin and his satellite-tracking group at the Goddard Space Flight Center.

In 1962, the year the M.I.T. workers reported the first laser reflection from the moon, the suggestion was made in the Princeton group of placing a corner reflector on the moon to enhance the strength of the returned signal and to sharpen its definition in time. Although initially motivated by a problem posed by the Brans-Dicke scalar-tensor theory of gravitation, the laser-ranging experiment in addition has great importance for a number of areas in geophysics and astrophysics. Following the publication in 1965 of a paper titled "Optical Radar Using a Corner Reflector on the Moon" the LURE (Lunar Ranging Experiment) group was formed. The membership of the group reflects the many areas of science on which the experiment bears and the broad base of knowledge required for the experiment's successful execution. Coordination of the group's efforts has been the responsibility of Carroll O. Alley, Jr., of the University of Maryland.

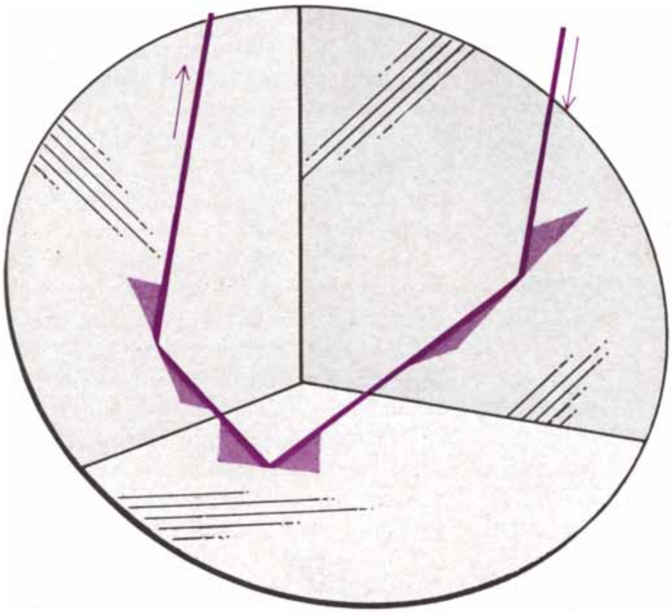
The retroreflector package that was placed on the moon last July consists of 100 "corner cubes" arranged in an 18-inch-square array [*see illustrations on next page and on the cover of this issue*]. Each of the 100 corner cubes is in effect an ultraprecise version of the reflectors used on bicycles and in traffic stop signs: it is designed to direct a beam of light back to its source regardless of the direction from which it arrives. Each cube does for the three-dimensional world of light what the corner of a billiard table does for the two-dimensional world of billiards. A billiard ball sent (without spin) into the corner of the table will, after two bounces, return along a path parallel to its incident direction. In the case of light three reflecting surfaces, all at right angles to one another, form a corner with the same retroreflective property.

The preliminary design for the array was suggested by one of us (Faller) after considering the many (and sometimes conflicting) requirements the array had to satisfy simultaneously in the lunar environment. Workers at the University of Maryland accurately calculated the spreading of the reflected beam from a corner cube, and they verified the performance of a cube of the suggested size (1½ inches in diameter) under lunar surface conditions with a solar simulator at the Goddard Space Flight Center. The final design, fabrication and testing of the array package, based on a detailed thermal analysis, was done by Arthur D. Little, Inc., in cooperation with members of the LURE team. The Perkin-Elmer Corporation and Boxton-Beel, Inc., produced the extremely precise corner cubes. The Aerospace Systems Division of the Bendix Corporation carried the overall engineering responsibility for the array's inclusion in the Early Apollo Scientific Experiments Package.

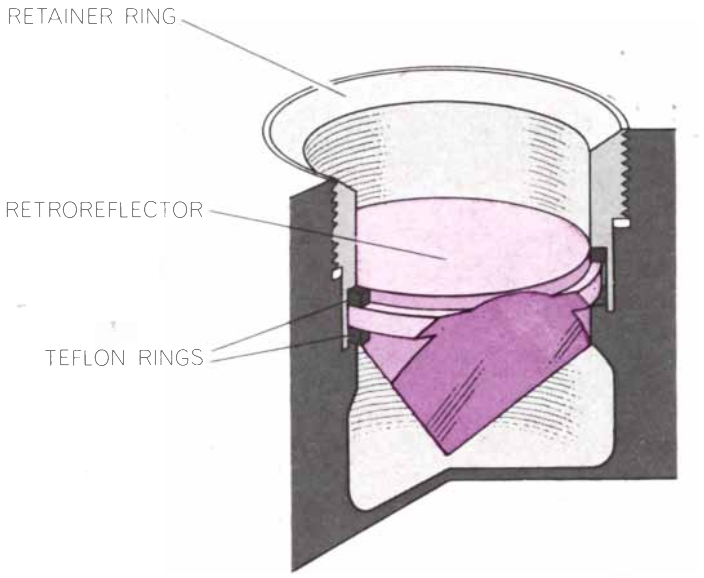
In theory the optimum size of corner reflector for lunar ranging can readily be determined. The returned light intensity is maximized by using a single diffraction-limited (optically perfect) retroreflector as large as weight restrictions will allow. In practice, however, the design must take account of two problems. The first is the fact that the returning laser beam will be displaced sideways because of the relative motion between the moon and the laser transmitter (velocity aberration); the second is the thermally induced optical distortion that occurs as a result of direct solar heating and the wide variation in temperature on the lunar surface (from −170 to +130 degrees Celsius).

The effect of the velocity aberration is to displace the center of the returned beam about a mile from the point of origin of the outgoing beam. Because of this shift the use of corner cubes five inches or more in diameter on the moon would require that the receiving telescope be spatially separated from the transmitting instrument in order to intercept a portion of the returning beam. For cubes less than about five inches in diameter, however, the diffraction pattern is wide enough so that the transmitting telescope will still be somewhat illuminated by part of the returned

