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# Group Report 1964-65

# Draft Program Description for Radar and Radiometric Lunar Surface Studies

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Lexington, Massachusetts

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

MILLSTONE HILL FIELD STATION

# DRAFT PROGRAM DESCRIPTION FOR RADAR AND RADIOMETRIC LUNAR SURFACE STUDIES

*P. B. SEBRING, Editor*

*Group 31*

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ABSTRACT

This document describes a program of radar and radiometric measurements on the surface of the moon of such a nature that valuable knowledge may be deduced concerning the suitability of the lunar surface to support "soft" landings. The lunar observations and measurements could be made by the Lincoln Laboratory of M.I.T. and the Center for Radiophysics and Space Research of Cornell University. M.I.T. and Cornell personnel participated in the planning of this project, and the description which follows includes a program of observations with the Arecibo radar facility in addition to observations to be made with instruments under the control of Lincoln Laboratory.

Measurements of limited accuracy and resolution have supported credible conjectures concerning the dielectric constant, the "percent roughness" at various wavelengths and the r.m.s. slopes of the larger elements. More recent small area evidence from the Ranger 7 photographs seems to corroborate some of these interpretations of radar data. The described measurements with Lincoln Laboratory's Millstone, Haystack, and millimeter wave facilities, and with Cornell University's Arecibo radar facility would not only greatly improve the accuracy of the overall statistical estimates of the surface characteristics, but also should yield estimates of the surface roughness, porosity and r.m.s. slope in areas as small as 2 km x 2 km or less.

In general, the programs are mutually complementary and complement earlier work as well.

Results from Millstone, Arecibo, and the millimeter wave observations could be available in 1 1/2 years while the other efforts described would require 2 1/2 years.

Accepted for the Air Force
Stanley J. Wisniewski
Lt Colonel, USAF
Chief, Lincoln Laboratory Office

# PREFACE

This report has been prepared in response to the question, "What information on the nature of the lunar surface, having an important bearing on attempts to land man on the moon, can be gotten from earth-based radar and radiometric systems ?" The program in radio selenography described would involve the use of some of the most powerful radars, equipped with the largest antennas in existence today, to make the measurements over a wide range of wavelengths, and with varying degrees of resolution. A summary of results to be expected is presented as is an estimate of the time required to carry out the several portions of the program.

The contributions of Dr. J. V. Evans, Dr. T. Hagfors, Dr. M. L. Meeks, Dr. J. W. Meyer, all of M.I.T. Lincoln Laboratory, and of Prof. T. Gold and Dr. G. H. Pettengill, of Cornell University, Center for Radiophysics and Space Research, to the material presented here are gratefully acknowledged.

P. B. Sebring, Editor

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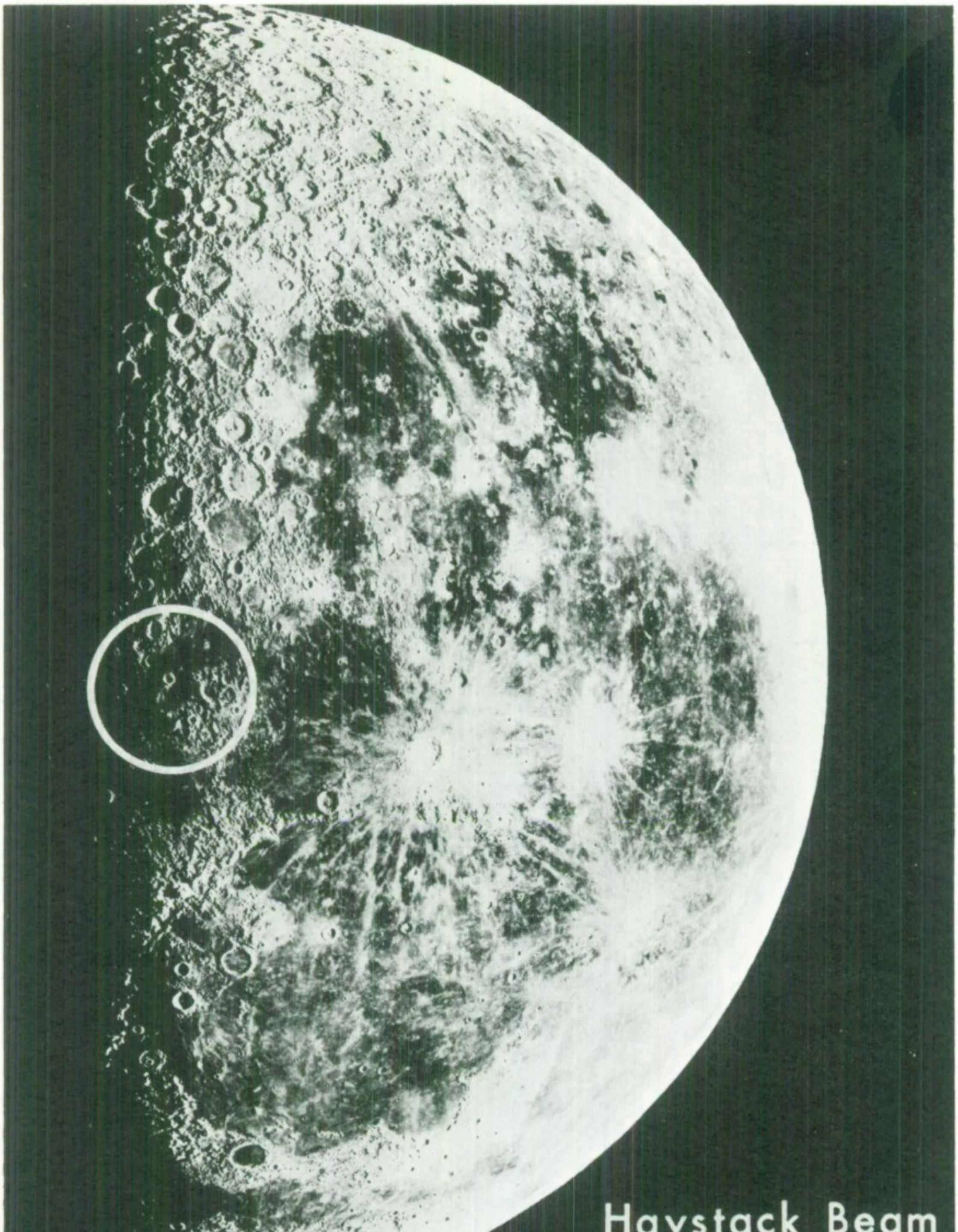


Lunar area subtended by beam of "Haystack" at 3.6 cm wavelength. Circle also approximates beam size of 28-foot antenna at 0.86 cm.

# DRAFT PROGRAM DESCRIPTION FOR RADAR AND RADIOMETRIC LUNAR SURFACE STUDIES

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## I INTRODUCTION

Vehicles designed for actual "soft" landing on the surface of the moon must, in order to be successful, be designed to match the sort of surface they will encounter. Present NASA designs may not be successful on a surface strewn with large boulders, one that slopes by more than a few degrees, or one which is so soft that the "footpads" sink appreciably. Until the recent Ranger pictures were obtained, hard landing and fly-by missions had not provided data of appreciable value in estimating these properties. Since ground-based experiments are more tractable and cheaper, it still appears wise to pursue these wherever it appears they can throw light upon any of the major problems.

Radiometric and radar studies of the lunar surface have been carried out over the past few years and now provide the basis of credible theories concerning its nature. Specifically, certain statistical properties of an overall surface have been derived, such as the r.m.s. slope of the larger elements, the average dielectric constant and thermal inertia (which bear upon the bulk density) and the percentage of the surface that appears "rough" at the scale of the several wavelengths employed.

It is of value to note that study of the new Ranger 7 pictures appears in some particulars to verify the general ideas resulting from radar studies of the lunar surface to date. While forthcoming Rangers can provide, at most, a detailed view of several selected small areas, ground-based measurements can be employed systematically to provide a picture of vast areas of the surface. Because the radar and radiometric measurements respond to the surface conditions down to several meters below the optically observed skin, it is likely that the physical properties of interest to soft landing designs will correlate more readily with the long wavelength measurements than with distant optical surveys. Once a suitable environment has been established by close observation or landing in one area, the radio properties of this area may be sought elsewhere, with some confidence that the mechanical properties will be similar where the correlation of the directly observed quantities is high. The lack of sensible lunar atmosphere, and therefore the absence of highly local environmental influences, means that the outer crust of the moon has in all places been subjected to very much the same external treatment during its lifetime, and should not show nearly the extreme variations found on earth. Correlations of properties discovered for some regions would thus have a wide applicability.

It is proposed herein that major facilities be utilized for the extension of the above-mentioned research resulting in much improved statistical estimates of the overall properties. Further, selected areas of the surface, judged from present data to be favorable for lunar landings, could be studied in considerable detail with narrow-beam radar techniques, and at several frequencies, to permit scale-of-roughness and slope determinations of sufficient accuracy to be useful in forecasting probable landing conditions. More accurate and localized determination of the dielectric constant, $\epsilon$, utilizing both radar and radiometric measurements, will be useful in estimating bulk density of the material in the localized area, though not necessarily its firmness. Radar and radiometric polarization experiments designed to study Brewster angle effects can be valuable in determining depth of wave penetration before major reflection, thus indicating possible depth of a porous or powdery surface layer.

Although not specifically described herein, it is likely that an optical radar could be built, based upon a high-power laser and associated optical systems, that would have extremely high resolution in range (1-2 meters) and angle (1 second arc). This radar should be useful in measuring scale of roughness in a direct manner at the subterrestrial point on the lunar surface. The approach being considered will be discussed in a separate Lincoln Laboratory document.

It should be stressed that, until the excellent small area photographic results from Ranger 7 were obtained, only radar results provided information about the surface roughness on a scale of less than about 400 meters. Radar studies have thus far been statistical, in that they give only the average roughness over the entire surface. A detailed map indicating areas where percent roughness is small even at a scale of one meter or less might be the most useful contribution the ground-based program, outlined here, could make.

It will be helpful, in the following sections, to touch briefly upon the experiments performed to date and the present estimates of the lunar surface characteristics derived from them. A specific program of further experiments will then be outlined, together with estimated time schedules.

## II REVIEW OF MEASUREMENTS TO DATE

### A. Radar Cross-Section Measurements

Figure 1 summarizes the published[1,2] values, expressed as a percentage of the projected area ($\pi a^2$), for the radar cross section of the moon. Although an accuracy of $\pm 1$ db is claimed for some of the values, probably none is more accurate than $\pm 3$ db. Hence it is not possible to infer reliably any dependence of the total cross section upon wavelength. An average value is perhaps 0.07 of the projected area.

### B. Average Scattering Properties

Figure 2 shows the average scattering behavior of the moon at 68-cm wavelength as measured at Millstone.[3] Data gathered with the West Ford ground terminals (3.6 cm)[3] and the Lincoln millimeter wave system (8.6 millimeters)[4] as well as Millstone yield the curves of Fig. 3. These results show a clear dependence on wavelength. In effect, the moon shows a "highlight" at 68 cm which becomes less intense with decreasing wavelength until at visible wavelengths the disk is almost uniformly bright.

These results can be employed in estimating (a) the backscatter gain, g, of the surface, (b) the fraction of the surface covered with structure "rough" on the scale of the wavelength employed, and (c) the average distribution of the slopes of the larger elements of the surface (and hence the r.m.s. slope).

### C. Mapping Experiments

With the West Ford terminal (3.6 cm; beamwidth 6' arc) and the millimeter wave facility (8.6 mm; 3' arc) a view of a fraction of the lunar surface was possible. Thus, the scattering behavior of various areas could be studied directly by moving the beam. In the case of Millstone, the UHF (68 cm) beam ($2^{o}.1$) illuminated the entire moon, prompting the development of the range-doppler mapping technique.

