# A millimeter-wave lunar radar

**Dans les années 1960, la NASA prépare les missions Apollo et ausculte nôtre satellite naturel.
Il n’y a pas de préamplis GaAs fets à l’époque et les amplis paramétriques nécessitent une énergie de pompe à minimum 10 fois la fréquence de travail …Pas facile même pour les pros.
La réalisation d’un réflecteur parabolique de grande précision « par rotation » de la matière en transition vers la phase solide est à noter. Cette technique est toujours utilisée en hyper, optique, X etc….
Vue la taille transversale du faisceau antenne, la température du système de réception est largement définie par la température de la lune et la pénétration de l’onde millimétrique dans la surface.
Le régime « multi-modes » du guide circulaire a été utilisé malgré l’à priori des spécialistes.
L’utilisation et la gestion pragmatiques du réseau de filtres en peigne est également intéressante. A noter l’incontournable dégradation du bruit de phase par la multiplication, dégradation que l’on retrouve évidemment dans les techniques plus modernes.**

**Bonne lecture**

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# A MILLIMETER-WAVE LUNAR RADAR

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The Lincoln Laboratory lunar radar that employs millimeter waves was conceived about ten years ago. There were two motivating ideas, of which one was the realization that crowding of the spectrum and demand for bandwidth pointed clearly to the eventual need for exploiting the stretches of spectrum that lie above 20 GHz. The other incentive was a desire to push antenna gain to new high values, and beamwidths to correspondingly low values — for the sake, respectively, of deep-space communications and high-resolution radar.

The program was inaugurated by Jerome Freedman, head of the Radar Division, and his associate Dr. James W. Meyer. The basic item was to be a paraboloidal antenna with a diameter of at least 1000 wavelengths. Tolerances were to be such as to make the dish perform well at 35 GHz, with good performance at higher frequencies a desideratum.

The dish was made by applying a principle that has been known as a matter of theory for a long time. Consider a round container of fluid — perhaps a pail of water — rotating about its axis of symmetry at constant angular velocity $\omega$. The surface of the fluid, since it cannot resist tangential forces, must take a shape such that the forces exerted by the neighboring material on an element of the fluid there have a resultant that is normal to the surface. These forces must combine with the weight of the element to produce the centripetal force that is needed in order to make the element revolve. The condition is satisfied when a vertical plane through the axis cuts the surface in a curve defined by $y = (\omega^2/2g)x^2$; the surface is, therefore, a paraboloid of revolution.

The ingenious R. W. Wood, of Johns Hopkins, used the paraboloidal figure of a dish of spinning mercury as a mirror for an astronomical telescope.[1] The Kennedy Company of Cohasset, Massachusetts undertook to make a paraboloidal antenna by rotating a dish of plastic while the material was setting. This unlikely method was a success. The critical problem was making the turntable rotate with constant angular velocity. With help from some of Lincoln Laboratory's servo engineers,

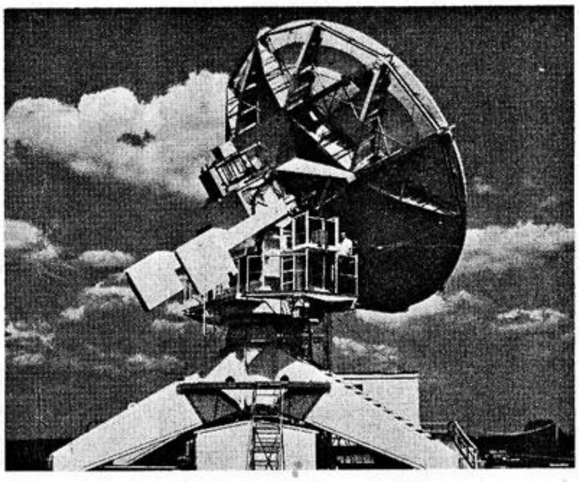

**Fig. 1 — The MIT Lincoln Laboratory 8.6-mm Lunar Radar.**

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* *Operated with support from the U. S. Air Force and the U. S. National Aeronautics and Space Administration.*

