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RADAR STUDIES OF THE LUNAR SURFACE

EMPHASIZING FACTORS RELATED TO

SELECTION OF LANDING SITES

Status Report   1 July to 31 December 1966

FOREWORD

This report discusses the studies carried out during the period of 1 July to 1 December 1966 on NASA Research Grant NGR-33-010-024 titled "Radar Studies of the Lunar Surface, Emphasizing Factors Related to Selection of Landing Sites." (The projects to be carried out under this grant are a mapping of the lunar surface at 430 Mc/s (λ = 70 cm) and measurement of the radar cross section of the moon at 40 Mc/s (λ = 7.5 m), using the facilities at the Arecibo Ionospheric Observatory (A.I.O.).[*] The major portion of this report deals with the mapping of the reflectivity of the lunar surface.

Section I discusses the technical aspects of the mapping studies based on measurements made at A.I.O. in 1964. Section II discusses the time scheduling for this study and the progress made to date. Section III discusses the plans for completing the study.

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[*] The Arecibo Ionospheric Observatory is operated by Cornell University with the support of the Advanced Research Projects Agency under a research contract with the Air Force Office of Scientific Research.

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I. RADAR MAPPING OF THE LUNAR SURFACE
AT 430 Mc/s AT A.I.O.

Earth-based radars with high gain and high transmitter
power capabilities provide an important tool for
investigating the lunar surface. The extension of the
results of in situ observations, which are necessarily
limited both in number and area, to the entire visible
lunar surface is the primary objective of the program at
A.I.O. The present program can contribute valuable
information for this extrapolation by measuring the
degree of uniformity of radar scattering from the lunar
surface.

An immediate problem is that of investigating those
properties of the lunar surface which would be dangerous for
the landing of space vehicles. The present program
provides valuable information on this problem by
determining the relative roughness of areas on the moon.
Since the polarization of radar backscattering is
sensitive to the roughness at the scale of the operating
wavelength, the present study emphasizes the investigation
of this property of radar returns from the lunar surface.

The potentialities of mapping the radar reflectivity
of the lunar surface with the 430 Mc/s radar at A.I.O.
was clearly demonstrated in 1964, when several regions

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of the moon were mapped (Thompson, 1965; Thompson and
Dyce, 1966). A preview of possible findings in the work
under way and an appreciation of the procedures to be
followed can be obtained by a review of the 1964 measurements.

A. Review of 1964 Measurements

The relation between radar echoes and their
reflecting area on the lunar surface is shown in Figure 1.
The sampling in delay establishes the echo on an annulus,
D, concentric with the line passing through the radar
and the center of the moon. A sampling in frequency
establishes the echo on a semi-annulus, F, parallel to
the plane containing the apparent axis of rotation and
the line joining the radar and center of the moon. A
simultaneous sampling in delay and frequency obtained by
spectral analysis of the delay samples establishes the
echo at the intersections of these two annuli. Since
two intersections exist, however, an ambiguity arises.
This ambiguity is resolved at A.I.O. by illuminating
one intersection with the main beam of the antenna, which
has a beam width of 10' at 430 Mc/s. This is approximately
one-third the angular width of the moon.

A radar map of the lunar surface is constructed by
plotting echo strengths over corresponding reflecting
areas. The transformation of delay and frequency to

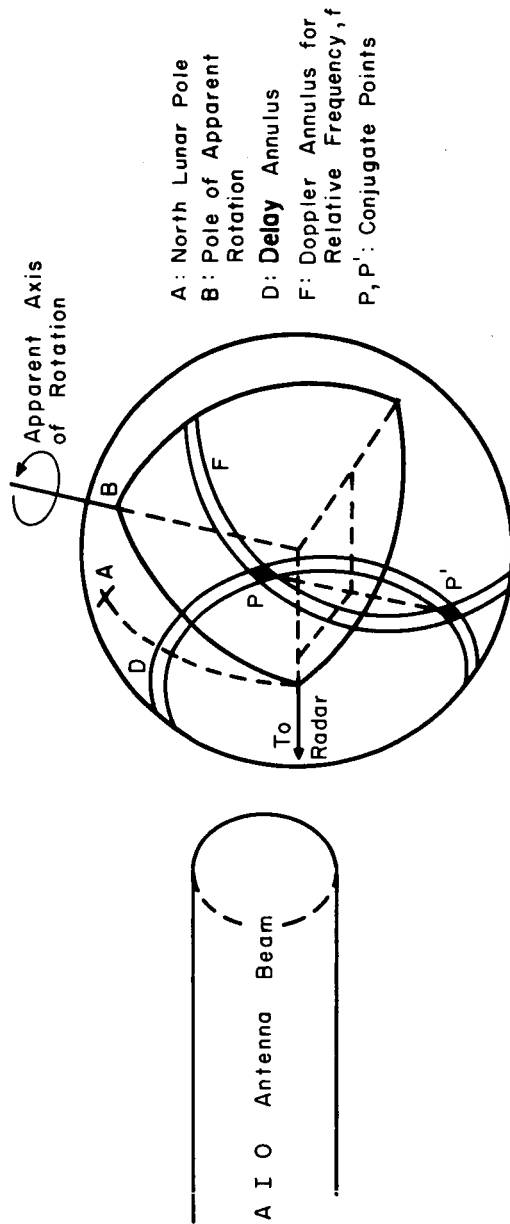FIGURE 1. Geometry of Radar Echoes from the Lunar Surface. (The antenna beamwidth is approximately 1/3 the angular width of moon, which allows resolution of reflection of conjugate reflecting areas P and P'.

A: North Lunar Pole
B: Pole of Apparent Rotation
D: Delay Annulus
F: Doppler Annulus for Relative Frequency, f
P, P': Conjugate Points

Apparent Axis of Rotation

To Radar

A I O   Antenna Beam

selenographic position requires only the selenographic co-ordinates of the radar (the subradar point) and their rates of change.

The mapped radar echoes are given as a normalized reflectivity; that is, the ratio of the observed power to the power predicted, assuming homogeneous scattering. A change in this ratio with respect to the ratios of a surrounding area is a definite indication of local change in lunar surface characteristics. The predicted power accounts for variations in delay as predicted by a mean scattering law, variations in frequency as predicted by the scattering area associated with the intersection of delay and frequency annuli, and the variation in power resulting from the antenna gain pattern. The area that can be mapped is restricted to that illuminated by the main beam, where the ambiguity can be resolved.

