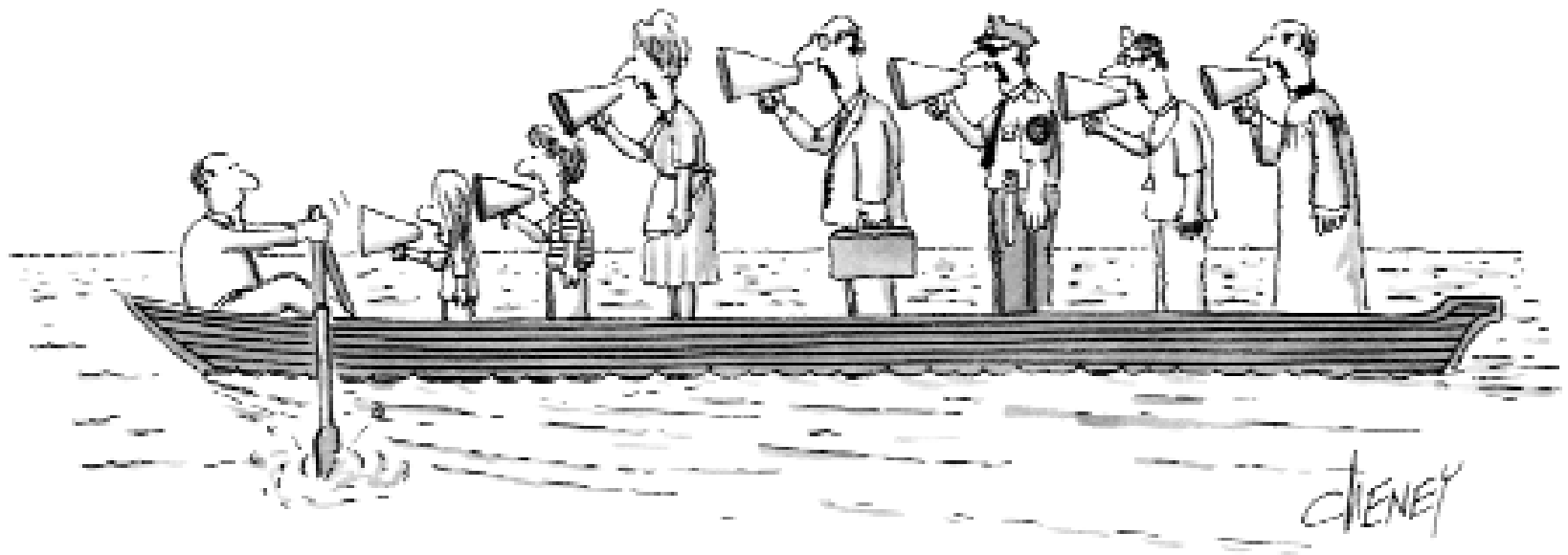


Goddard Talk
Lunar Laser Ranging
Jim Faller

JILA (NIST and University of Colorado) and the
University of Glasgow

The Archives, University of Colorado at Boulder Libraries, holds the James Faller Collection. The collection contains Dr. Faller's Lunar Laser Ranging papers etc. Currently, Archives personnel are surveying the collection to create an initial finding aid. For more information, please email <arv@colorado.edu>





Laser Ranging to the Moon

How Evolving Technology
Enables New Science; And...
How Do Ideas Come About.

Measurement Capability –
The Enabler of Scientific Progress

Pastorale

(Andantino) (♩ = 56)
legato

Gt. G.O. Astrophysics Biological Computational
Fluids Optical Nuclear

Precision Measurement

Plasma Chemical History Condensed Matter Atomic Polymer

Fundamental Constants

Materials Particle Education
Gravitational Physics

**I have always enjoyed
building things...**

ERECTOR

DEVELOPED AT THE
GILBERT HALL OF SCIENCE

THEY
WHISTLE

THEY'RE
ALL-
ELECTRIC

THEY
BUZZ
WITH ACTION



“The stumbling way in which even the ablest of scientists in every generation have had to fight through thickets of erroneous observations, misleading generalizations, inadequate formulations and unconscious prejudice is rarely appreciated by those who obtain their scientific knowledge from text books.”

James Bryant-Conant (1940), President of Harvard University; and also a very good chemist.

“It is almost a miracle that modern teaching methods have not yet entirely strangled the holy curiosity of inquiry; for what this delicate little plant needs more than anything, beside stimulation, is freedom.”

A. Einstein, Philosopher-Scientist.
The Living Philosophers, Inc., Illinois (1949)

The Indiana University Period

- Milo Sampson, Ken Ford...go to Princeton
- Where's that
- That's were Einstein lives
- Richard Eden

The Princeton Period 1955-1963

Remembered Colloquiums

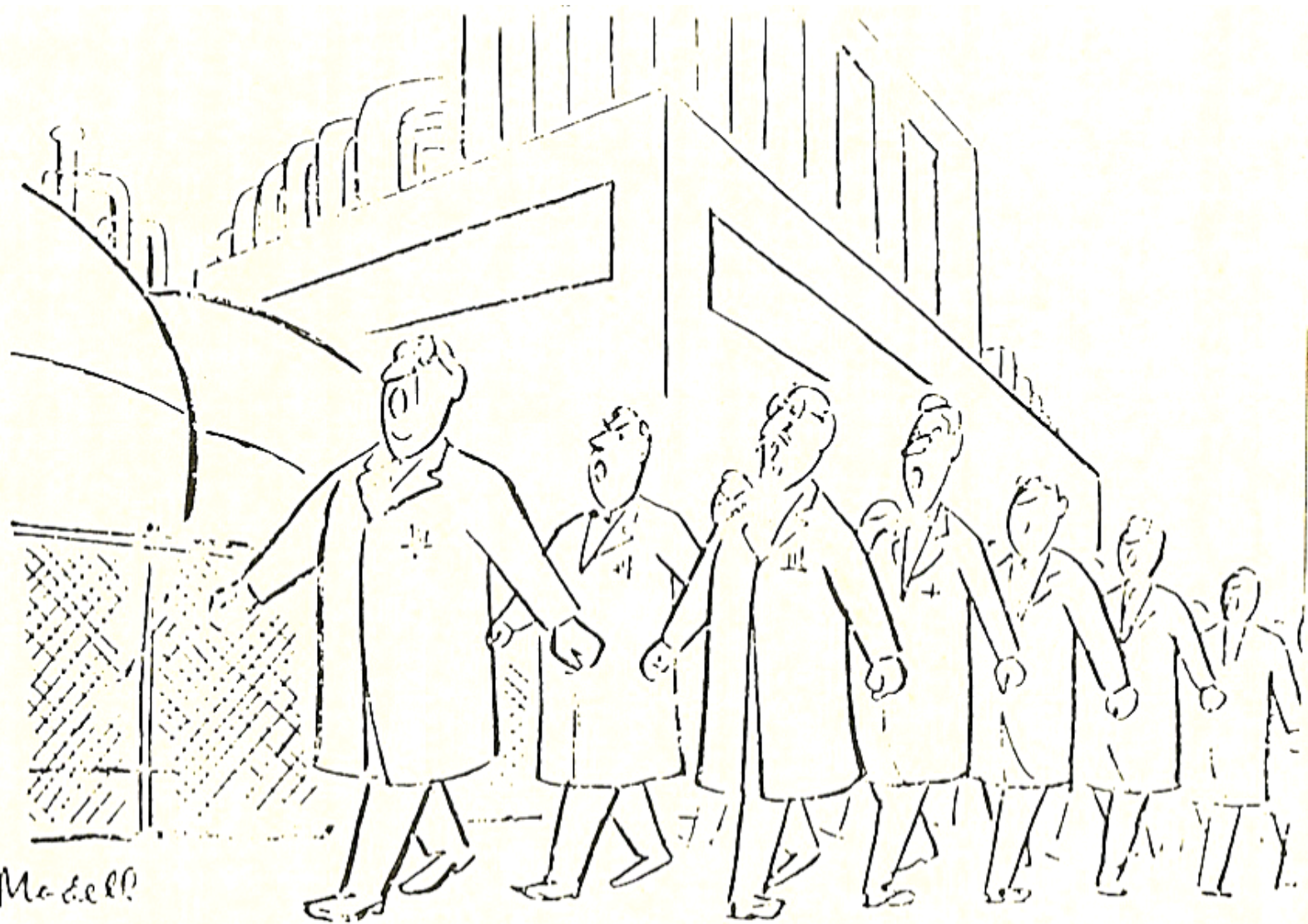
- Wu (Columbia)...Parity Violation
- Weber (Maryland)...Gravity Waves
- R.V. Jones (Aberdeen)...Design of Apparatus
- Bohr (Copenhagen)...
- ...
- Javan (MIT)...He-Ne Gas Laser

Swain Hall Graffiti

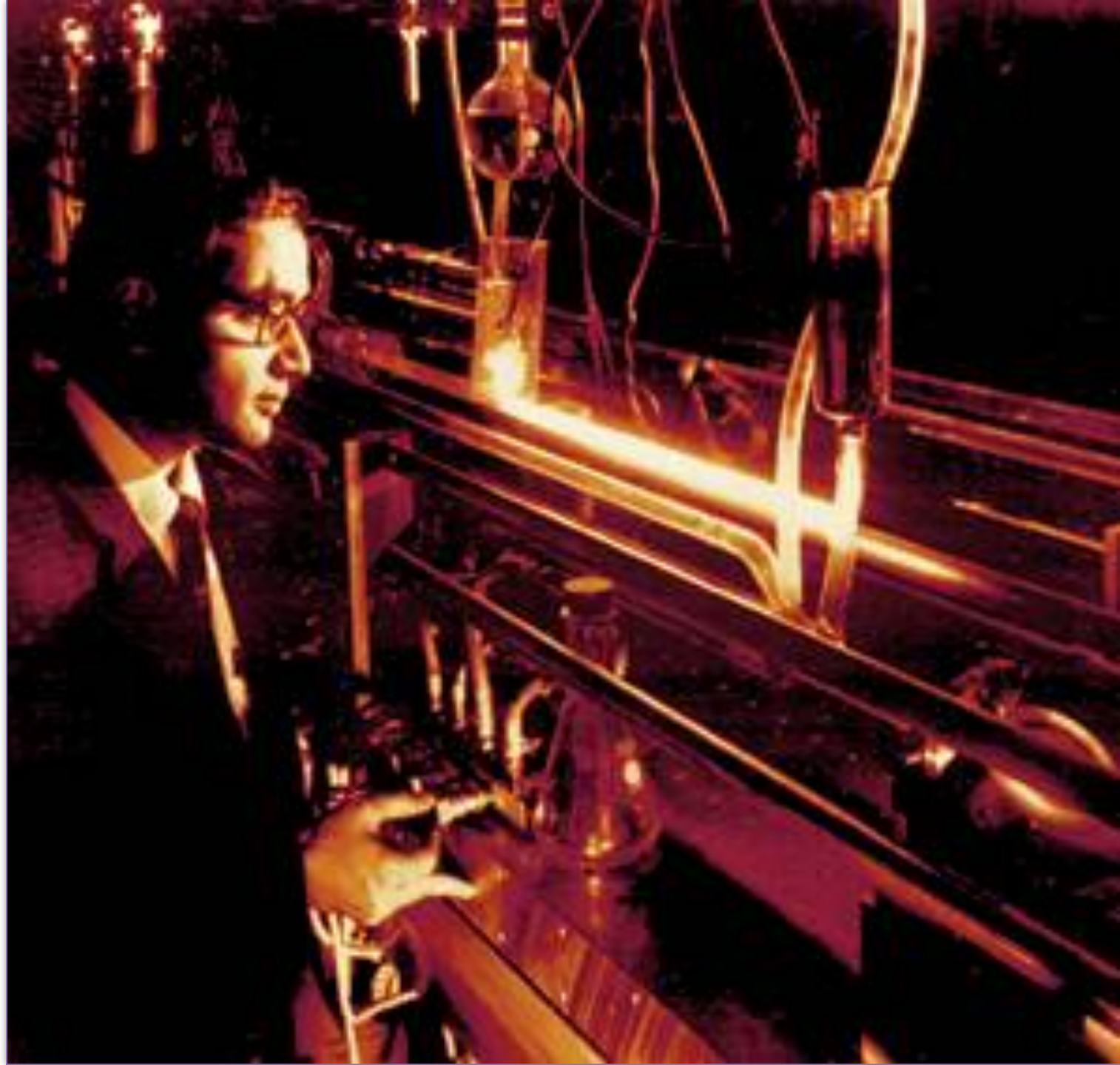
(Men's Room, Princeton Mathematics Department circa 1960)

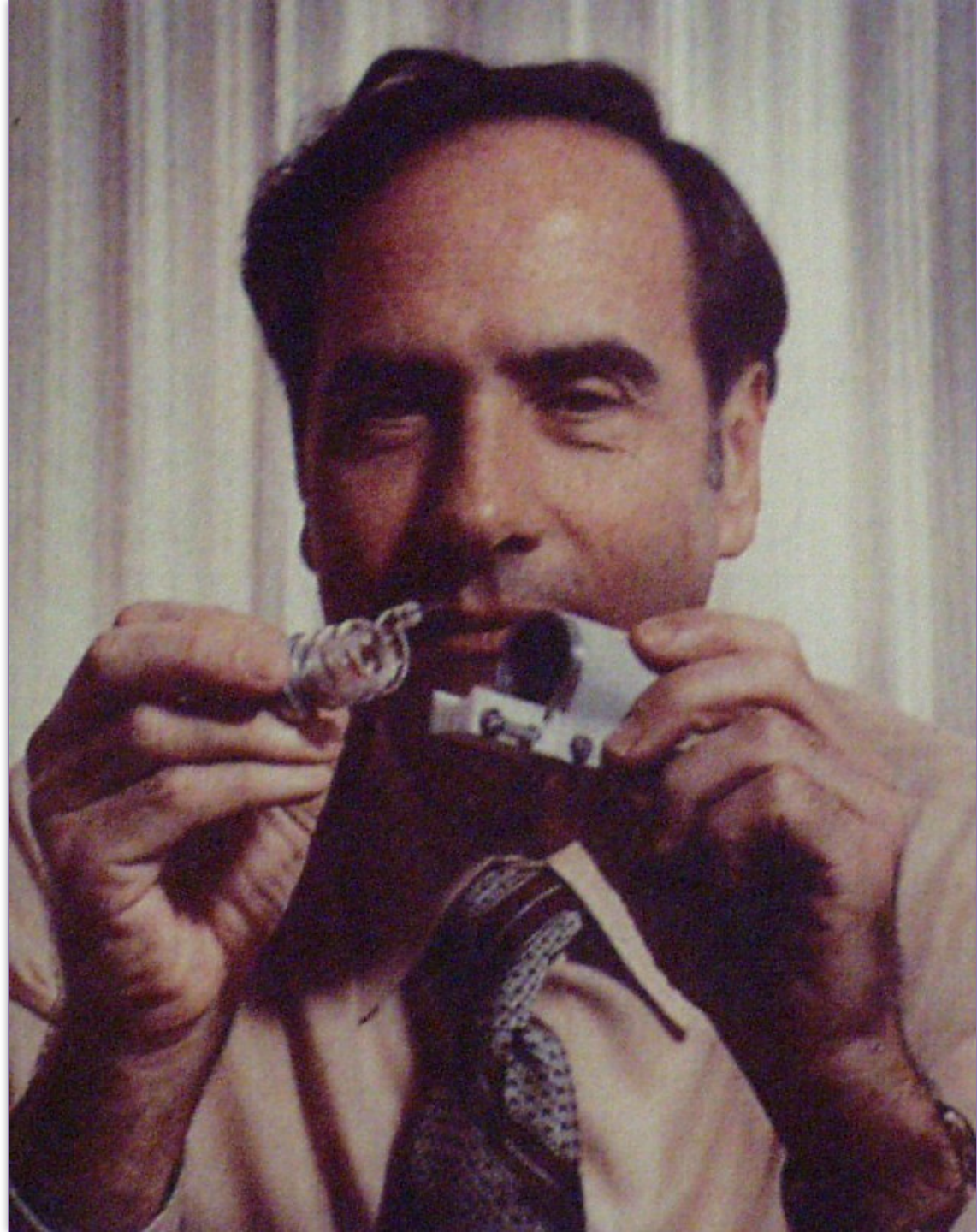
$$2+2 = 5$$

...for large values of 2



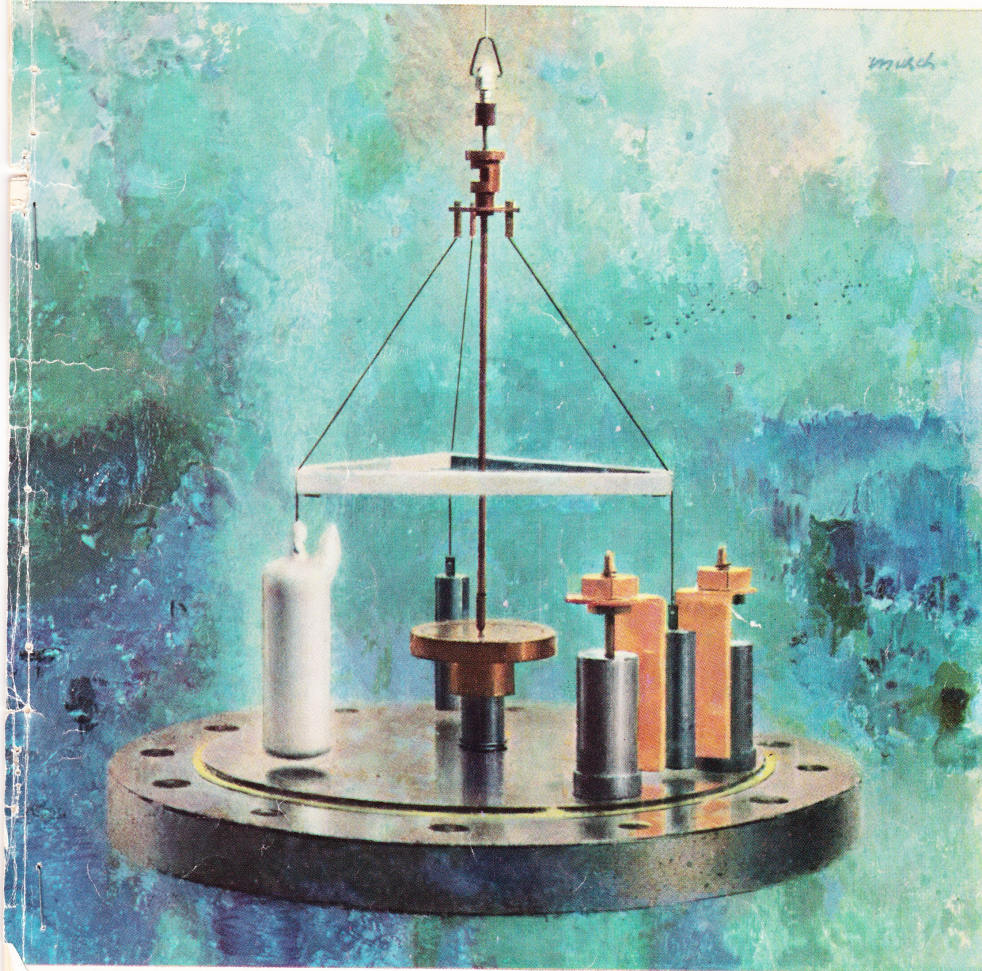
"From the cyclotron of Berkeley to the labs of M.I.T.
We're the lads that you can trust to keep our country
strong and free."