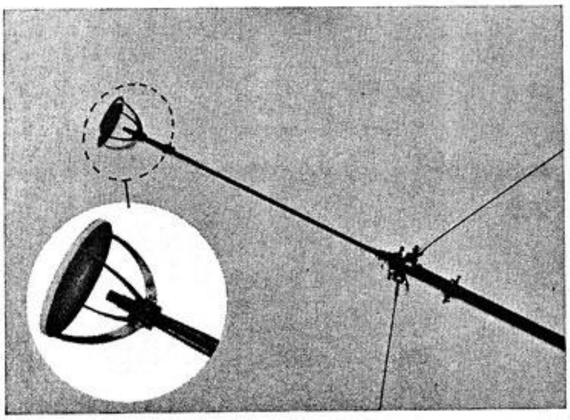

Fig. 2 — The antenna feed.

this problem was solved, and a paraboloidal surface 28 feet in diameter, with 12-foot focal length, was the result. A flame-sprayed zinc coating supplied the surface conductivity needed to make the paraboloid into a mirror. The plastic lies on a Fiberglass mould that is secured to the "star of David" aluminum frame seen in Fig. 1, to supply rigidity. When not in use, the dish is stowed in the position in which it was formed, its axis pointing to the zenith. White paint protects the zinc coating. The dish has weathered seven Massachusetts winters with no evident deterioration.

The feed, visible in Fig. 2, is a limiting version of the Cassegrain configuration, in which a hyperboloidal secondary reflector focuses the rays to a position accessible to the observer — in the microwave case, into a waveguide. The design in Fig. 2 is a limiting one because the secondary reflector is a plane. The waveguide, instead of terminating in a horn near the apex of the dish, extends to within about two inches of the focus. An inch or so from its end, there is a plane copper-clad aluminum plate about five inches in diameter. Behind the plate lies the image of the end of the waveguide; focussing the antenna consists of placing this image at the focus of the paraboloid.

Because loss in standard waveguide at 35 GHz approximates 0.1 dB per foot, R.F. is generated and received in a cab mounted on the rear of the dish. Since the focal length of the dish is 12 feet, the waveguide feed that runs from the cab to near the secondary reflector has to be about 13 feet long. It has a circular cross section, in order to permit the use of any desired polarization. If it were so small as to support only the dominant mode, for operation at 35 GHz it would have a diameter of 0.26 inch and an attenuation of 1.2 dB each way. In the original design (1961), this high loss was evaded by using oversize waveguide; an orifice 0.351 inch in diameter provided good illumination of the dish, and a pipe of that inside diameter, made of coin silver and 13 feet long, has a calculated loss of 0.9 dB each way. The actual loss (one way) for a silver-lined copper pipe of that I.D., installed in 1962, was 1.4 dB.

When using horizontal polarization at 35 GHz, the antenna had a gain (over all, including the waveguide) of 67.5 dB. This figure implies an antenna efficiency (not including loss in the guide) of 55 per cent.

The antenna was used in 1963 to measure the reflectivity of the moon for millimeter waves.[2] This was, we believe, the first time that the moon was examined with a radar beam narrow enough to illuminate only a portion of the moon's surface; the two-way 3 dB beamwidth was 3 minutes of arc, just a tenth of the angle subtended at the earth by the moon. Thanks to the high gain, it was possible to detect the echoes with a transmitter power of 12 watts, obtained from an Elliott 8FK1 floating-drift-tube klystron oscillator. The receiver was a triple-conversion superheterodyne with a bandwidth of 170 Hz. In order to stabilize the frequency of the transmitter, the klystron was phase-locked to a signal from a multiplier chain driven by a crystal-controlled oscillator. The pulse length was 2.4 seconds, the time for a round trip to the moon.

In order to improve the signal-to-noise ratio, a larger transmitted power was needed. It was to be obtained by putting a travelling-wave tube between the klystron and the antenna. The Watkins-Johnson 266 was developed for this use, but before it could be delivered, a cut in Lincoln Laboratory funding made it necessary to shut down the radar.

