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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

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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.

*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 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

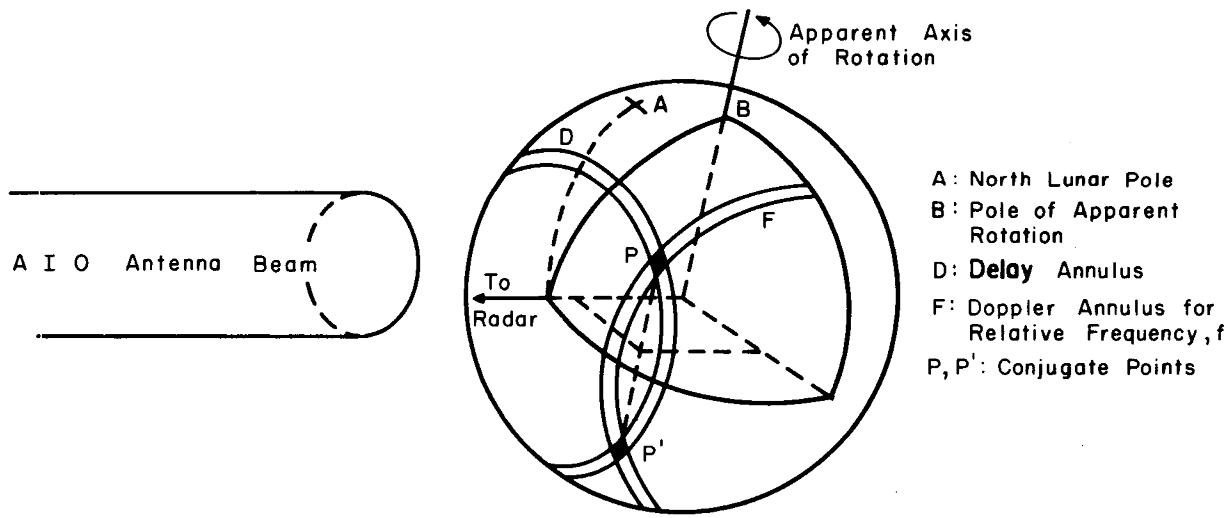


FIGURE 1. Geometry of Radar Echoes from the Lunar Surface. (The antenna beamwidth is approximately 1/3 the angular width of moon, which allows resolution of reflection of conjugate reflecting areas P and P'.

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.