SCIENTIFIC AMERICAN

G. Fuller



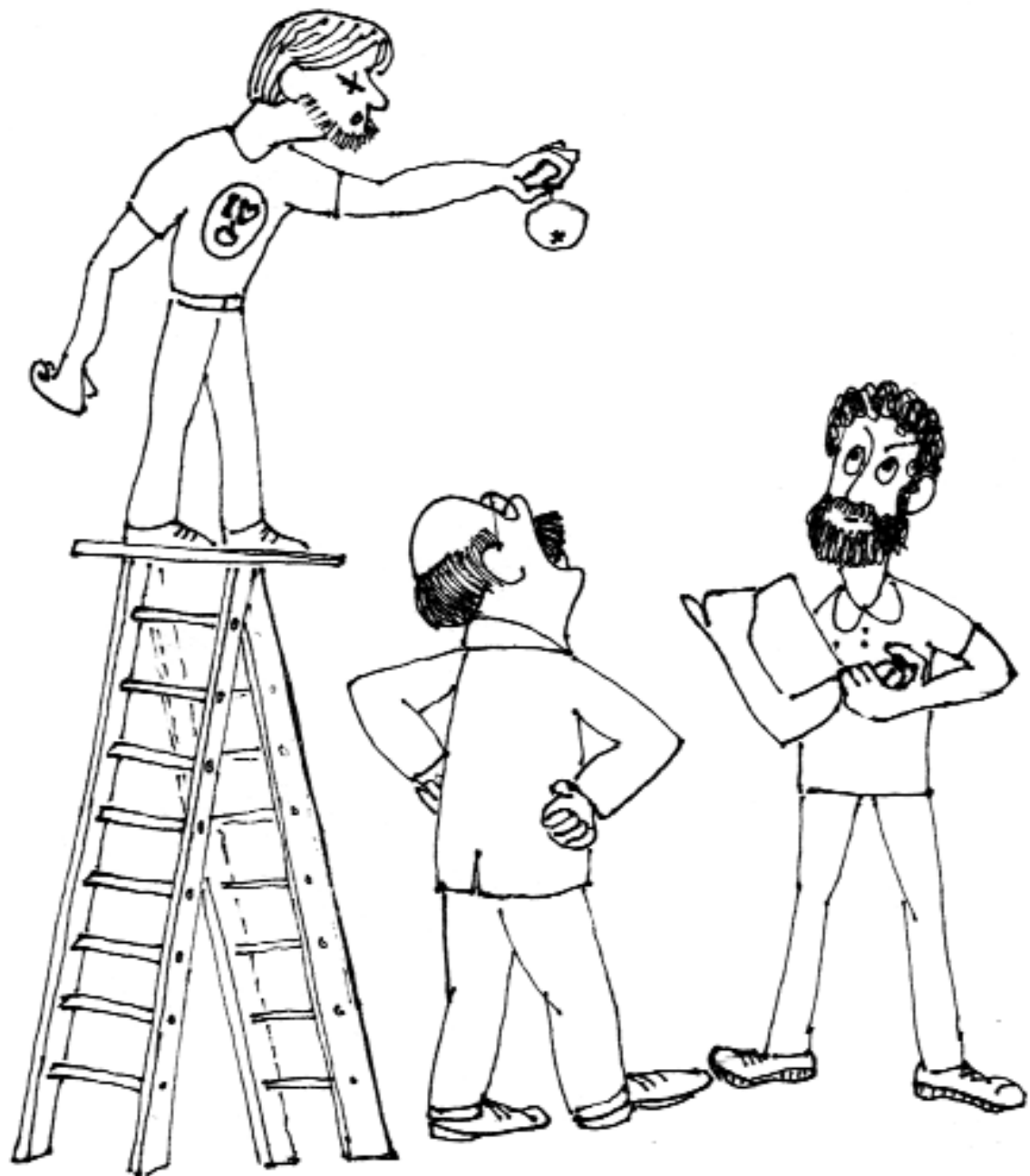
GRAVITY EXPERIMENT

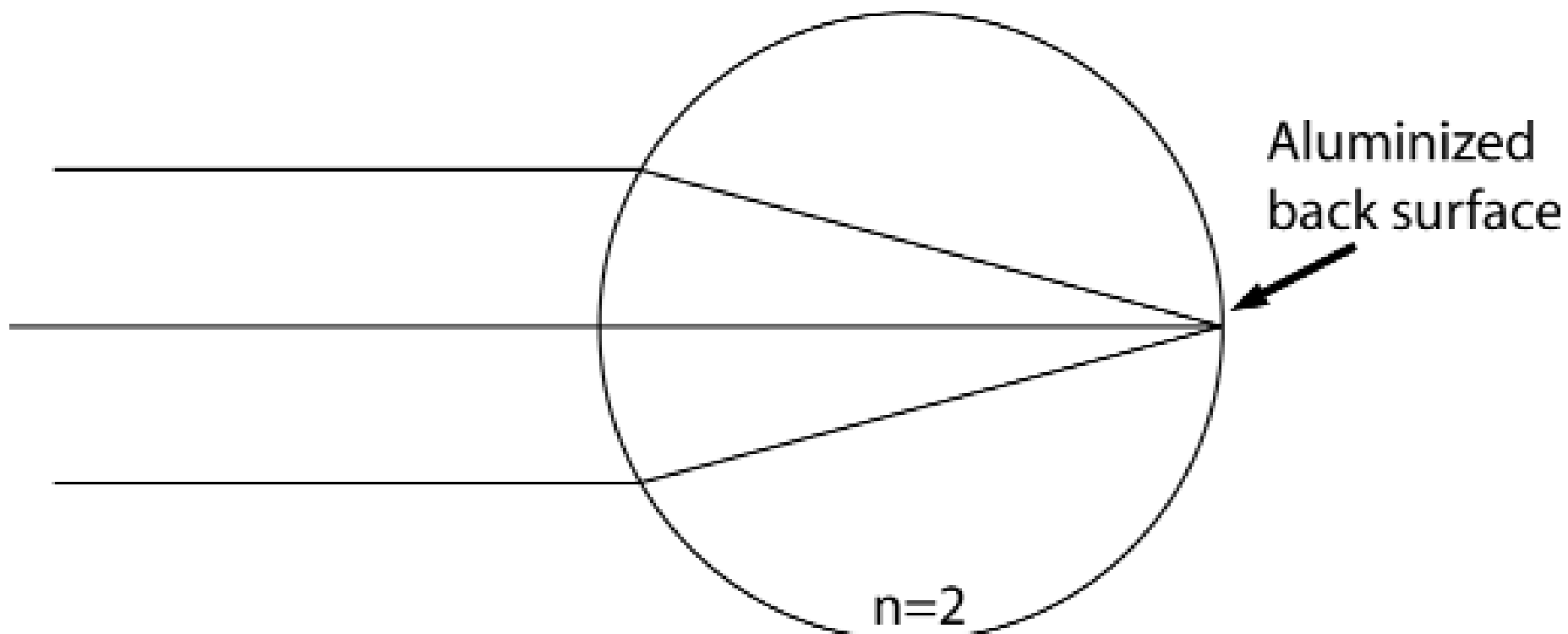
FIFTY CENTS

December 1961

Hycon Eastern... became Itek

[Were trying to measure g interferometrically using a using a Meggers Hg 198 spectral lamp for the light source to permit submarine navigation]





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OUR REF.

YOUR REF.

DATE

FT/HN.

25th July 1958.

Mr. James E. Faller,
Palmer Physical Laboratory,
Princeton University,
PRINCETON. New Jersey.

Dear Mr. Faller,

I am in receipt of your letter of 13th July,
but regret I am unable to help you in the matter of
glass spheres.

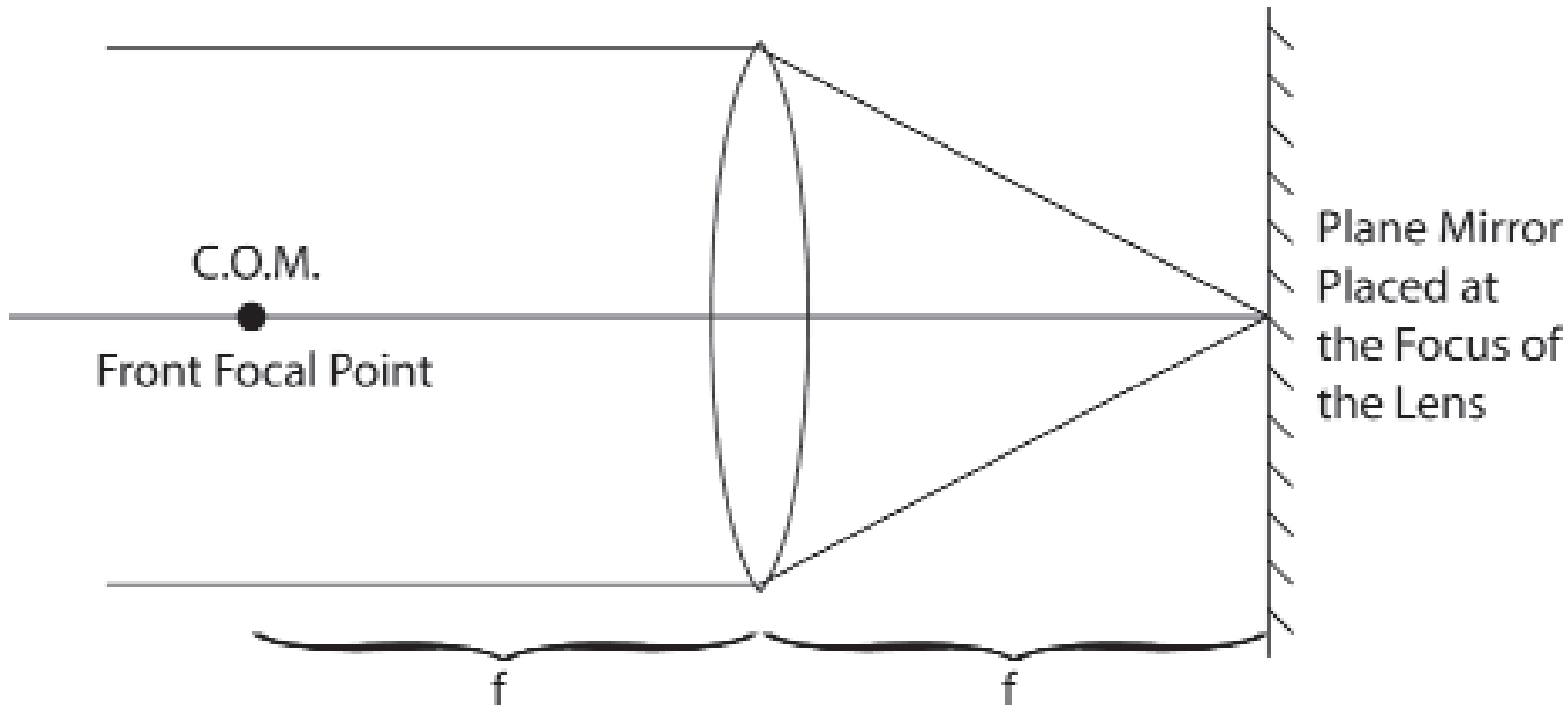
We have not had to make any for a considerable
number of years, and the only optical glassworker we
had that could do so has now passed away.

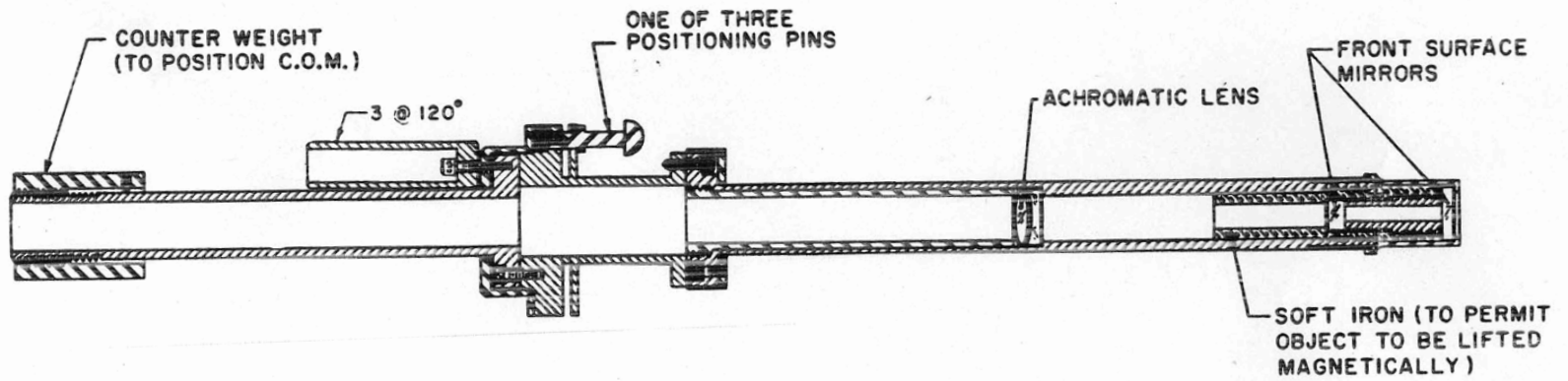
I do not know anyone in this country who makes them;
their application is too limited for regular production.

Regretting my inability to help you in the matter,
I remain.

Yours sincerely,

F. Twyman
F. Twyman.

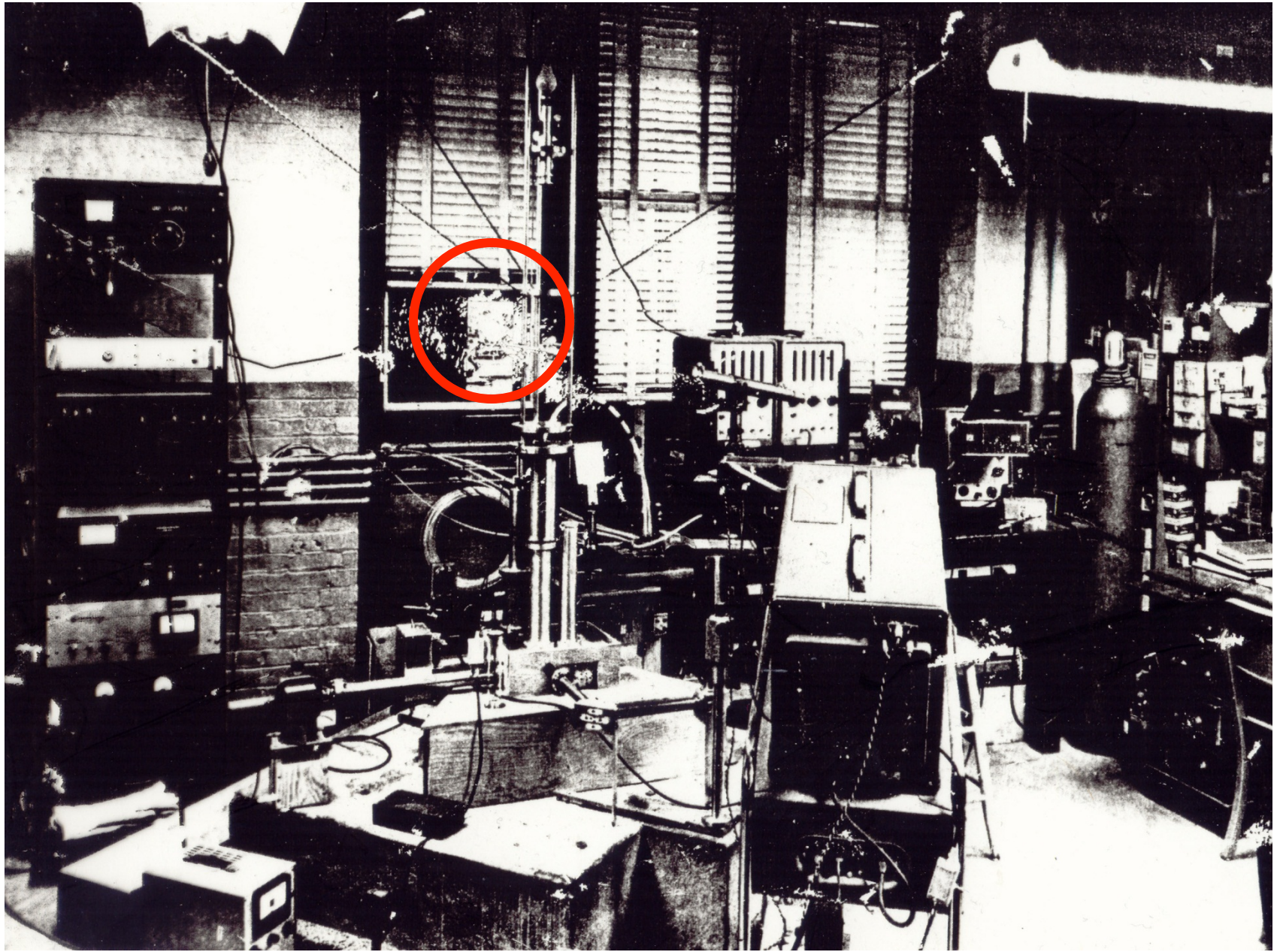


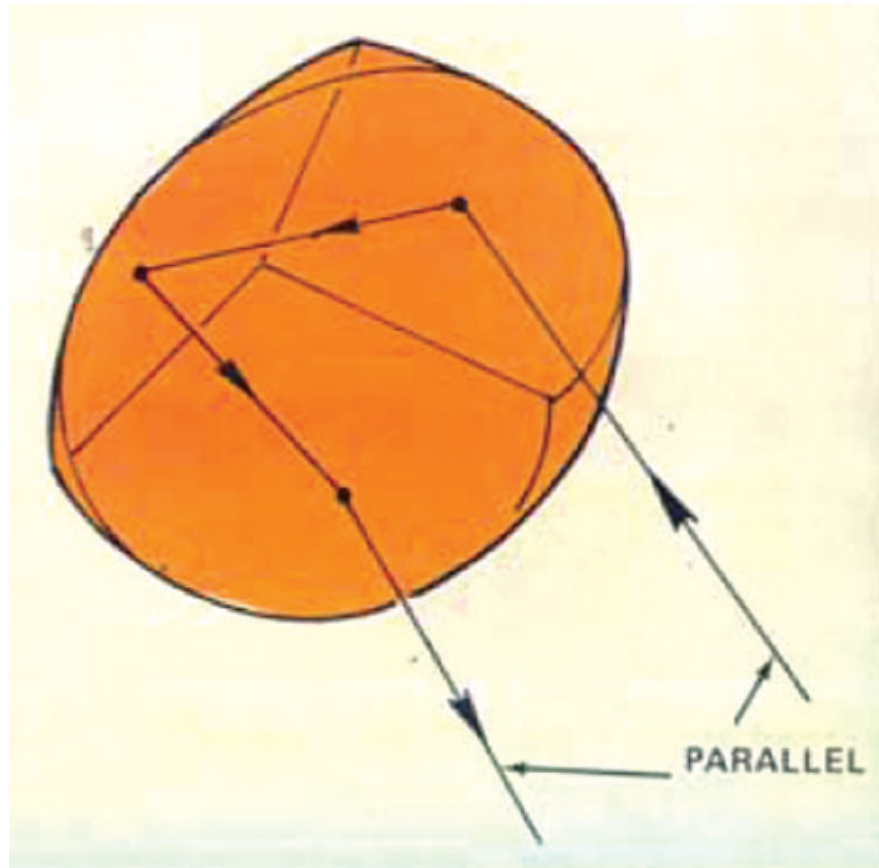


 STAINLESS STEEL (Non-magnetic Type)

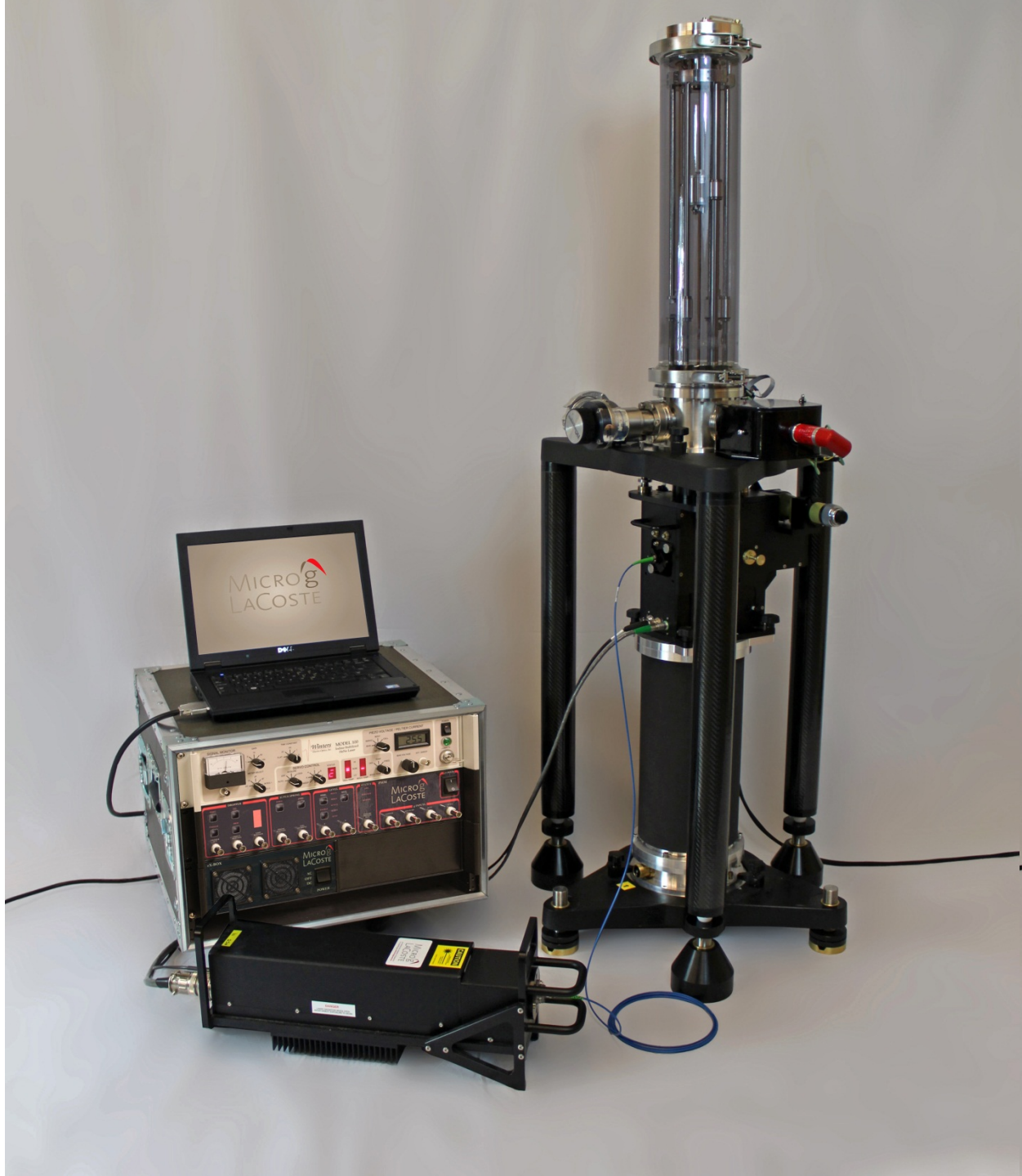
 ALUMINUM

DROPPED OBJECT (INTERFEROMETER "MIRROR")





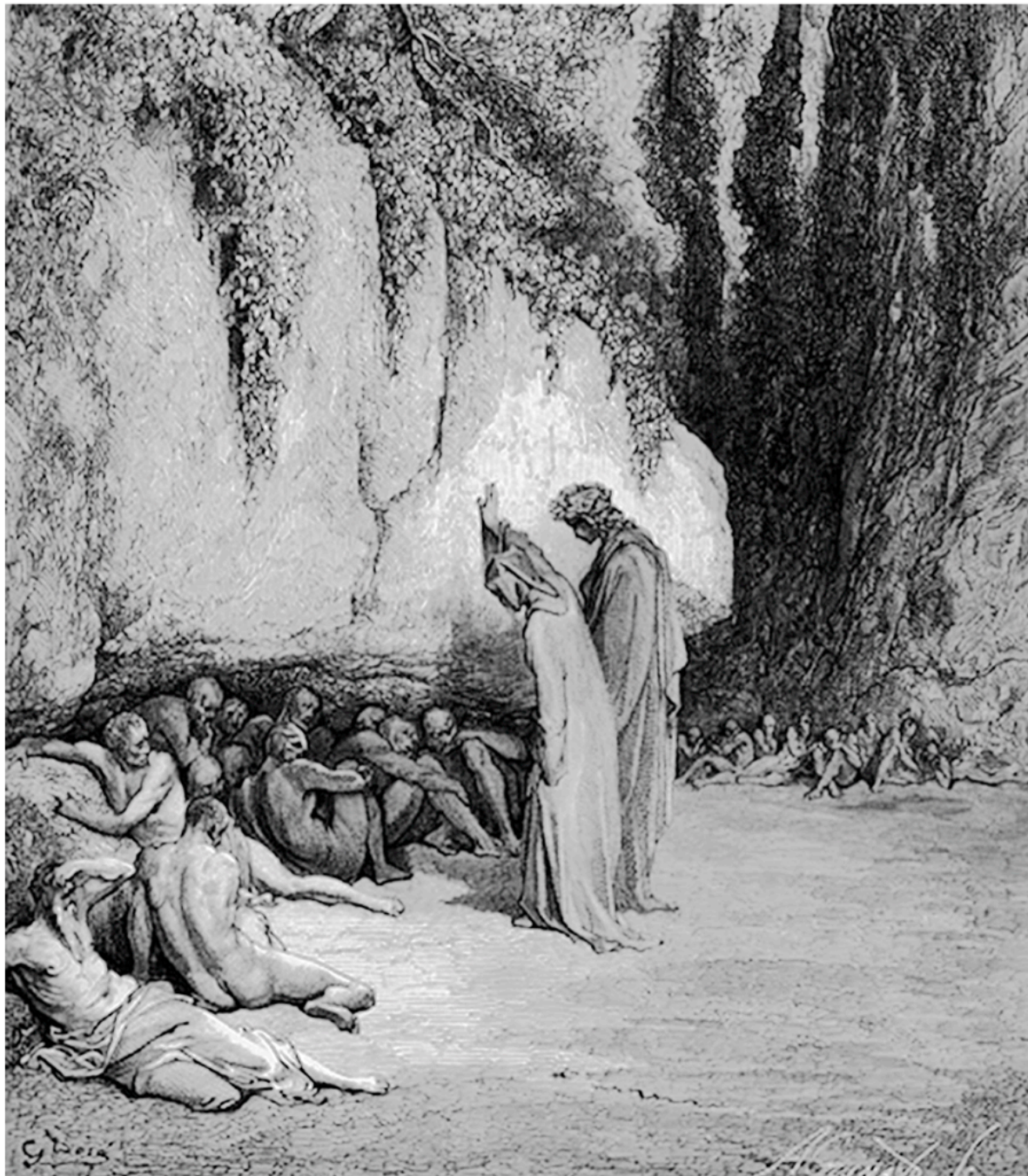






I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth. No single space project...will be more exciting, or more impressive to mankind, or more important...and none will be so difficult or expensive to accomplish...".