In 1965, the desire by NASA for improved reflectivity measurements — in connection with the Apollo program — led to renewed funding of the millimeter lunar radar. By this time, it appeared possible to procure a klystron amplifier with an output of about a kilowatt and with enough gain to make the oscillator klystron superfluous. This scheme had great appeal, because it eliminated the need for phase locking an oscillator to a control signal; the control signal itself could, after amplification, be the transmitted signal.

Early in 1966, Varian Associates accepted an order for klystrons with 47 dB of gain at 34.56 GHz, and an output of at least 700 watts. For a reason that will be discussed later, we wanted to be able to narrow the receiver bandwidth to 10 Hz; the frequency must for that purpose have a stability on the order to $10^{-10}$. We also wanted spectral "hash" resulting from phase modulation to be at a level of $-15$ dB, or lower, with respect to the signal. In view of this need for frequency stability, we were advised that 5 MHz is about the optimum frequency for the crystal-controlled source. To get from there to 35 GHz involves multiplication of the frequency by 7000, and an inexorable consequence is the multiplication of phase modulation by $(7000)^2$, which is 77 dB. Phase modulation in the 5 MHz source had therefore to be at least 92 dB below the signal, and degradation of the signal by the multiplier had to be kept near the theoretical minimum.

In order to provide the low-noise 5-MHz source, Hewlett-Packard devised a modification of their Model 107BR Quartz Oscillator; this modification is designated as H-30 Model 107BR, and it is now available on order.

The specifications for the multiplier chain were so stringent that requests for quotation were mostly answered by "No bid." Sylvania Electronic Systems in Williamsville, New York, accepted the order and produced an all-solid-state multiplier that meets the specifications and performs well. The multiplication factor is 6912, which is $2^8 \times 3^3$; the signal frequency, consequently, is 34.560 GHz.

To avoid the need for isolating the signal source during reception, the multiplier is keyed off. Consequently, local-oscillator power has to be supplied by a second multiplier, driven at a slightly different frequency from the first. Hewlett-Packard provided a second quartz oscillator, just like the first except that it generates 5.004340 MHz, which after multiplication by 6912 differs from the signal by 30 MHz. It drives a multiplier just like the one used for generating the transmitted signal. It would have been possible, of course, to time-share a single multiplier, using it to generate first the signal and then the L. O. power. However, it is desirable to have two multipliers, so that the quality of the spectrum can be assessed by beating them together and observing the resulting spectrum with an analyzer working at 30 MHz.

Each multiplier consists of an octupler and a quadrupler based on step-recovery diodes, and a 160 MHz amplifier that raises the level to 20 watts, after which the signal undergoes three doublings and three triplings by varactor diodes. The input is 10 mW at 5 MHz, and the output is 100 mW at 35 GHz. We regard this multiplier as a fine achievement on the part of the vendor.

The transmitter consists, then, of three main units: the low-noise quartz oscillator, the multiplier, and the Varian 928A klystron amplifier. The klystron, described in an accompanying article by James & Zitelli[3], has six cavities, a gain of 50 dB or more (depending on tuning) and an output in excess of one kilowatt when operated at 12 kV and 1 ampere on the beam. Since the multiplier output and the klystron gain both exceed the specifications laid down at the beginning of the development, there is plenty of reserve power.

Monitoring equipment indicates drive power, klystron output power, and reflected power returning from the antenna. Through a light pipe, a photoelectric detector views the klystron window, in order to shut off the input to the klystron within 5 microseconds if there is an arc near the window. Since the klystron was installed in the transmitter, this protective device has never been called into play by an arc.

The original waveguide in the antenna caused concern while the multiplier and the klystron were being developed. The 1.4 dB loss in the waveguide was painful when operating at 1.2 watts, but it promised to be downright troublesome when the kilowatt transmitter was installed, because if 1000 watts were fed into that pipe, 275 of them — about 20 watts per foot — would go into warming it up. A low duty cycle was a possible answer, but an unwelcome one. During tests, it would certainly be more convenient to be able to operate CW. Besides, the 1.4 dB was hard on our pride. Short of rebuilding the antenna — converting it, for example, to a more normal Cassegrain configuration that would have only a short waveguide — the only way of diminishing the loss seemed to be by enlarging the waveguide, which runs through a series of holes inside the suporting mast. The largest tube that would fit comfortably through the existing holes had an inside diameter of about 0.480 inch. The hitch was that the orifice in front of the secondary reflector had to stay 0.351 inch in diameter in order to preserve the proper illumination of the main dish.