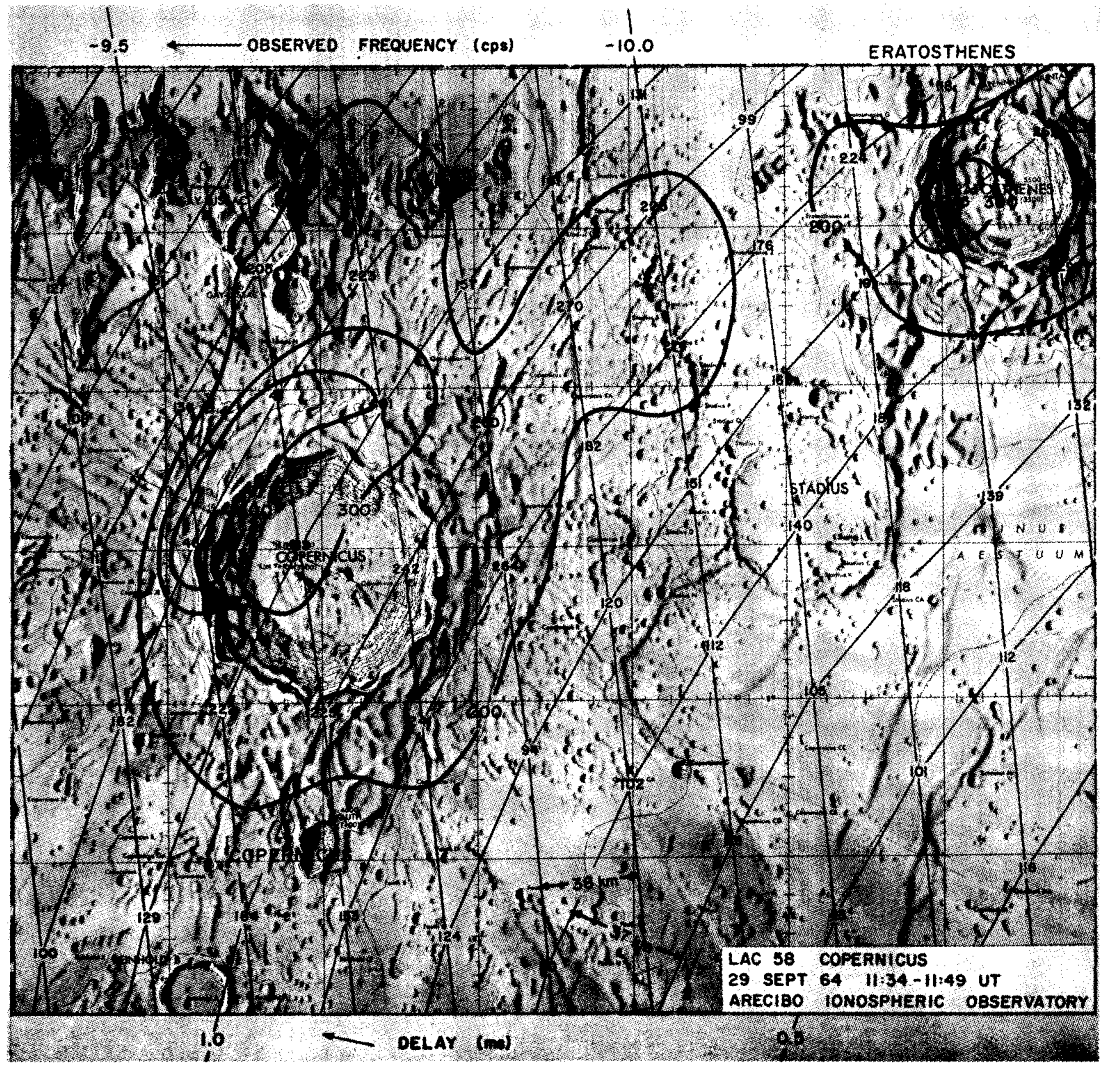


FIGURE 2. Radar-scattering Map of Craters Copernicus and Eratosthenes Plotted on LAC Chart No. 58. (Power contours of 200, 300, and 400; background approximately 100; polarized component.)