President John F. Kennedy, May 1961



And you're certain that none of you want to learn about science?

Dicke group evening meetings

Faller

PRECISION OPTICAL TRACKING OF ARTIFICIAL SATELLITES *

W. F. Hoffmann, R. Krotkov and R. H. Dicke
Palmer Physical Laboratory, Princeton University

July 15, 1959

INTRODUCTION

The authors are serving as a committee for the whole group to study the problem of instrumentation for precision optical position measurements of artificial earth satellites. Our interest in this problem concerns the use of artificial satellites for precision experiments on gravitation. These interests were briefly described in a letter to Dr. Clemence of the Naval Observatory, dated May 8, 1959. A copy of this letter is attached.

The following ideas are not wholly those of the authors, but in part are due to the whole group: J. Brault, R. H. Dicke, J. Faller, W. Hoffmann, L. Jordan, R. Krotkov, S. Liebes, R. Moore, J. Peebles, J. Stoner, and K. Turner.

The precision tracking of a satellite reduces to determining its position relative to axes fixed in the earth or relative to the star field. There is a substantial advantage in determining position relative to the star field as this removes systematic errors associated with thermal tilt in telescope mountings.

In the techniques to be discussed the background star field is recorded photographically. A photographic recording of the satellite position is employed when a sufficient number of photons is available. When the number of photons

* Supported by the U. S. Atomic Energy Commission, the Office of Naval Research and the Higgins Scientific Trust Fund.

March 25, 1962

~~Proposed Lunar Package~~
~~(A Corner On The Moon)~~
Reflector
A Corner On The Moon

This note describes what is felt to be both a useful and at the same time a practical lunar package. The total weight involved would be only 2 to 3 pounds, and it could be constructed to withstand a rather hard landing. Once there, the only requirement for it to function successfully is that its landing leave it free to bounce and roll until it comes naturally to rest.

~~Such a~~ ^{This containing an optical corner} lunar package has been built.

Recently there has been considerable discussion concerning the possibility of bouncing a laser off the "naked" moon, and detect the reflected light returning to the earth. ~~In addition to this being "nice to do",~~ ^{This} it would permit a precise earth-moon distance measurement to be made. (~~That is~~ The distance here being, ~~for example,~~ measured to one of the larger maria).

In order for this to be done, a rather large aperture is needed to collect the reflected photons as is seen from the following calculation.

$$30 \text{ joules/laser burst} \sim 10^{20} \text{ photons/burst}$$

All of which will hit the moon and scatter back into a solid angle of approx. 2π steradians. The number of the reflected photons

collected will be $\frac{\text{Solid \& } \mathcal{A} \text{ collector}}{2\pi} = \frac{\left(\frac{30}{4 \times 10^{10}}\right)^2}{2\pi}$

^{if we use} ~~assuming~~ a 12 inch telescope (30 cm.) ~~and~~ ^{Assuming} 1/10 of the photons which hit the moon are reflected, ^{the number collected by our telescope} will be

$$10^{20} \times \frac{1}{10} \times \frac{(30)^2}{(4 \times 10^{10})^2} \times \frac{1}{2\pi} \sim 1 \text{ photon/laser burst}$$

which is not ^{very encouraging} ~~terribly many~~. (With a 100 inch telescope one

~~one~~ collect, ~ 81 photons/burst.)

Perhaps we could
discuss this.
Bib D.

Professor Dicke,
Would you see if this makes
any sense.
Jim Fallon

A Proposed Lunar Package
(A Corner Reflector on the Moon)

This note describes what is felt to be both a useful and at the same time a practical lunar package. The total weight involved would be only 2 to 3 pounds, and it could be constructed to withstand a rather hard landing. Once there, the only requirement for it to function successfully is that its landing leave it free to bounce and roll until it comes naturally to rest. This lunar package containing an optical corner has been built.

Recently there has been considerable discussion concerning the possibility of bouncing a laser off the moon and detecting the reflected light returning to the earth. This would permit a precise earth-moon distance measurement to be made. (The distance here being measured to one of the larger maria.)

In order for this to be done, a rather large aperture is needed to collect the reflected photons as is seen from the following calculation:

$$30 \text{ joules/laser burst} \sim 10^{20} \text{ photons/burst}$$

All the photons will hit the moon and scatter back into a solid angle of approx. 2π steradians. The number of reflected the reflected photons that will be collected is given by

$$\frac{\text{Solid } \angle \text{ of collector}}{2\pi} = \left(\frac{30}{4 \times 10^{10}} \right)^2 / 2\pi$$

if we use a 12" (30 cm.) telescope. Assuming 1/10 of the

photons which hit the moon are reflected, the number collected by our telescope will be:

$$10^{20} \times \frac{1}{10} \times \frac{30^2}{(4 \times 10^{10})^2} \times \frac{1}{2\pi} \sim 1 \text{ photon/laser burst.}$$

which is not very encouraging. (With a 100" telescope one collects

~ 81 photons/laser burst.)

The lunar package proposed here would permit a substantial improvement to be made in the number of returning photons that are collected. First note that for a fixed payload (all other things being equal) it would be best to put a single large corner on the moon rather than a lot of smaller ones. This may be seen as follows:

$$\text{Number of corners} \sim \frac{1}{l^3} \quad (l = \text{linear size})$$

$$\text{Collect area for light offered} \sim \text{Number of corners} \times l^2 \text{ or } \sim \frac{1}{l}$$

The size of the spot on earth resulting from diffraction in the corners affecting the returning photons is given by

$$\left\{ 2 \times \frac{l}{2} \times (\text{Earth-Moon Distance}) \right\}^2 \sim \frac{1}{l^2}$$

It therefore follows that the efficiency which is proportional to collection area on moon/diffraction area on earth $\propto l$.

Therefore So it is better, so to speak, to put all the photons in one corner. In practice (to minimize the possibilities of landing mishaps) it would be best to place several corners on the moon rather than "the ideal" single corner reflector.

A one-pound corner cube (the one used in the model package) offers a collection area of approx. 40 cm². Using a 12" (30 cm.) telescope to set the diffraction size of the spot on the moon (an idealization neglecting practical difficulties both in reference to actual lasers and to atmospheric disturbances), the area on the moon is given by:

$$\left(2 \times \frac{8 \times 10^{-5}}{30} \times 4 \times 10^{10} \right)^2 \sim 3 \times 10^{10} \text{ cm}^2$$

The number of photons returned will be those collected, namely:

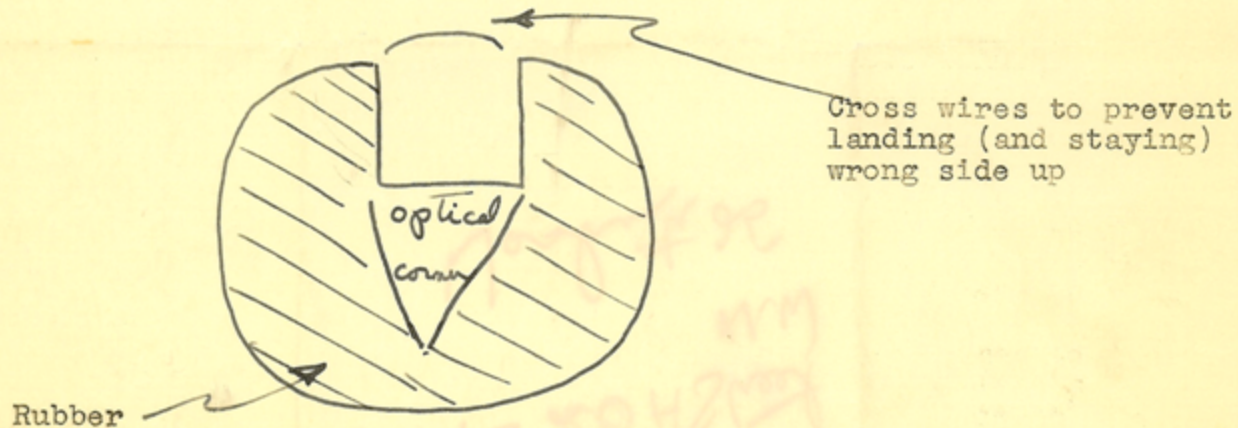
$$\frac{40}{3 \times 10^{10}} \times 10^{20} \sim 10 \text{ " photons/burst}$$

These will form a larger patch on the earth due to the smaller size of our corner (compared to our 12" telescope), but ^{now} ~~not~~ we have a larger photon collecting area. The net effect of this is that we again ~~lose~~ ^{lose} by the same factor, namely 10^{-9} resulting

in 100 photons being collected in this case. Here, in principle, the number of photons collected goes as the fourth power of the telescope aperture so that going to a larger telescope is even more useful ~~than~~ than in the case of bouncing photons simply off the moon where improvements are only proportional to the square of the aperture.

In addition to permitting the afore-mentioned experiment, a group of corners on the moon would provide the long-desired marking stripes on the moon and thereby permit precise period measurements to be made. The moon would then be a precision gravity clock.

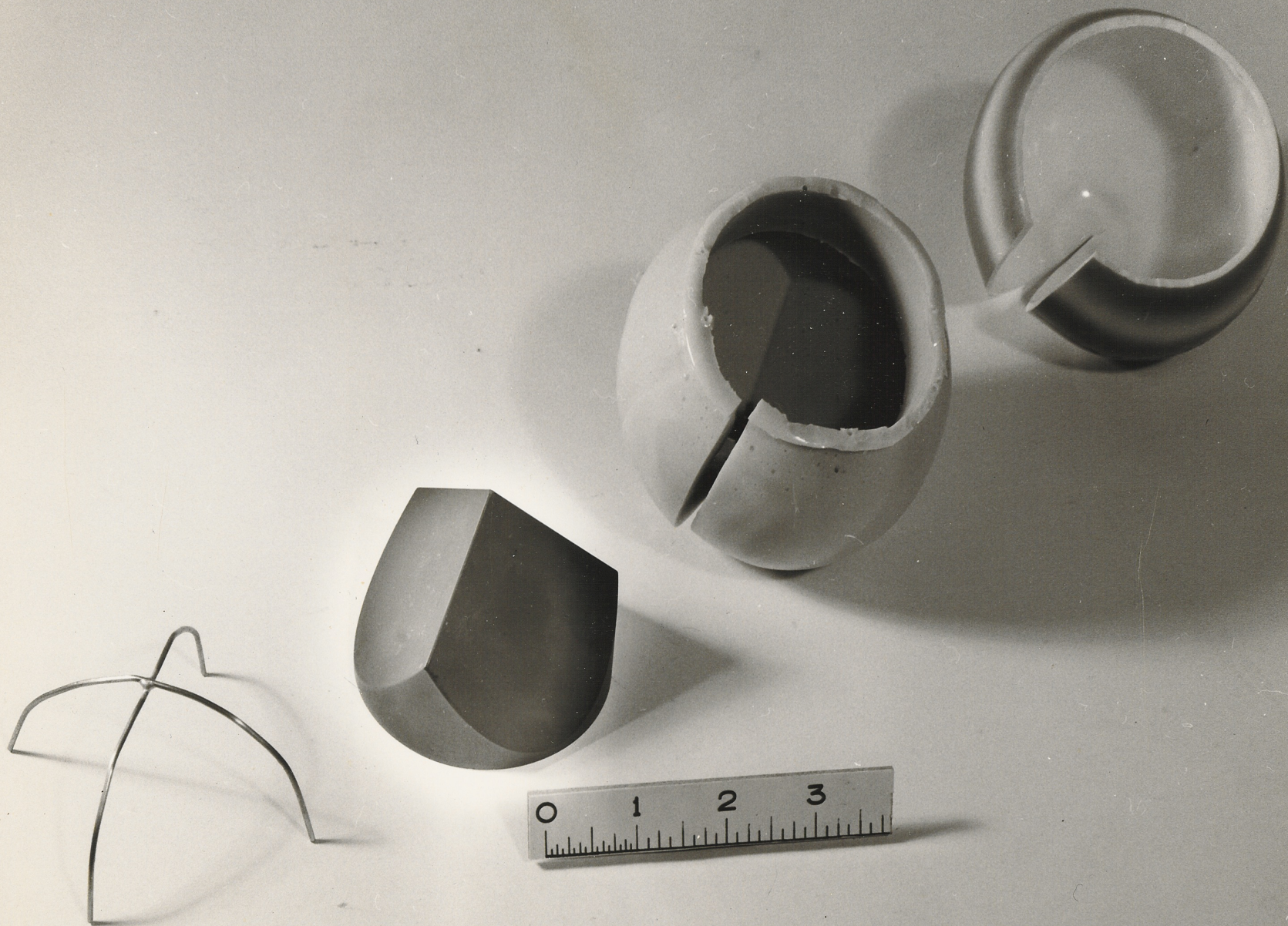
Proposed package (cross section)

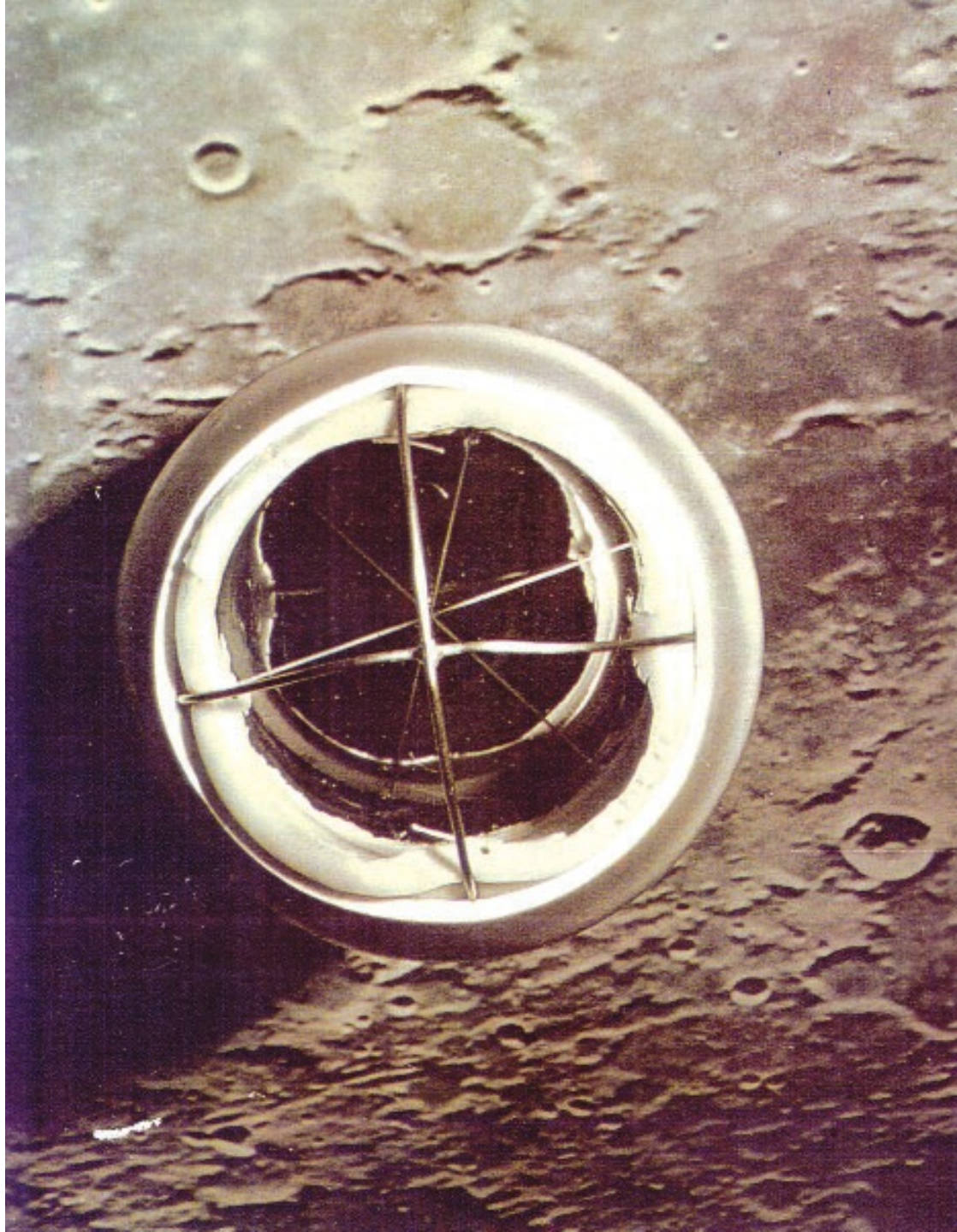


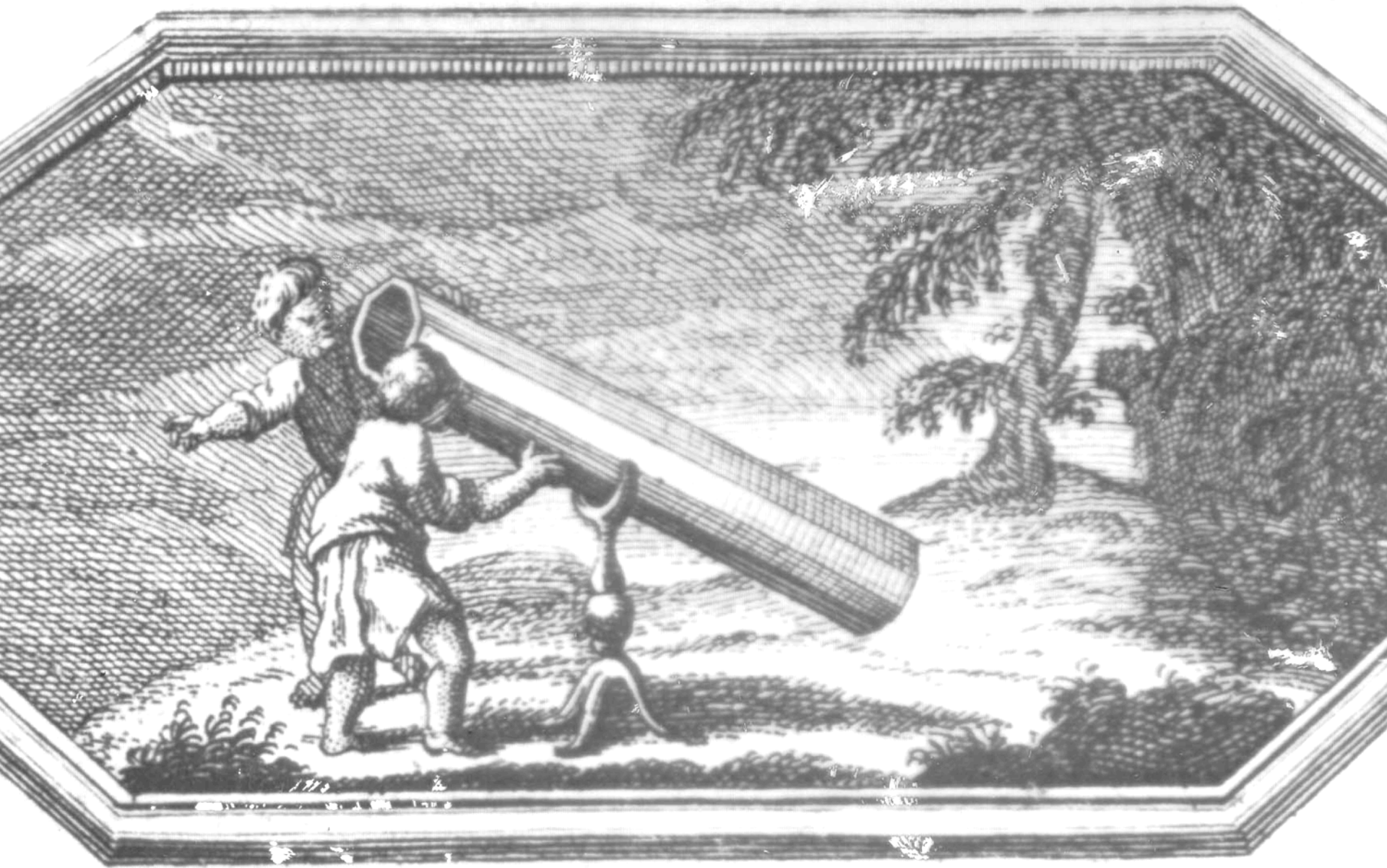
Note that the COM is arranged to be below the center of the ball when the corner is properly positioned, and therefore the package will position itself with the corner pointing up.

“A month or two in the laboratory will save you an hour in the library.”

Experimental Physicist' s Motto







July 1962

Project Luna See*

In order to determine some of the possibilities of optical maser radar we conducted experiments with the Moon as a target.

PREDICTED PERFORMANCE

The basic system was conceived as consisting of a pulsed transmitter and a receiver. The transmitter was to be a ruby maser, radiating at 6934 Å, and focused by a 12-inch reflecting telescope. The receiver was to be a photomultiplier tube illuminated by light collected in a 48-inch reflecting telescope. The photomultiplier output was to be displayed on a suitably delayed oscilloscope trace (the A-type radar display).

If the light from the ruby were perfectly coherent over the cross section, and illuminated the 12-inch telescope uniformly, the beam divergence, given by λ/D , would be about 2×10^{-5} radians. Even allowing for a beam width 100 times greater, the resulting spot on the Moon, at a range of 200,000 miles, would constitute a point source for re-radiation to the Earth. Thus, if we assume the reflected light to obey Lambert's law, we get a modified "radar" equation, in which the received light energy W_R at the photocell varies as R^{-2} instead of R^{-4} .

$$W_R = W_T \frac{A\rho}{\pi R^2} K_a^2 K_T K_R$$

where A is the area of the receiving aperture, R is the distance to the Moon, W_T is the energy of the transmitted pulse, K_a is the transmission through the atmosphere, K_T and K_R are the optical efficiencies of the receiving and transmitting system respectively, ρ is the normal albedo of the lunar surface. We estimated (or knew) the constants of our system to have the following values: $A = 1 \text{ m}^2$, $K_T = 0.75$, $K_R = 0.37$, $K_a = 0.85$, $\rho = 0.15$ (for a bright spot on the Moon), $R = 384,000 \text{ Km}$, and thus $W_R/W_T \approx 6.5 \times 10^{-20}$. If $W_T = 50 \text{ joules}$ at $\lambda = 6934 \text{ Å}$, there would be about 12.5 photons incident on the detecting photosurface per pulse.