The RF experts whom we consulted warned us that it would be folly to have an oversize waveguide taper to a smaller orifice or nozzle, because that would result in trapping of some of the unwanted modes, causing lossy resonances that would be closely spaced because the pipe is so long (several hundred wavelengths). We thanked them and took them seriously, but we tried it anyway. At 35 GHz, the 0.480″ circular pipe that we chose supports six modes, and three of them are trapped by the taper in front of the secondary reflector. However, an extensive set of measurements — on the bench, and later *in situ* — says that the absorption dips are only about 0.1 dB in depth. The loss in the pipe is between 0.7 and 0.8 dB; a kilowatt of input causes heating at a rate less than 10 watts per foot, and this amount has no discernible effect on the gain or the boresight.

As originally described,[4] the secondary reflector was held in place by a thin hemispherical shell of low-loss high-melting foamed plastic, of which the equator encircled the reflecting disk and the pole gripped a circular guide that was an extension of the feed pipe.

When the Varian 928A pumped a kilowatt into such a feed in the laboratory, the plastic promptly melted. The present feed has four brass arms that support the disk, and the assembly is kept weather-tight by means of a Teflon disk that closes the orifice and also acts as a tuner. The thickness of the disk, 0.090″, is such as to produce a VSWR about the same as that of the orifice-and-plate combination. The spacing between orifice and disk, which is noncritical for the functioning of the antenna, is adjusted so that the VSWR at 34.56 GHz is less than 1.05.

The antenna is focussed by looking at a transmitter atop a water tower six miles away. This distance puts the test transmitter only marginally in the far field of the antenna; the focus can be adjusted for infinity by moving the feed by a calculated amount, 0.070″.

Pointing of the antenna is indicated by 17-bit optical encoders on the azimuth and elevation shafts. These permit pointing at invisible targets, with pointing errors considerably less than a beamwidth. For pointing at the moon, it has been more direct to use optical observation. The dish has two 4″ holes, and behind one of them there is a closed-circuit TV camera that looks through a telescope along a line parallel to the antenna boresight. The telescope includes a reticle that carries two circles, one the size of the 3-dB two-way beamwidth, the other approximately the size of the moon. The antenna range has a light beside its transmitting antenna, and parallelism is obtained by moving the reticle until the light is centered against it.

Aligning the antenna and telescope boresights by means of the antenna range has a serious drawback. It supposes that refraction in the atmosphere is the same for millimeter waves as for optical waves. In winter, this supposition is usually valid, but in summer there are times when it is not. Moisture in the air can enhance the refraction of millimeter waves, so that the test transmitter looms above the light by a beamwidth (0.07 degree) or more, though looming by more than a

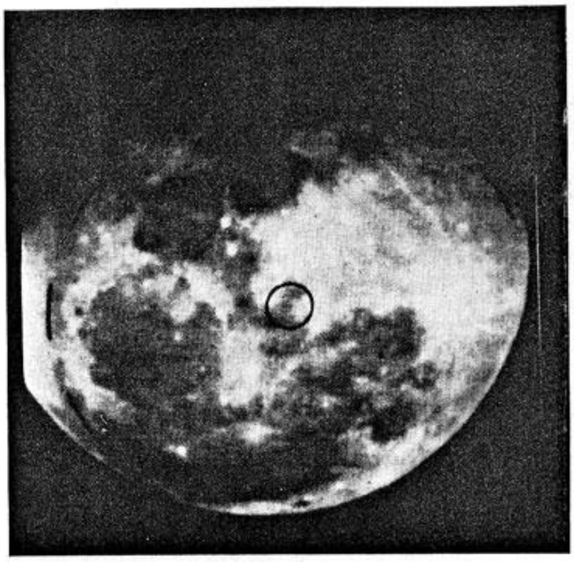

**Fig. 3 — The moon displayed at the pointing-control console. The small circle marks the radar beam 3-dB profile.**

beamwidth is rare. Fortunately the alignment is mechanically stable, and it can be checked by connecting a radiometer to the antenna and using that to locate the limbs of the moon while watching the TV screen.