Figure 4 is of assistance in understanding the operation of the technique in developing a useful coordinate system. Typically, in early moon experiments at Millstone, Pettengill and colleagues employed a pulse length of

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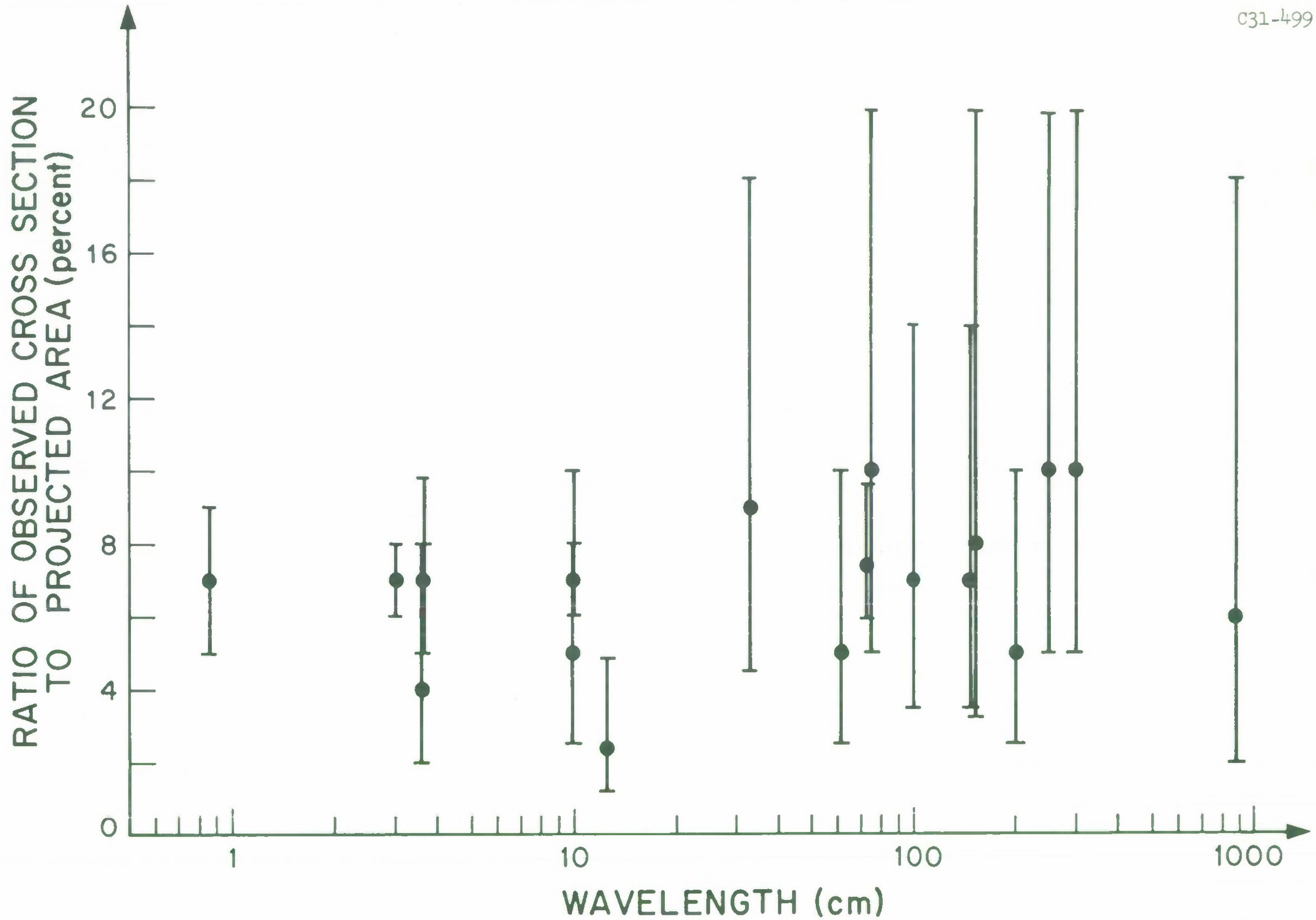


Fig. 1. The radar cross section of the moon as a function of wavelength. The values shown are expressed as a fraction of the physical area of the moon's projected disc ($\pi a^2$).

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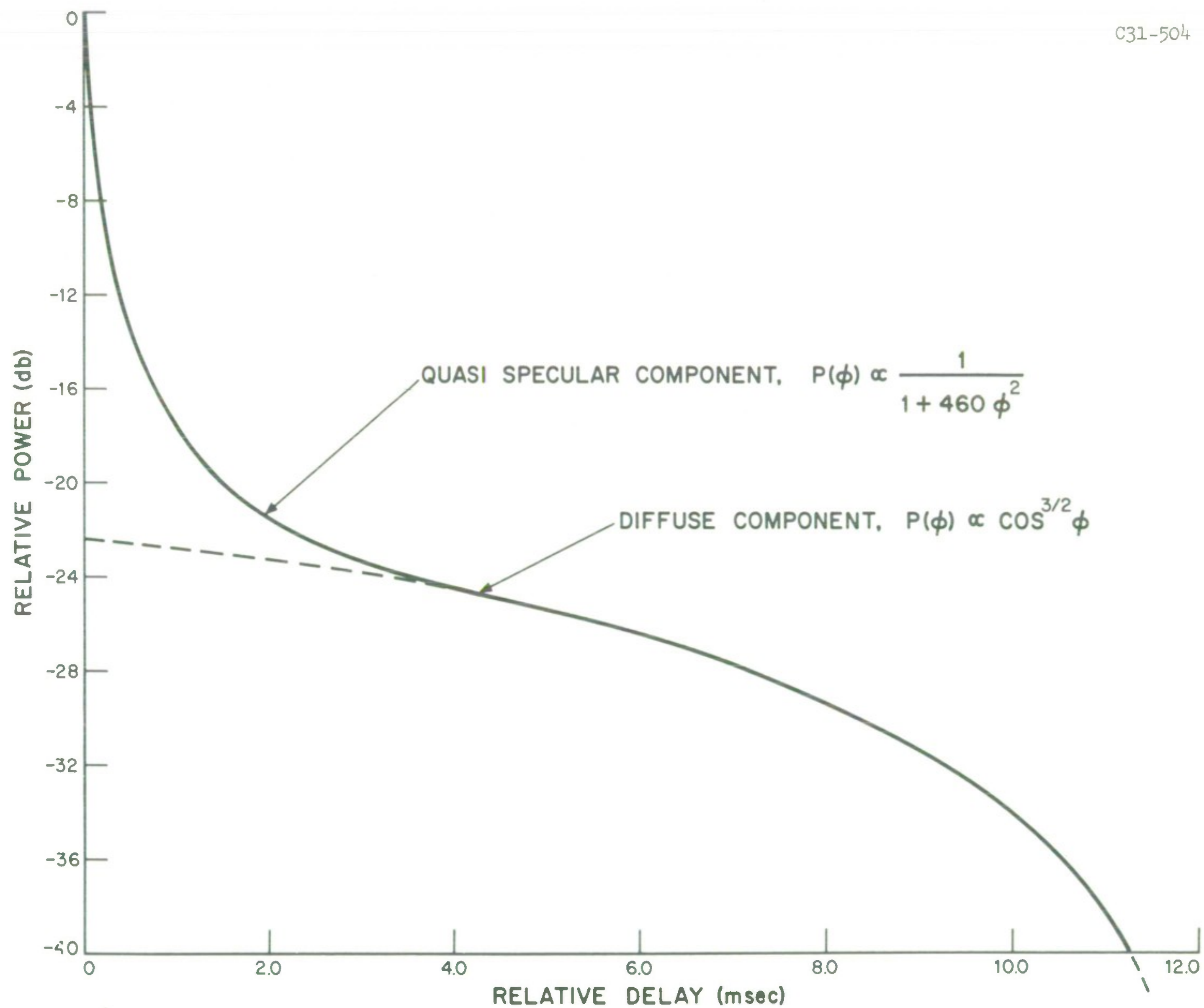


Fig. 2. The average echo power vs delay P(t) observed when 12 μ sec pulses are reflected by the moon at 68 cm wavelength (Evans and Pettengill, 1963).

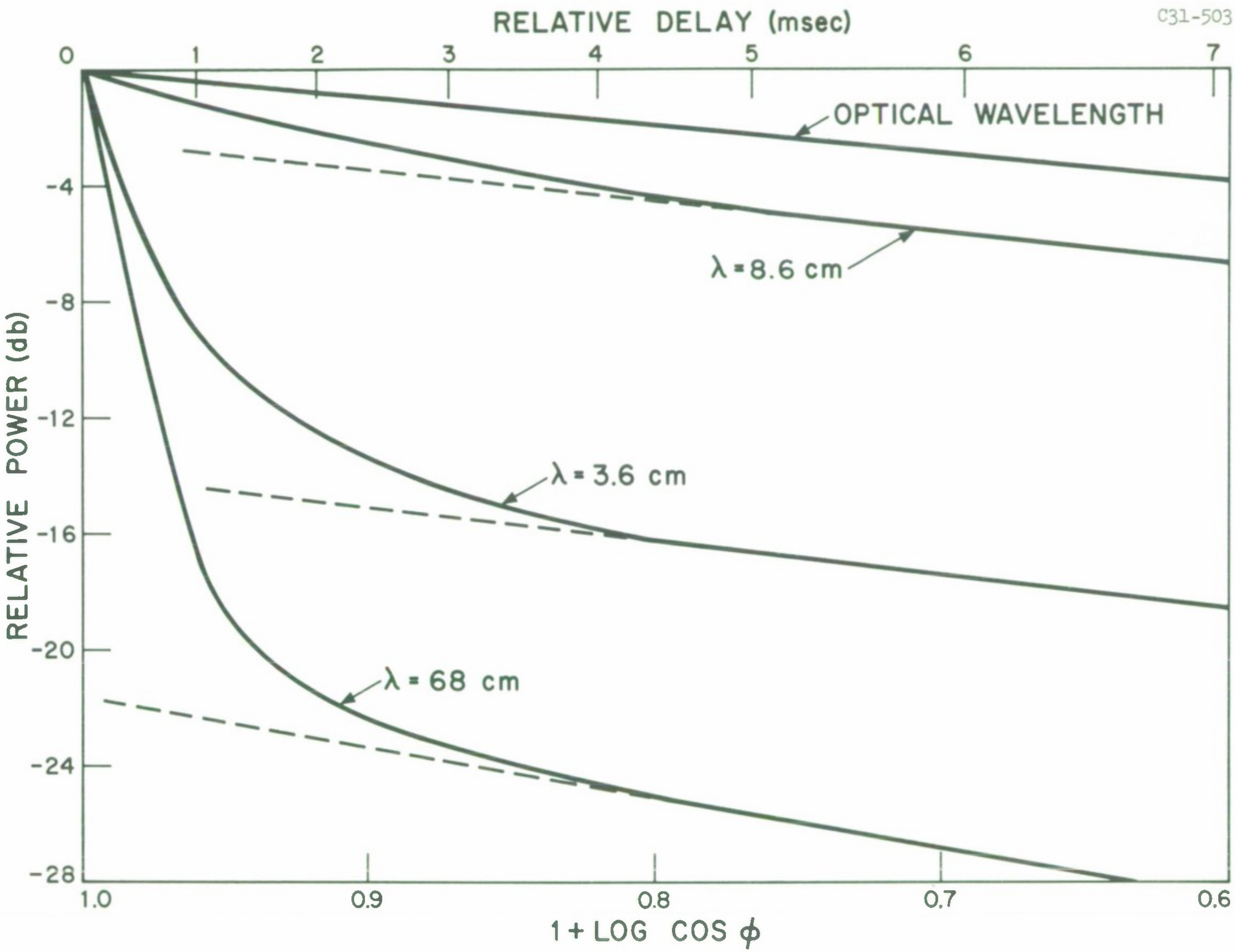


Fig. 3. The average echo power plotted as a function of 1 + Log cos $\phi$ ($\phi$ = i = angle of incidence and reflection) at wavelengths of 8.6 cm, 3.6 cm and 68 cm. A clear wavelength dependence in the scattering behavior of the moon is evident from these results, which have been normalized at the origin.