Competing with our own signal are three noise sources: the dark current emitted by the photosurface, the ambient light from the lunar surface, and light scattered in the atmosphere and the telescope. Manufacturer's data indicated dark currents for a cooled photomultiplier corresponding to about 10 photoelectrons/sec. Since the maser pulse is about $\frac{1}{2} \times 10^{-3} \text{ sec}$ in duration, the expected, received photon flux is of the order of 2.5×10^4 photons/sec. At 6900 Å the efficiency of the photo surface is about 3 per cent, so that the expected signal component is about 750 photo electrons/sec. Thus, the dark-current noise was expected to be negligible. At night, and aiming at the dark side of the Moon, the principal interfering sources are the Earth-light and the scattered light of the crescent. The new Moon appears in the sky too early in the daytime, with a consequent high level of scattered light in the atmosphere. In addition the earthshine on the dark portion of the Moon is maximum at new Moon. Near full Moon, the dark portion of the Moon is darkest, but the large amount of light scat-

tered from the sunlit surface would make operation very difficult. The brightness of the dark side of the Moon varies by about a factor of 15 from just after new Moon to shortly before full Moon (a variation of 100° in phase).¹ From published data² it is estimated that the power density in the visible range, incident on the Earth, reflected from the dark side of the Moon at first quarter, is $S = 3.3 \times 10^{-15} \text{ watts/m}^2 \times (\text{km}^2 \text{ of Moon area})$. In a bandwidth of 7 Å, centered at 6934 Å, this corresponds to a power density of about $0.7 \times 10^{-17} \text{ watts/m}^2 \text{ km}^2$, or about 28 photons/sec (meter)² (kilometer)². Existing estimates of scattered light indicate an intensity 1 to 10 times greater than the above number.

The field of view of the receiving system was assumed to be limited by an aperture to an area on the Moon of about 5000 km². Thus the background signal received by our 1 m² telescope was expected to be about 1.4×10^6 photons/sec due to Earth light, plus a component up to 10 times greater due to scattered light. Assuming 5×10^6 photons/sec, and then including K_R and K_a , we find a "noise" flux of 160,000 photons/sec incident on the photocell. The maser pulse duration is about $\frac{1}{2} \times 10^{-3} \text{ sec}$, and thus the expected background photon flux per pulse length would be about 80, and might be as low as 30.

These numbers indicate that the signal-to-noise ratio to be expected, for the parameters chosen, might be of the order of 0.5 or less.

DESCRIPTION OF THE APPARATUS

The telescope used for transmitting was of a Cassegrainian reflecting type, focal length 4.55 meters, aperture 0.29 meter (12 inch). The maser unit, except for small modifications to the cooling system, is as described by Bowness, Missio and Rogala. (See next communication, this page.) Each of the four flashlamps is connected through a 0.3-mH choke to an 840-μF bank of capacitors, charged to 2200 volts. In laboratory tests the output of the maser, as measured with a calorimeter, was observed to be about 50 joules. Since the cooling in the telescope installation was improved over that used in the above tests, the actual radiated energy may have been somewhat greater. The maser beam is focused (Fig. 1) by a lens of 102-mm focal length onto the focal plane of the transmitting telescope. Measurements were made of the size of the focused spot by burning holes through an aluminum foil. The resulting holes had a diameter of about 0.9 mm. If the hole size is assumed to indicate the image size, the beamwidth radiated by the telescope is 0.2 mrad, maximum. The receiving telescope (Fig. 2) was also a Cassegrainian reflector of focal length 18.2 m and collecting area of 1.00 m² (48-inch diameter).

A dichroic mirror was used to separate the red part of the spectrum so that the residual green light could be used for viewing through an eyepiece. The red portion of the

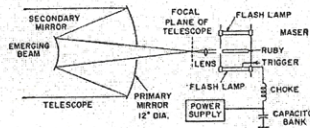


Fig. 1—Simplified diagram of transmitter.

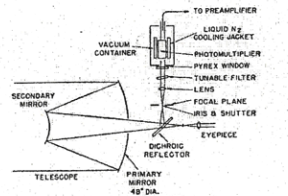


Fig. 2—Simplified diagram of receiver. The interference filter was tuned by rotating its plane with respect to the optical axis of the system.

TABLE I

1	2	3	4	5	6	7
Eastern Standard Time	Region of the Moon	Number of Flashes	Number of Intervals	Average Noise	S.D.	Average Count in Expected Interval
May 9, 1962; 21 ^h 56–22 ^h 07	Albatengius 15°58'E	11	15	1.11	0.28	1.91
May 10, 1962; 21 ^h 52–22 ^h 34	Copernicus 10°N20°W	23	16	1.39	0.22	1.74
May 11, 1962; 21 ^h 57–22 ^h 50	Tycho 43°S10°W	30	22	1.42	0.16	1.83
22 ^h 54–23 ^h 15	Lomonosovianus 50°S20°W	16	17	1.52	0.19	2.32

spectrum passed through a camera shutter and iris assembly at the focal plane, and was then collimated by a lens. The adjustable iris allowed us to modify the field of view accepted by the photomultiplier. Throughout the experiments the diameter of the circular opening of the diaphragm was 3.6 mm, equivalent to a field of view of 0.2 mrad. After the diaphragm and lens the red light passed through a combination of blocking filter and narrow-band tunable interference filter having a bandwidth of 7 Å. The filtered light fell on the surface of an EMI 9558-A photomultiplier tube which was cooled to liquid nitrogen temperature. The signals from the photomultiplier were preamplified and then displayed on one trace of a double-beam oscilloscope. On the second trace, timing signals from a Time Mark Generator were displayed. The 20-msec sweep was delayed by about 2.6 seconds, differently on each night according to the distance to the Moon. Each trace was photographed. The distance to the Moon was computed with the aid of Ephemeris data.

In order to obtain accurate synchronization between the maser pulse and the delayed sweep, the firing was initiated by a 1-sec repetition rate trigger pulse, derived from the timer and gated by a push-button

circuit. This trigger pulse also activated the delayed oscilloscope sweeps.

RESULTS

The experimental results are summarized in Table I. The experiments are grouped in four series. The number of consecutive flashes in each series is given in column 3. Column 5 gives the average signal level (number of counts) obtained in a $\frac{1}{2}$ -msec interval, due to Earth light and scattered light. The average was computed from actual counts in $\frac{1}{2}$ -msec intervals at time delays different from the expected round-trip time delay of the signal. Column 6 gives the standard deviation of the background level. The total number of intervals used in establishing the background is given in column 4. Column 7 gives the average photoelectron count obtained in that 0.5-msec interval where echoes were expected, and is therefore a measure of the signal-pulse noise.

It is evident that signal-pulse noise (column 7) exceeds the average noise by a significant amount in all the experiments, but especially in the first and last ones. After completion of the experiments there were no

signs of damage to the various optical elements of the transmitter. The focusing lens of the maser showed slight evidence of dust burned into the anti-reflecting coating.

We wish to acknowledge the help of J. Daley, Jr. of Lincoln Laboratory in the adjustment and use of the telescope; of G. Hardway and S. Kass of Raytheon Company in the testing and use of the maser; and of G. McGrath of Lincoln Laboratory in computing the Ephemeris data.

L. D. SMULLIN
G. FIOCCO
Dept. of Elec. Engrg. and
Res. Lab. of Electronics
Mass. Inst. Tech.
Cambridge, Mass.

* Received June 4, 1962; revised manuscript received June 7, 1962. This work was supported in part by the U. S. Army Signal Corps, the Air Force Office of Scientific Research, and the Office of Naval Research.

¹ A. Danjon, "Albedo, color and polarization of the Earth," in "The Solar System," vol. II, G. P. Kuiper, Ed., The University of Chicago Press, Chicago, Ill., 1954.

² M. Minnaert, "Photometry of the Moon," in "The Solar System," vol. III, G. P. Kuiper and B. Middlehurst, Eds., The University of Chicago Press, Chicago, Ill., 1961.

³ The filter was manufactured by Thin Film Products, Inc., Cambridge, Mass.

* Received June 4, 1962.

In 1963 moved to JILA where I told Peter Bender and Jan Hall about my idea for lunar laser ranging.

A Prototype Lunar Transponder

MAHLON S. HUNT

Air Force Cambridge Research Laboratories
Bedford, Massachusetts

The development of a prototype lunar transponder for Air Force Cambridge Research Laboratories by General Dynamics/Astronautics demonstrates the feasibility of designing future transponders for hard landings on the moon. Table 1 provides some of the design characteristics of the prototype transponder. Advanced solid-state circuitry, stripline microwave techniques, and special environmental packaging were used in its design [General Dynamics/Astronautics, 1963].

Figure 1 shows an expanded view of the prototype I lunar transponder components. On the moon the transponder functions essentially as a frequency-modulated transceiver, which receives a 5052-Mc/s carrier frequency from an earth-based tracking system. The carrier frequency is modulated by a 4-kc/s range measurement signal, which is retransmitted through the same transponder directional antenna on a nominal 5000-Mc/s carrier frequency to the earth-based tracking system. Also, a course modulation frequency of 160 cps is used for ambiguity resolution in the range measurement determination. The voltage-controlled oscillator and the phase detector form a phase-lock loop,

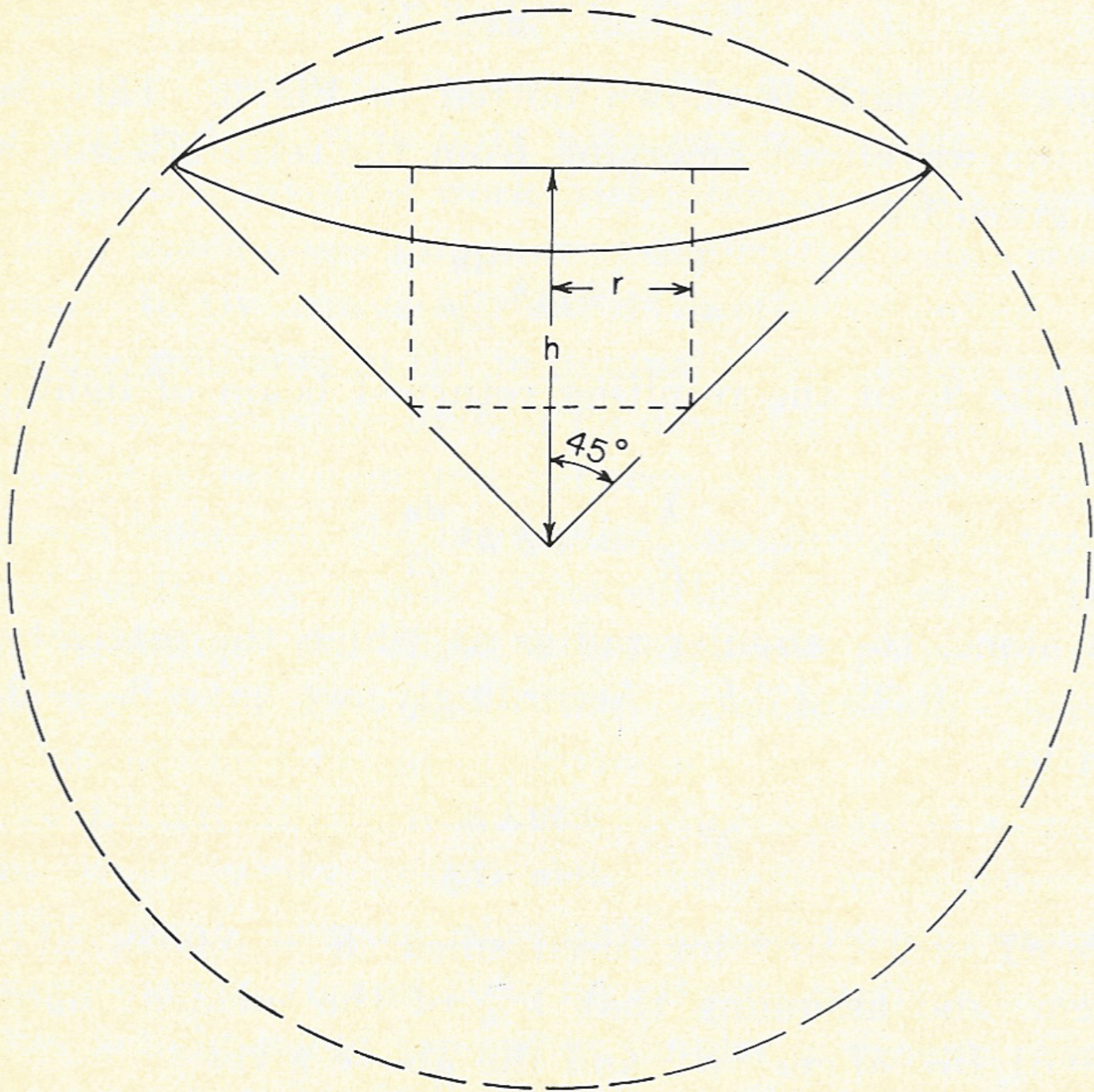
which has sufficient bandwidth for retransmission of the range measurement signal.

A continuous wave (CW) ranging technique was selected over a pulse radar technique for the prototype development. Beach *et al.* [1962] made a theoretical analysis of both techniques based on accuracy limitations imposed by thermal noise. Results indicated that the CW carrier was superior, when phase coherent, and compared with equal signal to noise density ratios for both techniques.

An input carrier frequency in the 5000-Mc/s range was selected to minimize tropospheric and ionospheric effects. At a true elevation angle of 15° the tropospheric range error is 9 meters. Standard correction methods can be used to reduce this error to about 1 meter. At frequencies greater than 1000 Mc/s, ray bending due to the ionosphere can be disregarded. Tropospheric ray bending is less than 0.1° for a true elevation angle of 10°. The number of free electrons in the ionosphere depends on numerous variables, such as the sun's activity, the observer's geomagnetic latitude, seasonal changes, and time of day. As a result, accurate corrections to an apparent ray path are difficult. However, at a

TABLE 1. General Design Characteristics of the Prototype I Lunar Transponder

Characteristics	Capabilities
Input frequency	5052 Mc/s
Output frequency	96/97 of phase-locked input frequency
Modulation frequency	4 kc/s, 160 cps
Shock	3000 <i>G</i> 's in any direction for a duration of 3 msec
Weight (without batteries)	1.8 kg
Volume	1190 cm ³ (12.9 cm × 14.2 cm × 6.5 cm)
Configuration	Rectangular parallelepiped
Controlled operating temperature (inside survival package)	0° to 30°C
Voltage input	25 to 31 volts dc
Power consumption	Not more than 15 watts at 28 volts dc
Output power level	100 milliwatts minimum
Warm-up time	Not more than 1 minute at operating temperature



PALMER PHYSICAL LABORATORY
PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

October 12, 1964

Archives
University of Colorado
Boulder Libraries

Dr. J. Faller
Joint Institute for
Laboratory Astrophysics
1511 University Avenue
Boulder, Colorado

Dear Jim:

As you know, optical corner reflectors on the moon have been discussed informally for years but, to my knowledge, nothing has appeared in print on this subject. Hunt's recent letter, a copy of which is enclosed, has brought the situation to a head. Unless the advantages of an optical corner are pointed out soon, someone might actually send a microwave transponder to the moon.

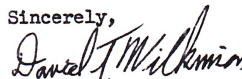
Last spring Bob Dicke and I did a few calculations on the accuracy of an optical radar measurement of the distance to a corner reflector on the moon, and also did some thinking about how the measurement could be used. Therefore, we have taken it upon ourselves to write the enclosed letter, which we propose to send to the Journal of Geophysical Research.

Since you have expressed interest in this project in the past, we would like to include your name in the author's list. Joint authorship seems like a good idea for two reasons. First, the letter is mostly a collection of old ideas which have been kicking around for years. And secondly, the letter might be used as a basis for arousing official interest in corner reflectors on the moon and it would seem to be good strategy to have authorship by physicists at several laboratories.

Please contact Bob Dicke or me no later than Wednesday, October 21 as to whether or not you want your name included and to suggest changes in the letter. We hope that any changes will be minor so that another draft will not have to be circulated.

Thank you for your interest and we look forward to hearing from you soon.

Sincerely,



David T. Wilkinson

609: 452-3000

452-4371

DTW:mf

Encl.

cc: C. Alley, Univ. of Maryland
P. L. Bender, Joint Inst. Lab. Astrophys., Boulder
P. Franken, Univ. of Michigan
R. H. Dicke, Princeton University

Optical Radar Using a Corner Reflector on the Moon

C. O. ALLEY,¹ P. L. BENDER,² R. H. DICKE,³ J. E. FALLER,² P. A. FRANKEN,⁴
H. H. PLOTKIN,⁵ AND D. T. WILKINSON³

In a recent letter *Hunt* [1964] described a microwave transponder that can be landed on the moon and that can be used, in conjunction with a modified Glotrac station, to measure the distance between station and landing site. He also suggests several interesting measurements that could be made on the earth-moon system if the range accuracy were sufficiently well developed. The purpose of this letter is to point out the capabilities and possible advantages of an optical radar system which uses a corner reflector on the moon's surface.

Smullin and Fiocco [1962] have demonstrated that laser beams can be scattered from the moon's surface and detected back at the earth; however, the return signals were too weak and too spread out (in time) to be used for precision ranging. *Hoffman et al* [1960] have pointed out the advantages of using corner reflectors on an artificial satellite to permit precision tracking. More recently, *Plotkin* [1964] has described an optical radar system that is capable of making precision range measurements to satellites which have been equipped with corner reflectors.

A typical optical radar system is shown schematically in Figure 1. The laser beam (pulsed or continuous wave) is sent through a transmitting telescope which tracks the corner reflector on the moon's surface. A small part of the reflected light is collected by the receiving telescope, which also tracks the reflector. (If a single telescope with a T/R switch is used, there is some sacrifice of received intensity owing to

velocity aberration.) The correlator measures the light travel time to the reflector and back. The efficiency of such a system, that is, the ratio of the number of received to the number of transmitted photons, is given approximately by

$$\eta = \frac{1}{4} \frac{A^2 D_T^2 D_R^2}{r^4 \theta^2 \lambda^2 D_L^2} T_a^2 T_e$$

where

A is effective area of the corner reflector, $\approx 150 \text{ cm}^2$.

r is range to the corner reflector, $\approx 3.7 \times 10^{10} \text{ cm}$.

λ is wavelength of laser light, $\approx 7 \times 10^{-5} \text{ cm}$.

θ is angular radius of laser beam divergence, $\approx 10^{-1} \text{ rad}$.

D_R is diameter of receiving telescope, $\approx 100 \text{ cm}$.

D_T is diameter of transmitting telescope, $\approx 100 \text{ cm}$.

D_L is diameter of laser rod, $\approx 2 \text{ cm}$.

T_a is transmission through the atmosphere, $\approx 85\%$.

T_e is transmission through optical elements, $\approx 30\%$.

For a system having the parameters given above, the efficiency is $\approx 3.3 \times 10^{-12}$; thus, we see the need for a high power laser as the light source. The expected return from the corner reflector is some 100 times stronger than that due to diffuse scattering by the lunar surface.

For pulsed radar applications, a Q -switched ruby laser can be used as the light source. The parameters used above for estimating η are typical of a system employing a ruby laser which is available commercially and is capable of delivering 10^{18} photons in a pulse of 10^{-8} second duration. With this laser as the light source and with a detector of 8% quantum efficiency, we estimate a return signal of 1 photoelectron per transmitted pulse. Therefore, the probability of getting a return signal from a given trans-

¹Department of Physics, University of Maryland, College Park, Maryland.

²Joint Institute for Laboratory Astrophysics, Boulder, Colorado.

³Palmer Physical Laboratory, Princeton University, Princeton, New Jersey.

⁴Department of Physics, University of Michigan, Ann Arbor, Michigan.

⁵Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, Maryland.

LURE (Lunar Ranging Experiment)
Team was created in 1965

The Lunar Laser Ranging effort was proposed as an Apollo experiment in December of 1965

A. DESIGN CONSIDERATIONS

The major design requirements for the LRRR Array³ were as follows:

- The array shall be capable of withstanding the Apollo mechanical environment. (The specific levels of vibration, acceleration, and shock are discussed in Section VI.)
- When deployed in the lunar environment, the array must provide passive thermal control to minimize temperature gradients in the retro-reflectors and thereby ensure satisfactory optical performance.
- The array must align the individual retro-reflectors such that the pointing direction of each is within $\pm 2^\circ$ of the mean array pointing direction.
- The total weight of the array, including the 100 retro-reflectors (each weighs 0.077 pound), must not exceed 34 pounds.
- The array must be fabricated of space-approved materials, and, as a design goal, should have a ten-year life in the lunar environment.

The interface with the Bendix pallet and aiming mechanism⁴ required, in addition to exact fit between mating brackets, that:

- The mean array pointing direction of the array mounted on the pallet must be within $\pm 1/4^\circ$ of the nominal pallet pointing direction.
- The array thermal design must provide for the conductive and radiative heat transfer between the array and the pallet.

The array design also had to be compatible with the retro-reflectors,⁵ for example:

- The retro-reflector mounting must be compatible with the mounting tab configuration and manufacturing tolerances of the fused-silica retro-reflectors.
- The retro-reflectors must be handled, prior to assembly in the array and during handling and shipping of the assembled arrays, in such a manner as to prevent contamination or damage to the retro-reflectors.

Because of NASA's interest in including a astronaut-undemanding and passive experiment in the Apollo 11 scientific payload, the Lunar Ranging Experiment was accepted.