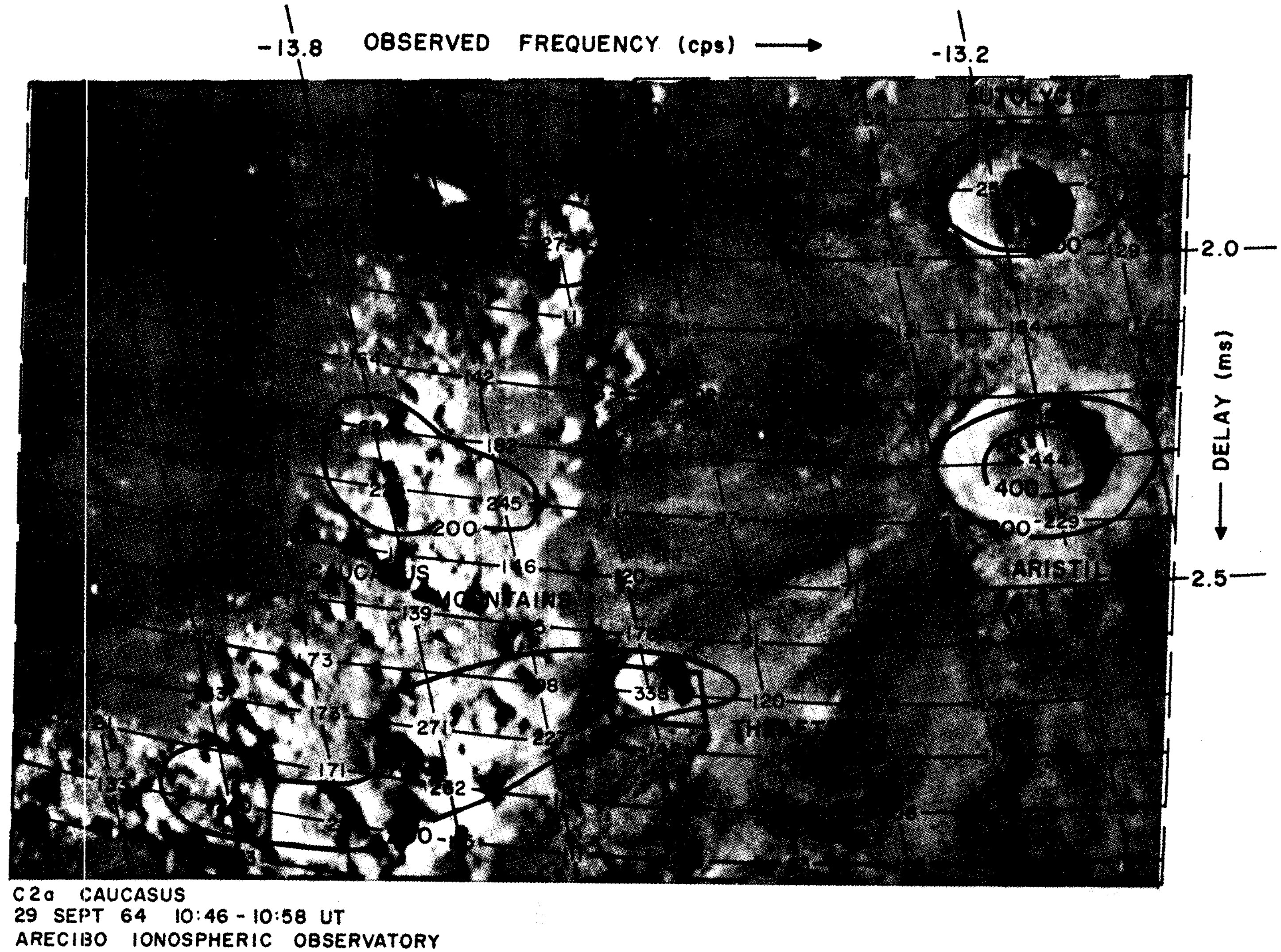


FIGURE 3. Radar-scattering Map of an Area of Map No. C2a of Orthographic Lunar Atlas. (Power contours of 200 and 400; background approximately 100; polarized component.)