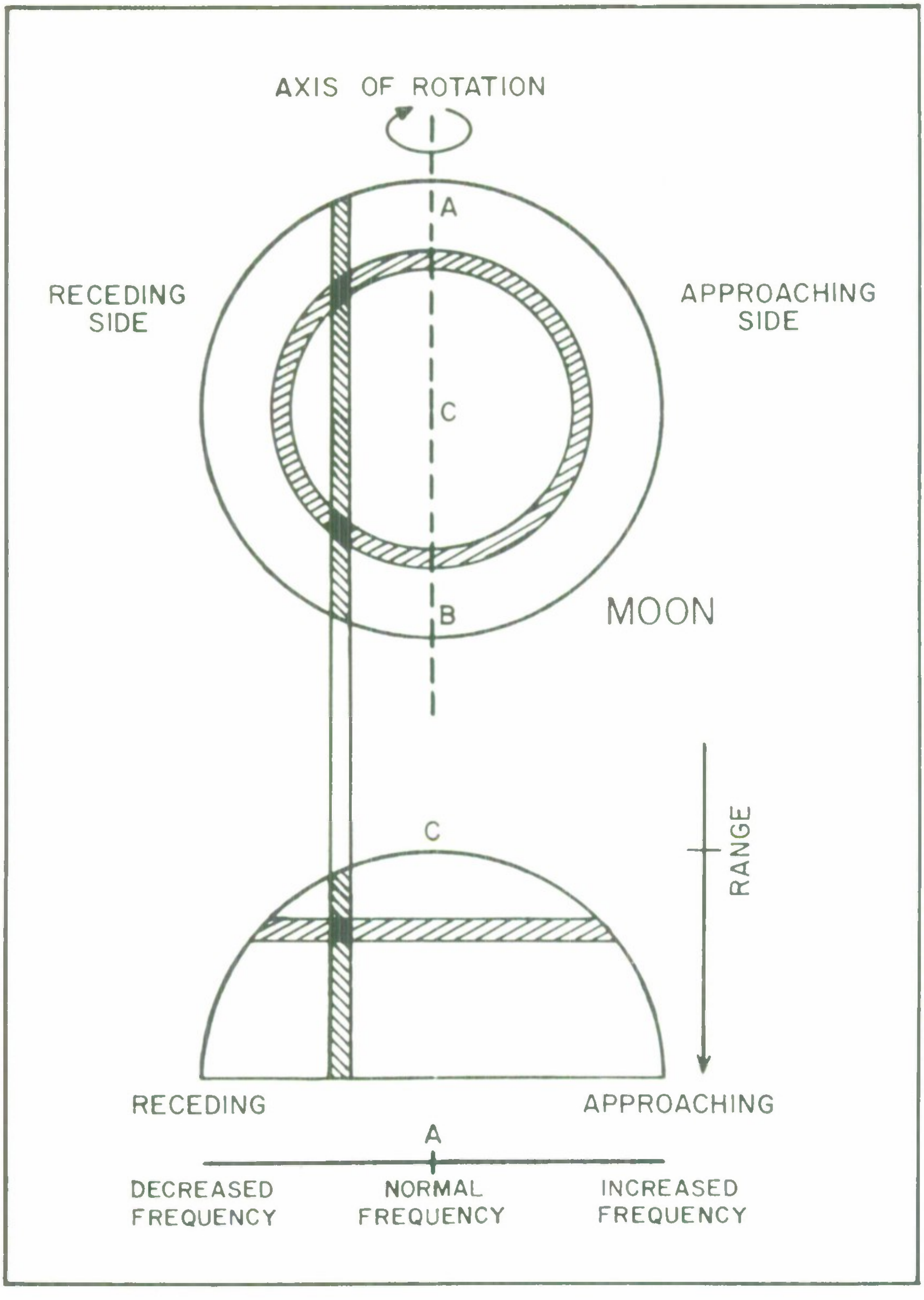


Fig. 4. Diagram showing the visible lunar hemisphere in two projections. Top: the lunar disc as viewed from the radar, with representative contours of range and doppler frequency shown, respectively, as a circular and linear strip. Bottom: the same configuration as viewed from the side, illustrating how the two types of contours form a useful coordinate system.

500 microseconds, dividing the moon into some 26 range elements. The phase and amplitude of the returned signal in each range element were stored each pulse period. Subsequent Fourier analysis of the stored samples over a number of seconds of data permitted determination of the power versus frequency spectrum for each range element to a resolution depending upon the time over which the data extended. In Pettengill's work, a typical 10-second span of data yielded a frequency resolution of 1/10-cycle per second.* Since, at peak libration rates, the maximum differential doppler across the face of the moon for $\lambda$ = 68 cm is about 11 cps, the experiment yielded at most some 110 elements in the doppler coordinate.

Figure 4 shows an ambiguity between range-doppler cells equally displaced above and below the lunar "librational equator" and within the same doppler element. This would be best resolved by radar beams small compared to the angular extent of the moon.

Figure 5 exemplifies the sort of computer display made possible with the above technique. Utilizing this technique and an expanded display of a restricted lunar area, Pettengill and Henry[5] showed that the crater Tycho is an anomalously bright scatterer.

More recently, working at a similar wavelength of 70 cm, Pettengill and Thompson at Arecibo have found similar results for all the other rayed craters as well as for many other lesser features. The common feature of these presumably young objects appears to be an unusually and perhaps completely rough surface, with a surface density (below the optical skin) somewhat higher than characteristic for most portions of the lunar surface.

D. Optical Radar Experiment

Utilizing a ruby laser in a 10-inch transmitting telescope and a photodetector in a 48-inch receiving telescope, Smullin and Fiocco[6,7] with the

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*In coherent integration experiments utilizing a hard target (Syncom) it has been shown experimentally that the short-term frequency stability of the present Millstone is about 0.01 cps—entirely adequate for this sort of work.

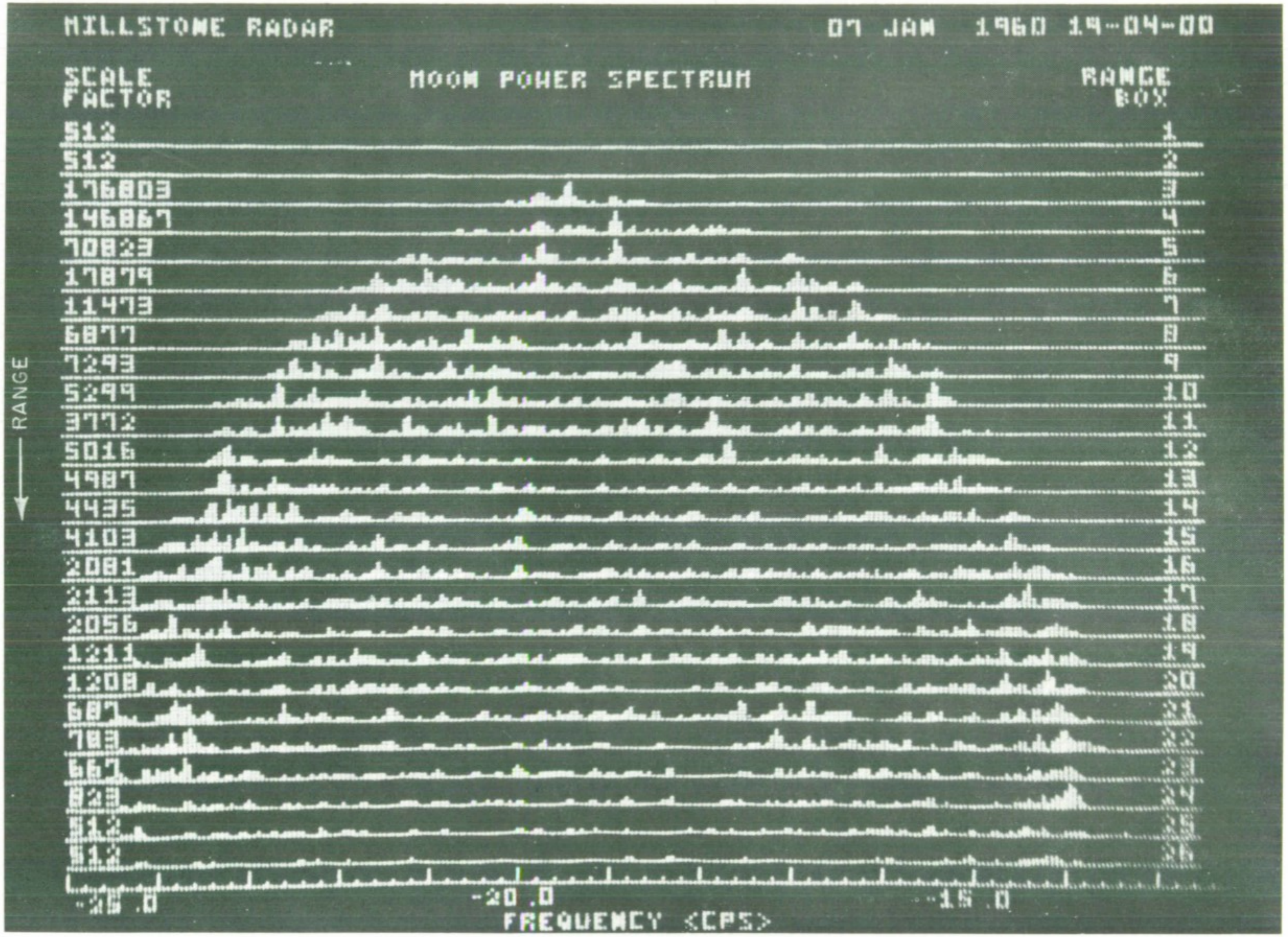


Fig. 5. Range-doppler-intensity "mapping" of lunar surface. $\lambda$ = 68 cm. Millstone before 23 cm conversion.

support of Lincoln Laboratory personnel, succeeded in obtaining echoes from the moon at $\lambda = 6934\ \mathring{A}$, with a signal-to-noise ratio on the order of 0.5. The transmitted signal was a 500-microsecond pulse with an energy of 50 joules.

This experiment serves primarily to demonstrate a working optical radar capable of detecting the moon. For useful surface studies, much higher performance would be required.

E. Temperature versus Lunar Phase (Radiometric)

The thermal behavior of the lunar surface has been studied intensively by many observers but particularly by Russian workers, e.g., V. S. Troitsky at the Lebedev Geophysical Institute.

At wavelengths of $\geq 10$ cm the lunar temperature shows no variation with phase. At shorter wavelengths (which are emitted from points nearer the surface) there is a monthly temperature variation which lags behind the solar illumination. Troitsky concludes that a homogeneous surface layer can be made to explain his observations, and deduces a value for the dielectric constant of 2.0 or less, and a thermal inertia consistent with a very porous substance.

Using the Haystack and 28-foot antennas these measurements should be repeated and checked.

F. Polarization Studies (Radiometric)

By comparing the brightness of the lunar surface observed in orthogonal planes of polarization Brewster angle effects can be observed. These measurements require a high degree of angular resolution, and have only been made by Soboleva in the U.S.S.R. (at 3.2 cm) using the 72-foot Lebedev antenna and by Heiles and Drake in the U. S. (at 21 cm) using the 300-foot Green Bank instrument. Soboleva deduced a value of 1.5 - 1.7 for the dielectric constant, while Heiles and Drake's value is $2.1 \pm 0.3$. It is important that these measurements be repeated at a number of wavelengths. If the roughness of the surface is known (from radar measurements) polarization measurements seem capable of yielding accurate values of the dielectric constant.

## III SURFACE CHARACTERISTICS SUGGESTED BY MEASUREMENTS

Radar mapping experiments showing the major craters as unusually strong scatterers appear to support the conjecture that possibly solid rock is exposed in their vicinity and that they are quite rough at the scale of 70 cm, the longest wavelength employed.

Determination of the average scattering properties at several wavelengths from optical to UHF permits the following inferences:

a. The lunar surface is almost everywhere covered with rough structure at least on the scale of 8.6 mm.

b. At the scale of 0.67 m, however, only about 10 percent of the surface appears to be rough.

c. The r.m.s. slope of areas "smooth" to 0.67 m appears to be of the order of one in ten ($\approx 6^{\circ}$).

d. Estimates of the backscatter gain, g, from the scattering properties, together with the total cross-section measurements have permitted the computation of the reflection coefficient of the material ($\rho = \sigma/g$). From this, an average dielectric constant of $\approx 2.8$ (about 1/2 that of solid rock) has been estimated. This value, plus the thermal behavior observed radiometrically, seems consistent with a very porous substance having a bulk density of perhaps 50 percent.