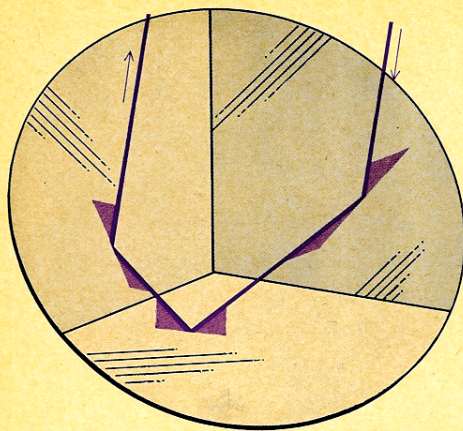
Wet Sand



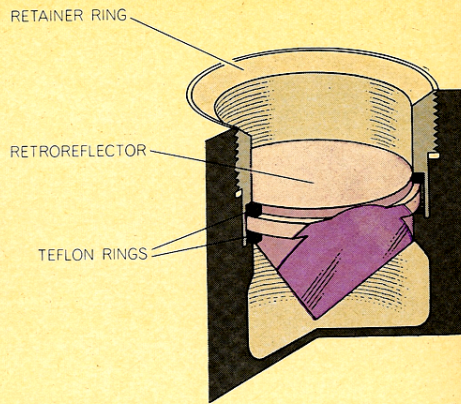


Apollo 17

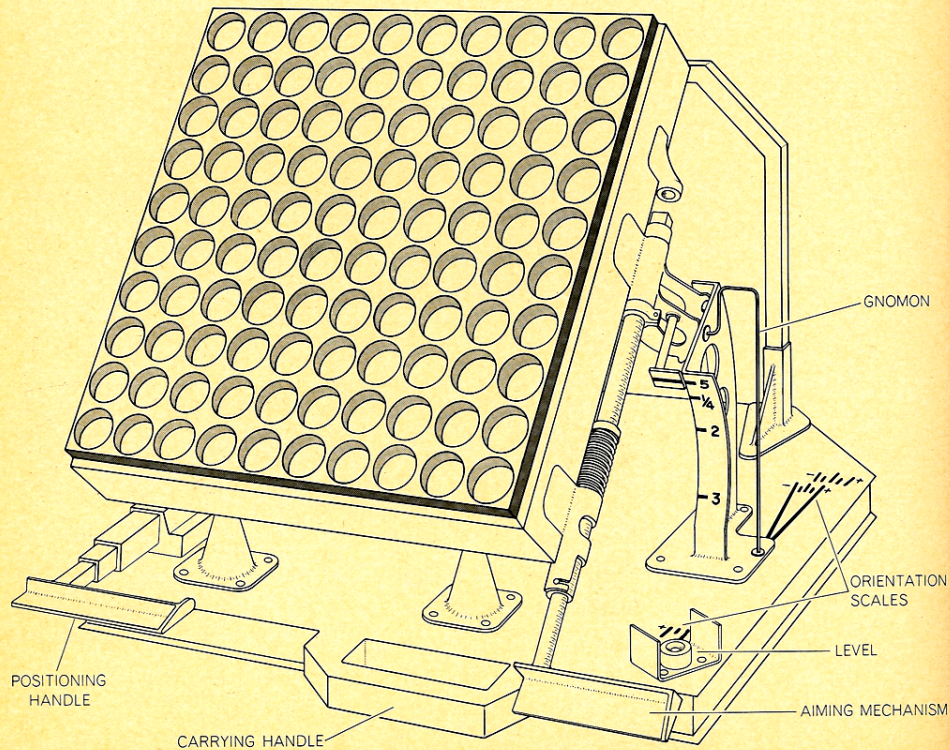




CORNER REFLECTOR, or corner cube, has the property of returning a ray of light (*color*) on a path exactly parallel to that of the incident ray. At each internal surface the angle of reflection equals the angle of incidence, as indicated by the colored triangles. The corner reflectors that were used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



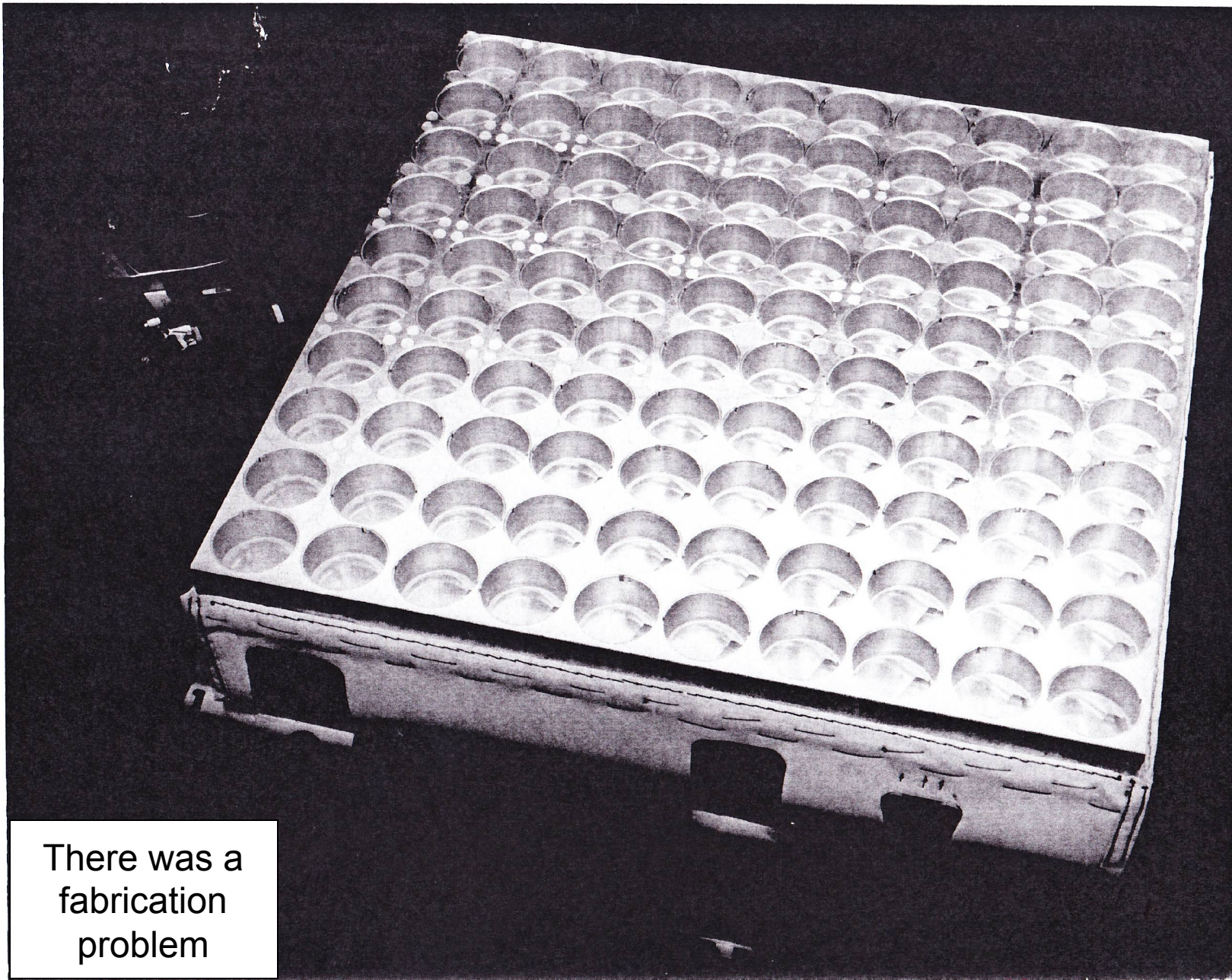
MOUNTING FOR CORNER CUBE was designed by Arthur D. Little, Inc., to withstand the vibration and acceleration of an Apollo lift-off and, once on the moon, to minimize thermal gradients that would affect the optical performance of the reflectors. Each corner reflector is recessed by about half its 1½-inch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

Here show Apollo Corner Cube



There was a
fabrication
problem



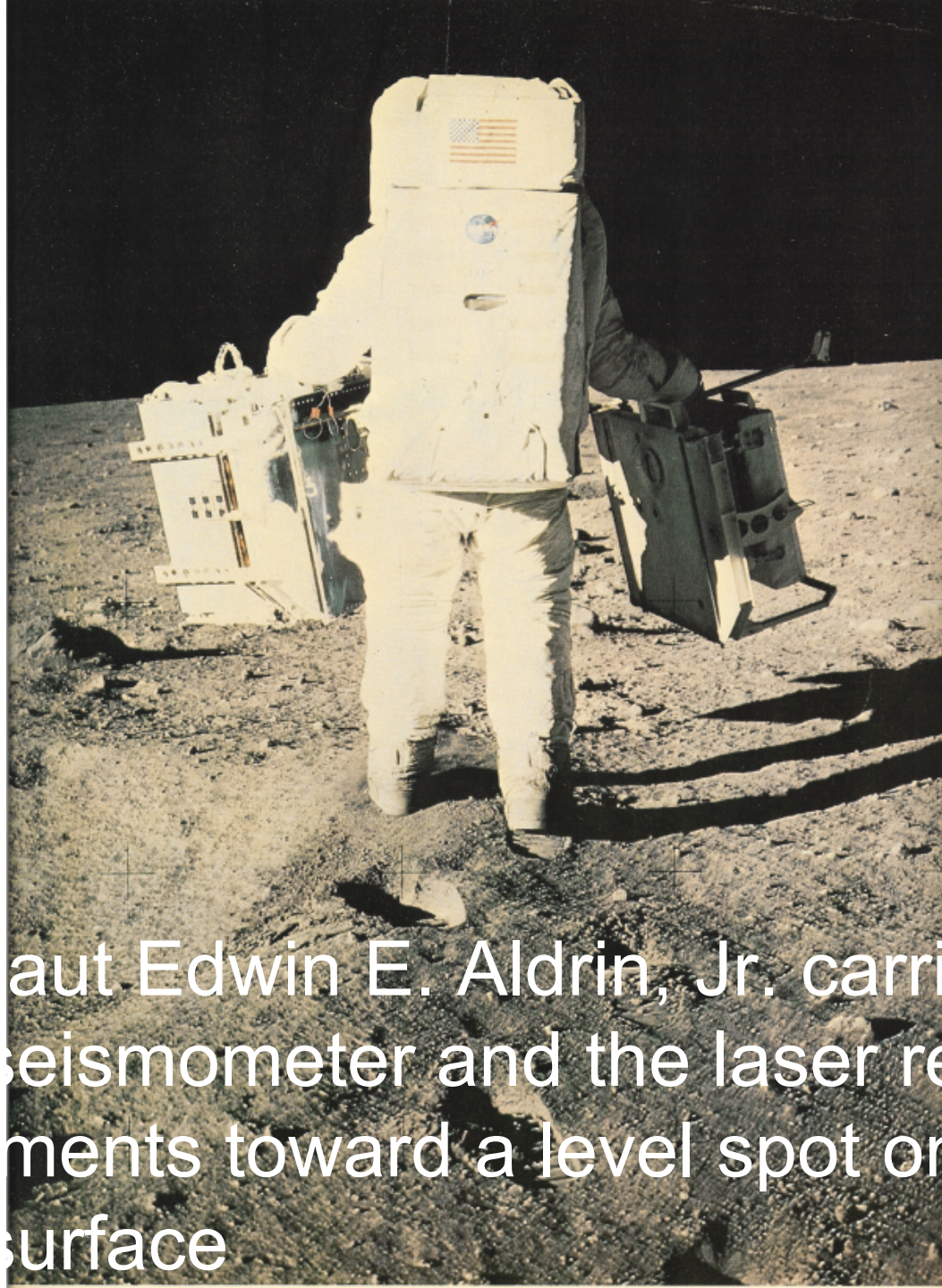
James Faller Collection
Box 5

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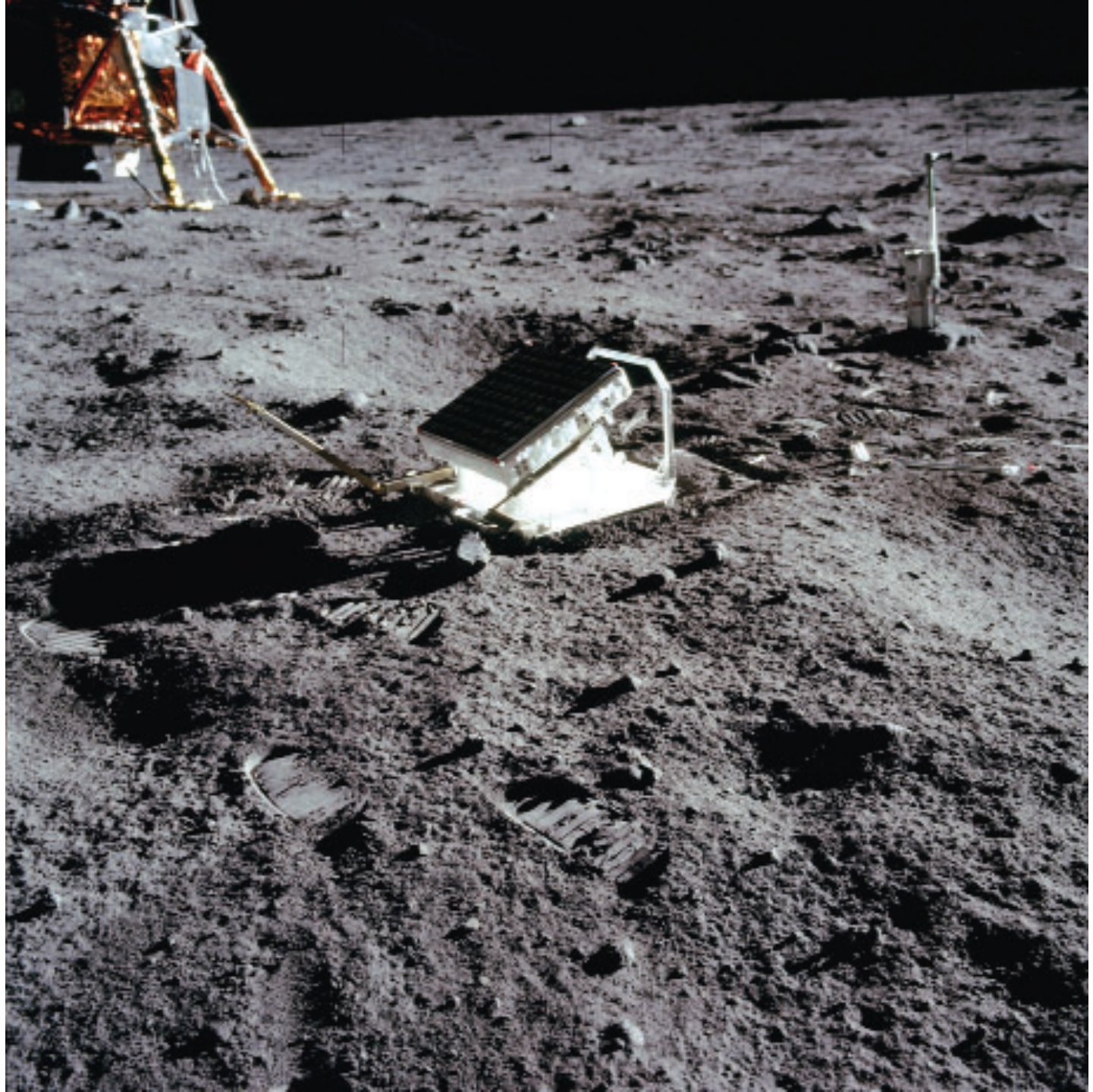
Lunokhod (the First, "0")
...blew up on the launch
pad in February of 1969

[This was 5 months prior to Apollo 11's lunar landing !]

Apollo 11, July 20, 1969

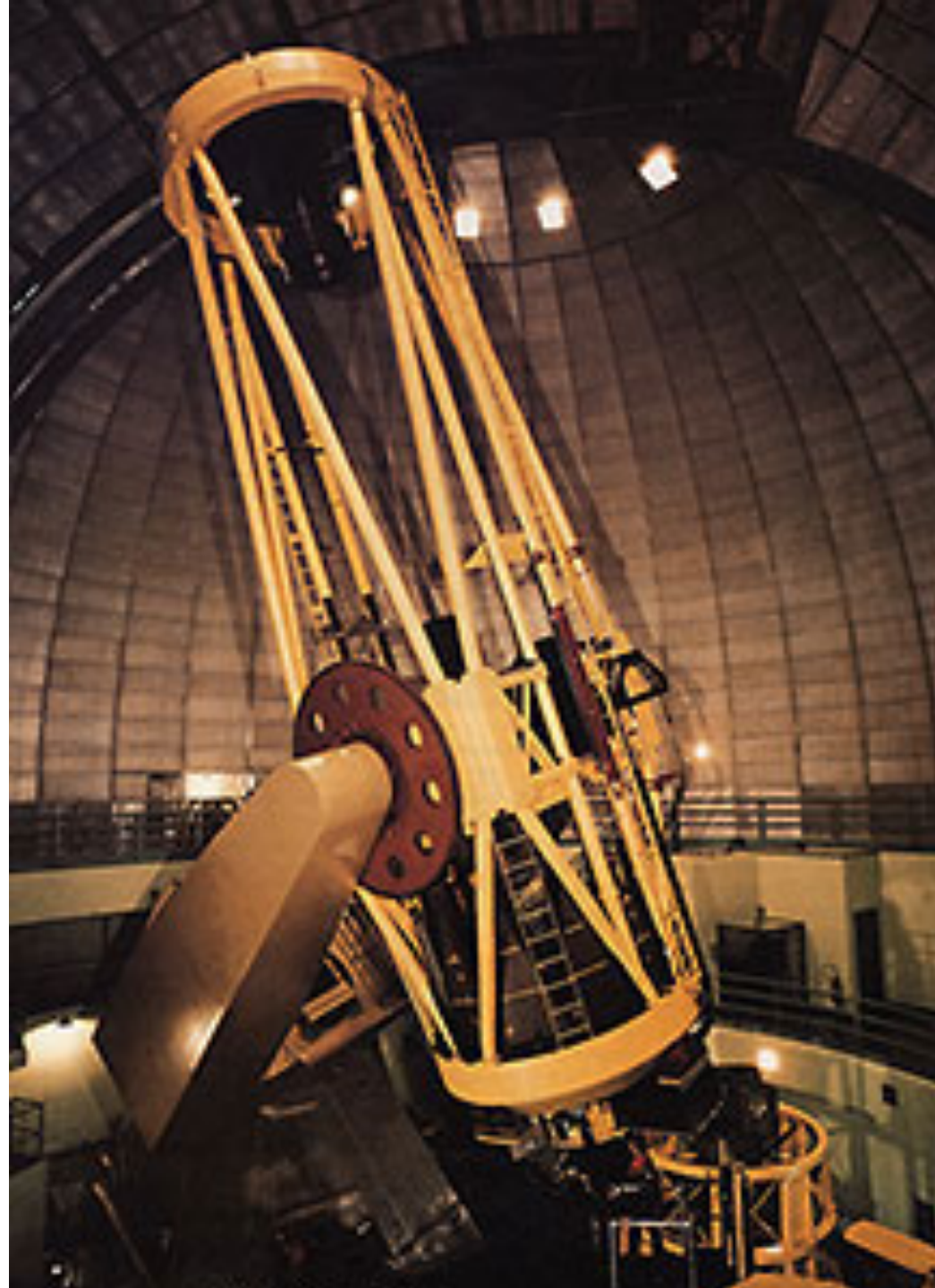


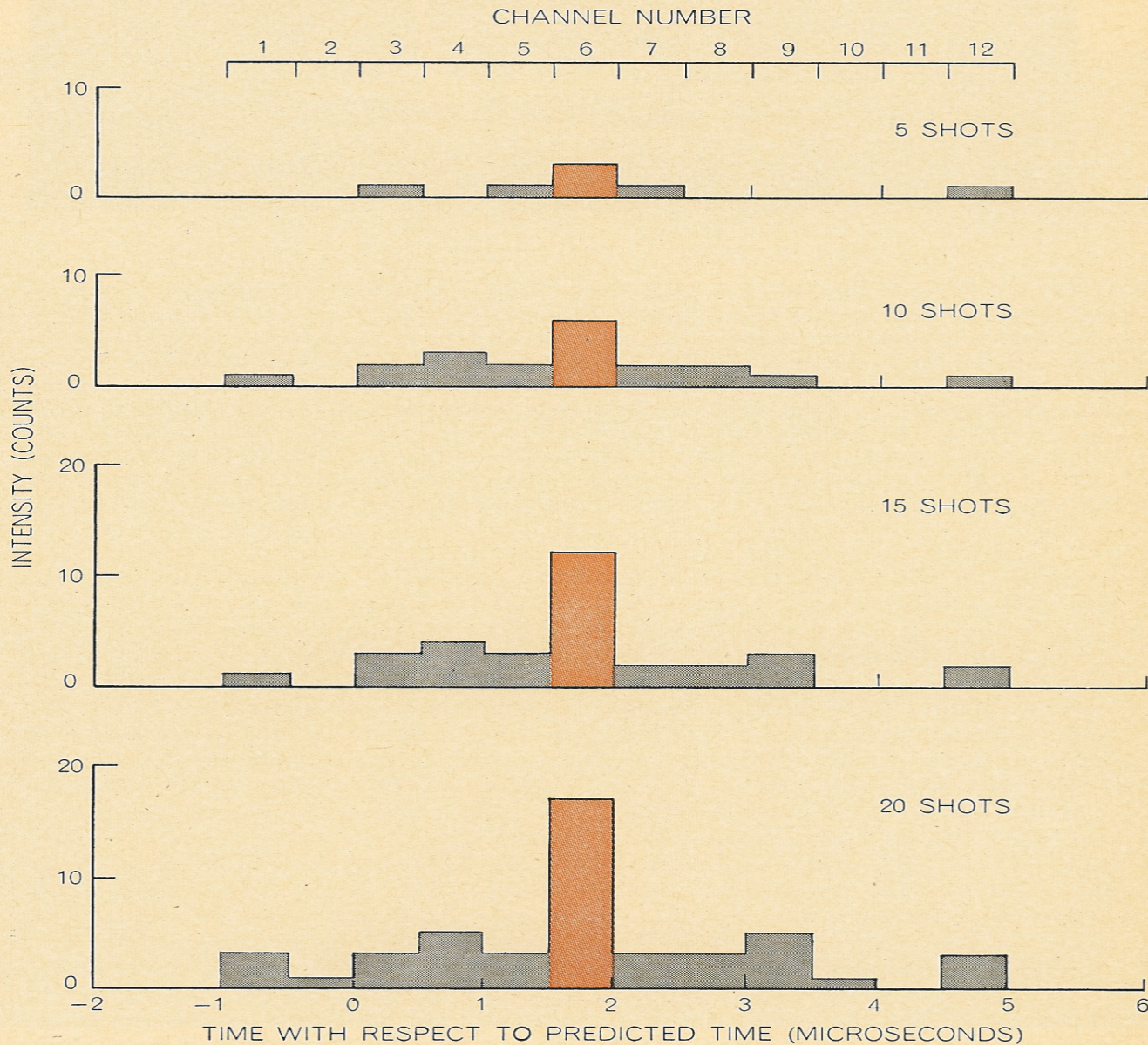
Astronaut Edwin E. Aldrin, Jr. carries the seismometer and the laser reflectors toward a level spot on the lunar surface