Examples of radar maps compiled in 1964 are shown in Figures 2 and 3. The background grid shows contours of constant delay and frequency spaced at intervals corresponding to the measurements, with normalized power given at each intersection of the grid. Contours of constant power enclose the appropriate intersections.
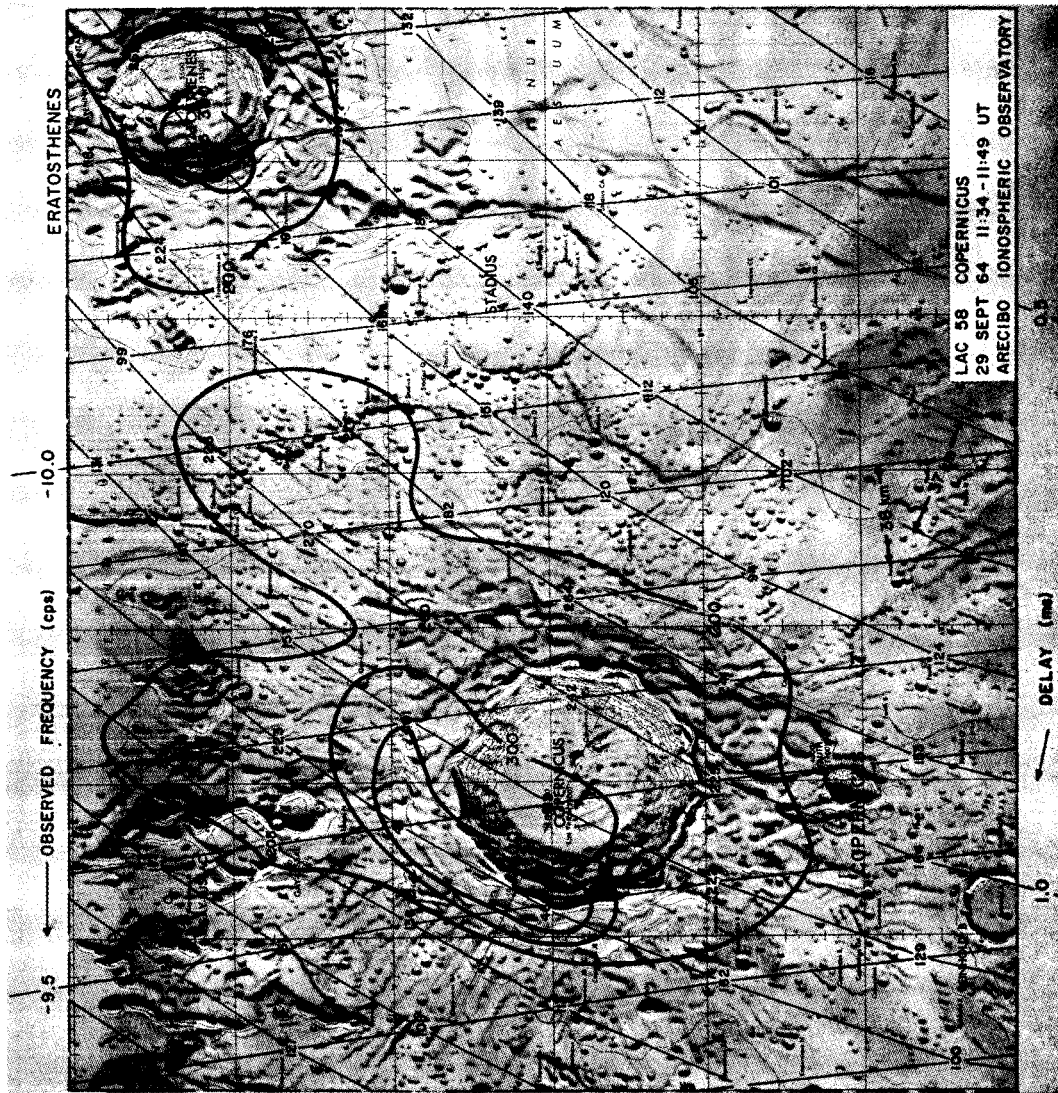
FIGURE 2. Radar-scattering Map of Craters Copernicus and Eratosthenes Plotted on LAC Chart No. 58. (Power contours of 200, 300, and 400; background approximately 100; polarized component.)

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FIGURE 3. Radar-scattering Map of an Area of Map No. C2a of Orthographic
Lunar Atlas. (Power contours of 200 and 400; background approximately
100; polarized component.)

The power at each intersection is independent of that of its adjacent intersections, and the resolution of the measurement is the separation of adjacent contours in the grid (i.e., 37 and 38 km in Figure 2; 25 and 35 km in Figure 3).

The 1964 results can be summarized as follows:

1. Rayed craters, such as crater Copernicus in Figure 2 and crater Aristillus in Figure 3, always had a higher reflectivity than their surroundings and often showed a halo of moderate enhancement extending outside the crater rims.

2. Young, nonrayed craters, such as crater Eratosthenes in Figure 2 and craters Autolycus and Theaetetus in Figure 3 showed reflectivity enhancements over their environs. These enhancements varied from moderate to as strong as the enhancements observed for the rayed craters.

3. In several instances mountain ranges, such as the Caucasus Mountains in Figure 3, showed moderate enhancements over the surrounding maria.

Also, there were indications that the highlands reflected about twice as much power as the maria. Observations of power versus delay were carried out for several equally spaced beam positions with constant

displacements of the antenna beam from the center of the disk. Typical results for these observations are shown in Figure 4.