Gold[8] calls attention to the close agreement between the picture of the average lunar surface deduced from radar observations and that actually observed on the high-resolution photographs gathered by Ranger 7. He points out that "the excellence of the agreement will increase the reliance on radar data in the future."

Two needs are clear from the overall picture presented in the foregoing sections of this document:

1. All measurements in any new program must be made with considerably greater accuracy. To make this possible, a means of accurately calibrating the overall gains of all

radar systems against some common standard is required. An orbiting metallic sphere of appropriate dimensions would be ideal.

2. Detailed studies of small areas are needed at several wavelengths to complement the results of today, most of which are statistical in nature, covering, as it were, the average properties of the entire moon.

## IV EXTENSIONS OF THE WORK

### A. General

The experiments described here are mutually complementary and augment earlier work as well. They constitute an integrated program, in the sense that the resulting estimates of the lunar properties will derive from evidence from all of the available facilities. Several facilities are required, for example, to yield a check of whether the total lunar cross section is a function of frequency. In other instances evidence from one facility or experiment will confirm or deny a theory resulting from another.

An attempt is made to diagram the contribution of each facility and experiment to the knowledge of each desired lunar characteristic, so that one may obtain a feeling for the loss to the final results of the failure or omission of any part of the experimental effort.

Four microwave radar studies are outlined below in Sections B-E and two radiometric measurements in G and H. The possibility of studies utilizing a high resolution optical radar is mentioned in Section F. We place greater emphasis on the radar measurements, in part because of the breadth of experience of the participants in this field, and in part because we believe that the radar studies have more direct application to the needs of the Apollo program. One reason for this latter belief is that the needs of the Apollo program require extremely good resolution on the lunar disc. This can be achieved with microwave radar by range-doppler mapping, and perhaps directly by an optical (laser) radar, but not by the antenna beams on which radiometric studies must rely.

### B. Radar Cross-Section Measurements

The greatest uncertainties in establishing an absolute radar cross section for the moon are usually those of determining the characteristics of the equipment to sufficient accuracy. Typically, the uncertainty in the gain of a large steerable antenna might be $\pm 1$ db. In a radar measurement this uncertainty enters twice, while other errors, such as in determining the transmitter power and the mean echo power, usually contribute at least another 1 db. The solution to these difficulties lies in obtaining a well behaved known test target against which many different radar systems may be calibrated. A metal sphere in an appropriate orbit would seem the most useful test target one could obtain. It is understood that the Lincoln Space Communications program proposes* the orbiting of such an object. <u>It is very important that this be done.</u>

Given such a sphere for standardizing the radars, the lunar cross section could be redetermined at $\lambda$ = 7.85 m using the El Campo solar radar, if it is available; at $\lambda$ = 70 cm (at Arecibo); at $\lambda$ = 23 cm (at Millstone); at $\lambda$ = 3.6 cm (at Haystack); and at $\lambda$ = 8.6 mm (with the 28-foot dish). The accuracy achieved in this way might be $\backsim \pm 1$ db and it would be possible both to refine the value of the dielectric constant and to discover whether it changes with wavelength. Such a change might occur if the surface is inhomogeneous, or if it has moderately high conductivity.

C. <u>Average Scattering Properties</u>

The average angular distribution of the reflected power can be determined very simply for broad-beam antenna systems by taking in each range element a mean of many returns obtained with very short pulses (echo power versus range delay). These measurements should be made at Millstone at $\lambda$ = 23 cm, particularly since no work has been done at that wavelength to date. Improved short-pulse measurements are planned by Arecibo at 7.4 m to investigate the mean slopes and degree of roughness near the long-wavelength limit.

The scattering laws at $\lambda$ = 3.6 cm and $\lambda$ = 8.6 mm have been determined once, but the uncertainty in the measurements was high due to poor signal-to-noise ratio in each case. New measurements should be made. These studies are required in order to obtain the backscatter gain, g, of the lunar surface and thence the reflection coefficient, $\rho$, from the radar cross section.

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*Specifically, the Space Communications Division has proposed that a metallic sphere having a geometrical cross section of 1 sq. m. be placed in orbit at a specific launching scheduled early in 1965. To have such a standard target at the earliest possible date is important to all studies making use of high-performance radar.

At all four of the above wavelengths, measurements of the depolarized component of the signals can be made for the first time. This would be important either in confirming or denying the interpretation placed upon the earlier 68-cm results, namely that the diffuse part of the echo is associated with rough structure at the scale of the wavelength.

These measurements, together with the values for the radar cross section of the moon (part B), would permit the dielectric constant to be obtained at each wavelength. Then a refined estimate of the porosity of the surface could be derived. Also, the new measurements at $\lambda = 7.4$ m and $\lambda = 23$ cm would add to our knowledge of the statistical nature of the lunar surface slopes.

D. Polarization Studies (Radar)

We have noted in C that by studying the depolarized component of the echoes at a number of wavelengths it should be possible to establish whether the diffuse scattering from the limb regions is indeed due to small-scale surface roughness. An alternative explanation for the diffuse scattering is that it arises as the result of an amorphous surface into which the incident waves penetrate, and are subsequently scattered out in a random fashion. This hypothesis can be tested by studying the scattering at points on the surface where the angle of incidence and reflection approaches the Brewster angle (50-60$^{\circ}$). If plane polarized waves are used it will then become important whether or not the electric field lies parallel to the mean surface or normal to it. Isolation of such surface areas can be achieved by range-doppler mapping.

An experiment of this sort will be conducted at Millstone ($\lambda = 23$ cm). It will require a feed system which is capable of generating plane polarized waves of any orientation with respect to the elevation axis of the antenna, and which also permits the reception of the transmitted and orthogonal components. It is anticipated that if the experiment is successful it will yield another measure of the dielectric constant of the surface (directly from the value of the Brewster angle) while if a negative result is obtained upper bounds can be set to the porosity and consequent penetration of radio waves into the lunar surface.

E. Narrow-Beam Radar Mapping

Normally where range-doppler mapping is employed to delineate localized regions on the lunar surface there is an ambiguity, as explained in II-C, resulting in two points on the lunar surface having the same range and doppler coordinates. This ambiguity can be resolved by employing a radar with a sufficiently narrow beam to isolate one or the other of the two regions. The technique can be applied for almost all parts of the surface except regions lying close to the instantaneous apparent rotational equator. However, the projected axis of the moon's apparent rotation changes its orientation with time by large amounts, so that the equator line shifts, allowing in time all the surface to be explored by this technique.

At the center of the lunar disc good range resolution is required if the N-S extent of the cell is to be limited, though it is comparatively easy to limit the E-W extent by doppler processing. The reverse is true near the limbs. By employing pulse lengths of $\leq$ 10 microseconds and a doppler resolution of $\sim$ 1/10 cps at X-band it is possible to define the region giving rise to a particular return as a cell with dimensions on the order of 2 x 2 km in the best case, e.g., where the cell is located near the axis of libration and about $45^{\circ}$ N or S of the librational equator. The use of the narrow-beam Haystack radar operating at 3.6 cm and the Arecibo radar at 70 cm to make radar maps of substantial areas of the lunar surface is therefore indicated.

Although the size of the cells in these maps will be at best only comparable to the resolution achieved in pre-Ranger photographs of the moon, use will be made of the polarization properties of the signals to establish whether these regions are rough on a scale comparable with the radar wavelength (i.e., measured in tens of centimeters).

The narrow-beam range-doppler mapping experiments probably represent the most important of the various radar approaches proposed here. By mapping large portions of the visible lunar surface with modest resolution it will be possible to generate separately scattering laws for those regions which appear visually smooth (selected maria), those regions which appear rougher (the highlands), and the centers of rayed craters. It is important to stress that only by studying the angular behavior of certain types of surface, i.e., by applying these techniques to a reasonably large fraction of the surface, can full advantage be taken of detailed measurements of regions of immediate and applied interest.

Similarly in studying the depolarization properties of selected surface regions, it is necessary to have a reasonably large sample of typical areas lying at various inclinations to the incident illumination. One of the more tempting possibilities is to form a "difference chart" showing the relative depolarization and therefore the distribution of roughness on the surface on a scale of the wavelength used.

Studies of this kind, in which a number of radio and optical properties are investigated over the entire accessible lunar surface, have the possibility of showing as yet unknown relationships in the data that may lead to a better understanding of the entire problem of the lunar surface. From this point of view it would be a mistake to restrict the investigation to regions of astronautical interest even if the aim were entirely restricted to obtaining information for astronautical purposes. An evaluation of the areas of present interest for such purposes will, of course, be given emphasis. It will be based upon our best understanding as a result of all the work.

F. Optical Radar Studies

If a radar could be developed that could illuminate at normal incidence a circular lunar surface area on the order of two kilometers in diameter with a signal waveform affording range resolution on the order of one meter, the intensity versus range distribution of the resulting echoes should rather directly indicate the scale of roughness within the area under observation. The curvature of a spherical moon makes the subterrestrial point 0.25 m closer, on the average, than the perimeter of the 2-km circle. Any further range broadening of the echo from such a radar would arise from surface roughness and the range distribution of echo power should serve as a rather direct indication of the scale of that roughness.

Though useful observations with such a radar could only be made near normal incidence, lunar libration would make it possible to study in small increments a surface area of considerable extent. Such a direct measure of lunar roughness would, if the results were consistent, provide much confidence in the lunar characteristics deduced from past work and the other experiments proposed herein.

The best microwave systems available have beamwidths sufficiently wide to make the above experimental approach difficult. However, Smullin and Fiocco[6, 7*] have demonstrated the obtaining of optical radar echoes from the moon. Indeed, it now appears possible, looking over progress[9, 10, 11, 12, 13] in lasers and in fast-rise time photodetectors, that a radar can be built, perhaps utilizing burst-pulse laser operation, that can yield the required angular resolution and a range resolution of a few nanoseconds with an echo signal-to-noise ratio perhaps two orders of magnitude better than obtained by Smullin and Fiocco.

In view of the experimental possibilities and the probable technical feasibility, Lincoln Laboratory plans to undertake the description of a feasibility and design study, with some supporting research, to determine whether techniques available or soon to be available can indeed provide the required radar. That description will also include the best estimates possible at this time of the total cost of a program to develop the radar and perform the experiments.

### G. Temperature versus Lunar Phase (Radiometric)

Highly sensitive radiometers will be available for Haystack at 6, 3.8

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*Parameters of the Smullin-Fiocco experiment are essentially as follows:

| | |
|---|---|
| Transmitter: | Ruby laser in 12-inch (0.29m) reflector |
| Receiver: | Photomultiplier in a 48-inch reflector (Lincoln Laboratory telescope) |
| Wavelength: | 6934 Å |
| Effective Beamwidth: | $\approx 2 \times 10^{-4}$ radian (subtends circular area of $\approx$ 70-km diameter on the moon) |
| Pulse Length: | $\approx$ 500 microseconds |
| Pulse Energy: | 50+ joules |
| Received S/N: | $\approx$ 0.5 |

and 2 cm and for the 28-foot dish at 0.8 cm. At all of these wavelengths better angular resolution will be available than has been previously employed in similar experiments. Most previous studies of temperature versus phase have been based on the study of average temperature over the lunar disc. With the Lincoln facilities it will be possible to separate out smaller areas on the moon and to look for differences in thermal behavior of various portions of the surface.

These studies could well lead to an increased understanding of the general physical nature of the lunar surface, though they would not, of course, contribute to a detailed knowledge about small areas in the same way as the radar data.

The study of temperature versus lunar phase will be faced with certain difficulties because of atmospheric absorption which varies from day to day, mainly due to varying water vapor content of the atmosphere.

### H. Polarization Studies (Radiometric)

With the Haystack radiometers there will be available rotatable feeds at 3.8 and 2 cm. The high resolution of the Haystack antenna will make it possible to detect linear polarization of the emission from the moon by rotating the feed. An obvious set of experiments would be to scan along various diameters of the moon while rotating the feed. This would provide a basis for estimates of dielectric constants and for the detection of variation in the surface properties over the lunar disc. It appears to be important that such studies be carried out in view of the consistent discrepancies between dielectric constants determined from this method elsewhere and from the radar results of Lincoln Laboratory. Variations in atmospheric absorption are not believed to be so serious in polarization measurements as in those described under IV-G.