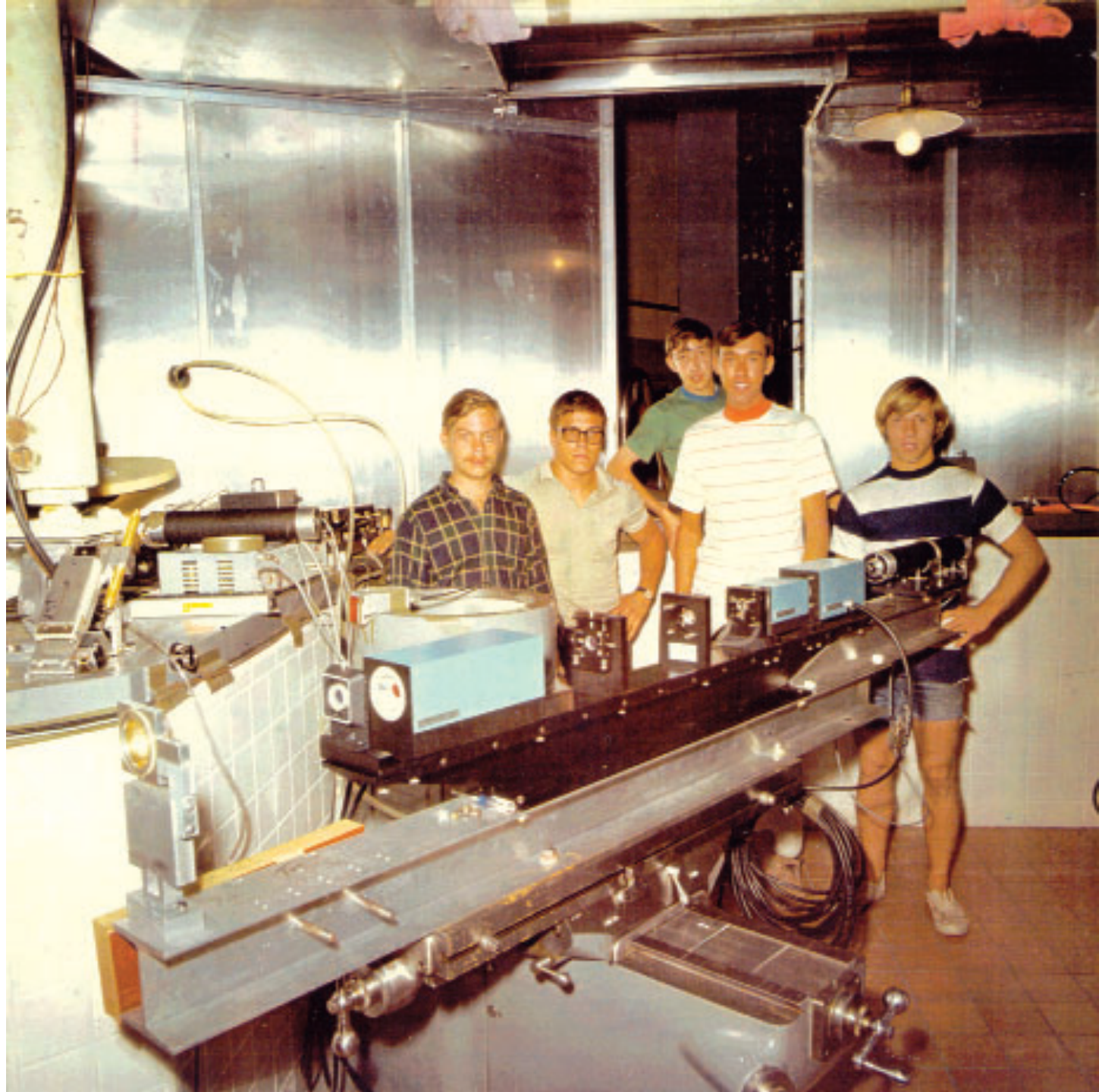








IDENTIFICATION OF REFLECTED LASER SIGNAL was done by dividing the output of the photon detector into 12 time channels embracing the predicted time of arrival, and observing whether or not one of the channels filled up faster than the others. The width of each channel could be varied from .25 microsecond 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.



WESLEYAN UNIVERSITY
MIDDLETOWN, CONN. 06457
DEPARTMENT OF PHYSICS

Address this mail to
SCOTT LABORATORY

March 18, 1969

Dr. Henry Plotkin
Optical Systems Branch
Goddard Space Flight Center
Greenbelt, Maryland 20770

Dear Henry,

I enclose a copy of the letter I am sending to Strickland. Yesterday evening I sent a telegram to him conveying exactly the same information. I think he needs to be made aware that given our head the group can move decisively and quickly.

As I related to you earlier, I would like NASA-Goddard to up-date and reactivate Tom-Johnson's laser for use at Lick; and to accelerate work on the timing system being put together for one of your other programs so that it can also be used at Lick on an interim basis. I will rely on your acquiring needed optical pieces for use at Lick (once they are firmly defined); and will need to make use of your experience on a number of technical matters.

Best wishes,

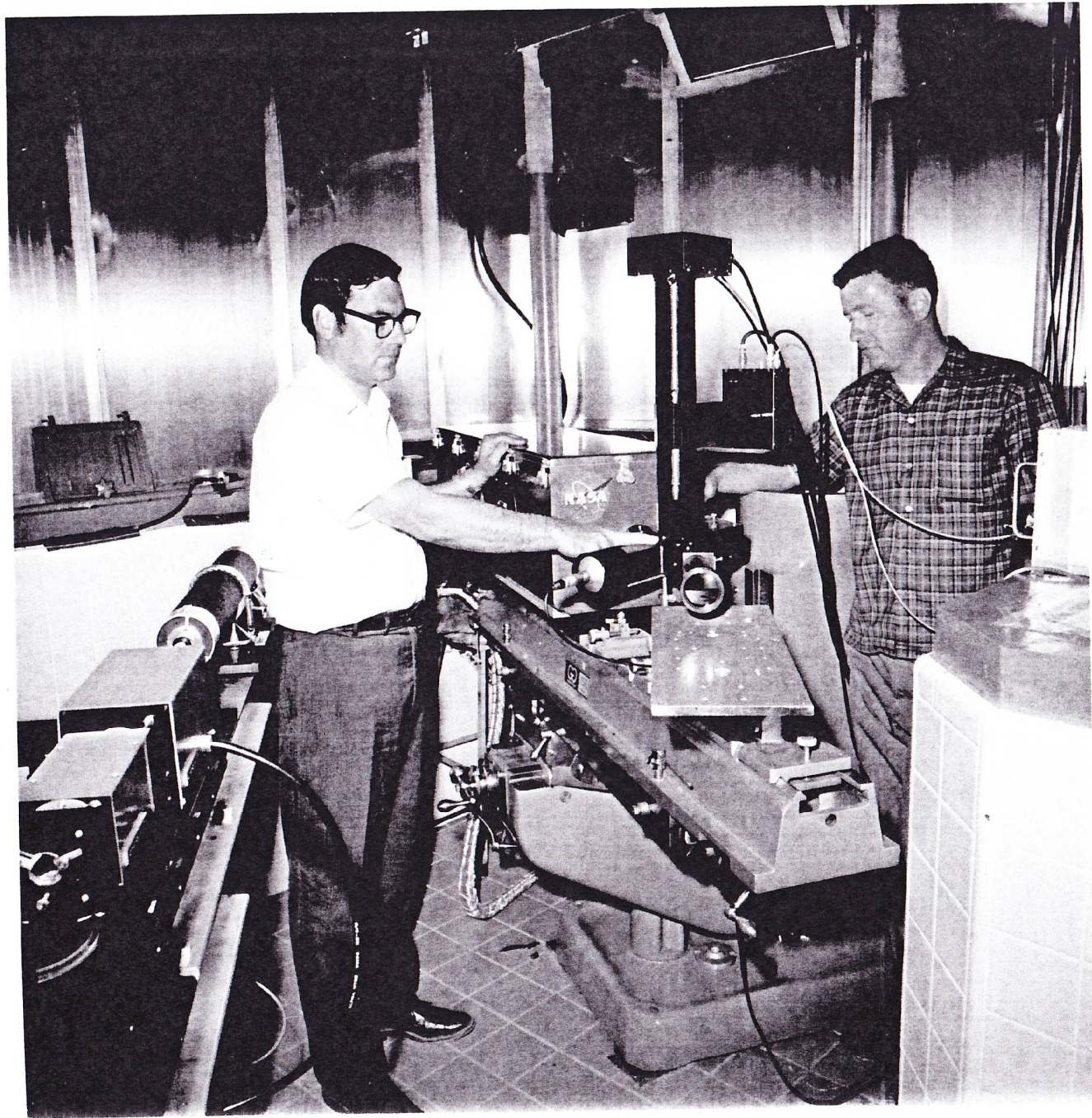


James E. Faller
Associate Professor of Physics

JEF:cy

c.c. Col. Arthur T. Strickland

Archives
University of Colorado
Boulder, Colorado



And what role did the Lick observations play...? They contributed an important “existence theorem” that the array was working!

PEANUTS

by SCHULZ

THIS IS HOPELESS!

A BLOODHOUND COULDN'T FIND ANYTHING OUT HERE!

I CAN'T FIND THE BALL!

WADDYA MEAN, PICK IT UP?!

HOW DO YOU EXPECT ANYONE TO FIND A BALL IN WEEDS LIKE THESE? WHAT DID YOU HIT IT OUT HERE FOR?

IT'S IMPOSSIBLE! OF COURSE, I'M LOOKING! I SAID I CAN'T FIND IT! IF I COULD FIND IT, WOULD I STILL BE OUT HERE?

THIS IS HOPELESS! NOBODY COULD FIND ANYTHING OUT HERE! YOU COULDN'T FIND A BATTLESHIP OUT HERE IF IT..

8-3
..WAIT A MINUTE...

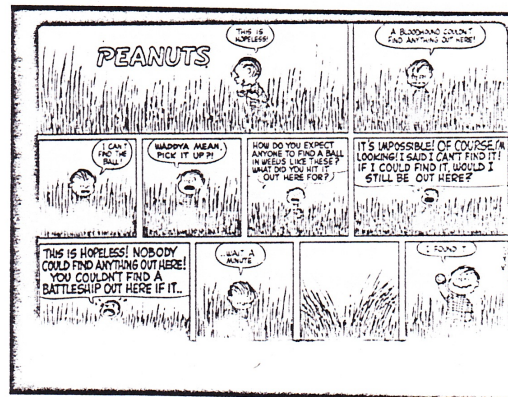
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Copr. 1958 by United Feature Syndicate, Inc.

I FOUND IT...

SCHULZ

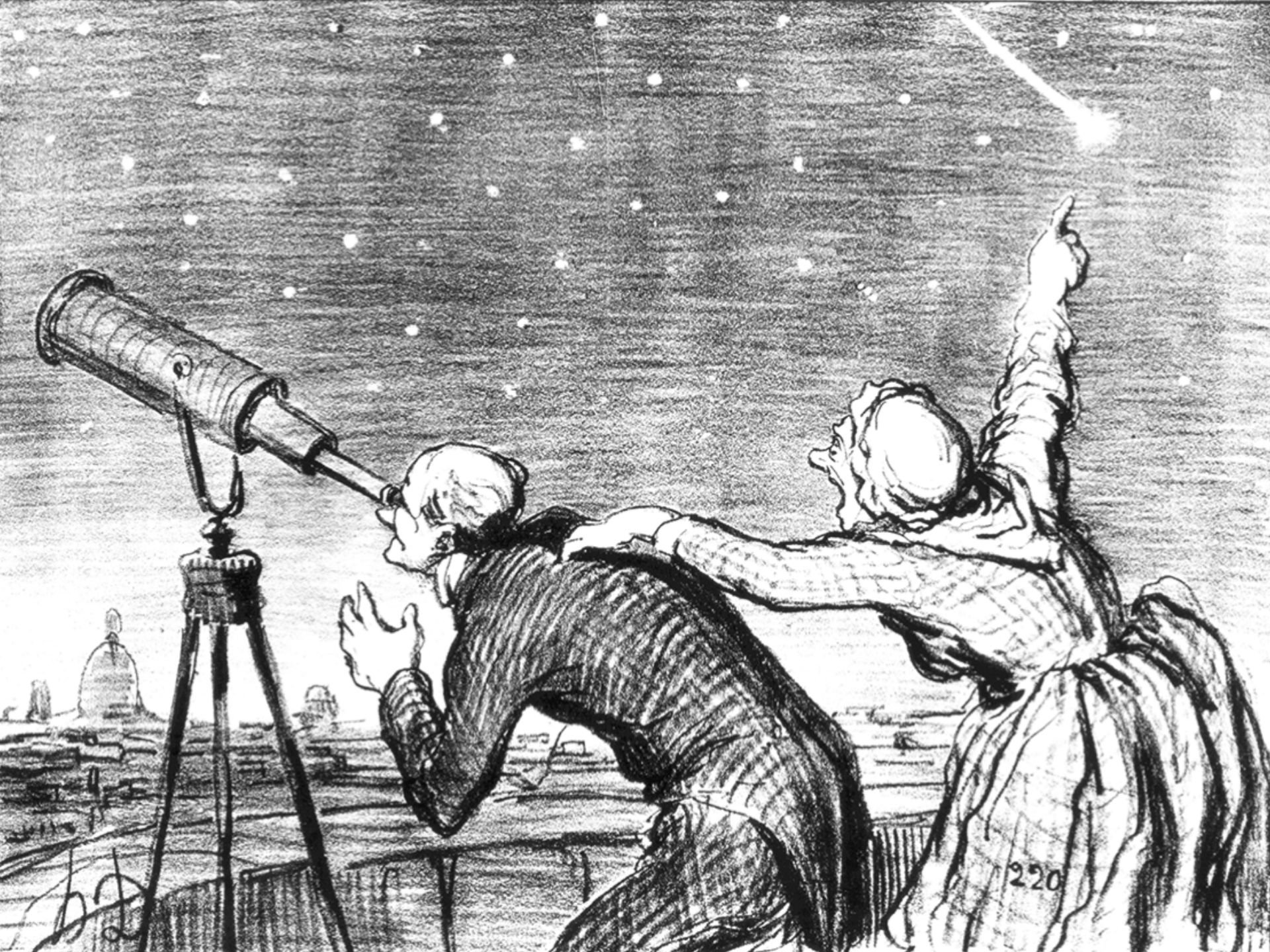
Sent to: *Lena Kaye Samp Exp.*
McDonald Obs.
Fort Davis Texas

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Boulder Libraries

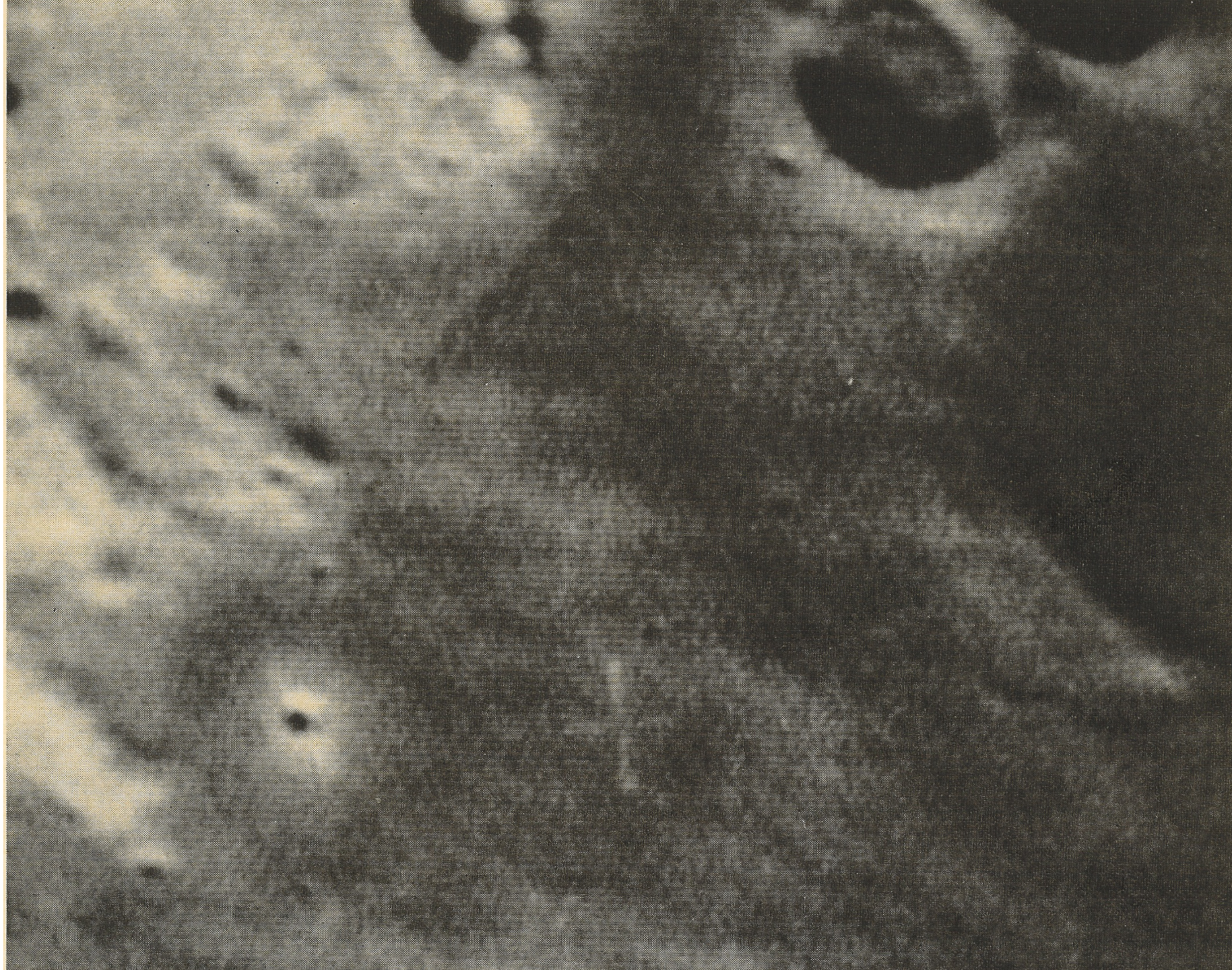


And for a while we were
also concerned that it
might be covered with
sand.....