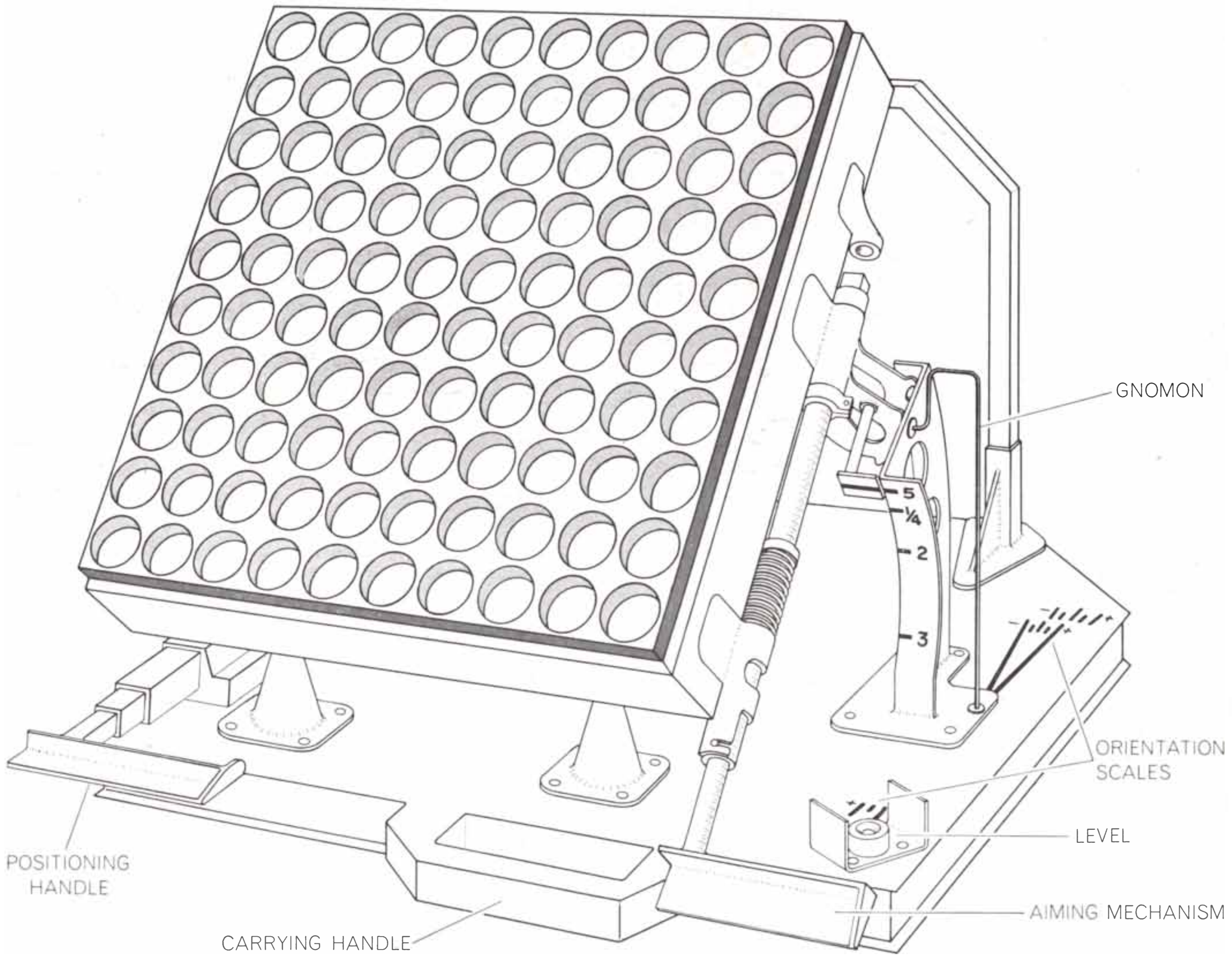
LUNAR-RANGING EXPERIMENT at the Lick Observatory, depicted on the opposite page, involved sending an intense pulse of laser light through the 120-inch telescope and detecting the pulse returned by the retroreflector array placed on the moon by the *Apollo 11* astronauts. The telescope optics limit the spread of the laser beam to a circle a little more than a mile in diameter on the moon. The portion of the returning laser light that enters the telescope is reflected by a movable mirror into a sensitive photon (light particle) detector. The outgoing pulse contains some 10^{20} photons, of which 25 or so return to the telescope 2½ seconds later. A low-power continuous laser, bore-sighted through the high-intensity pulsed laser, provides a continuous internal reference beam for aiming the telescope in conjunction with the television camera and reticle system shown at the lower left. Corner reflectors mounted near the front of the telescope intercept part of the laser light and send it back down the optical system, where it is superposed on an image of the moon in the aiming system. Two separate laser systems were available and were used by the group at Lick.



CORNER REFLECTOR, or corner cube, has the property of returning a ray of light (*color*) on a path exactly parallel to that of the incident ray. At each internal surface the angle of reflection equals the angle of incidence, as indicated by the colored triangles. The corner reflectors that were used in the array placed on the moon were cut from accurately polished cubes of fused silica.



MOUNTING FOR CORNER CUBE was designed by Arthur D. Little, Inc., to withstand the vibration and acceleration of an Apollo lift-off and, once on the moon, to minimize thermal gradients that would affect the optical performance of the reflectors. Each corner reflector is recessed by about half its 1½-inch diameter and is held by Teflon rings in a housing machined from aluminum.



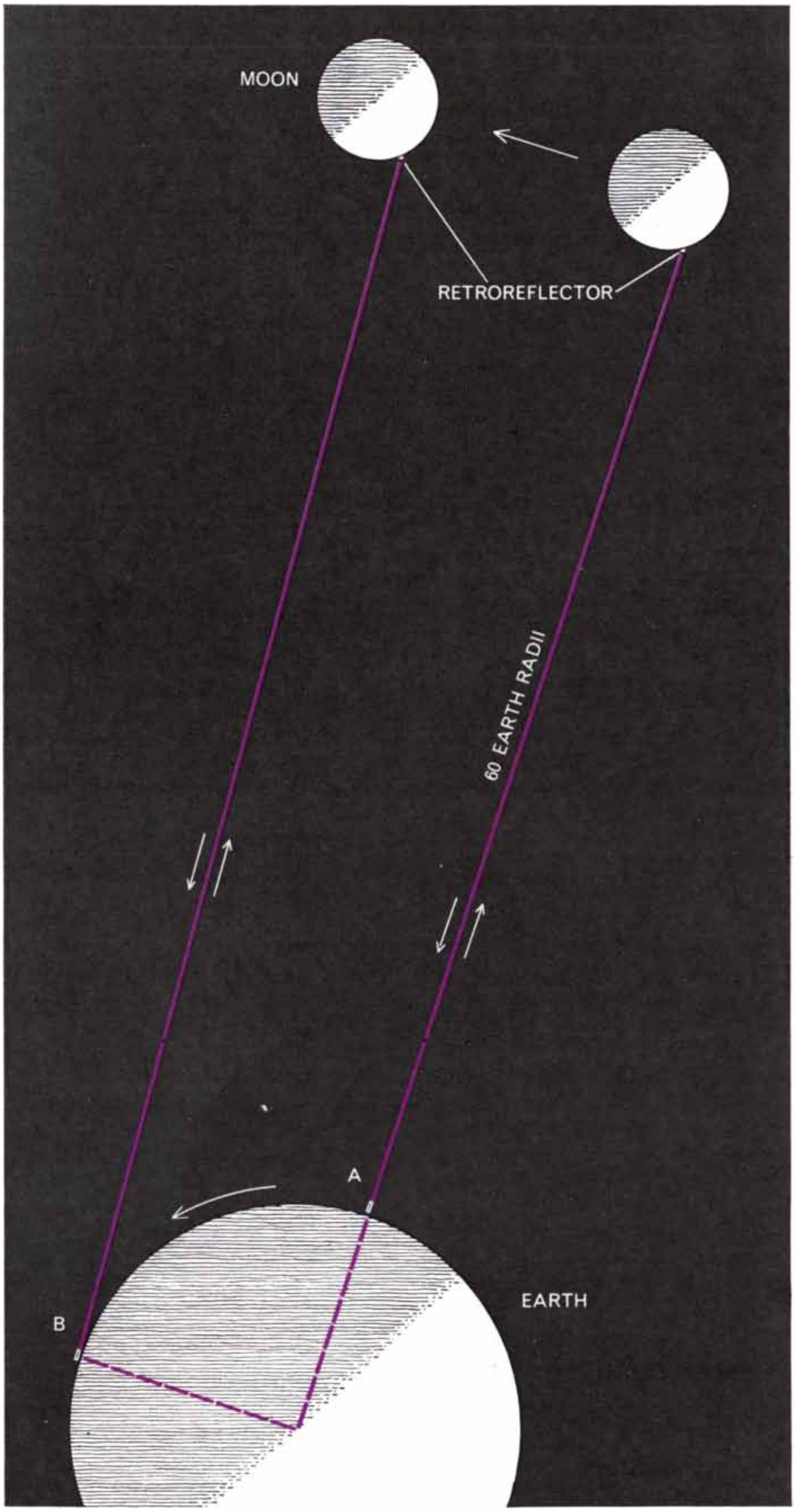
LUNAR LASER RETROREFLECTOR, 18 inches square, contains 100 corner cubes and can be adjusted to different angles to accommodate to different locations on the moon. Since it was actually placed close to the lunar equator at a point 23 degrees to the east of the subearth point, it was tilted up 23 degrees. Here the tilt is greater. The shadow of the gnomon provides east-west orientation.