The existence of localized differences in the lunar surface is clearly demonstrated in the radar results presented in Figures 2, 3, and 4, but it is also important to determine the factors responsible for these differences. This can be done by radar measurements in opposite polarizations. (One of the received polarizations is that which would be expected for normal incidence on a smooth reflecting surface, the "expected" or "polarized" component; the opposite polarization is the "depolarized" component.) Such a measurement is shown by the radar maps of the crater Werner in Figure 4. The radar echo from this crater and its environs is shown in the polarized component on the right (Figure 5-b) and in the depolarized component on the left (Figure 5-a). A depolarization of the echo is evident for both the interior and immediate vicinity of the crater, where the enhancement in the depolarized component is higher than the enhancement in the polarized component. The theories of scattering from smooth and rough surfaces lead to the conclusion that
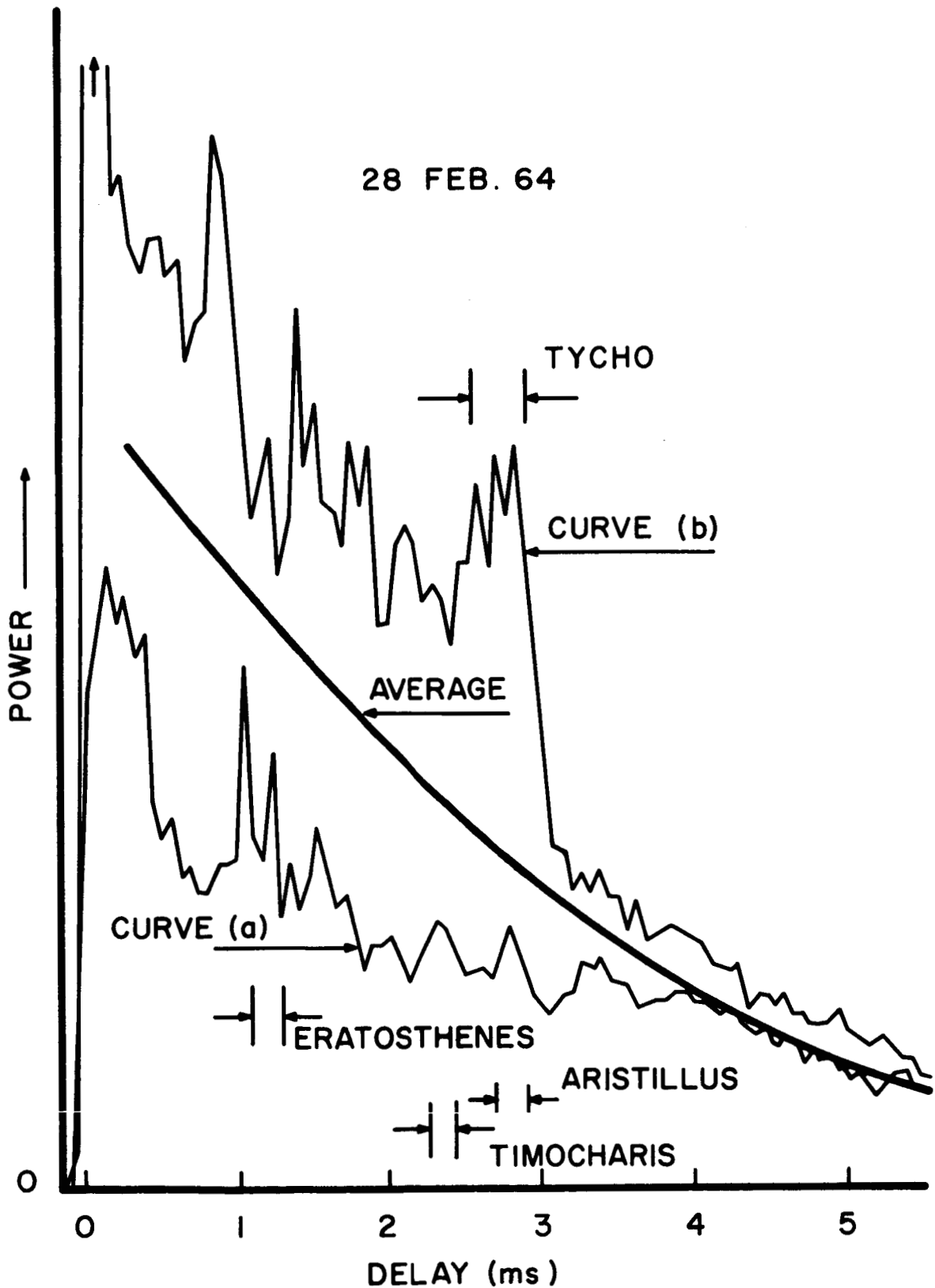
FIGURE 4. Power versus Delay for Maria (a) and Highland (b) with Antenna Beam Displaced Equal Distances from Center of Disk. (The mean of 8 equally spaced beam position is given by curve denoted "average.")

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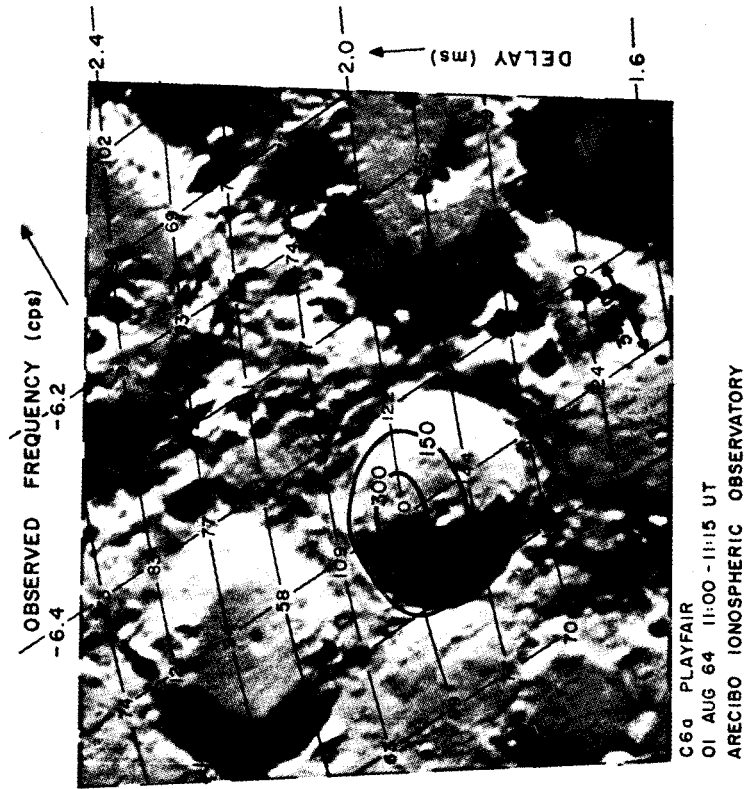
FIGURE 5. Radar-scattering Maps of the Crater Werner in Opposite Polarizations: (a) Depolarized Component (Power contours of 100 and 200; background approximately 50); (b) Polarized Component (Power contours of 150 and 300; background approximately 75).

these areas must be rougher than the surrounding area, on the scale of a meter.