### J. Summary of Experimental Approach

In this section an attempt is made to list concisely the experiments proposed here and to show diagrammatically, as best one can, how these are mutually complementary and the sorts of conclusions to which they can lead. The listing and diagram then provide a basis against which the ordering of the experiments according to probable value can be attempted.

Table I lists the experiments by facility. This same source table can thus be referred to in the next sections where equipments, personnel, and time schedules are discussed.

Figure 6 then draws on Table I to show how different facilities and experiments contribute to an estimation of the various lunar properties of interest.

## TABLE I

### Summary Listing of Lunar Studies

1. Arecibo Radar ($\lambda$ = 7.4 m)
   - 1.1 Total cross section
   - 1.2 Echo power vs. range delay (whole moon using short pulses, both polarizations)
2. Arecibo Radar ($\lambda$ = 70 cm)
   - 2.1 Detailed range doppler mapping over entire surface, two polarizations, resolution 20 x 20 km
   - 2.2 Fine-scale range doppler mapping over selected regions of surface, resolution 10 x 10 km
3. Millstone Radar ($\lambda$ = 23 cm)
   - 3.1 Total cross section
   - 3.2 Echo power vs. range delay (normal and depolarized components)
   - 3.3 Fine-grain polarization studies using R-R mapping (Brewster angle search)
4. Haystack, Radar ($\lambda$ = 3.6 cm)
   - 4.1 Total cross section (spoiled beam ? )
   - 4.2 Echo power vs. range delay (spoiled beam ? ) (normal and depolarized components)
   - 4.3 Narrow-beam and R-R mapping (study depolarized return, small areas)
5. Haystack, Radiometric ($\lambda$ = 6, 3.8, 2 cm)
   - 5.1 Thermal inertia of surface
   - 5.2 Polarization observations
6. 28-Foot Millimeter Wave, Radar ($\lambda$ = 0.86 cm)
   - 6.1 Total cross section
   - 6.2 Echo power vs. range delay
7. 28-Foot Millimeter Wave, Radiometric ($\lambda$ = 0.86 cm)
   - 7.1 Thermal inertia of surface
8. Optical Radar ($\lambda$ = near IR) (included for completeness--not described herein)
   - 8.1 Roughness by extreme (1-2 ft) range resolution on very small elements of lunar surface

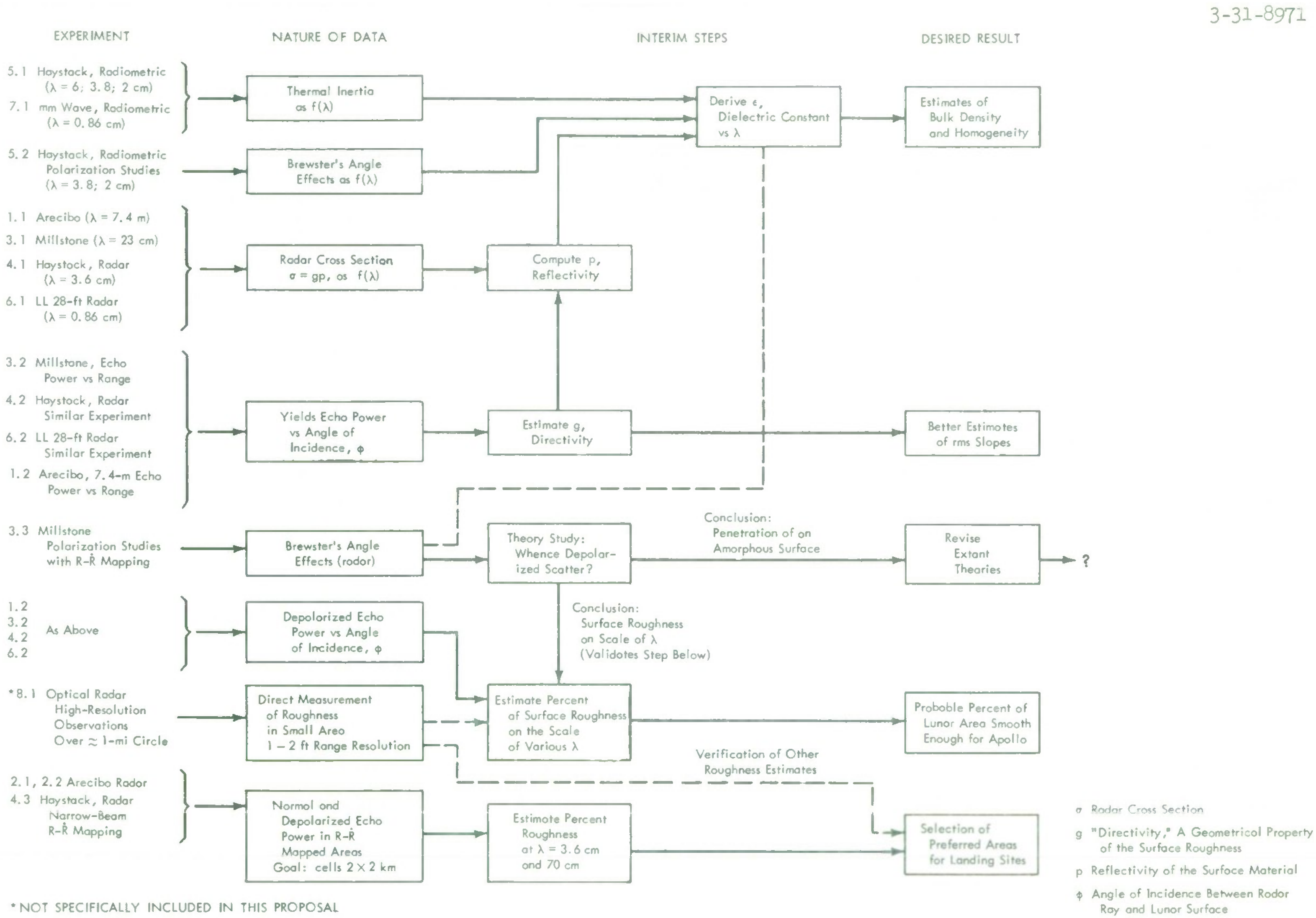


Fig. 6. Plan for Lincoln Laboratory moon studies.

## V PERSONNEL, NEW EQUIPMENTS AND TIME SCHEDULES

### A. Cornell University, Center for Radiophysics and Space Research

All the work described in this section will be done at the 1000-foot diameter radar facility operated by the Center for Radiophysics and Space Research of Cornell University near Arecibo, Puerto Rico. This facility has an 8' arc two-way (radar) beamwidth at 430 Mcps, and a $2^{\circ}$ beamwidth at 41 Mcps. Transmitters with short and long pulse capability, coherent detectors and a CDC 3200 digital computer are available on site for the necessary measurements, ephemerides and data processing. Personnel will be drawn primarily from the existing staff there, or in some cases, from Ithaca, New York.

At 430 Mcps (70 cm) the present program of mapping selected regions of the lunar surface in one polarization with a resolution of about 20 x 40 km will be extended to cover all accessible regions of the surface in two polarizations at a resolution of about 20 x 20 km. This work will form a solid base for analyzing the fine-scale measurements to be made at selected portions of the lunar disc to be designated by NASA. (Note that areas selected which fall too close to the center of the visible disc may not be suitable for this type of analysis; most areas mentioned to date, however, lie outside this forbidden zone.) It is hoped that the fine-scale measurements may approach a resolution of 10 x 10 km where the geometry is favorable.

Using the 41 Mcps (7.4 m) system, a firm measurement of the total cross section as well as a full picture of the short-pulse (10 microsecond) angular power spectrum in both polarizations can be obtained. The high signal-to-noise ratio available should permit a good determination of scattering out to the lunar limbs, and thus a good estimate of roughness to the scale of 7 meters over the average surface.

As shown in Fig. 9, it is estimated that a complete set of measurements can be taken, reduced and written up by the end of January 1966. Approximately 120 runs are planned to give redundant coverage in both polarizations of the entire visible lunar disc. Current experience indicates that about 10 hours of computer processing are required for each 1/2 hour observation.

## B. Millstone Radar, MIT Lincoln Laboratory

As outlined in IV, the lunar cross section and the average scattering properties can be accurately evaluated at the new Millstone wavelength of 23 cm. Polarization observations are also indicated, both as additional evidence in the matter of scale of roughness and in a search for Brewster angle effects.

### 1. Personnel

Personnel will include a part-time principal investigator and his assistant together with staff level computer programming assistance. These people, as well as some eight staff concerned primarily with system operations and instrumentation, will be drawn mainly from the existing Station complement. An additional programmer must be obtained for a six- to twelve-month period under subcontract.

As will be noted under "2. Equipment," some support will be provided from the Laboratory's Radar and Engineering Divisions in connection with certain required modifications.

### 2. Instrumentation, Millstone

#### a. Microwave System

The system must be made adjustable so that it can generate either accurately circularly polarized signals or linear polarization at any angle with respect to the elevation axis of the antenna. Further, the system must receive both the transmitted and orthogonal polarizations with an inter-channel isolation on the order of 25 db.

#### b. Data Processing

The required extensive use of range-doppler mapping will make highly desirable the use of the new SDS-9300 computer planned for Millstone. As a result, it must be interfaced with the radar.

A lunar ephemeris program must be prepared that will give, in addition to the usual ephemeris data, the angle between the lunar libration axis and the projected polarization reference plane of the Millstone antenna. Programs for processing the data on the 9300 computer must also be written, checked out, and utilized.

3. Time Schedules (based upon a nominal starting date of 1 Jan. 1965)

Present estimates of equipment lead times, check-out times, projected experiment time and Station work load make it appear that the following schedule could be met:

Steps beginning as soon as possible

a. Initiate steps to ensure availability of suitable lunar ephemerides, including modifications to 7094 programs required to generate them.

b. Initiate procurement of hardware listed above.

c. Press for the decision to launch the orbiting calibration sphere. This is important for all radar experiments, since data are complementary and valid comparisons of target strengths must be possible.

November 1964 - January 1965

a. Install, check out and calibrate the modified feed system and high-power TR switch.

b. Install, check out and prepare initial routines for SDS-9300.

c. Check out Millstone in the configuration required for the experiments.

January 1965 - July 1965

a. Experimental data gathering.

b. Data processing to proceed as near concurrently as possible. NOTE: a and b are expected to require the equivalent of six days per month of Millstone facility time during this period.

c. Interim report issued July 1965.

July 1965 - February 1966

a. Continue processing and interpretation of data. Contract assistance on data reduction may be required.

b. Reduce schedule of experimental operation on experiments indicated by early results. NOTE: a and b are expected to require the equivalent of three days per month of Millstone time during this period.

c. Final report issued by March 1966.

For ease of reference, this time schedule is shown graphically in Fig. 7.

C. Haystack Research Facility, MIT Lincoln Laboratory

The program for Haystack includes accurate determination of total radar cross section and statistical scattering behavior at 3.6 cm. It includes also the radiometric studies at 6, 3.8 and 2 cm. The most demanding experiments (and probably the most valuable), however, will be the narrow-beam radar mapping at 3.6 cm.

1. Personnel

Carrying out the Haystack investigations will require part-time services of three scientific investigators, a computer programming supervisor and a digital processing engineer. These people, plus some ten staff for Haystack operations, maintenance and instrumentation, will be drawn from the Station complement as required. Two additional computer staff are required for an 18-month period and these must be obtained under subcontract.

To a greater extent than in the Millstone effort, support must be provided from the Data Systems, Radar, and Engineering Divisions of Lincoln Laboratory in connection with Haystack instrumentation required in this program.

2. Instrumentation, Haystack

Commitment to the program described here will require that there be provided, according to a definite early time schedule, a number of fairly major items. Among these are:

a. Short-pulse (10-20 microsecond) capability for the present 100-kw CW coherent transmitter in the radar/communications RF box.