beam. It turns out after some analysis that there is a wide range of corner sizes (from about 1½ to five inches in diameter) for which the ranging efficiency for a single transmitting and receiving site is almost independent of corner diameter and depends only on the total mass of corners used.

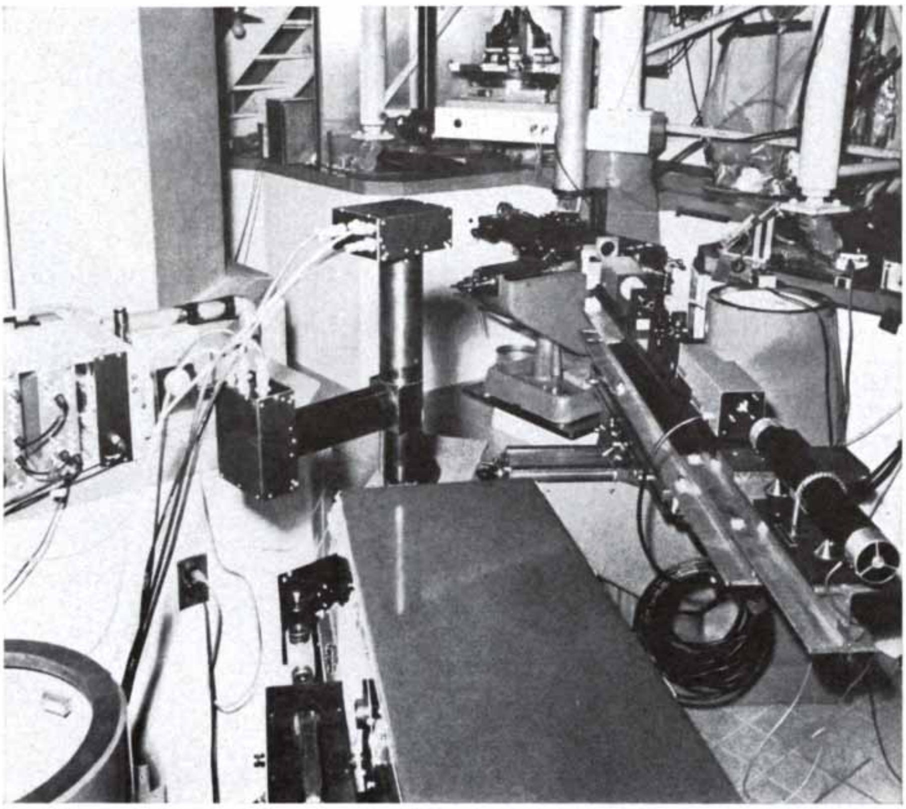
In order to minimize the thermal gradients that would distort the diffraction pattern of the returning beam, we therefore sent to the moon the smallest efficient size (1½ inches), simply using enough corner cubes to produce a reflected signal of reasonable strength. The temperature gradient is further minimized by recessing each reflector by half its diameter in a circular socket. Each reflector is tab-mounted between Teflon rings, which afford as much thermal insulation as possible. The mounting structure provides passive thermal control by means of its surface properties as well as by cavity geometry and insulation. In order to increase the lifetime of the array and to avoid added thermal distortion, we accepted about a two-thirds reduction in signal strength by relying on total internal reflection rather than aluminizing the back surfaces of the individual retroreflectors. Corners smaller than the 1½-inch ones that were sent to the moon would spread the returned light too thinly with the result that less would be collected by a given receiver area. As it is, the light reflected by one of the corners spreads because of diffraction to almost 10 miles in diameter in traveling the 240,000 miles back to the earth.

As the array was being developed our group was not certain which Apollo flight would carry it to the moon. To our delight, a little more than a year ago the National Aeronautics and Space Administration told us that our laser reflector was to be taken on the first flight, the flight of *Apollo 11.* On July 20 millions watched on television as Aldrin removed the unit from the bay of the *Eagle,* carried it out about 60 feet from the craft and set the array on the lunar surface. At that point Armstrong, using both the array-tilting handle and the deployment handle, tilted the unit so that the face of the array was approximately perpendicular to an imaginary line from the landing site to the earth. Finally he aligned the array to within a degree or two of an east-west orientation by using a shadow cast by a gnomon positioned on the base pallet [*see bottom illustration on opposite page*]. The entire task took about five minutes.