Another source of greater backscattering can be seen in the radar maps of Figure 5. In the polarized component, only a high reflection from the rim of the crater furthest from the radar is apparent. These areas show an enhancement because they are tilted toward the radar, which would increase their backscattering. This effect is greater in the polarized component because the scattering law has a greater variation with angle of incidence. Finally a higher dielectric constant, resulting from either a denser or different material, can result in greater backscattering.

Separation of these three sources of scattering differences - rougher surface, higher dielectric constant, or local inclination, can therefore be obtained by constructing radar maps in opposite polarizations. A rougher surface will depolarize the echo, yielding higher enhancements in the depolarized echo. A local increase of dielectric constant (i.e., a local increase of radar albedo) would preserve the polarization ratio and would give equal enhancements in both polarizations. For enhancements resulting from localized areas being tilted more toward the radar,

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enhancements should be higher in the polarized component and should occur only at the rims of crater.

Thus, radar mapping in opposite polarizations should indicate local differences in the lunar surface and differentiate qualitatively between increased roughness, increase albedo (i.e., increased dielectric constant), or where applicable, a local decrease in tilt around the radar.

B. Improvements for the 1966-1967 Lunar Mapping

For the present program, several improvements have been made on the 1964 study. From the discussion of the preceding section, one obvious improvement is the extension of the observations to two polarizations.

It is also important to find a suitable calibration, so that the variations observed between maria and highlands, and between maria and mountain ranges can be studied further. An absolute calibration of the radar system would be very difficult. An alternative is to choose a specific area on the moon and define its relative reflectivity as unity. The control area chosen is a featureless region of Mare Imbrium. It appears at a delay of 3-4 ms from the leading edge and will never

be near the "wings" of the spectra, where mapping is impossible.

The resolution in delay and frequency is reduced by a factor of five. The most severe limitation is on the frequency resolution, which is related to the amount of time that the moon is observable. A frequency resolution of 0.02 c/s has been achieved for the 1966-1967 measurements. This gives 72 independent spectra for an observation of an hour's duration, which in turn yields a statistical fluctuation of 12 percent in the radar return. The one-hour observation is well-adapted to present ephermeris accuracies and to the mode of operation at Arecibo. A similar five-fold improvement in delay resolution over 1964 observations requires observations at 20 μsec pulse widths, which is well within the capabilities of the 430 Mc/s radar.

These delay and frequency resolutions expressed as kilometers on the lunar surface are shown in Figure 6. Range resolution is defined as the distance of the lunar surface between independent delay samples, and is a function of transmitter pulse length and the angle of incidence (or equivalently delay from the leading edge). Range resolutions of 3 – 8 km are obtainable with the 20 μsec pulse length. Similarly,
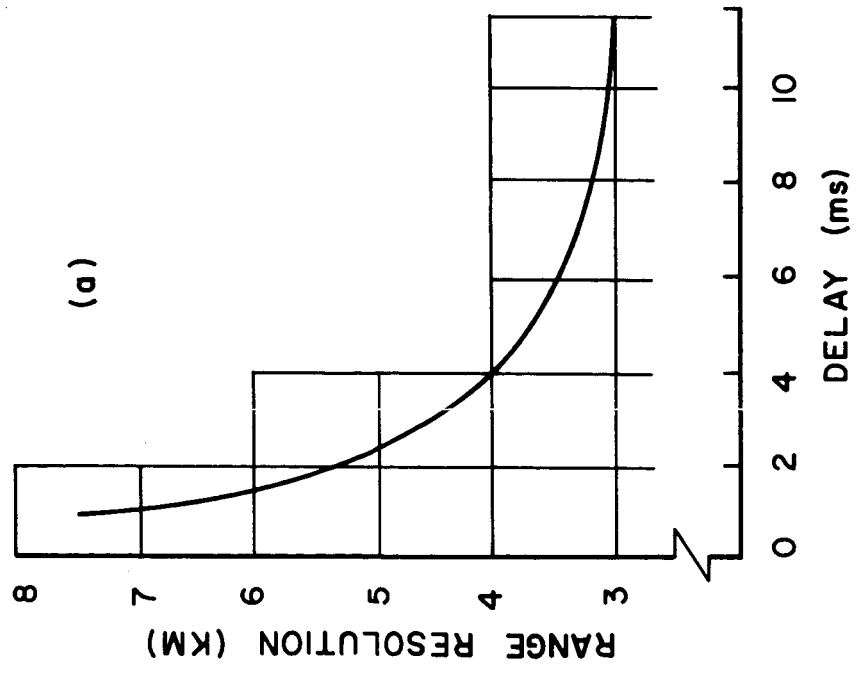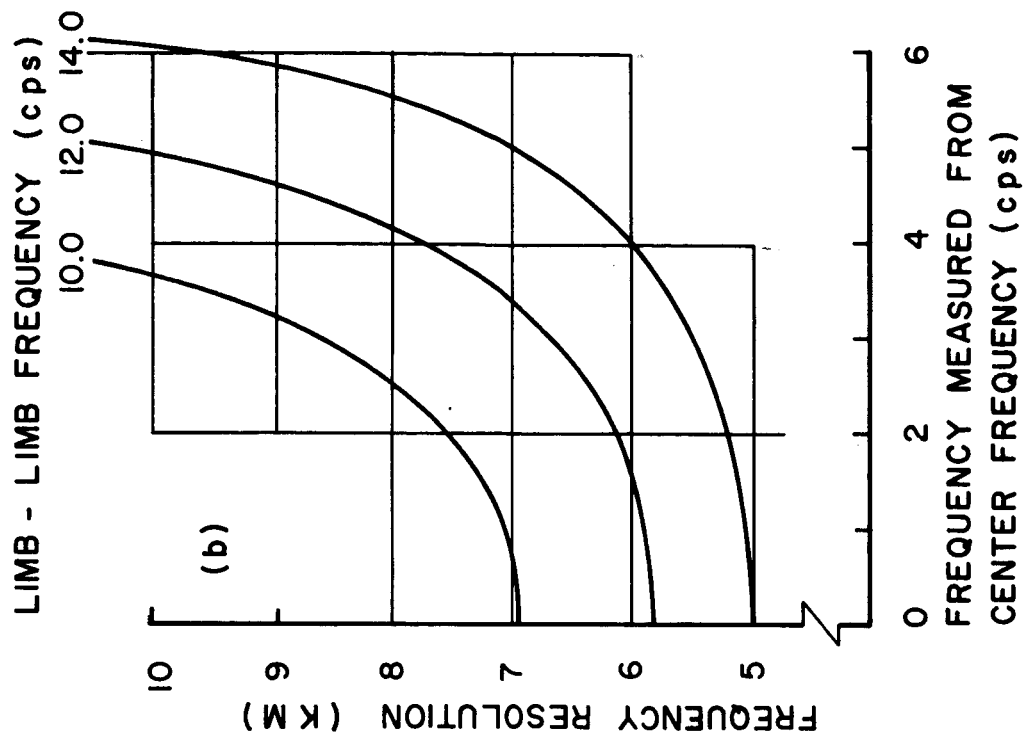
FIGURE 6. (a) Range Resolution for Transmitter Pulse Length of 20 μs. (b) Frequency Resolution for Bandwidth of 0.02 c/s and for Typical Libration Conditions at A.I.O.