3-31-8972

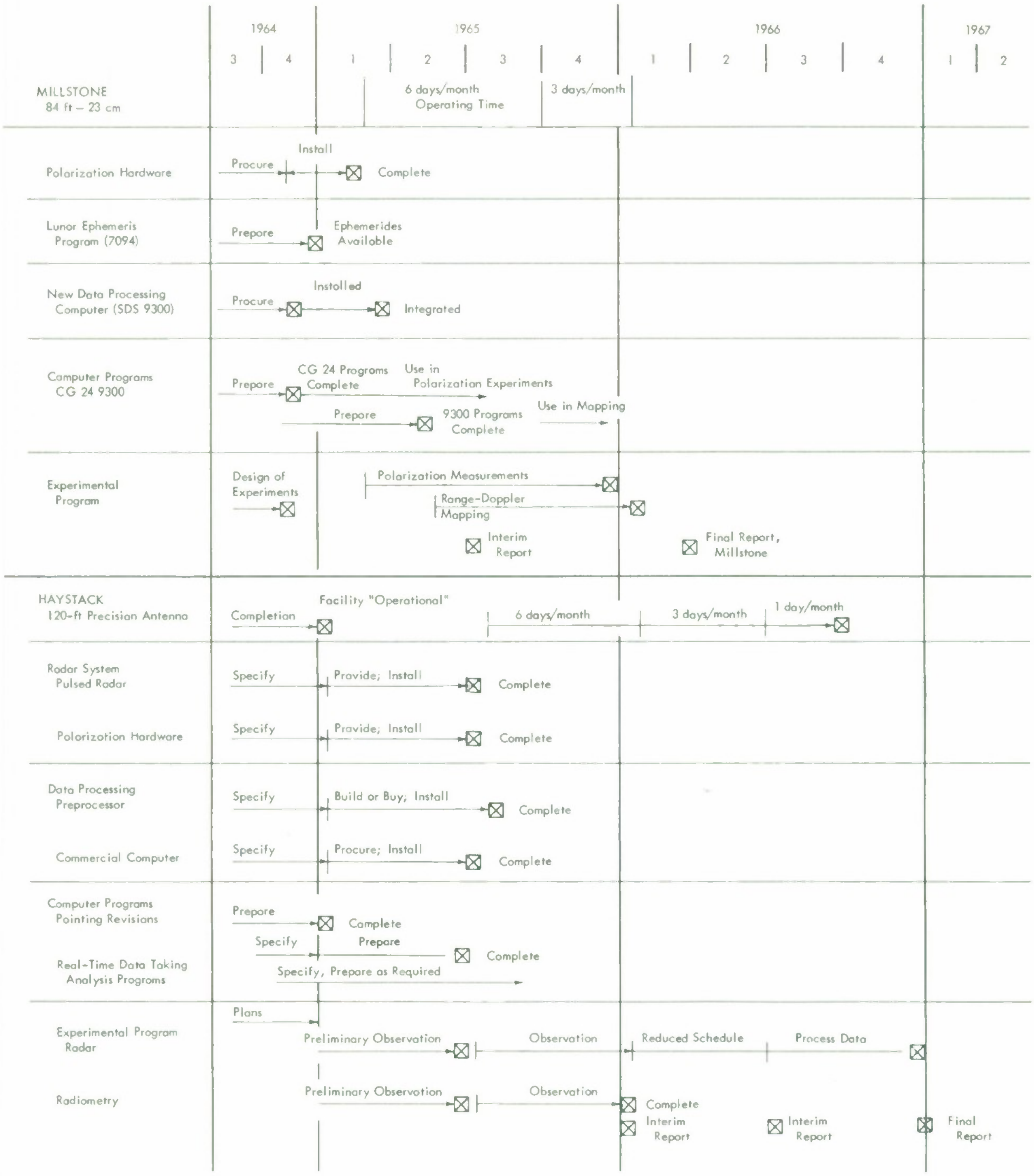


Fig. 7. Time schedules for Millstone and Haystack programs.

b. Ability to transmit varying polarizations and to receive both transmitted and orthogonal polarizations.

c. High-speed A/D conversion equipment to convert the radar and radiometer data to digital form for processing. Special equipment not formerly planned for the Station is required.

d. A special pre-processing and interfacing digital machine that can, by performing certain simple operations, feed partially processed data into a commercial computer for final processing and recording, thus enabling the processing and recording operations to keep up with the vast amount of data generated during high-resolution radar astronomy experiments.

e. An intermediate-size commercial computer that could handle the remainder of the data processing task, after pre-processing. Perhaps one full shift on such a machine for up to one year will be required to reduce the data from these experiments. One-fourth of an additional shift will be required for program check out, data gathering, etc.

f. Completion of radiometric capability at all of the frequencies mentioned in IV-F and -G is required. These are part of the planned basic Haystack instrumentation.

g. Since the Haystack beam looks at a small portion of the moon, and since the antenna is in an opaque radome, a telescopic camera on an instrument quality servo mount and slaved to the Haystack antenna should be provided in order that pictures may be obtained showing accurately the portion of the surface studied. Though small, the assembly should follow Haystack with an accuracy of better than 1/2 minute of arc (1/6 mrad).

h. Preparation of the following major computer programs:

- Test and calibration programs.
- Harmonic analysis programs for range-doppler plots.
- Non-real-time analysis programs for converting data to useful maps.
- Programs in support of theoretical interpretations of the data.

It is estimated that these programs will require two man-years of contract effort in excess of the in-house capability.

3. Time Schedules

Since Haystack is not a completed facility at this writing, the time schedule outlined here cannot be considered as firm as the Millstone schedule. Barring some major failure of the antenna system to perform, however, it would seem that the following schedules could approximately be met, assuming that work at about the level given herein were in effect by 1 January 1965.

Beginning as soon as possible

a. Work on the design of the various experiments.

b. Study the signal waveform and general data processing problems for radar and radio astronomy experiments. Specify the special-purpose pre-processor and a commercial data processing machine. Place upon the Radar Division the task of short-pulsing the transmitter.

c. Complete the program, now in progress, of integrating the Haystack facility as a system, checking it out and evaluating its performance with both active and passive RF boxes. Completion scheduled for 1 January 1965.

Beginning January 1965

a. Procure the data-processing computer (probably rental agreement).

b. Initiate design and procurement (or in-house construction) of A/D converters and pre-processor.

c. Initiate design and procurement of feed system having the necessary polarization flexibility.

d. Conduct preliminary qualitative lunar observations utilizing the 3.8-cm radar system then available (probably long-pulse) and the available radiometric equipment.

e. Initiate preparation of processing programs for the Haystack experiments, if an appropriate computer is available. If an SDS-9300 is chosen, the Millstone computer may be used for advance program preparation. NOTE: Approximately an equivalent of three days per month of Haystack time will be utilized during this period.

Beginning July 1965

a. Install and check out data-processing computer and, hopefully, pre-processor.

b. Install and calibrate the feed system having polarization flexibility.

c. Begin the planned program of lunar observations with short-pulse radar and the radiometer box. It would appear that about six equivalent days per month of Haystack time should be scheduled for these operations. Probably many of the operations will be conducted at night for correlation with simultaneous photographs.

Beginning January 1966

a. Prepare an interim report on the results to date.

b. Continue processing of stored data.

c. Initiate changes to the program and equipment indicated by the first six months of operation.

d. Reduce schedule such that about three days per month of Haystack time are utilized.

July 1966

a. Prepare an interim report on the results to date.

b. Continue the processing of stored data.

c. Reduce the data-gathering schedule, leaving perhaps one Haystack day per month for special experiments.

December 1966

a. Prepare a final report.

For ease of reference, this schedule is shown graphically in Fig. 7.

D. Lincoln 28-Foot Millimeter Wave Facility

Studies utilizing the Lincoln millimeter wave facility will include careful redetermination of the statistical scattering properties of the moon as a function of angle of incidence, together with cross-section measurements at 8.6 mm wavelength. These measurements, together with those from other facilities will provide data concerning the variation of cross section with wavelength. They will also yield a vital "point on the curve" concerning the scale of the lunar surface roughness relative to the wavelength. From these data also will come further evidence concerning the dielectric constant of the lunar surface.

It is not proposed to attempt experiments involving range-doppler mapping at 8.6 mm wavelength. Apart from the technical difficulties involved, it seems that little would be learned since apparently the surface is almost everywhere covered with structure on this scale or larger (see Fig. 3). Since it is possible to derive lunar cross section and scattering properties without spatial resolution beyond that available from the sharp antenna beam (see Frontispiece), the radar system proposed here can be a relatively simple one.

The parameters utilized by Lynn et al[4] in the 1963 lunar observations at this wavelength are given below:

| | |
|---|---|
| Frequency | 34, 990 Mcps |
| Wavelength | 0.857 cm |
| Peak power | 12.0 watts |
| Effective pulselength | 2.5 sec |
| Antenna (see Fig. I-5) | |
| Diameter | 28 ft; 853 cm |
| Gain | 67.5 db |
| Effective area | 31.5 $m^2$ |
| Half-power beamwidth | 4.3 min arc; 1.25 mrad |
| Receiver | |
| Noise temperature | 3300°K |
| IF bandwidth | 250 cps |
| Video integration time | 2.5 sec |
| Estimated losses | 4.4 db |

Figure 8 shows an analog recording of the video integrator output from a single 2.5-second return. The ordinate is integrator output voltage and the horizontal axis is marked in one-second intervals. After approximately 5 seconds, the recording indicates essentially system noise. Manual processing of many such returns was required to provide usefully accurate estimates of the returned lunar power.

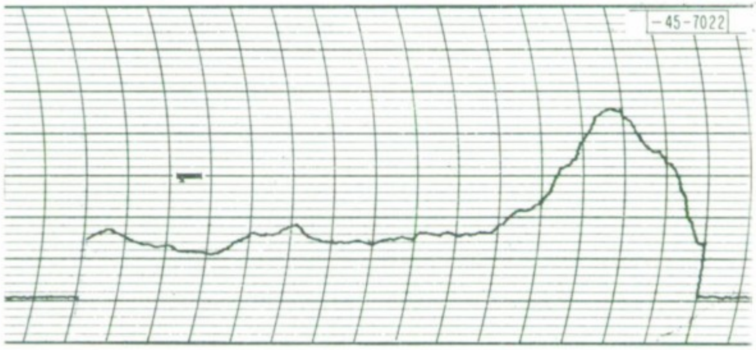


Fig. 8. Return from a single 2.5-second pulse.

The advancing state of the art will soon make possible an improved simple radar of the type used in the above experiments but which can provide single-pulse signal-to-noise ratios perhaps 25 db better than those achieved to date. Two principal developments are required: (a) a 1000-watt average-power transmitter developed around the Watkins-Johnson TWT (WJ-266), and (b) a low-noise parametric amplifier or maser front-end for the receiver system.

The pedestal drive system of the 28-foot antenna is inadequate in itself for closed-loop servo control to a sufficient accuracy ($\approx \pm$ 0.1 mrad) for this application. Initially, a new mount, at an estimated cost of $500,000 was considered. Further checks using a boresight TV system, however, have shown that the antenna as it is can be pointed well enough, with the help of the TV system, to make the measurements envisioned.

Radiometry equipment is available at 0.85 cm for this antenna and will be used in the temperature vs. lunar phase measurements mentioned in IV-G. Lynn et al[14] made preliminary lunar drift scans with this equipment shortly after the antenna became available.

1. Personnel

Personnel for implementation of this program will be drawn from the Laboratory's Radio Physics program and from the Radar Division. Some five staff and corresponding non-staff appear to be required.

2. Time Schedules

It would appear that the proposed work could be carried out within the following time periods, assuming a start is made in January 1965:

<u>January 1965</u>

a. Initiate work on 1-kw transmitter.
b. Initiate work on low-noise receivers.
c. Plan radar and radiometric measurements.
d. Make certain mount is in good condition, including boresight TV system.
e. Install radiometric equipment.

March 1965

a. Begin part-time radiometric studies.

July 1965

a. Interim report on equipment developments.

b. Preliminary report on radiometric observations.

c. Continue radiometric studies, if indicated.