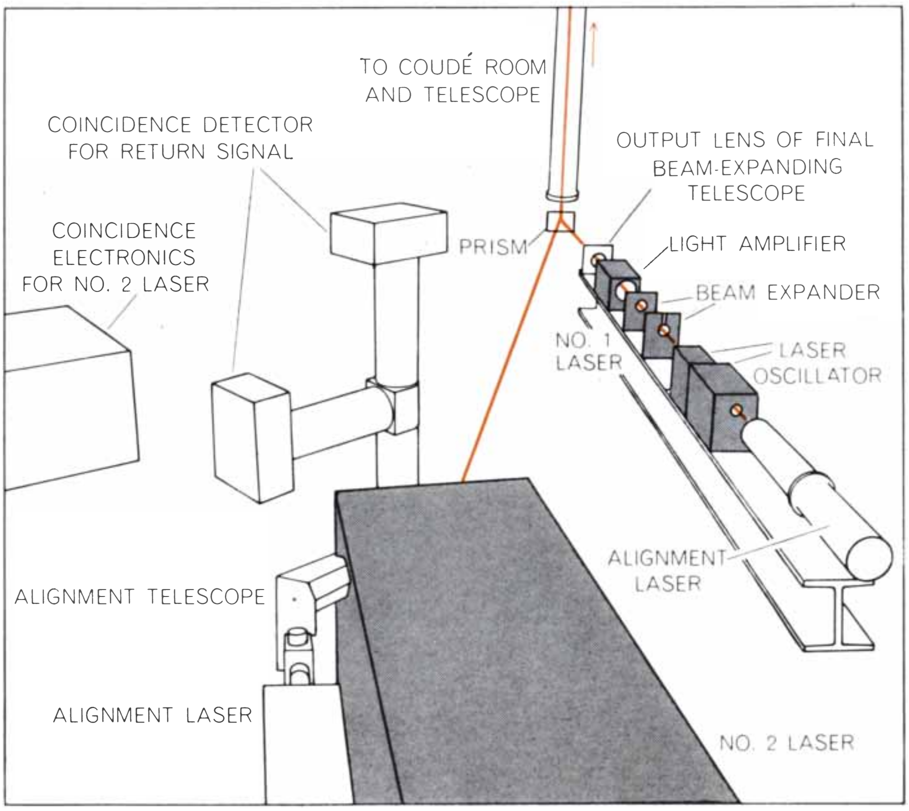
At the time of the *Apollo 11* landing



LUNAR-RANGING EXPERIMENT, in its simplest form, might involve measuring the distance to the moon at two instants six hours apart. The first measurement (*A*) is made when the observing station crosses an imaginary line connecting the center of the earth and the retroreflector on the moon. The second measurement (*B*) is made when the earth has rotated exactly 90 degrees. Account must be taken, of course, of the moon's motion: in six hours it travels about three degrees in its orbit. When corrections are made, the difference between the two values gives the station's distance from the axis of the earth's rotation.



EXPERIMENTAL AREA in a basement room below the 120-inch Lick telescope contained two laser systems, the guidance system for pointing the laser beam at the landing site on the moon and the equipment for detecting the weak return pulse (*see diagram below*).



EXPERIMENTAL APPARATUS for the lunar-ranging experiment at the Lick Observatory included two high-intensity ruby lasers. One (*right*) could fire twice a minute with a pulse duration of 10 nanoseconds; the other (*center foreground*) could fire 20 times a minute with a pulse duration of about 60 nanoseconds. The output of each of the lasers approached eight joules per pulse. With these lasers the authors and their colleagues obtained the first reflections from the retroreflector array on the moon on August 1 and August 3, 1969.

several observatories in the U.S. were standing by, ready to send laser pulses to the array and to try to detect the reflected light. At present two sites are still active. One utilizes the 107-inch telescope at the McDonald Observatory in Fort Davis, Tex., where observations are being carried out by the observatory staff in cooperation with the LURE group. The other, run by the Air Force Cambridge Research Laboratories, employs a 60-inch metal-mirror telescope located in the Catalina Mountains outside Tucson, Ariz. The first returns from the retroreflector array were recorded by a third station involving workers from Wesleyan University, the Goddard Space Flight Center and the University of California at Santa Cruz. It utilized the 120-inch telescope of the Lick Observatory on Mount Hamilton in California, which was specifically instrumented and made available for the purpose of cooperation in the initial attempts to detect reflected light signals from the array left on the moon.

Although the experiment was designed so that telescopes of moderate size could receive the reflected signals, NASA asked the Lick Observatory, with its excellent facilities, to cooperate in the initial attempts to detect the retroreflector. By using the 120-inch Lick telescope, the nation's second-largest, NASA hoped to maximize the chances of early detection of the return signals from the retroreflector on the moon. It is probably obvious that the larger the aperture of the telescope, the larger the amount of the weak return signal that is collected. What may be less obvious is that up to a certain size the larger the telescope, the greater the intensity of laser light that can be concentrated on the reflector package on the moon so that it can be reflected back.

Without any telescope at all the intrinsic beam divergence of the laser would spread the pulse of light to a diameter of about 300 miles by the time it reached the moon. Just as a telescope normally operates by taking light from an object subtending a small angle and making it appear to subtend a large angle, it can be operated in reverse to decrease the beam divergence of light sent through it. The amount by which beam divergence is reduced by a telescope is simply the ratio of the telescope aperture to the diameter of the laser. Although in principle the size of the laser spot on the moon continues to decrease as the telescope aperture is increased, in practice the turbulence in the earth's atmosphere sets a lower limit of a little more than a mile in diameter. Even for the highest-quality high-power ruby lasers a telescope with an aperture of 100 inches or so is needed to reduce the divergence of the laser beam to match this limit set by the atmosphere under good seeing conditions.

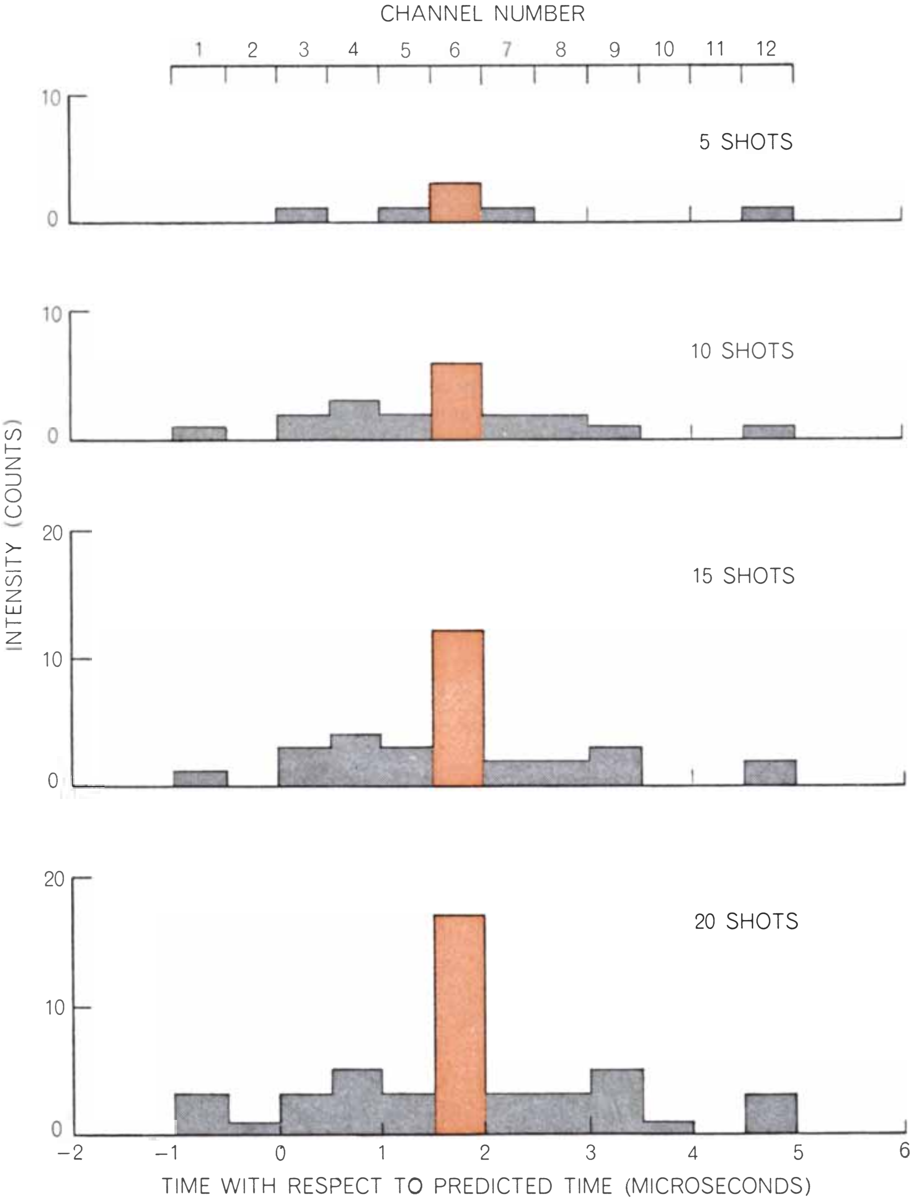
Two separate ranging systems were used at Lick. Each had its own high-power ruby laser and detection electronics. One of the laser systems could fire 20 times a minute. The other could fire only twice a minute but had a somewhat lower beam divergence. A small Galilean telescope was coupled to the output of each laser and served to increase the beam diameter from about three-quarters of an inch to two inches. The two-inch laser beam could be handled with ordinary optics without the severe risk of damage to the elements that would be caused by the more intense beam of smaller diameter.