Jim + Joe

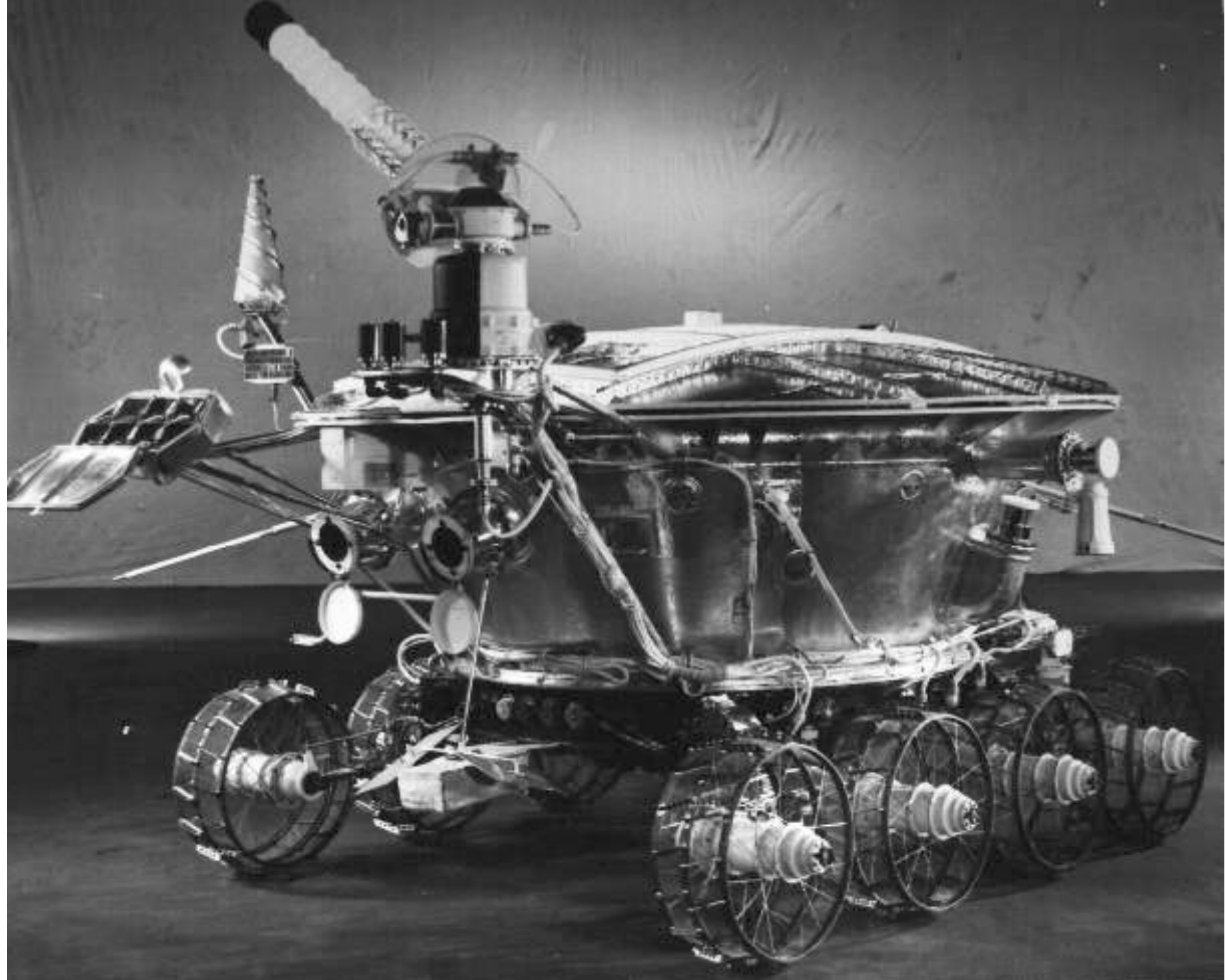


220

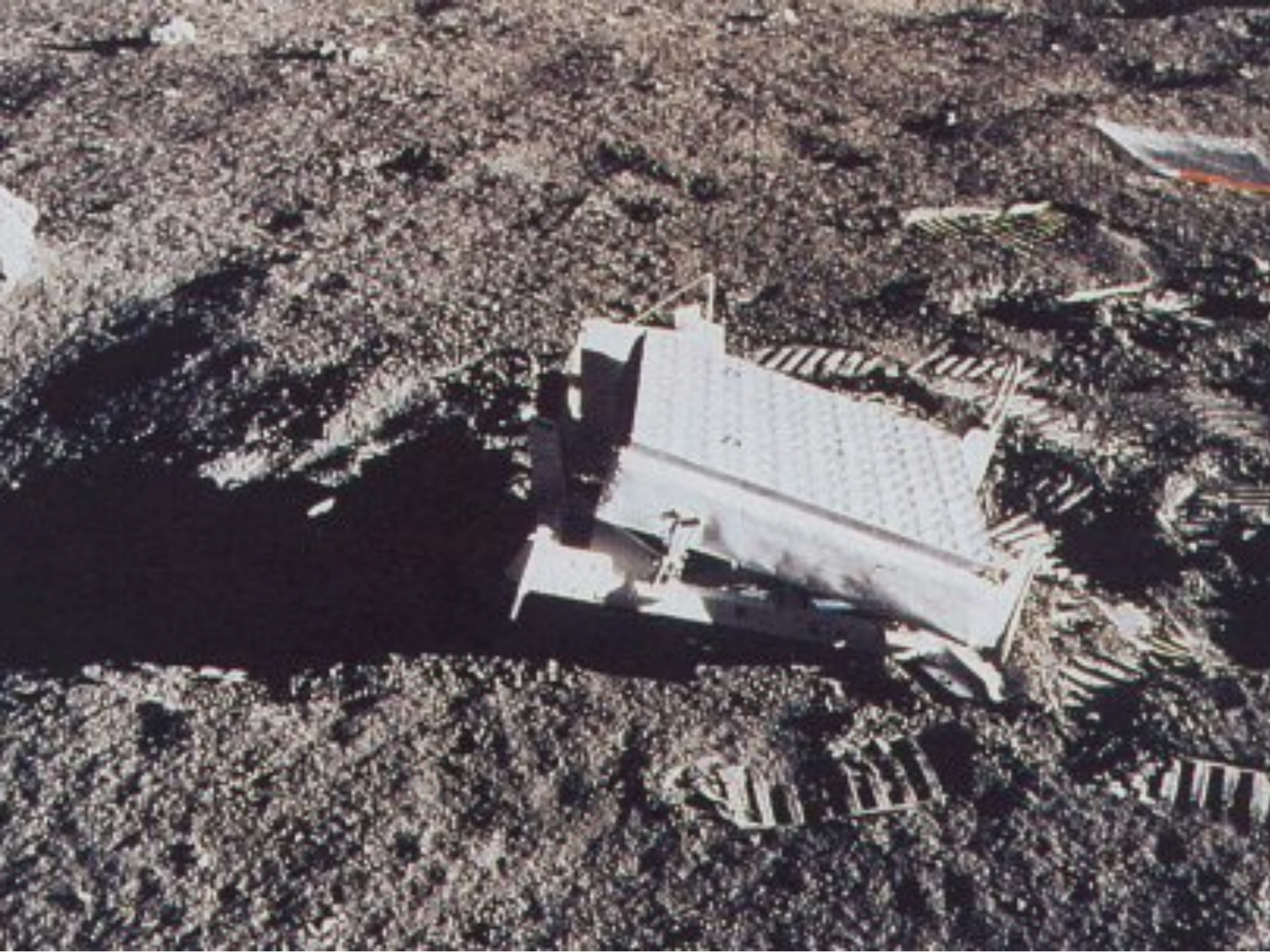


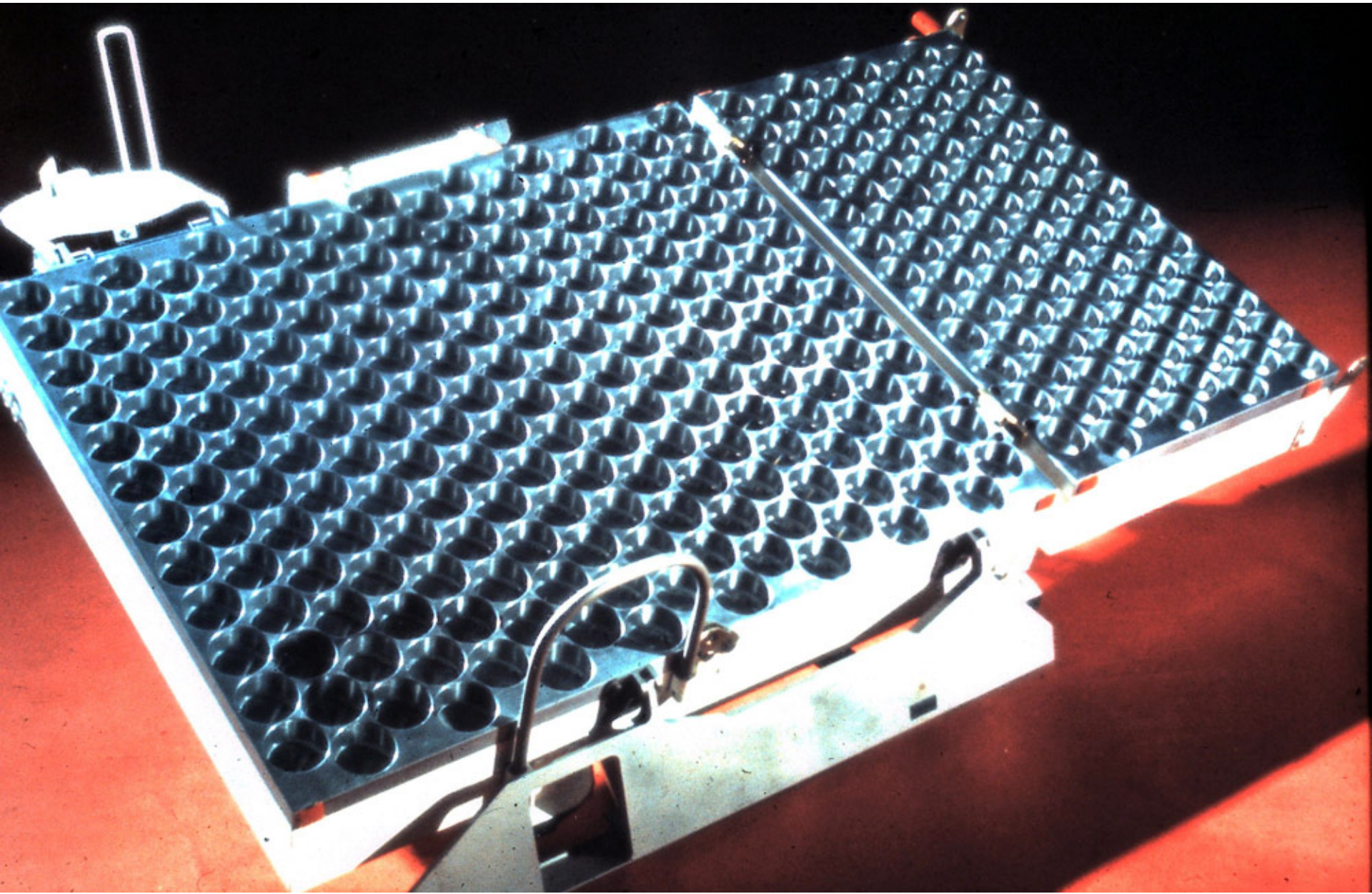
Lunokhod 1, November 1970

[Luna 17]

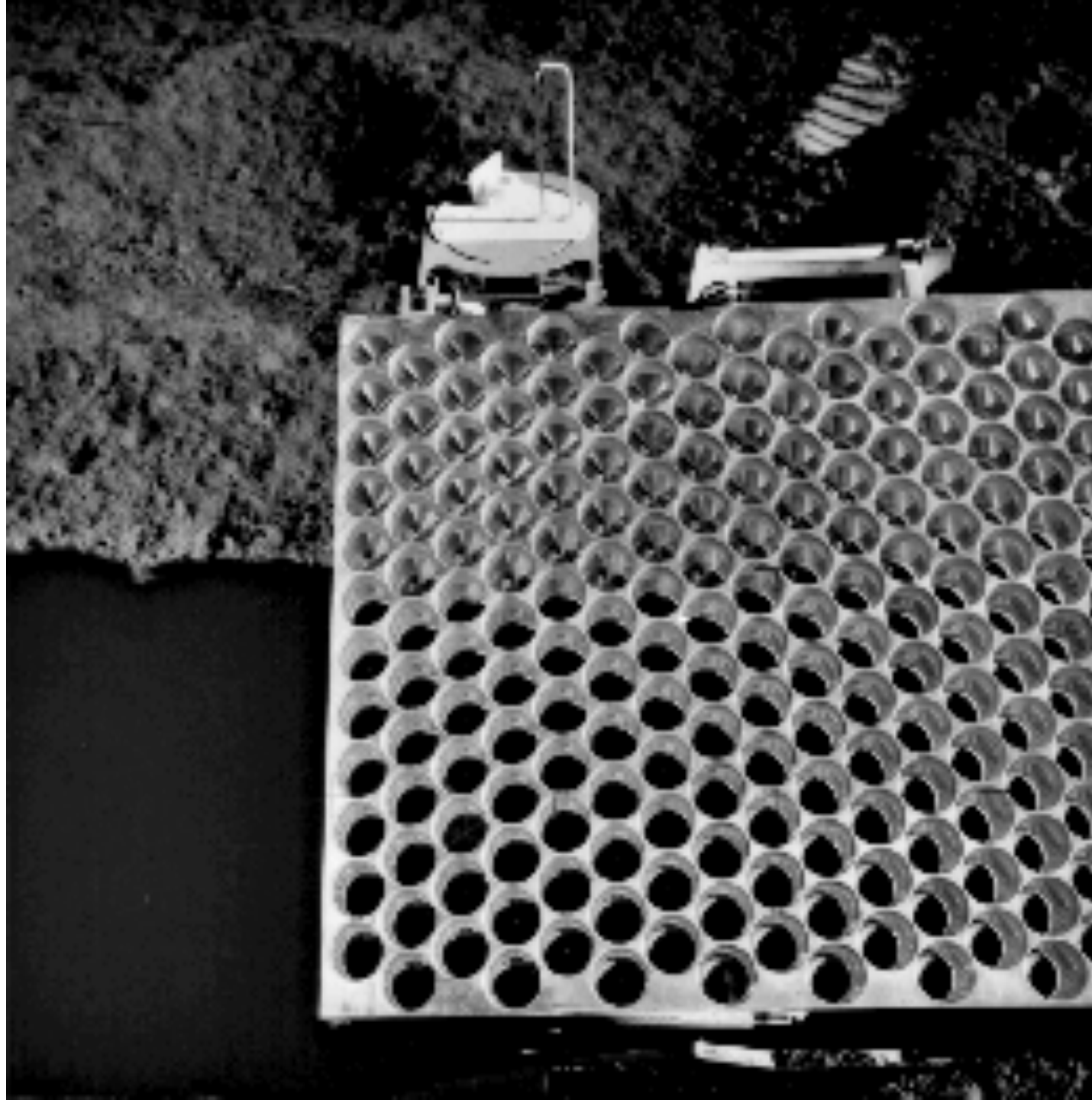


Apollo 14 February 5, 1971



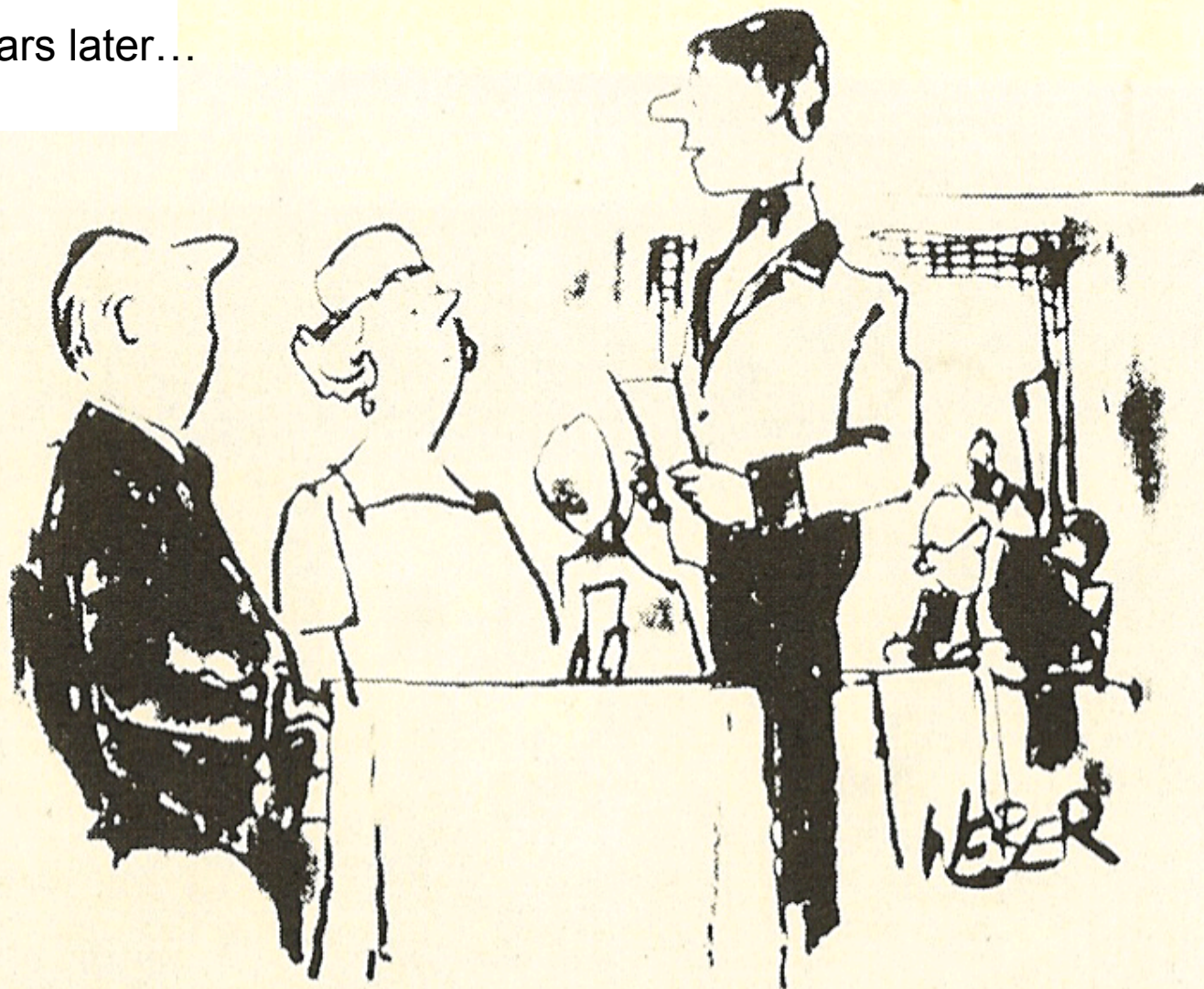


Apollo 15, July 31, 1971





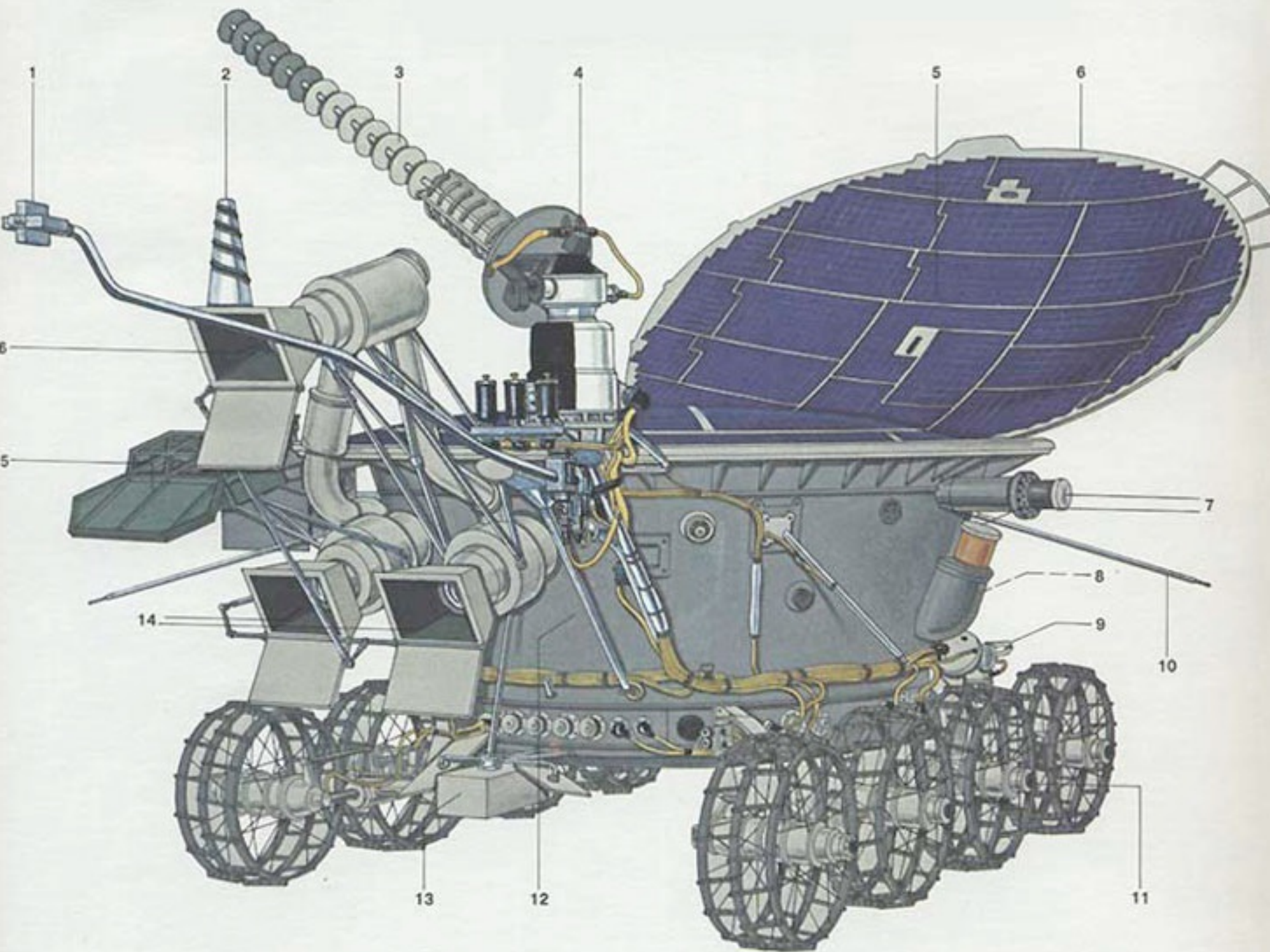
But only 13 years later...

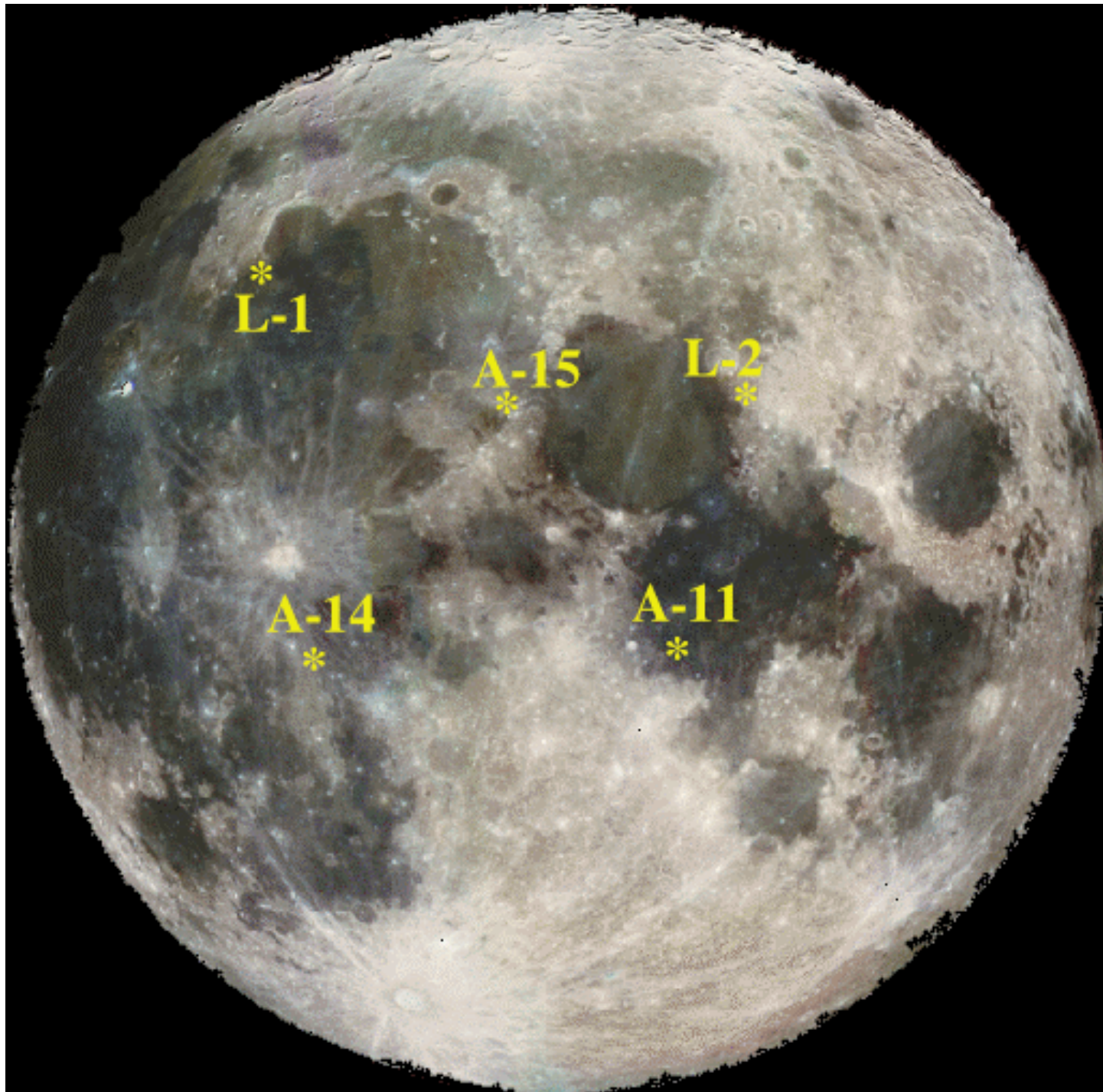


"Good evening. I'm George Graham, Harvard '71. I have an A.B. cum laude in physics, and I can recommend the roast duck unreservedly."

Lunokhod 2, January 1973

[Luna 21]





*
L-1

A-15
*

L-2
*

A-14
*

A-11
*



July 17, 1973

Professor Irwin I. Shapiro
Department of Earth and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Professor Shapiro:

The Lunar Ranging Team would be glad to cooperate with your group in studies of selenodesy and the lunar librations. The combination of differential ALSEP VLBI data with laser range data should give some kinds of information more accurately than it can be obtained by either technique alone. For other kinds of information, the two techniques will provide a valuable check on the mutual consistency of the results.

Our present ability to fit the lunar range data is described in the article for Science which was recently sent to you. In addition to the LURE-1 ephemeris discussed in the article, other ephemerides produced recently at the University of Texas and at JPL are available for research purposes if you wish to make use of them. Although they do not have substantial advantages in terms of fitting the data up to June, 1972 which has been used in most of our comparisons, the differences in the ephemerides may come in differently in analyzing the VLBI data. Please feel free to contact any of the people working on the lunar range data directly for further information about these ephemerides or about other current work on improving the range calculations.