December 1965

a. Install 1-kw transmitter and low-noise receivers.

b. Check out and equipment evaluation.

c. Final report on radiometric studies.

February 1966

a. Begin 0.8 cm radar observations.

July 1966

a. Report on 0.8 cm radar studies.

This schedule is included graphically in Fig. 9.

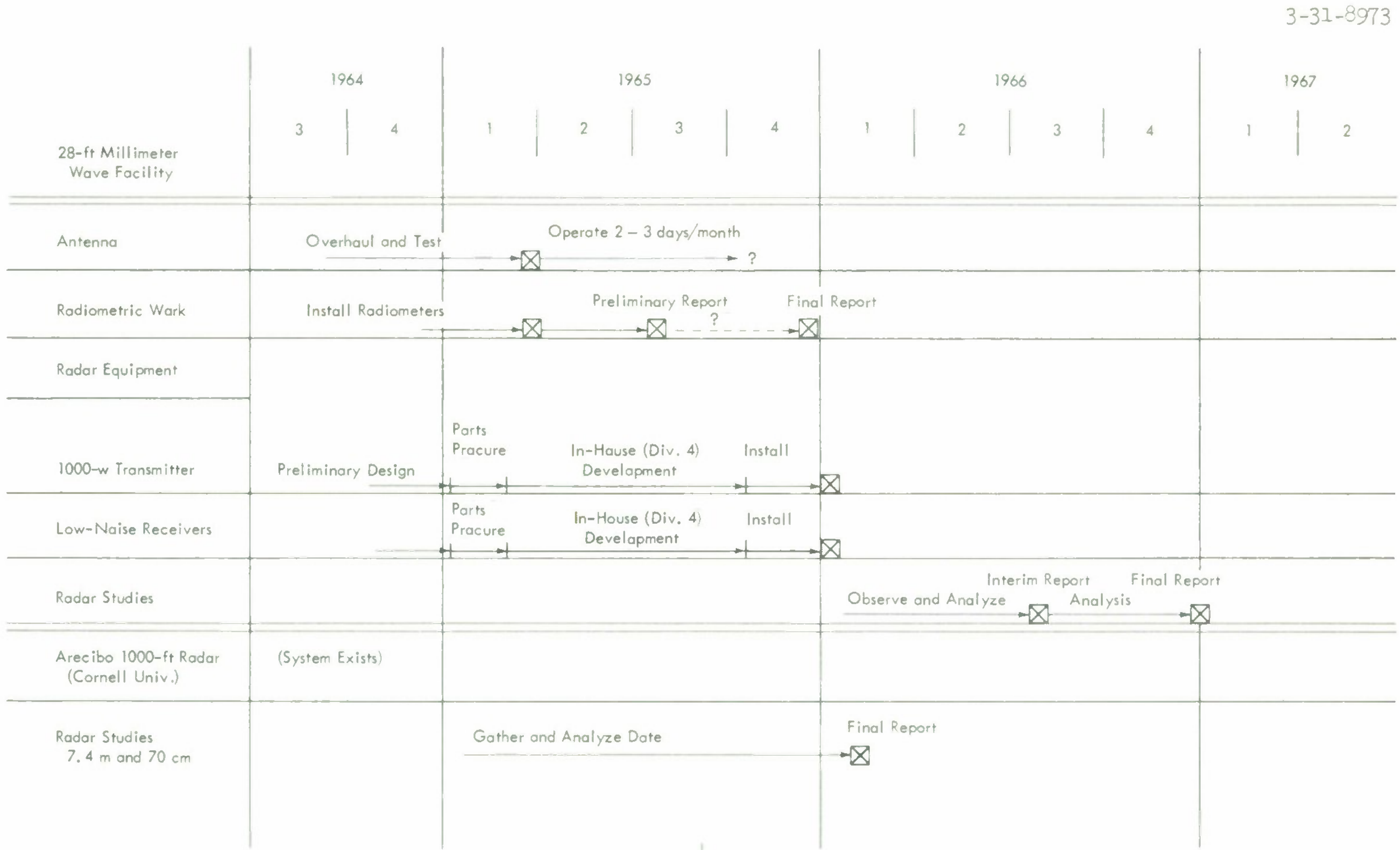


Fig. 9. Time schedules for millimeter-wave and Arecibo programs.

## APPENDIX I

Compendium of Photographs of Facilities

Considered in Program Description

For Radar and Radiometric Lunar Surface Studies

P501-33

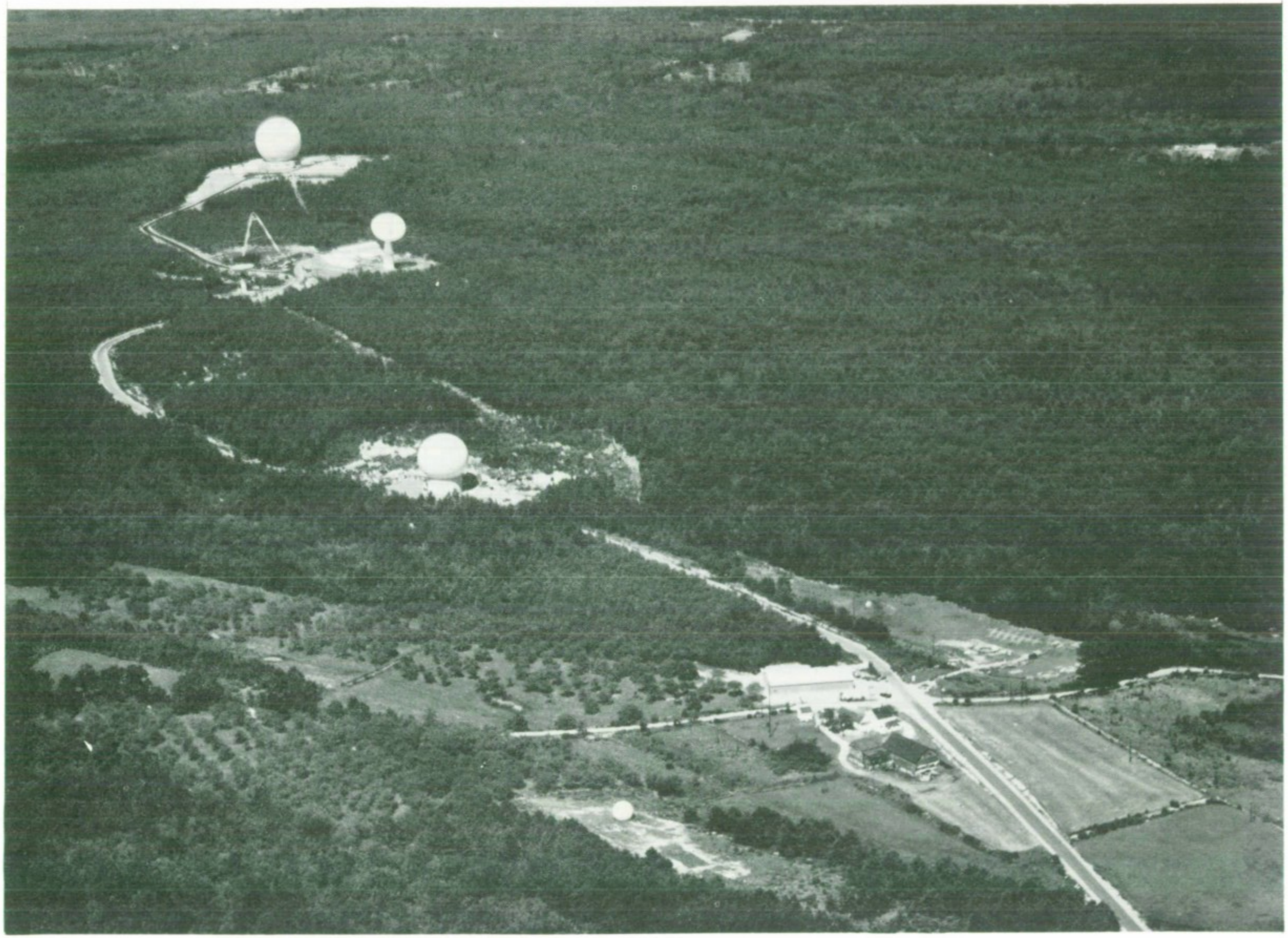

Fig. I-1. The M.I.T. Lincoln Laboratory Millstone Hill Complex in Westford, Tyngsboro and Groton, Massachusetts.

P489-605

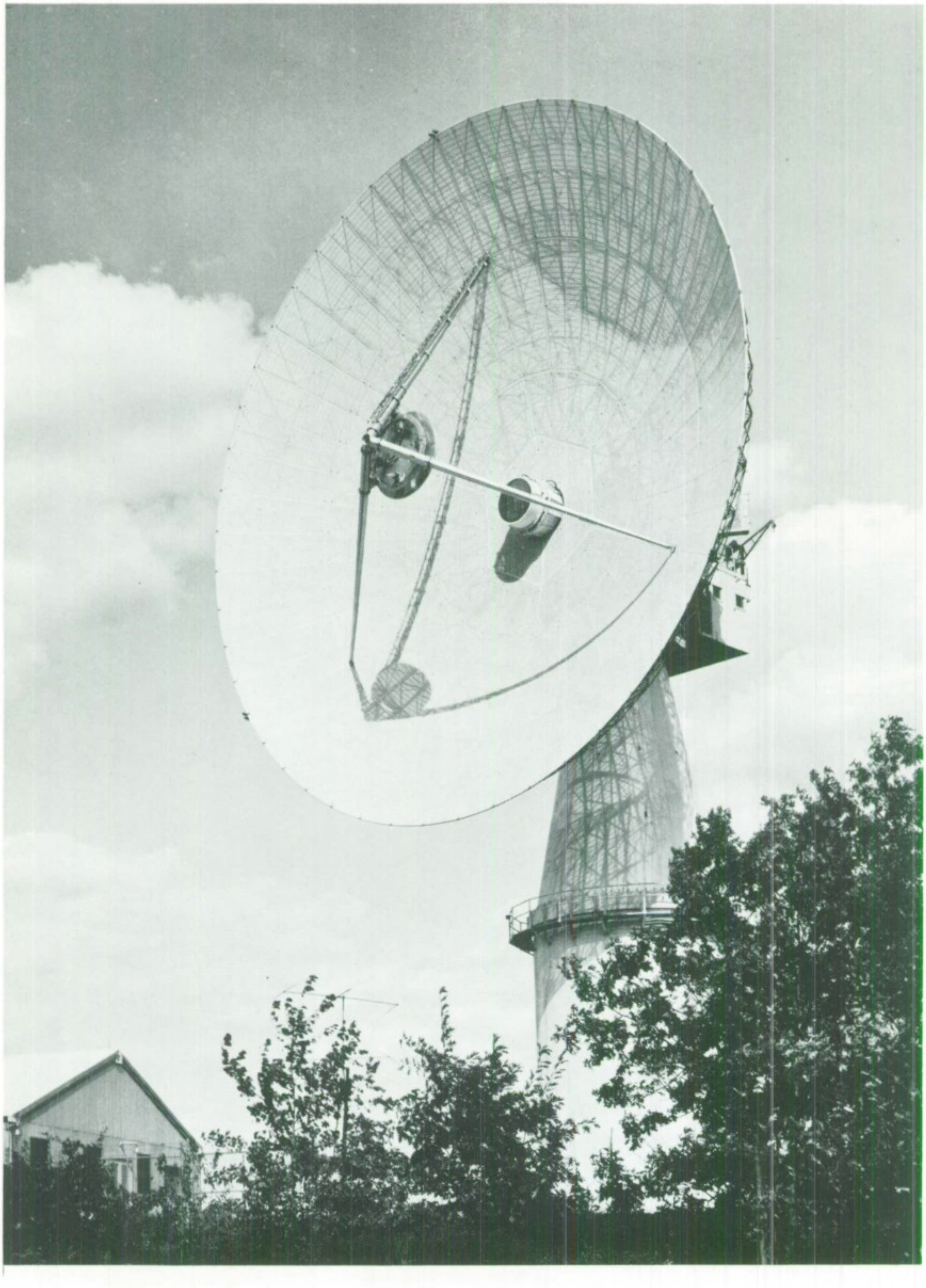

Fig. I-2. The 84-foot, 23 cm tracking antenna at Millstone.