After leaving the two-inch Galilean telescope mounted in front of the laser, the beam was bent upward by means of a prism toward a beam splitter [*see illustration on page 40*]. The prism served the dual purpose of sending the light to the beam splitter and acting as a switch between the two laser systems. Before reaching the beam splitter this parallel two-inch beam was caused to diverge by means of a negative lens chosen to make the laser light just fill the aperture of the 120-inch telescope. On leaving the telescope the beam was 10 feet in diameter and was diverging by only about one foot in 50 miles. The beam splitter was made to be 99 percent reflective for light at the wavelength of the laser and to be transparent to light of shorter wavelengths. As a result ordinary blue and green light from the moon could pass freely through the beam splitter and be reflected by a mirror into a field-viewing system that was used to set and guide the telescope.

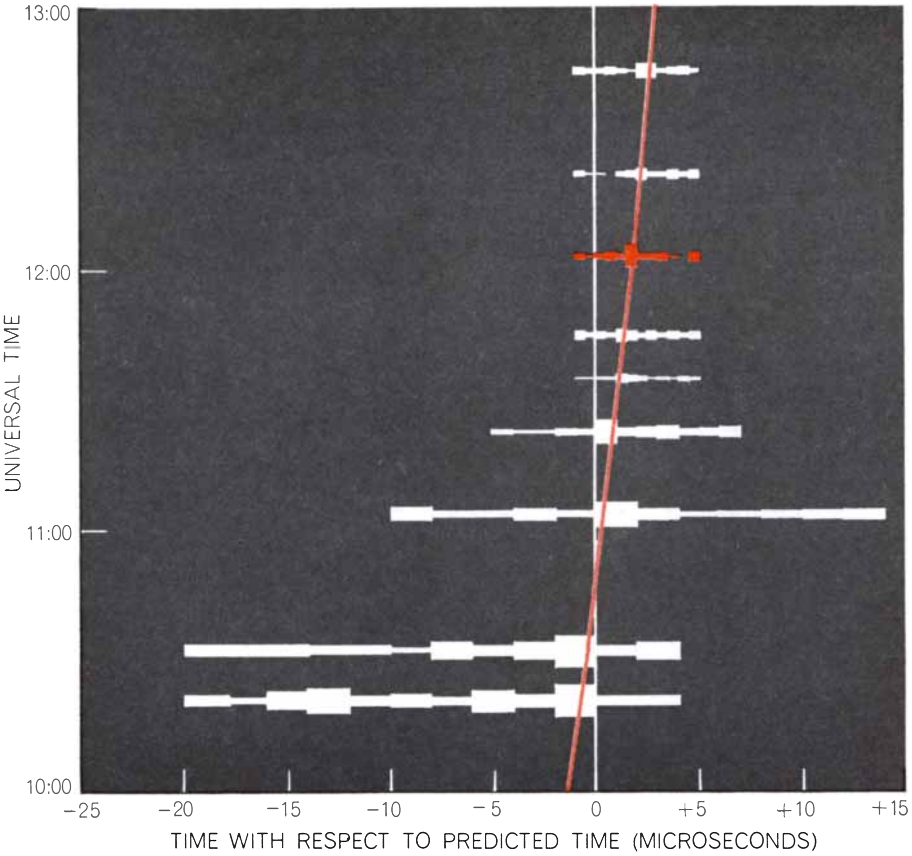
The return signal from the retroreflector followed in reverse the path taken by the transmitted laser pulse, eventually passing through the output lens of the two-inch Galilean telescope. Behind this lens was mounted a small mirror that could be flipped into position after the laser fired, thereby deflecting the return signal into the detector. The detector was located behind a pinhole that reduced the amount of background light reflected from regions well away from the landing site. In addition the detector was covered by a filter that prevented light other than that at the laser wavelength from reaching it.

The guidance system used blue-green moonlight that passed through the beam splitter to provide a view needed to aim the telescope at the landing site. The image of the moon was mixed with light from three projection reticles and then focused onto a viewing television camera. By setting the positions of the reticles to those of known lunar craters and then moving the telescope so that the images of the craters are superposed on the image of the reticles, the telescope could be accurately pointed to the landing site, which was on a flat and nearly featureless region of the moon [*see illustration on page 47*].

Several small corner cubes were mounted in front of the 120-inch mirror so as to intercept a part of the beam as it left the telescope and return it along a path exactly parallel to the outgoing pencil of light. When the laser was fired, somewhat less than 1 percent of the returned light passed through the beam splitter and entered the guidance system. This small sample of the outgoing light produced a momentary bright spot on the television monitor and showed accurately the point on the moon at which the telescope was aimed when the laser was fired. By holding the reticle images on the preselected craters and then monitoring the location of the flashes returned from the corner cubes



IDENTIFICATION OF REFLECTED LASER SIGNAL was done by dividing the output of the photon detector into 12 time channels embracing the predicted time of arrival, and observing whether or not one of the channels filled up faster than the others. The width of each channel could be varied from .25 microsecond to four microseconds. On the run shown here, made on August 1, 1969, at the Lick Observatory, the width of each channel was .5 microsecond. One channel, No. 6, filled more rapidly than the others, confirming that the returning photons were indeed coming from the retroreflector array on the moon.