The elevation of the antenna test range is 0.22 degrees. For the elevations at which celestial objects are viewed — five degrees or more — millimeter waves and visible light undergo essentially the same refraction, and the telescope can be used with assurance.

For point-to-point communications on the ground, looming of millimeter waves may have some importance. The beamwidths would perhaps be larger than that under discussion here, but the antenna separations would presumably be greater than the six miles of our test range. For fixed paraboloids, refraction that deflects the millimeter waves by one beamwidth would cause the signal strength to drop by something like 15 or 20 dB.

The radar receiver is a triple-conversion superheterodyne using a balanced mixer with a noise figure of about 12.5 dB for a signal present in only one of the sidebands. The first I.F. is centered at 30 MHz, the second at 2.2150 MHz, and the third at 2500 Hz.

When the moon comes over the horizon, rotation of the earth is carrying the observer toward the moon at several hundred miles per hour, and the opposite effect occurs when it is setting. The distance to the moon is also varying because of noncircularity of its orbit around the earth. For these reasons lunar echoes are Doppler shifted, and because a narrow bandwidth is needed for noise limitation, the continually changing Doppler shift is a serious complication.

For several reasons, the Doppler shift is not the same for all parts of the moon. As seen from the earth, the moon has a rocking motion called libration. At 35 GHz, echoes from opposite limbs of the moon may differ in frequency by about a kilohertz. Our beamwidth is one-tenth the width of the moon, so our receiver bandwidth needs to be on the order of 100 Hz. To provide some margin for error and for shortcomings of the earlier phase-locked transmitter, the 2500-Hz I.F. has a 3-dB bandwidth of 170 Hz.

An error of 85 Hz in the allowance for the Doppler shift will, if uncompensated, produce an error of 50 percent in a measurement of the strength of an echo. Since the Doppler shift may be as large as 70,000 Hz, making the correction is a fussy matter.

The Doppler shift is allowed for by programming the second local oscillator, which is a Hewlett-Packard Model 5100A Frequency Synthesizer operating near 28 MHz. The program changes the synthesizer frequency in 50-Hz steps, in accord with a punched paper tape prepared from a computer output that, along with other items like pointing data, tells what the synthesizer setting should be at each minute of local civil time, provided that the radar is looking at the center of the moon's disk.

For looking elsewhere on the moon, it is necessary either to use more elaborate calculations, or to proceed empirically. The latter course seemed more attractive; to implement it, the receiver output passes through a comb filter with 170-Hz passbands at 2300 to 2700 Hz in 100-Hz steps. The filter output goes to a multipen recorder. The gains are adjusted so that when the input to the comb is at 2500 Hz, the pens for 2400, 2500, and 2600 Hz all have the same deflection. When an echo from the moon produces the same deflection on all three pens, one knows that the second local oscillator is correcting properly for the Doppler shift generated by whatever part of the moon is in the beam. Of course, it is not necessary to have the oscillator tuned exactly right, because from the ratio of deflections on the 2400- and 2600-Hz pens, the tuning loss in the 2500-Hz channel can be inferred from a calibration. The operating procedure is to start at the center of the disk, using the calculated Doppler correction, and then to feel one's way toward other areas by gradually offsetting the second local oscillator from its programmed frequency, using the comb-filter "discriminator" for guidance.

The purpose of this radar is to measure the reflectivity of the moon for millimeter waves. Because of their small wavelength, millimeter waves are reflected only by the lunar material that is very close to the surface. By comparing the lunar reflectivity for millimeter waves with similar measurements already made at several longer wavelengths by other radars, it is expected that something can be learned about the variation of lunar material with depth. To be sure, the first visitors may soon be coming back with several handfuls of the stuff, and they may even have made some borings, but the area they cover will be small. The information that they bring back should, in fact. offer a basis for new, more certain, and more detailed interpretation of the data on electromagnetic reflectivity that have been gathered by radar for the whole visible side of the moon.