As a first step in utilizing both range and VLBI data together, it might be desirable to employ the libration parameters, reflector coordinates, and lunar ephemeris discussed in the Science article in the initial analysis of your ALSEP data. The libration model we have used is described by Williams, Eckhardt, Kaula, and Slade in their paper from the Houston meeting, which is to be published in The Moon. I understand that the LURE-1 ephemeris can be supplied to you on request either by JPL or the University of Texas.

As soon as we have other ephemerides or improved libration models which do a substantially better job in fitting the range data than the present ones, we will certainly let you know. Please feel free to call on us for any assistance we can provide in utilizing the VLBI data. Conversely, we would welcome any suggestions from your group on ways in which the VLBI results can be utilized to give improvements in our analysis of the laser range data.

Sincerely,

James E. Faller, Chairman,
Lunar Ranging Experiment Team

JEF:ob

A NEW TEST OF THE EQUIVALENCE PRINCIPLE FROM LUNAR LASER RANGING*

R. H. Dicke,¹ J. G. Williams,² P. L. Bender,³ C. O. Alley,⁴ W. E. Carter,⁵
D. G. Currie,⁴ D. H. Eckhardt,⁶ J. E. Faller,³ W. M. Kaula,⁷ J. D.
Mulholland,⁸ H. H. Plotkin,⁹ P. J. Shelus,⁸ E. C. Silverberg,¹⁰ W. S.
Sinclair,² and D. T. Wilkinson¹

1. Princeton University, Princeton, New Jersey 08540
2. Jet Propulsion Laboratory, Pasadena, California 91103
3. Joint Institute for Laboratory Astrophysics, Boulder, Colorado 80309
4. University of Maryland, College Park, Maryland 20742
5. University of Hawaii, LURE Observatory, Kula, Maui 96790
6. Air Force Cambridge Laboratories, Bedford, Massachusetts 01731
7. University of California, Los Angeles, California 90024
8. University of Texas, Austin, Texas 78712
9. Goddard Space Flight Center, Greenbelt, Maryland 20771
10. McDonald Observatory, Fort Davis, Texas 79734



Chris
Allen

PHYSICAL REVIEW LETTERS

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New Test of the Equivalence Principle from Lunar Laser Ranging*

J. G. Williams, R. H. Dicke, P. L. Bender, C. O. Alley, W. E. Carter, D. G. Currie, D. H. Eckhardt, J. E. Faller, W. M. Kaula, J. D. Mulholland, H. H. Plotkin, S. K. Poultney, P. J. Shelus, E. C. Silverberg, W. S. Sinclair, M. A. Slade, and D. T. Wilkinson
Jet Propulsion Laboratory, Pasadena, California 91103, and Princeton University, Princeton, New Jersey 08540, and Joint Institute for Laboratory Astrophysics, Boulder, Colorado 80309, and University of Maryland, College Park, Maryland 20742, and University of Hawaii LURE Observatory, Kula, Maui 96790, and Air Force Cambridge Research Laboratories, Bedford, Massachusetts 01731, and University of California, Los Angeles, California 90024, and University of Texas McDonald Observatory, Austin, Texas 78712, and Goddard Space Flight Center, Greenbelt, Maryland 20771

(Received 8 December 1975)

An analysis of six years of lunar-laser-ranging data gives a zero amplitude for the Nordtvedt term in the Earth-Moon distance yielding the Nordtvedt parameter $\eta = 0.00 \pm 0.03$. Thus, Earth's gravitational self-energy contributes equally, $\pm 3\%$, to its inertial mass and passive gravitational mass. At the 70% confidence level this result is only consistent with the Brans-Dicke theory for $\omega > 29$. We obtain $|\beta - 1| \leq 0.02$ to 0.05 for five-parameter parametrized post-Newtonian theories of gravitation with energy-momentum conservation, or $|\beta - 1| \leq 0.01$ if only β and γ are considered.

It was pointed out by Dicke in 1961 that the ratio of the gravitational mass to inertial mass for astronomical bodies could be slightly different from unity if the gravitational self-energy of a body varied with its position in the gravitational potential of another body.¹ When the total mass of a test body is a function of its position in a static gravitational field, an anomalous "gravitational" force must act on the body if energy is to be conserved. This possibility is not included in

equivalence principle in the metric theories of gravity.⁴ To do this, he extended the parametrized post-Newtonian (PPN) formulation of metric theories and calculated for the first time how the deviation from unity of the ratio of gravitational mass to inertial mass would depend on the various parameters. He showed that the results correspond to a new aspect of relativistic gravity which has not been measured in other gravitational experiments, and suggested three possible ex-

Verification of the Principle of Equivalence for Massive Bodies*

Irwin I. Shapiro and Charles C. Counselman, III

Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Robert W. King

Air Force Cambridge Research Laboratories, Bedford, Massachusetts 01731

(Received 10 December 1975)

Analysis of 1389 measurements, accumulated between 1970 and 1974, of echo delays of laser signals transmitted from Earth and reflected from cube corners on the Moon shows gravitational binding energy to contribute equally to Earth's inertial and passive gravitational masses to within the estimated uncertainty of 1.5%. The corresponding restriction on the Eddington-Robertson parameters is $4\beta - \gamma - 3 = -0.001 \pm 0.015$. Combination with other results, as if independent, yields $\beta = 1.003 \pm 0.005$ and $\gamma = 1.008 \pm 0.008$, in accord with general relativity.

Verification of the principle of equivalence has been of concern to physicists at least since the time of Ioannes Grammaticus in the 5th Century.¹ Laboratory experiments performed over the past 300 years have allowed increasingly stringent limits, from 1 part in 10^3 to 2 parts in 10^{12} , to be placed on the independence on composition and size of the ratio of the inertial to the passive gravitational masses of diverse objects.² However, despite their impressive accuracy, these experiments fail utterly to test whether gravitational binding energy contributes equally to inertial and gravitational mass. For a meter-sized laboratory object, the gravitational binding energy represents only about 1 part in 10^{23} of the total energy, about eleven orders of magnitude too small to detect with present laboratory techniques. To test this aspect of the principle of equivalence, the cornerstone of general relativity, it is necessary to utilize planetary-sized bodies since the ratio, Δ , of the magnitude of the

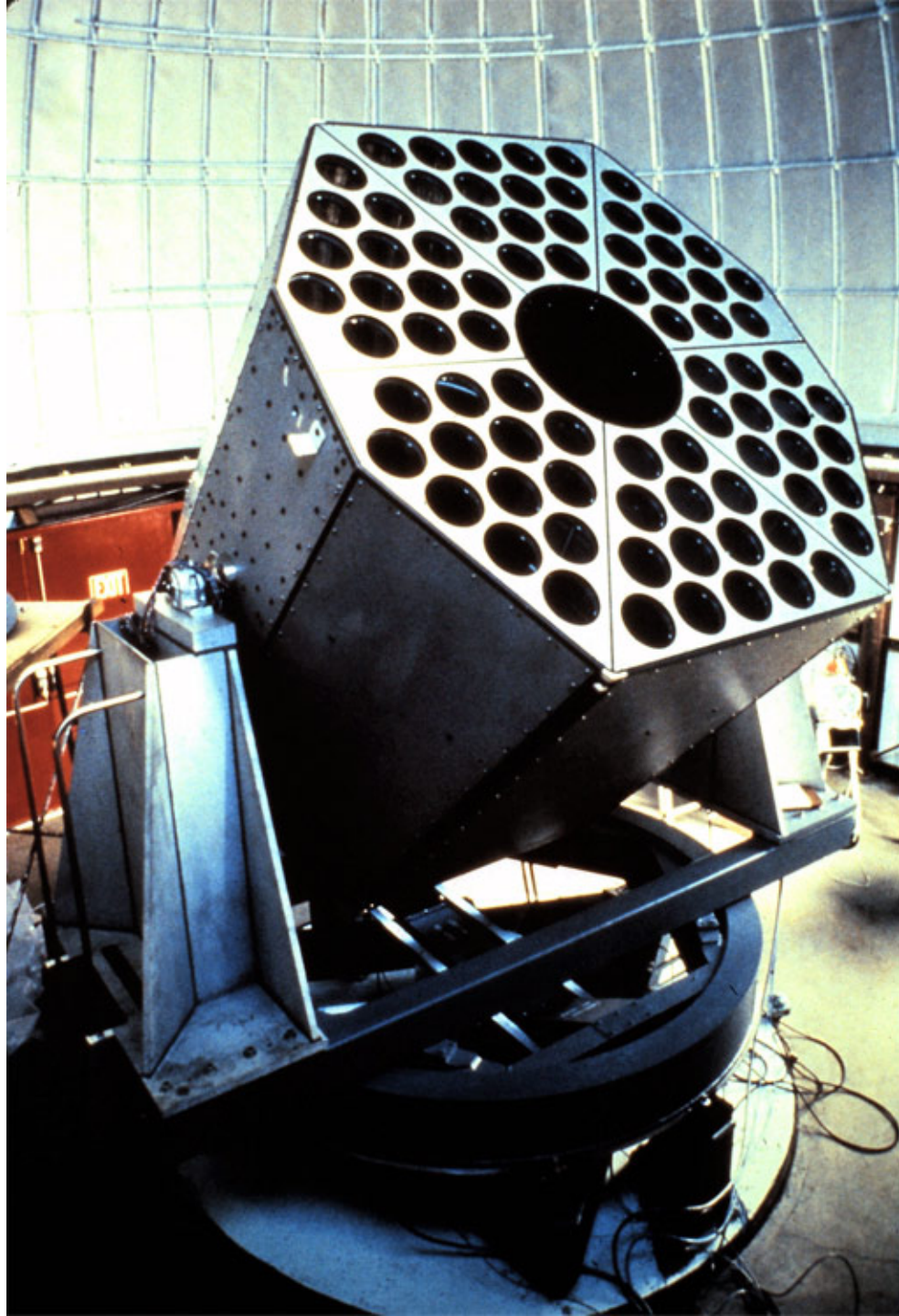
gravitational binding energy to the total energy scales as the square of a typical length. For a homogeneous sphere, $\Delta = 0.8\pi G\rho R^2/c^2$, with G the constant of gravitation, c the speed of light, ρ the density, and R the radius.

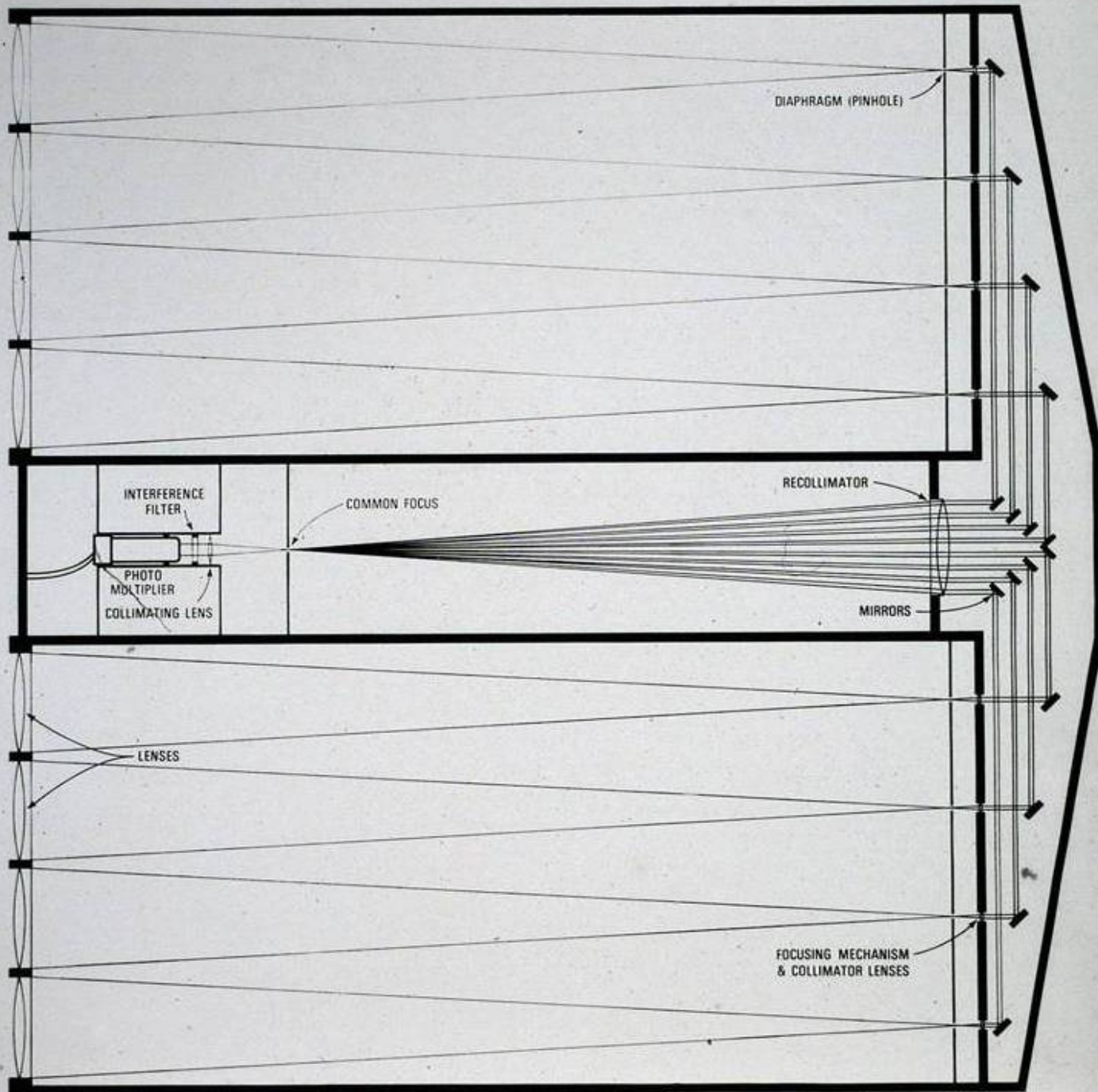
To verify the principle of equivalence or to detect a violation for such massive bodies, one must monitor their orbital behavior. However, without independent measurements of mass, three or more bodies are required to detect a violation. Nordtvedt³ pointed out that for this purpose the Earth-Moon-Sun system would be useful since laser measurements⁴ of the Earth-Moon separation, made possible by the optical corner reflectors on the moon, would allow a significant test to be made.

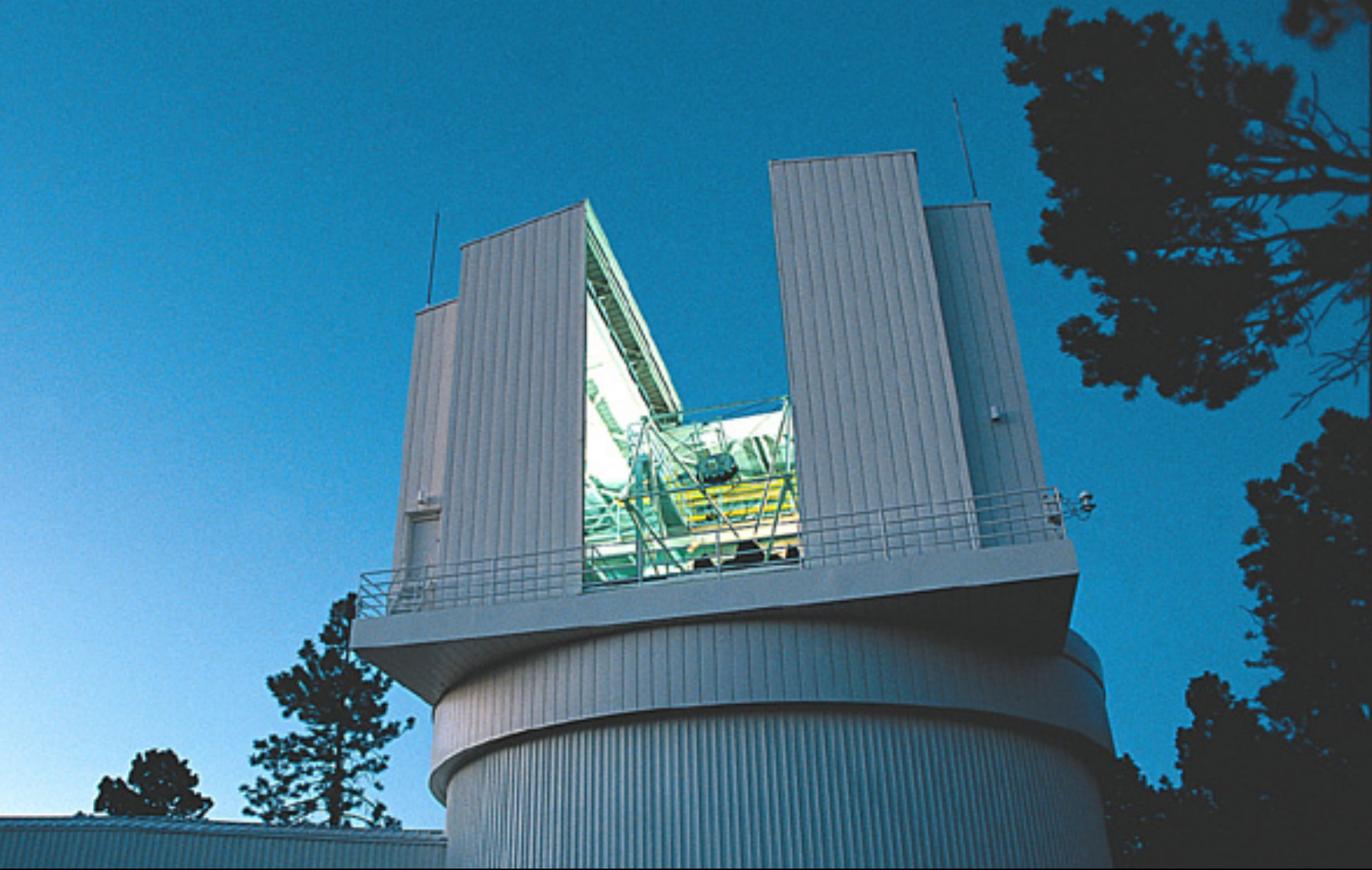
To describe the orbital effects of a violation, we consider the simplified Newtonian equations of motion for the geocentric orbit of the Moon, neglecting terms of order Δ^2 and perturbations of all bodies except the Sun:











They're not "Allstate" but for lunar laser ranging the Apache Point Observatory rangers are the "Good Hands" people

Benediction

ROBERT H. DICKE
PRINCETON UNIVERSITY
Department of Physics
JOSEPH HENRY LABORATORIES
JADWIN HALL
Post Office Box 708
PRINCETON, NJ 08544

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 developed in collaboration with Carl Brans.

The gravitation 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 measuring the orbital period. The period was to be measured by 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 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. Alley was successful. Later an advisory committee was established with members from both inside and outside the Princeton group.

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, 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. 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 observations.

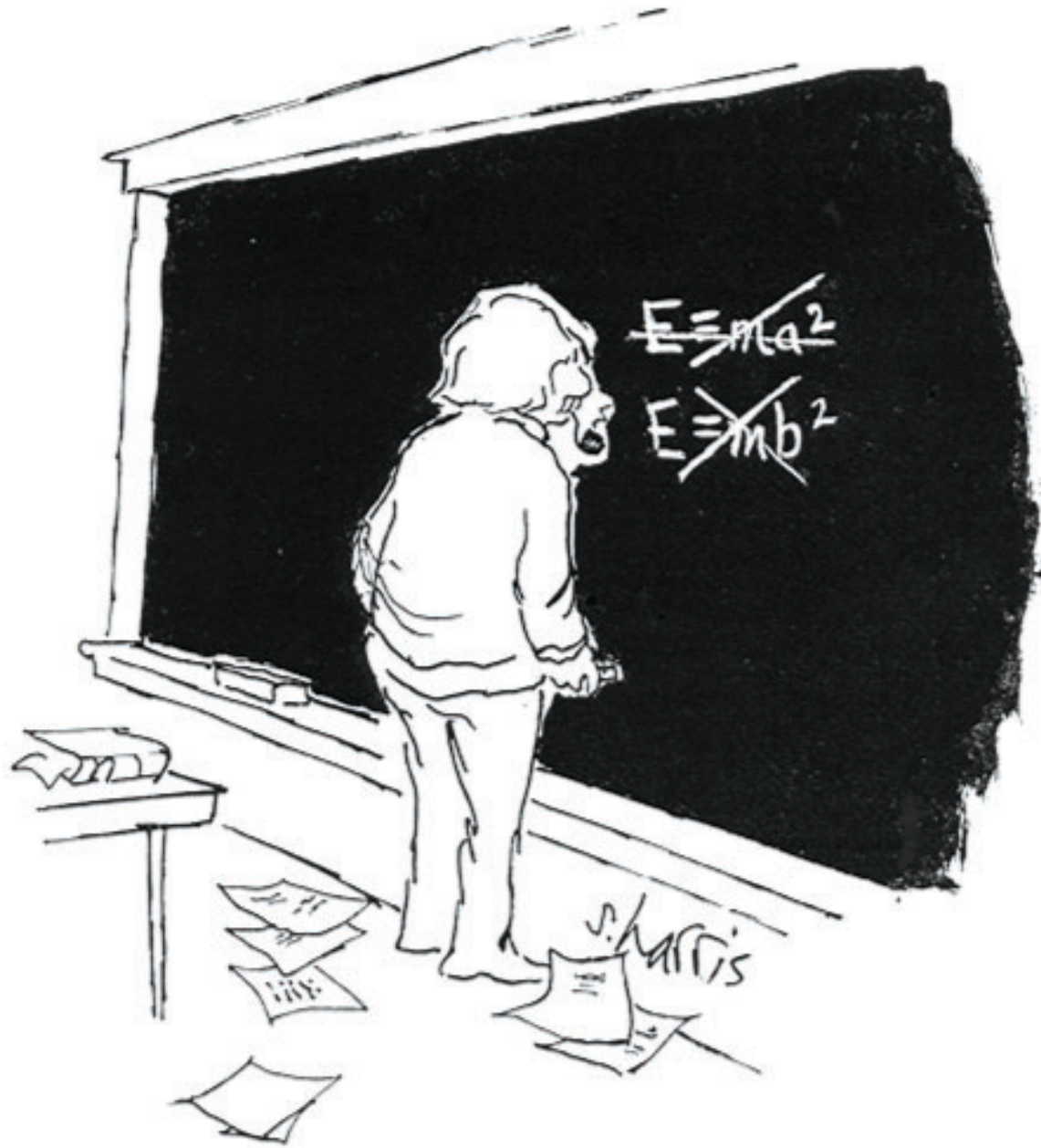




It is oftentimes difficult to recognize the source of a problem

**“More things are known than
are actually true.”**

J. R. Pierce



“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.”

ALBERT EINSTEIN

Henry Cavendish, were he alive today, would describe the Lunar Laser Ranging Experiment by using the same words he used in regard to his (1778) “Experiment to Determine the Density of the Earth” namely, “The apparatus is very simple.”

And were Einstein alive today, he would simply say, in spite of its apparent simplicity, “The Lunar Laser Ranging Experiment is a Thick Board!”

Thanks for listening.