DEPARTURE FROM PREDICTED ARRIVAL TIME presented a puzzle during the lunar-ranging runs made on August 1, the night return pulses from the retroreflector were first detected. Each horizontal bar represents a separate run; the thickness of each segment indicates the number of counts in each of 12 counting channels. The run illustrated on the preceding page, made at 12:03 Universal Time, is shown in color. The colored line drawn through the channels with the most counts indicates that the actual time of arrival of return pulses was at first earlier than the predicted time (*vertical white line*) and then fell behind by more than two microseconds. It was discovered that the 120-inch Lick telescope is actually some distance (about 1,800 feet) from the position used for calculating the range predictions. When the correct location is used, the predicted and actual arrival times agree.

mounted on the telescope it was possible to point the telescope with an error of less than a mile on the moon. The use of a television viewing system, which ensured that there was no danger from backscattered laser light to the eyes of the person correcting the motions of the telescope in order to hold the landing site in the field of the transmitted beam, also served to increase lunar contrast. During the daytime features were discernible on the television monitor that could not be seen by viewing the lunar image directly with the eye.

A number of problems were encountered and had to be solved before the experiment operated successfully. A particular concern was that the normal landing pattern for aircraft arriving at airports in the San Francisco Bay area takes them over the Lick Observatory. As a safety precaution the Federal Aviation Administration diverted aircraft from this normal pattern during laser operations. The first night we were allowed to fire at the moon was on the night of the lunar landing itself, July 20. Unfortunately the original range and position data were not known with sufficient accuracy. Moreover, the moon was so low on the horizon that we had only about an hour to conduct a somewhat random search for the retroreflector 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. The moon was also waxing, and this resulted in an increase in the background moonlight picked up by the detectors. Finally, the lasers themselves, which were being operated near the threshold of damage to their materials, demanded constant attention.

Four days after the 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 to use the time to work on the equipment and recheck every detail. On August 1 ranging was resumed from Lick with a new set of coordinates for the landing site from the NASA Space Flight Center in Houston. The first returns from the array were recorded at about 2:00 A.M. on August 1. Pulses fired repeatedly through the rest of the night (one every 30 seconds with an output energy of between seven and eight joules and a pulse length of approximately 10 nanoseconds) produced return signals that could only have come from the retroreflector sitting on the Sea of Tranquillity.

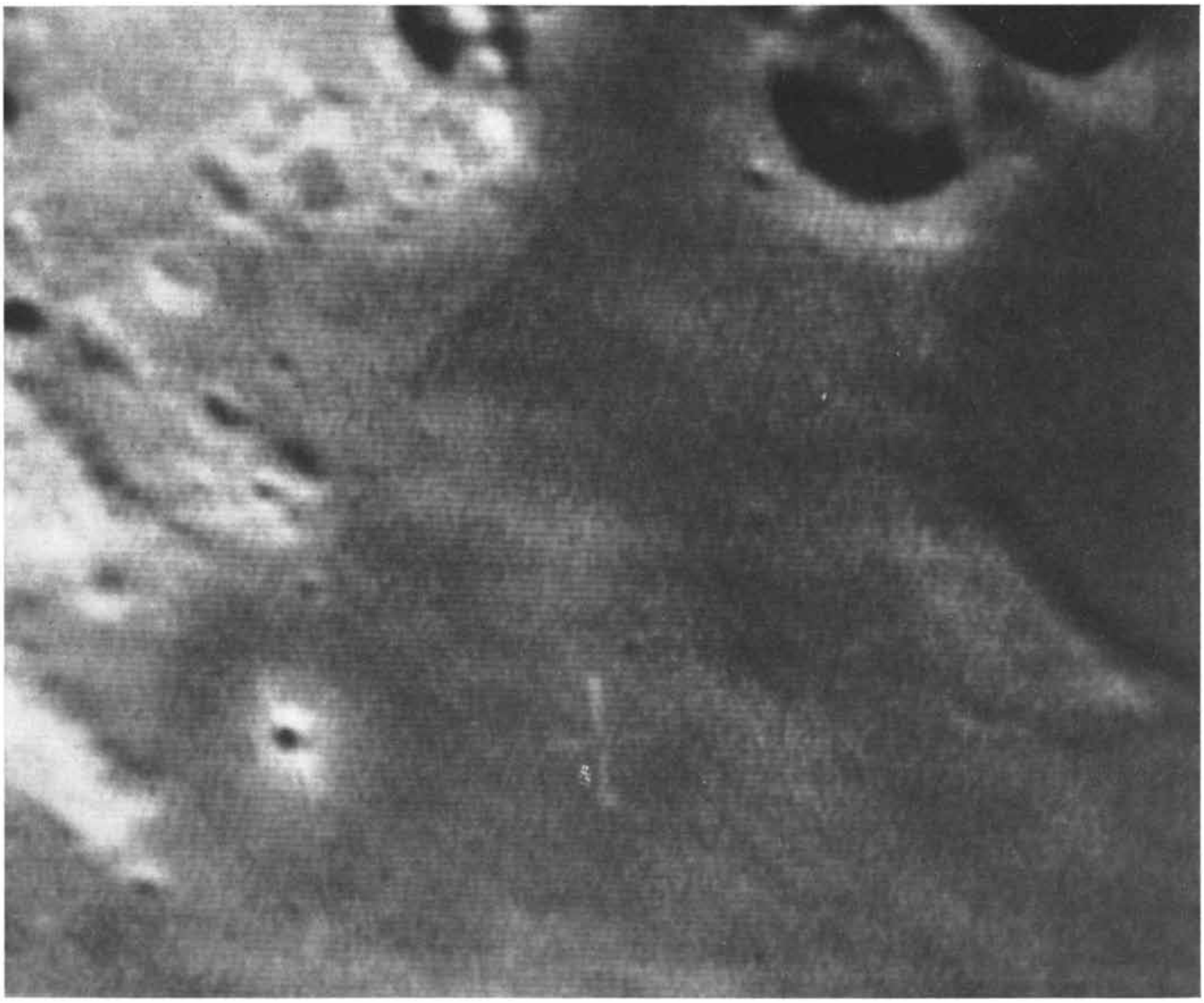
The method of counting the return pulses can be described briefly as follows. A photon, traveling at 186,000 miles per second, requires about 2½ seconds to make the 480,000-mile round trip to the moon and back. Accordingly 2½ seconds after a laser pulse is fired at the moon (the exact time delay being set for each shot according to range predictions provided by J. D. Mulholland of the Jet Propulsion Laboratory) 12 counters are activated sequentially to count any pulses that may be produced by the photodetector. The total time each counter is active can be adjusted from .25 microsecond to two microseconds. Therefore the total time available for detecting reflected photons could be varied from three to 24 microseconds. In 24 microseconds light will travel five miles; in three microseconds it will travel only 900 meters. Thus to be sure that we record the return signal we need to know the round-trip distance to the moon at any given time to an accuracy at least between these limits. The counting sequence can then be centered on the expected time of arrival. Sunlight scattered from the lunar surface produces a background that slowly fills the 12 counter channels in a random fashion. If, however, the laser beam is properly aimed at the retroreflector, and if the timing is correct, one of the channels will gradually fill more rapidly than the rest [*see illustration on preceding page*].