The area of the moon that is under scrutiny at any moment by the millimeter radar is determined merely by

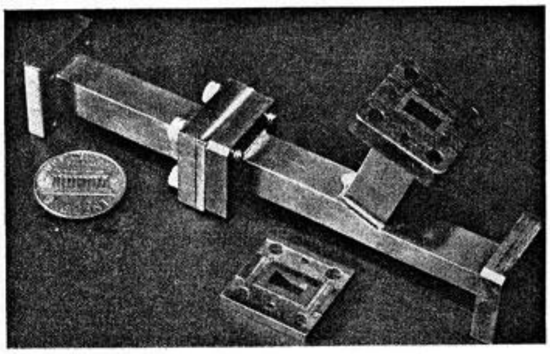

**Fig. 4 — Circular polarizer and orthogonal-mode transducer, showing design of gasketed joints.**

the beamwidth of the antenna, and it is recorded by photographing the TV display. Figure 3 is such a photograph. With a kilowatt of peak power and a balanced-mixer receiver, getting better range resolution by shortening the pulse does not seem feasible, so we still use the 2.4-second pulse. In principle, the examined area can be diminished by exploiting the libration, or rocking motion, of the moon, as has been done at the Lincoln Laboratory Haystack radar. Because of the libration, the area on which the pulse impinges does not all produce the same Doppler shift; returns from different parts of the area within the circle in Fig. 3 could therefore be observed separately by using narrow-band filters at the output of the receiver. The spectral width of the transmitter at the half-power points is not more than 3 Hz, and the variation in Doppler shift across the area delineated by the beam circle in Figure 3 is typically about a hundred hertz. Filtering, therefore, could split the observed area into ten strips. The transmitter design kept open the possibility of using this technique; though present plans do not include doing that, the spectral width of 1 in $10^{10}$ or more may be of interest in other connections.

The long pulse permits the transmit-receive switching to be done by remotely controlled waveguide switches. Each pulse is treated as a separate event. Overriding the antenna tracking motion by means of a joy stick, the operator positions the beam at the desired place on the moon and presses a button. An automatic sequencer shuts off the transmitter multiplier, shunts the transmitter output (low-level noise) into a load, connects the antenna to the receiver, and continues to manipulate the radar for 40 seconds, at which time an IBM printer disgorges a card. At 1.2 seconds after the transmitter shuts off, when the middle of the received wavetrain is being reflected from the moon, a photograph like Fig. 3, but containing a serial number, is exposed. The IBM card records the serial number, the date and time, the azimuth and elevation of the antenna beam, the transmitted power, the outputs of a two-channel receiver working with orthogonal polarizations, two readings of each receiver noise, and the receiver responses to a standard noise tube. Before being printed, the receiver outputs at 2500 Hz are squared and integrated; the energy in the echo can therefore be found by subtracting the receiver noise from the signal-plus-noise reading.

At the outset, there were some misgivings about whether a thousand watts CW would cause arcing at waveguide joints, overheating of switches, or similar difficulties. There has been no trouble, perhaps because all joints are made with the annealed and lapped copper gaskets illustrated in Fig. 4. The waveguide is WA28 of oxygen-free high-conductivity copper, water-cooled. In this time of concern about the structure of the moon, the data on lunar reflectivity that this radar will provide are of intrinsic interest. A further reason for building it was to promote the state of the millimeter art by procuring a high-power transmitter tube with a highly stable drive, and to gain experience in the use of millimeter waves. One indicator of their importance is that even the narrow-seeming atmospheric window near 35 GHz has a bandwidth equal to the whole of the presently exploited radio spectrum, from X-band on down. The exact future of millimeter waves is in doubt; what is not in doubt that this part of the spectrum does have a future, because that is where the megacycles are.

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**EVERETT A. CROCKER** joined the Radar division at Lincoln Laboratory in 1954, after two years in the U.S. Army, during which he was assigned to a missile-tracking radar at White Sands Proving Ground. After working for five years on the development of receivers for the Distant Early Warning radars, he moved into millimeter waves in 1959. He has been identified with the millimeter-wave lunar radar since its inception. He holds the A.E.E. degree from Northeastern University, and is a member of the Institute of Electrical and Electronics Engineers.