frequency resolution is taken to be distance on the
lunar surface between independent samples. This is
dependent upon the bandwidth of post-detection spectral
analysis, the apparent rotation of the moon (expressed
here in the limb-to-limb frequency difference that
it imparts to the moon), and the displacement of the
frequency annulus from the center frequency contour.
Frequency resolutions for the 0.02 c/s bandwidth for
typical limb-to-limb frequency differences range from
5 km to 10 km, as shown in Figure 6-b.

In summary, improvements in the observations
realized over the 1964 measurements are:

1. Simultaneous observations in opposite
polarizations.

2. Calibration of echo strength by normalizing the
observed intensities to that of a control area.

3. A five-fold improvement in the resolution of
the mapping.

There are, however, some limitations as to the
areas that can be mapped. The range resolution becomes
poorer for areas of the moon near the subradar point
(i.e., the leading edge of the moon as viewed by the
radar). This is evident in Figure 6-a in the increase
in range resolution for smaller delays. The lowest

possible delay that can be reasonably mapped is about
0.5 ms. A mapping at this delay is shown in Figure 2,
where it is clear that resolution in range is being
sacrificed. The limitations in frequency are that the
areas near the libration equator (the intersection of
the lunar surface with the plane perpendicular to the
apparent axis of rotation at the center of the moon),
cannot be studied because the antenna beam cannot
separate the conjugate reflecting areas near the
equator. Roughly speaking, the areas that can
be mapped must be more than 500 km from the subradar
point and away from the libration equator. During
a lunation, however, there is a great variation in
the inclination of the libration equator to the
actual equator and a small variation in the position
of the subradar point. This makes it possible to map
the equatorial regions farther than 500 km from the
average subearth point.

II. PROGRESS OF PROGRAM

It is clear from Section I that the 430 Mc/s radar can produce high-resolution maps of the radar reflectivity of nearly all of the visible lunar surface. For a single observation, the restrictions imposed by the radar are that the area to be mapped must lie within the main beam of the antenna. Another restriction is imposed by computer memory limitation; since for the number of delay and frequency samples must be on the order of 100 x 100. At the present resolutions, this will restrict the mapping to an area somewhat smaller than that illuminated by the main antenna beam; however this does not appear to be a severe restriction.

The time schedule for mapping the visible lunar surface is based on (1) the availability and number of optical maps, (2) the estimate of off-line computer time required to produce a map, and (3) the telescope time required, with the restriction that each mapped area lie within the antenna beam.

A. Available Lunar Maps

The best available maps are those given by the LAC
charts (USACIC, 1964) and the maps of Series I of the
Orthographic Lunar Atlas (Kuiper, 1963). Each of these
maps covers areas that can be illuminated by the main
antenna beam. There are about 20 LAC charts and 21
maps in the Orthographic Lunar Atlas (in some cases,
the maps of the Orthographic Lunar Atlas are given as
two smaller maps).

Priority for mapping is given to the equatorial
regions, because these regions are of primary interest
as first landing sites on the moon. However radar
observations of nonequatorial regions are also
important for correlating radar observations with observations at
optical and infrared wavelengths (which are available
for both equatorial and nonequatorial area of the moon).

B. Time Requirements for Telescope and Data Reduction

The mapping onto the LAC maps and the maps of the
Orthographic Lunar Atlas Maps should yield about 40 maps
in each polarization component, about 80 maps in all,
in six months of observation. The moon can be observed

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at A.I.O. for about 2 1/2 hours for 12 days every
4 weeks. During each 2 1/2 hours, two areas on the
moon can be observed. Thus, telescope time required
is 1-2 days for every week that the moon is observable.

The time requirements for off-line data reduction
is estimated to be 5 hours per map; i.e., 20 hours per
week for 5 months. This requirement is more difficult
to meet, but is being achieved.

C. Progress to Date

A schedule for carrying out the mapping based on
producing about 80 maps by 1 May 1967 is shown in
Figure 7. The first line of the schedule shows the
times that the moon can be observed. So far, there
have been 4 1/2 observation periods, and the moon has
been observed 11 times with echoes obtained for 18
different beam positions. There appears to be no
difficulty in obtaining observation time to collect the
data for the 80 moon maps.