P10.29-1120

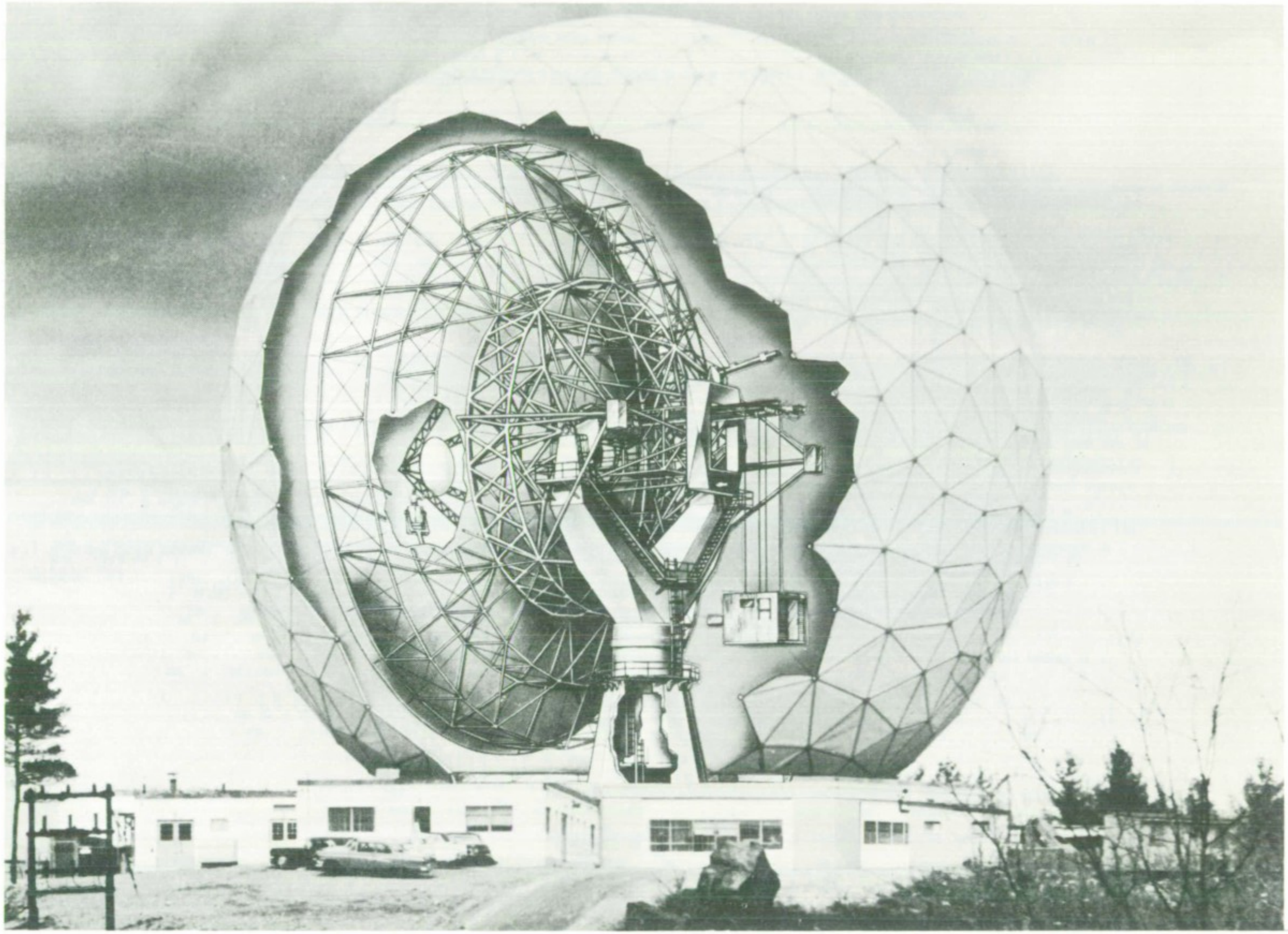

Fig. I-3. The 120-foot precision (3.6 cm) antenna at Haystack.

P10.29-1332

Fig. I-4. The radiometer box at Haystack.

P67-131

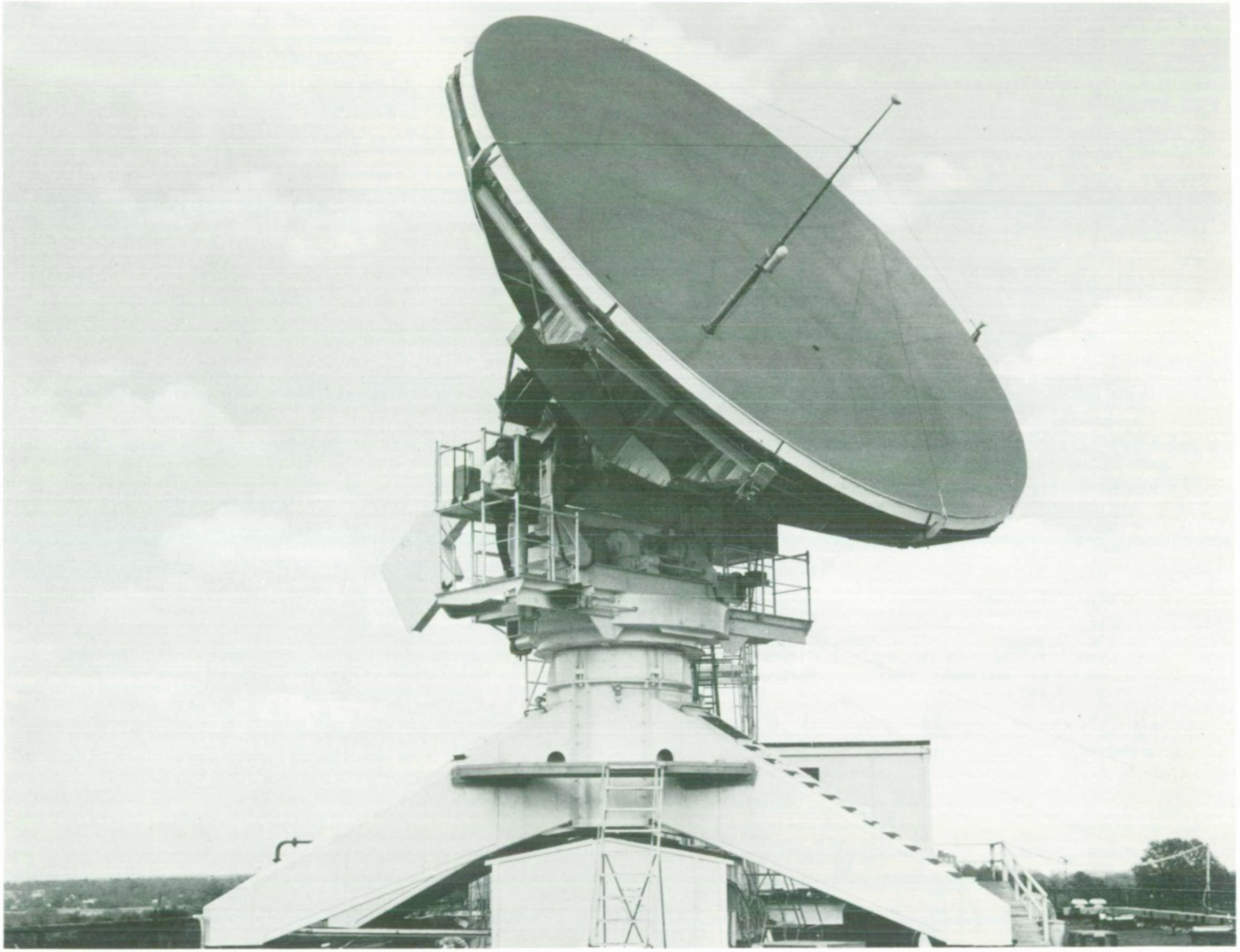

Fig. I-5. The 28-foot millimeter-wave antenna at Lincoln Laboratory, Lexington, Massachusetts.

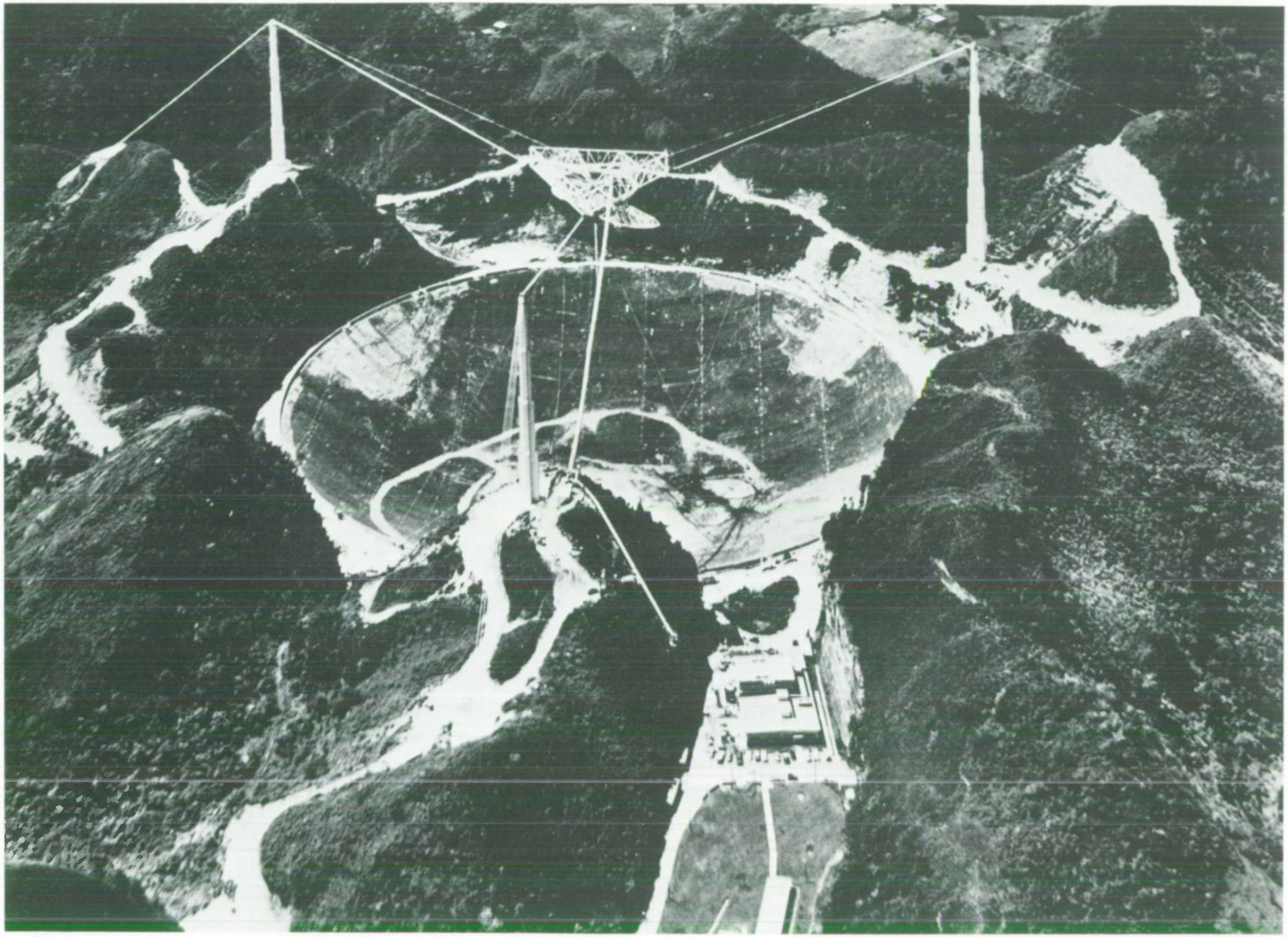

Fig. I-6. The Cornell University 1000-foot radar facility at Arecibo, Puerto Rico.

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13. ABSTRACT

This document describes a program of radar and radiometric measurements on the surface of the moon of such a nature that valuable knowledge may be deduced concerning the suitability of the lunar surface to support "soft" landings.

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