On August 1, the night of our initial success, the laser was fired 162 times in nine runs before the first returns were recognized. A final series of 120 shots, after various adjustments had been made, yielded 100 returns that exceeded the background level. Thus more than 80 percent of the shots produced a detectable return. On two of the runs we achieved a timing precision of .1 microsecond, which meant we had established the distance to the moon with an accuracy of ±25 feet. We were puzzled, however, by an apparent drift away from the predicted time of return [*see illustration on opposite page*]. Later the mystery was solved when we realized that the 120-inch telescope is located some distance from the spot given for the Lick Observatory in *The American Ephemeris and Nautical Almanac.* The significance of the laser experiment for geophysical measurements was thus evident the first night.

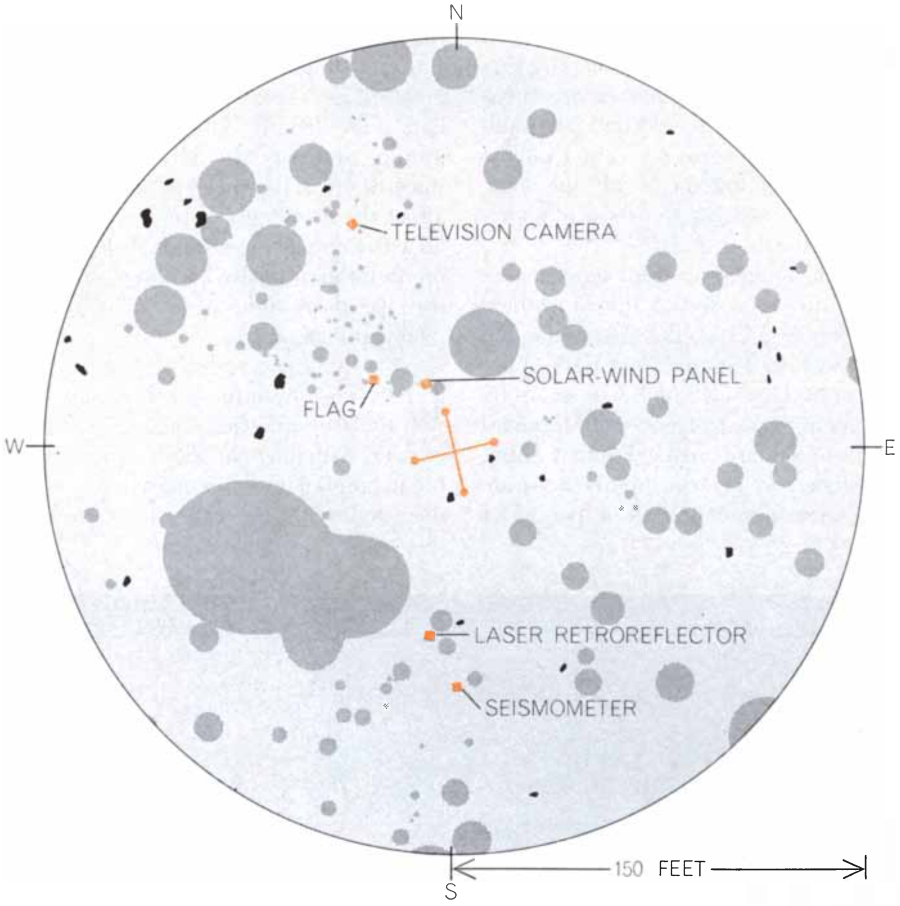
On August 3 the second laser system was operated successfully for nearly two hours. The data obtained in this run established the earth-moon distance with an error of only ±20 feet. The Lick results showed that the array had not been harmed by the *Eagle*'s blast-off, and that its operation in the lunar environment was as expected. In addition, the confirmation of the array's location on the lunar surface, together with the measured range, assisted the acquisition activities at the other stations.

Within the month return signals were successfully recorded at the McDonald Observatory and at the Air Force observatory near Tucson. The LURE apparatus at McDonald, which was set up by workers from the University of Maryland and the Goddard Space Flight Center, is designed to achieve highly accurate range measurements over a period of several years. The group there has recently been able to time the returning signal with an accuracy of two nanoseconds using a laser with a four-nanosecond pulse length. This corresponds to a range accuracy of one foot. The slight uncertainty in the speed of light does not affect the usefulness of the results, since all astronomical measurements are based on an internationally accepted value for the speed of light of 299,792.5 kilometers per second.

Let us now examine more closely the kinds of question one can hope to answer with an extended sequence of lunar-ranging measurements. An obvious result will be to define more precise-



INVISIBLE TARGET of the lunar-ranging experiment was the retroreflector array at the *Apollo 11* landing site in the Sea of Tranquillity. The guidance system that aimed a laser beam at the target through the Lick telescope incorporated a television camera, and this is a television view obtained while the astronauts were still on the moon. The landing site was located with respect to known craters. When the telescope was pointed so that a reticle fell on one of these craters, Moltke (*bottom left*), the target reticle was over the presumed position of the landing site (*bottom center*) some 25 miles away. (When this picture was taped, the data were not yet refined and so the target reticle is slightly misplaced.) In order to confirm the aim, a small portion of the laser light was returned to the television camera by retroreflectors in the telescope, so that a bright spot was superposed on the target reticle every time the laser fired.



TRANQUILLITY BASE, where *Eagle* landed, was mapped by NASA on the basis of photographs made from the landed module (*left half*) and of photographs made on an Orbiter mission and by the astronauts on the surface (*right half*). The map locates the module (*center*) as well as craters (*dark gray*), large rocks (*black*) and equipment left on the moon.

ly the motion of the moon in its orbit. The associated theoretical aspect, namely the attempt to adequately describe the motion of the moon, is among the oldest of scientific enterprises. Another experimental result will be a measurement of the lunar librations: the irregular rotations of the moon about its center that enable us to view some 59 percent of the lunar surface. Most of the apparent librations are caused by the lunar orbit's being elliptical, but residual motions are present because the mass of the moon is not evenly distributed. The retroreflector should lead to a large improvement in measuring these librations and provide the data for better calculations of the lunar mass distribution. From this knowledge it may be possible to infer something of the moon's history.

Another major objective is to learn more about the earth. Current theories suggest that the surface of the earth is subdivided into a number of large "plates" that move with respect to one another. These movements are believed to explain the drift of continents. For example, the Pacific plate is thought to be moving toward Japan at a rate of about four inches per year. After observing stations are established in Hawaii and Japan, the lunar-distance measurements will give the longitudes of these stations with such high accuracy that the expected motion should be observable within two or three years.

The data obtained from the lunar-distance measurements will also determine the position of the North Pole with an accuracy of about six inches, which is five or 10 times more accurately than it is now known. The position of the pole moves around on the surface of the earth in a rather complicated way, and it may travel nearly 200 feet along a roughly elliptical path during a year. The excitation mechanism for this polar wobble is still much in debate: it cannot be conclusively stated whether the mechanism is atmospheric mass shifts, variations in the coupling of the core and the mantle or mass shifts in the crust. The last hypothesis has been suggested by a correlation of pole shifts with major earthquakes, and hence better measurements may lead to a more complete understanding of earthquakes. The lunar-distance measurements will also allow more accurate determinations of the earth's rotation rate than have previously been possible.