The second line of the schedule shows the time
allotted to computer programming, which has been
successful. The working programs are:

Figure 7 - Time Schedule for Lunar Mapping
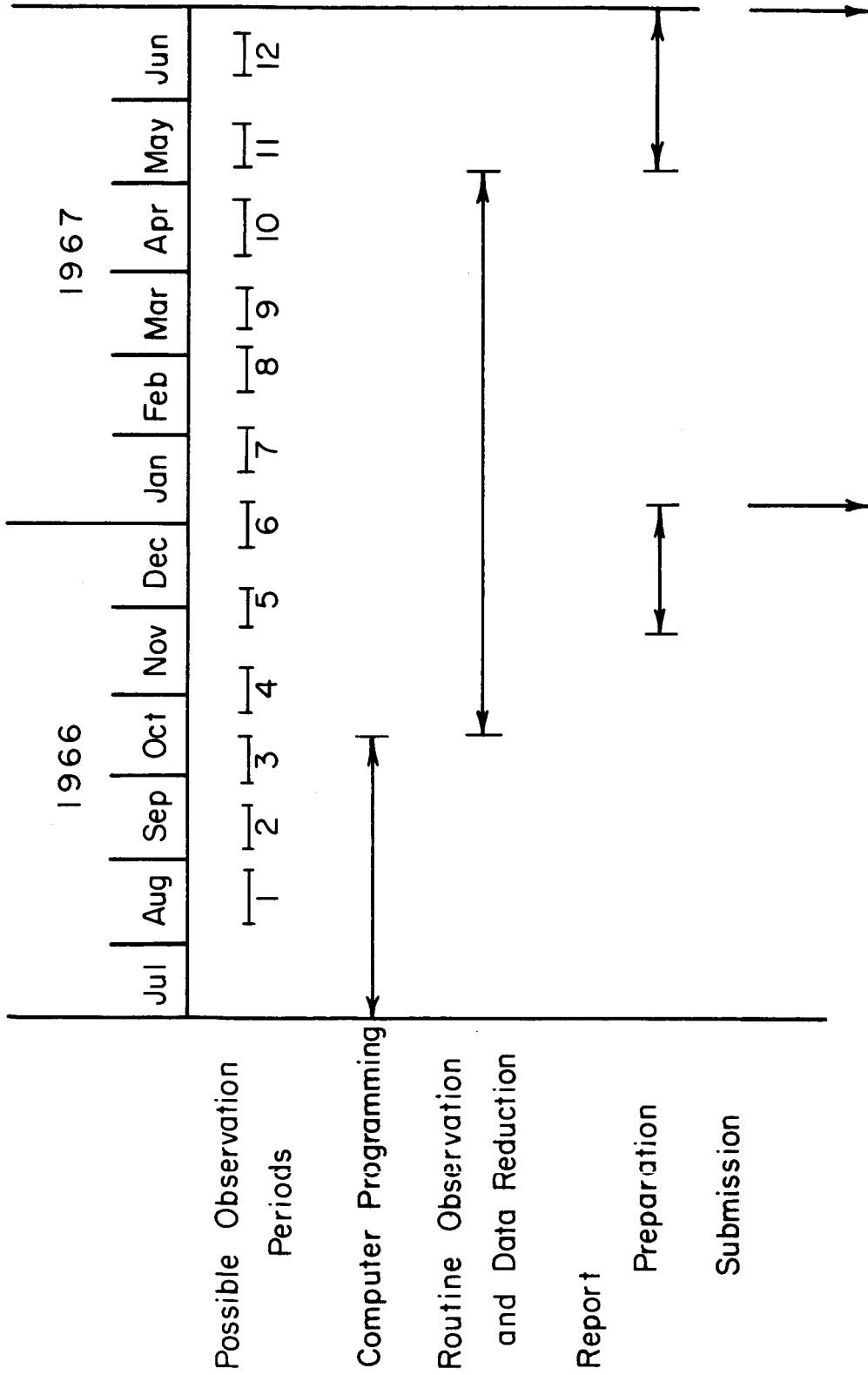
Estimated 1 July 1966
Accomplished 1 July 1966 - 1 Dec. 1966
Projected 1 Dec. 1966 - 1 July 1967

1. <u>Moon Ephemeris Program</u>: predicts the delay, frequency, and antenna co-ordinates of any selenographic position.

2. <u>Data-taking Program</u>: records the samples of the sine and cosine components of the radar echo as a function of echo delay.

3. <u>Tape-Edit Program</u>: alters the frequency of recorded sine and cosine components, so that the specified selenographic position appears at zero Doppler frequency.

4. <u>Spectral Analysis</u>: performs a spectral analysis of the radar echo using the Cooley-Tukey algorithm.

5. <u>Mapping Program</u>: takes the data on echo intensity, delay, and Doppler shift, normalizes the echo, and maps it onto selenographic co-ordinates.

When it was discovered that the simulated beating of echo to zero frequency permitted spectral analysis by the Cooley-Tukey algorithm, it was decided to incorporate this into the standard set of analysis programs at A.I.O., even though it delayed the schedule about a month. However, the use of this algorithm should decrease the time needed for spectral analysis significantly.

The next line of the schedule is the time
allotted for routine observation and data reduction.
The routine observations started on schedule with
observations in opposite polarizations during the early
part of November. The beginning of routine data
reduction, however, was delayed by the computer
programming. At present we are in the final stages of
computer program debugging and the initial stages of
data reduction. Routine data reduction should be under
way in January 1967. This is a critical point, since
the mapping program is limited by off-line, post-run
data reduction. If routine data reduction is not started
during January of 1967, then the number of maps will
be less than 80. This would mean that the mapping will
be restricted to the LAC charts. On the other hand,
the use of the Cooley-Tukey algorith may reduce the time
required to produce a map to about 3 hours, in which
case, there will be no difficulty in producing the
proposed 80 maps. There has not been enough data
reduction for an accurate estimate of the time required
to produce a map, and it is this time restriction that
will determine the number of maps that can be produced.

Finally, the last line of the time schedule shows
the time allotted for report writing. Preparation of

the final report will begin about 1 May 1967, at which
time the data reduction should be completed.

D. Maps Produced to Date

A radar-scattering map of the crater Tycho and its
environs is shown in Figure 8. The contours are of
constant normalized reflectivity. Selenographic
position is given in the usual direction cosines, ξ
and η. The area of this map corresponds roughly to
that of Map D7a of the Orthographic Lunar Atlas. The
absence of returns at the edges of the map resulted
from a limitation of delay and frequency samples imposed
by computer memory restrictions.

A radar-scattering map for the area of Map D2a of
the Orthographic Lunar Atlas is shown in Figure 9. The
mapped area is a maria showing many isolated peaks of
reflected power. Most of these are associated with
isolated young craters.

The radar-scattering maps of Figures 8 and 9 are
presented only to demonstrate that the computer programs
listed in Section II-b are working. The final form
of the maps will be greatly modified, with the background
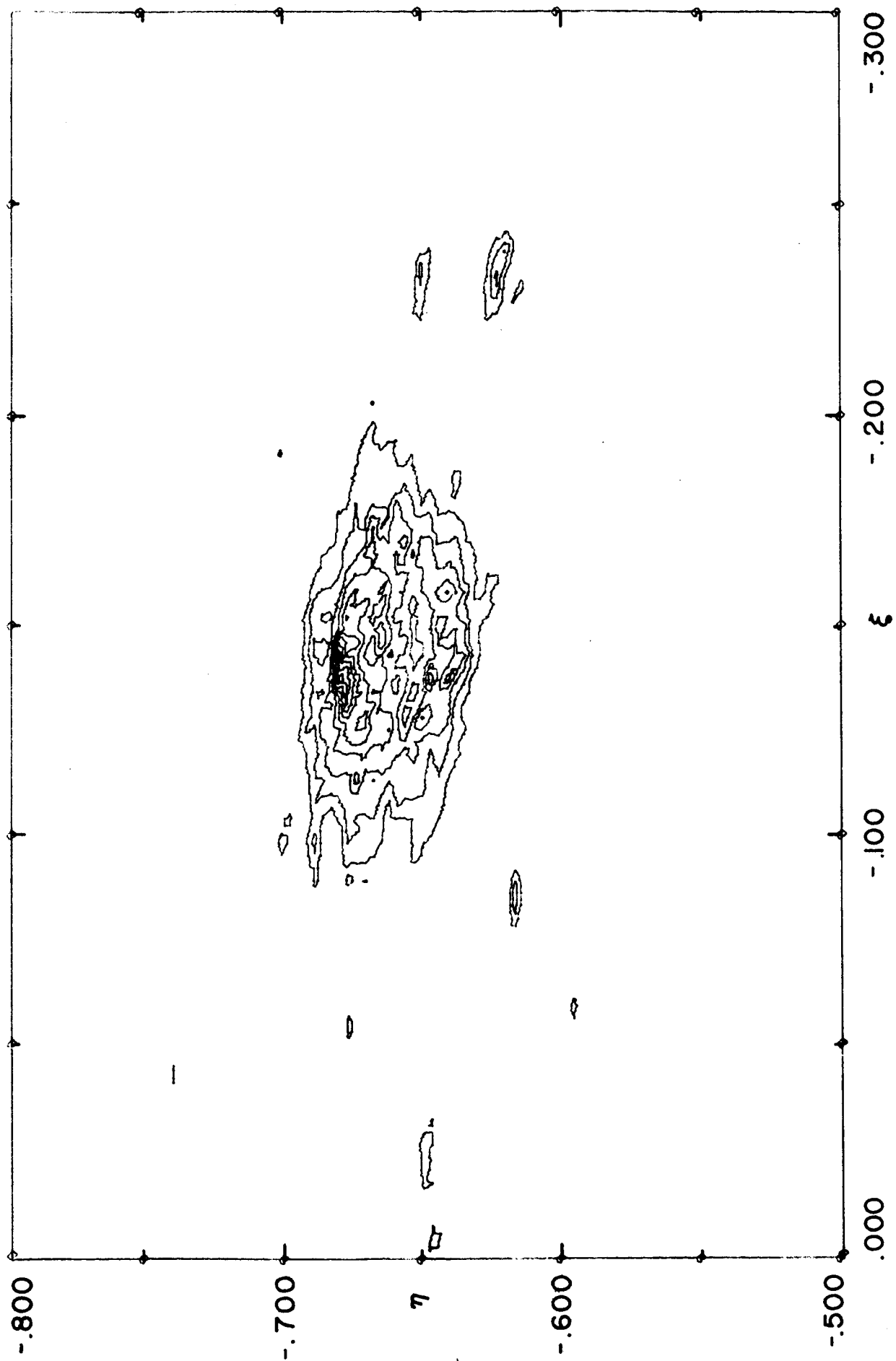grid of selenographic position probably presented as a

FIGURE 8. Contours of Constant Radar Reflectivity Mapped onto an Area
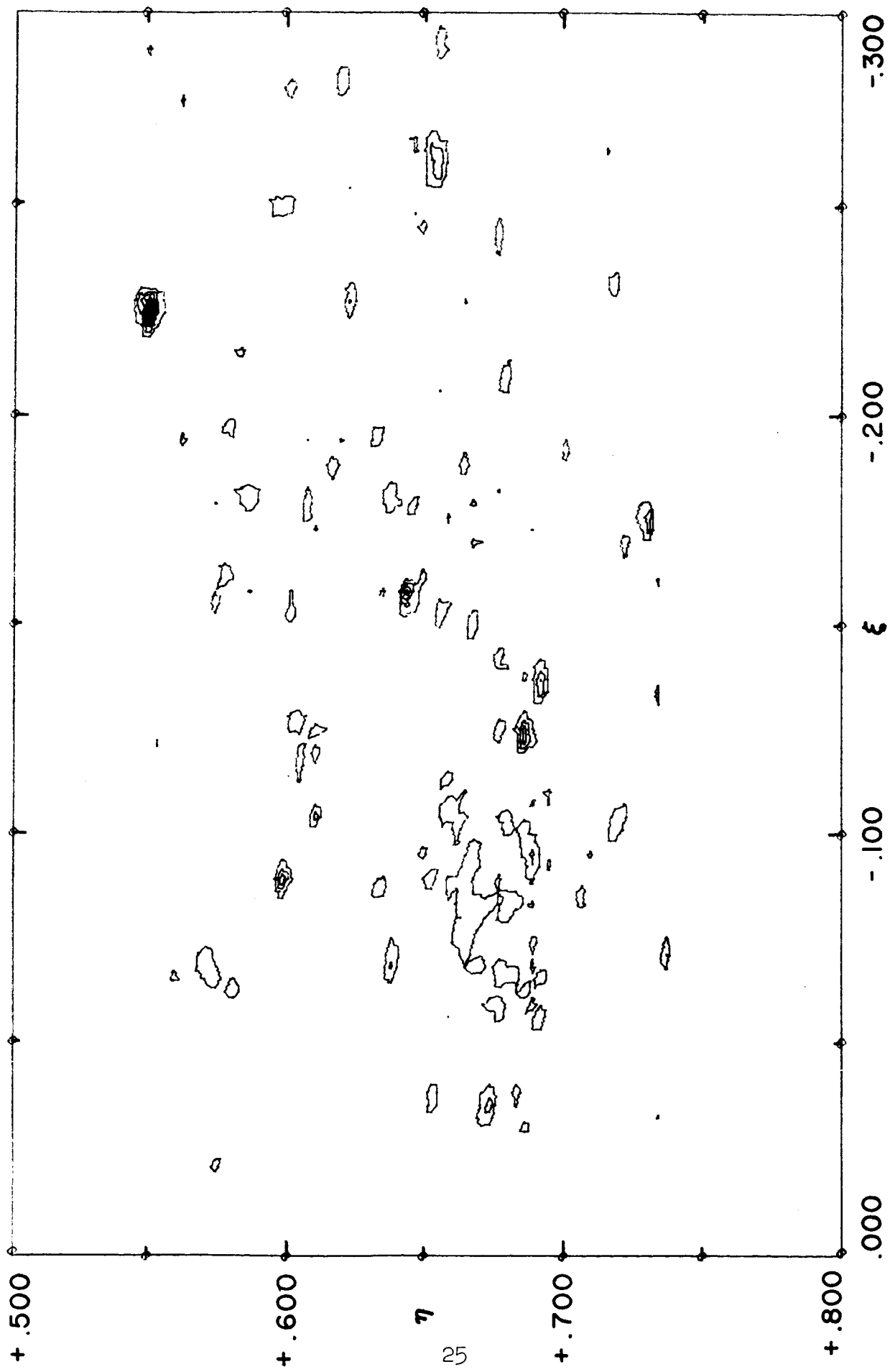Corresponding to Area in Plate D7a — TYCHO of Orthographic Lunar Atlas.