Finally, the sensitivity afforded by the presence of the array on the lunar surface will make it possible to use the moon again, as it was used by Newton, as a testing ground for gravitational theories. We are interested in seeing whether or not the Newtonian gravitational constant is slowly decreasing with time due to the expansion of the universe, as has been conjectured by a number of physicists. A definitive test of these hypotheses may be obtained by monitoring the motion of the moon. In addition, there is the possibility of seeing some very small but important effects in the moon's motion that are predicted by the general theory of relativity.

In principle the method of extracting scientific results by measuring the precise distance to the moon is straightforward, but in practice many subtle factors must be taken into account. In the simplest case one wants to measure the change in distance from a given observing station during a six-hour period [*see illustration on page 43*]. After various corrections have been made in the relative motion of the earth and the moon during this period, one ends up with the distance of the station from the axis of the earth's rotation. To do this in practice many readings are taken with the moon high in the sky, and the distance from the axis is computed from the amplitude of the 24-hour component. Other information about the station location can be obtained in a similar fashion.

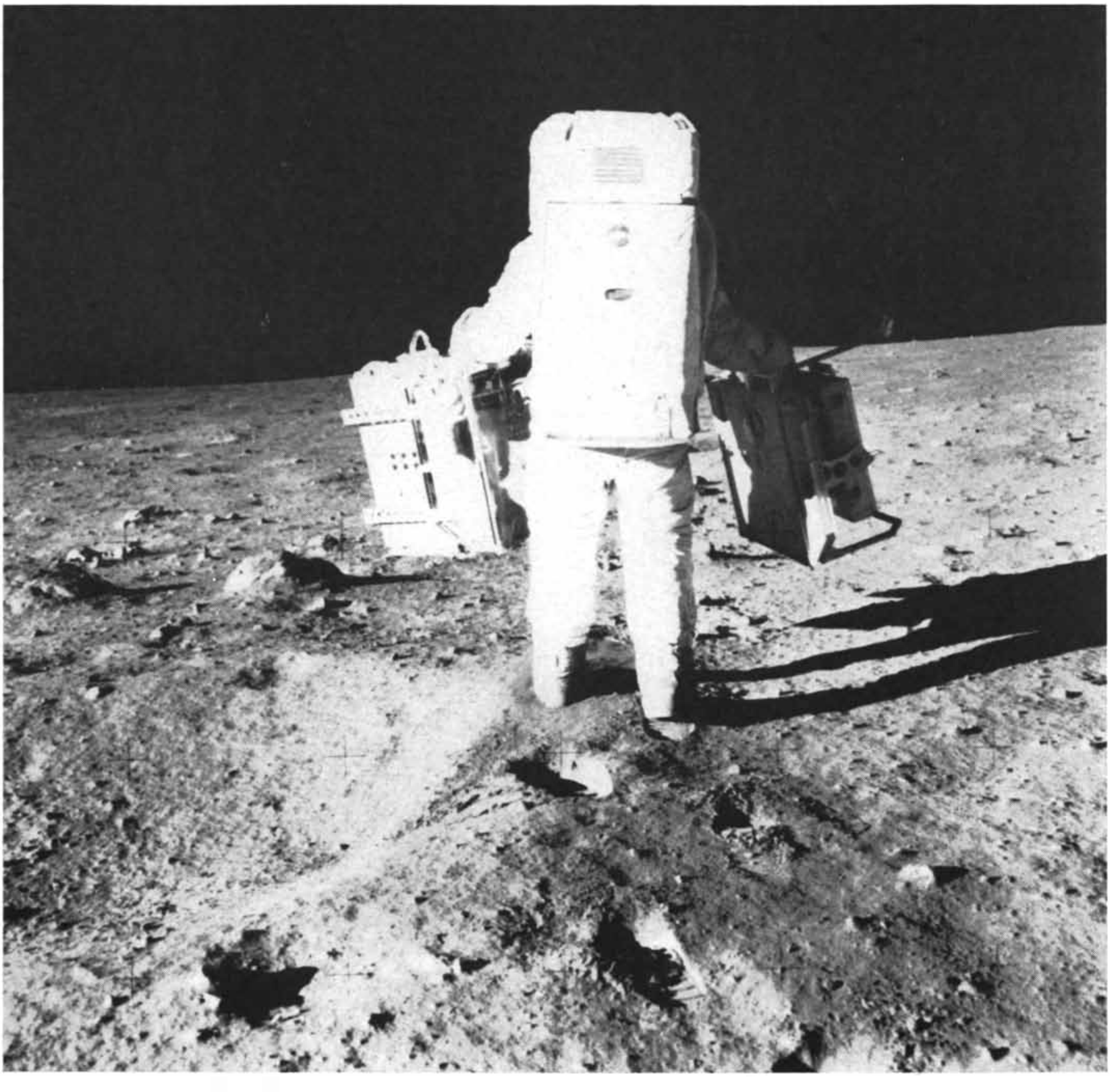
The major complexity that arises is that the moon's motion is not accurately known to begin with. A precise analytic theory of the lunar motion has been developed over the past 90 years by G. W. Hill, E. W. Brown and W. J. Eckert. The planetary perturbations have never been calculated with sufficient accuracy, however, to give the six-inch precision necessary to match the anticipated accuracy of laser ranging. Hence it is better to take advantage of modern electronic computers by calculating the entire lunar motion by direct numerical integration of the equations of motion for the entire solar system.

Once this has been done, the calculated lunar range as a function of time is compared with the range observed by bouncing the laser beam off the retroreflector. Improvements are then introduced to make the calculated result agree more and more closely with the observed one. If the basic theory of motion in a gravitational field is correct, the results should converge.

It is not obvious, however, how in this procedure one can separate information about the moon from information about the earth. One can imagine, for example, that some unexpected wobble in the earth's rotation (or a movement of one of the surface plates) might be interpreted as a perturbation in the moon's motion. This is not the place to explore how such possibilities can be disentangled. Suffice it to say that good methods for separating lunar from geophysical effects are believed to exist. With data from four or more observing stations at well-chosen locations, one can also separate local aberrations such as continental drift from motions of the earth as a whole.

Clearly if the lunar array is to be put to optimum scientific use, a number of observing stations around the world are needed. International cooperation is not only desirable but also essential to the full exploitation of this new astronomical tool. We are delighted to learn that colleagues in France, the U.S.S.R., Czechoslovakia and Japan are preparing to make lunar-range measurements.

The placing of the retroreflector array on the moon last July by the *Apollo 11* astronauts has resulted in a dramatic change in man's ability to measure the earth-moon distance. Since the array has now survived several lunar nights and days without apparent harm, we have reason to hope that it will continue to function as intended, providing a primary bench mark in space for many years to come.



LUNAR PORTER, Edwin Aldrin, was photographed by Neil Armstrong, commander of *Apollo 11*, as he walked away from the *Eagle*, carrying the laser retroreflector array in his right hand and the passive seismic experiments package in his left. Later Armstrong carefully positioned the retroreflector array on the lunar surface, about 65 feet from the landing module, as shown on page 39. There had been some concern that the blast of *Eagle's* ascent-stage rocket might cover the array with dust, but the concern proved unfounded.