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FIGURE 9. Contours of Constant Radar Reflectivity Mapped onto an Area Corresponding to Area in Plate D2a — PLATO of Orthographic Lunar Atlas.

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scaled version of the background grid of the optical
map.   Attempts are underway to make use of half-tone
techniques instead of contour plotting.

E. Progress on 40 Mc/s Measurements

The radar maps presented demonstrate that the lunar
mapping program, the primary objective of this
observation program, is progressing satisfactorily.   The
secondary goal is to obtain the radar cross section and
scattering law of the moon at 40 Mc/s ($\lambda = 7.5$ m).   The
measurement of radar cross section will utilize the
Lincoln Calibration Sphere (Prosser, 1965) which is
currently in orbit.   An accurate measurement of the radar
cross section will help establish its dependence on
wavelength.

It has not been possible to make these measurements
because the 40 Mc/s transmitter is not yet operable
in the pulsed mode.   Much effort is being made to achieve
pulsed mode, and the measurements will be made as soon
as possible.   Since the observations will take only a few
days and require only about a week of part-time off-line
data processing, there should be no difficulty in making
the measurements, once the 40 Mc/s system is operable.

III. PLANS FOR FUTURE WORK

The plans for future work at 40 Mc/s are obvious from the preceding section.

The mapping studies at 430 Mc/s are progressing well. The effort here will be the establishment of a routine data reduction program. Also, there is need for a good display technique as was discussed in Section II-B.

The possibility of mapping areas twice the present resolution will be investigated. The number of these special maps will of necessity be limited, because it will take approximately twice the time to map one-quarter of the area.

Preliminary attempts will be made to correlate the radar results with the results of optical and infrared observations of the moon.

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IV. SUMMARY

The characteristics of the lunar surface at radio
wavelengths are being studied at 430 Mc/s (λ = 70 cm)
and 40 Mc/s (λ = 7.5 m) at the Arecibo Ionospheric
Observatory. (The parameters for these radars are given
in Table 1.) The primary effort is a mapping of radar
reflectivity of the lunar surface at 430 Mc/s with a
resolution on the lunar surface of 5 - 10 km. A
normalized reflectivity is mapped, so that a change in
radar reflectivity can be directly related to a local
change in lunar surface. By observing the "expected"
and "depolarized" components, it should be possible to
establish whether this change is due to a change in the
roughness, with the roughness on a scale of one meter.
The mapping covers the areas shown on the LAC charts and
the map of Series I of the Orthographic Lunar Atlas,
except for a region near the subearth point that is
difficult to resolve by radar methods. It is hoped that
a small number of special maps at twice the resolution
can be produced.

TABLE 1

Parameters for 40 Mc/s and 430 Mc/s Radars at A.I.O.

Frequency	40.1 Mc/s	430 Mc/s
Wavelength	7.5 meters	.698 meters
Antenna Gain (one-way at zenith)	37.5 db	56 db
Beamwidth (one-way, half-power)	2.17 degrees	0.17 degrees
Maximum Transmitter Power	2.5 Mw peak 100 Kw average	2.5 Mw peak 150 Kw average
Antenna	1000' spherical reflector with steerable feeds	
Site Latitude	18° 20' 46" N	
Site Longitude	66° 45' 11" W	

REFERENCES

1. G. P. Kuiper, <u>Orthographic Atlas of the Moon</u>.
    Supplement No. 1 to the Photographic Lunar Atlas,
    University of Arizona, 1963.

2. R. T. Prosser, "The Lincoln Calibration Sphere,"
    <u>Proc. of I.E.E.E.</u>, <u>53</u>, 1672, 1965.

3. T. W. Thompson, <u>A Study of Radar-scattering Behavior</u>
    <u>of Lunar Craters at 70 Cm</u>, Ph. D. Thesis, published
    as Internal Report RS 64, CRSR, Cornell University,
    November 1965.

4. T. W. Thompson and R. B. Dyce, Mapping of Lunar
    Radar Reflectivity at 70 Centimeters, <u>Jour. Geo.Res.</u>,
    <u>71</u>, 4843-4853, 1966.

5. U. S. Aeronautical Chart and Information Center,
    Lunar Charts, LAC 39 through LAC 95, St. Louis,
    Mo., 1964.