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

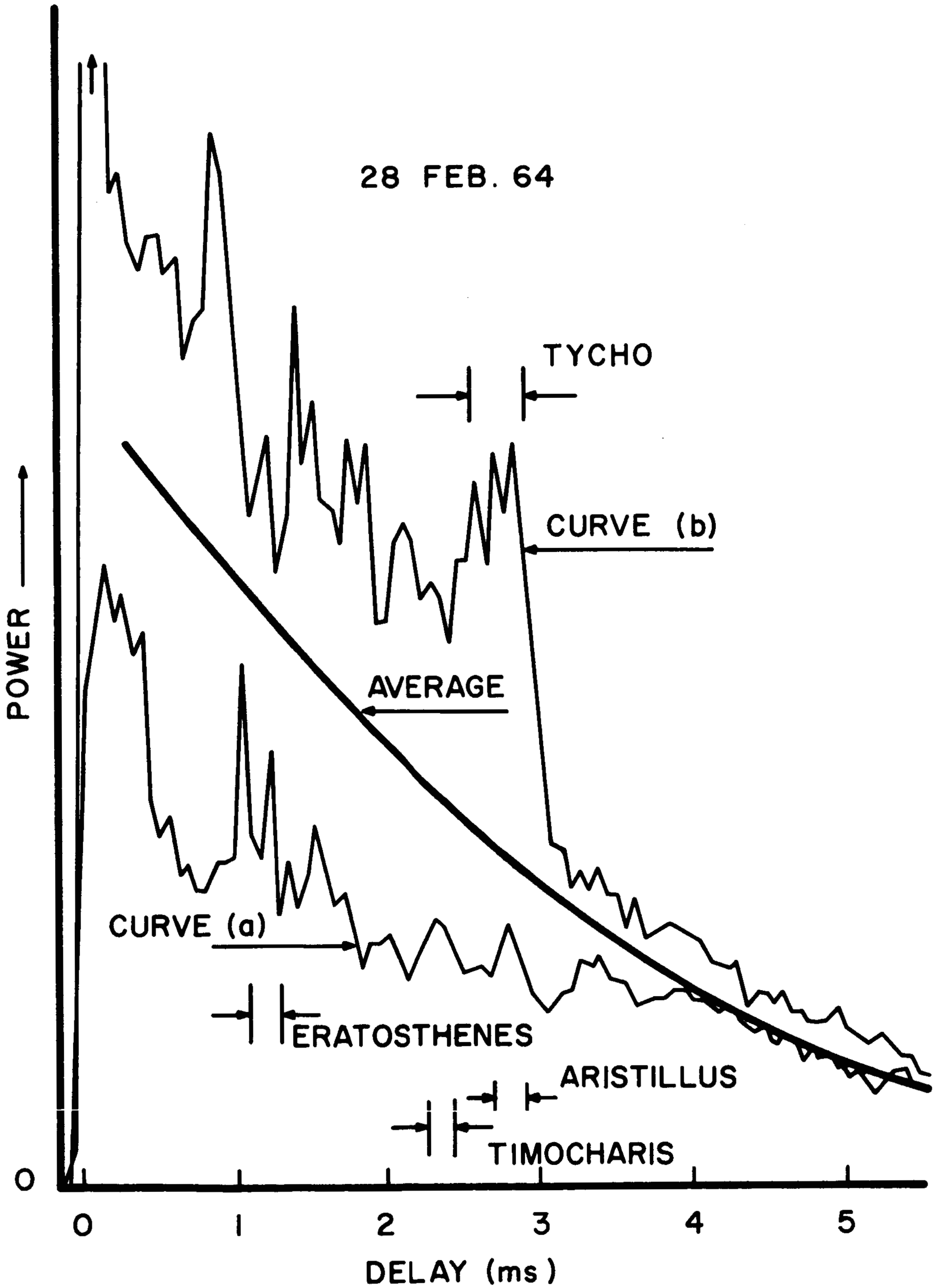
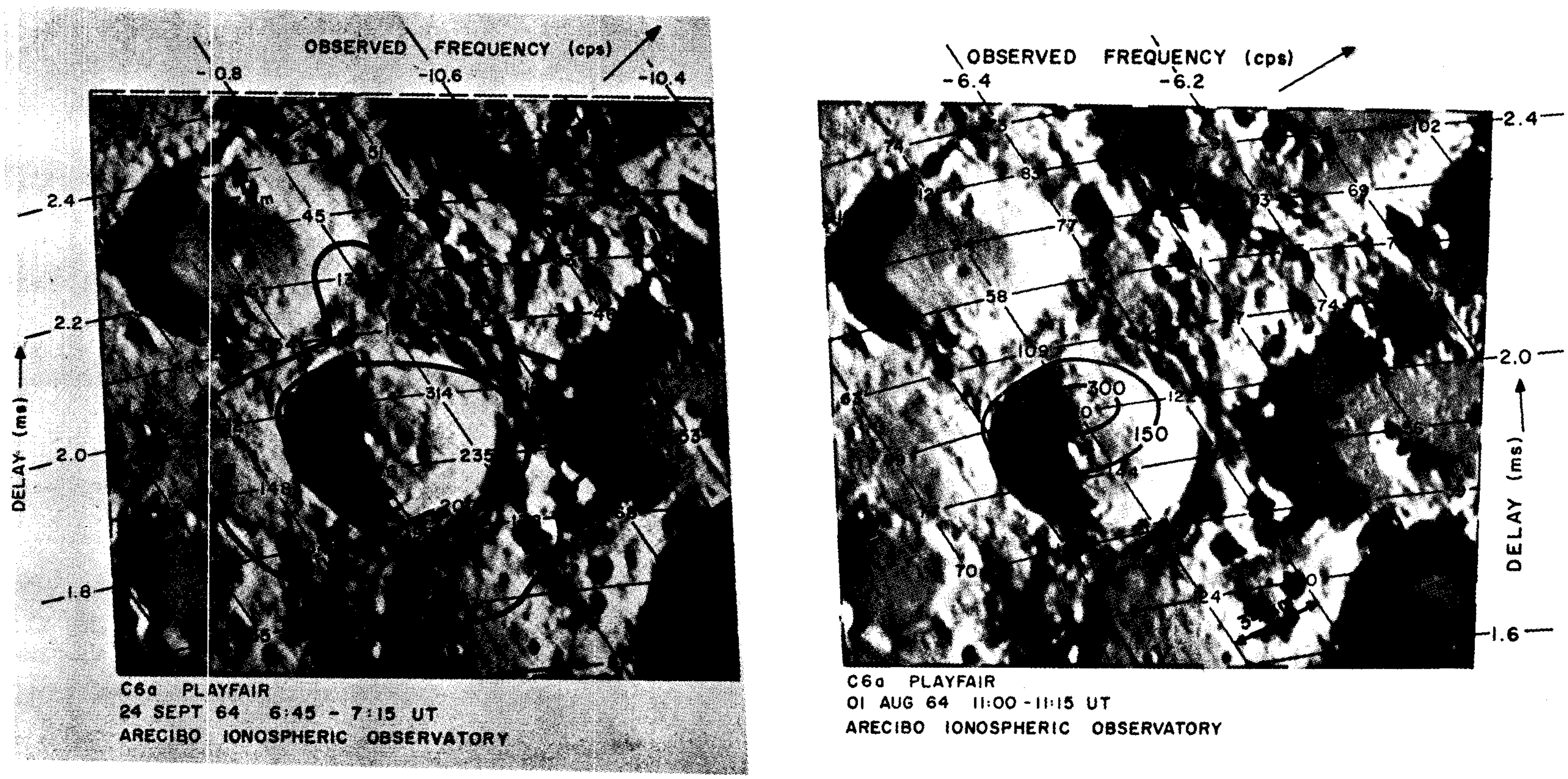


FIGURE 4. Power versus Delay for Maria (a) and Highland (b) with Antenna Beam Displaced Equal Distances from Center of Disk. (The mean of 8 equally spaced beam position is given by curve denoted "average.")



(a) (b)

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. Tn 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, 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,

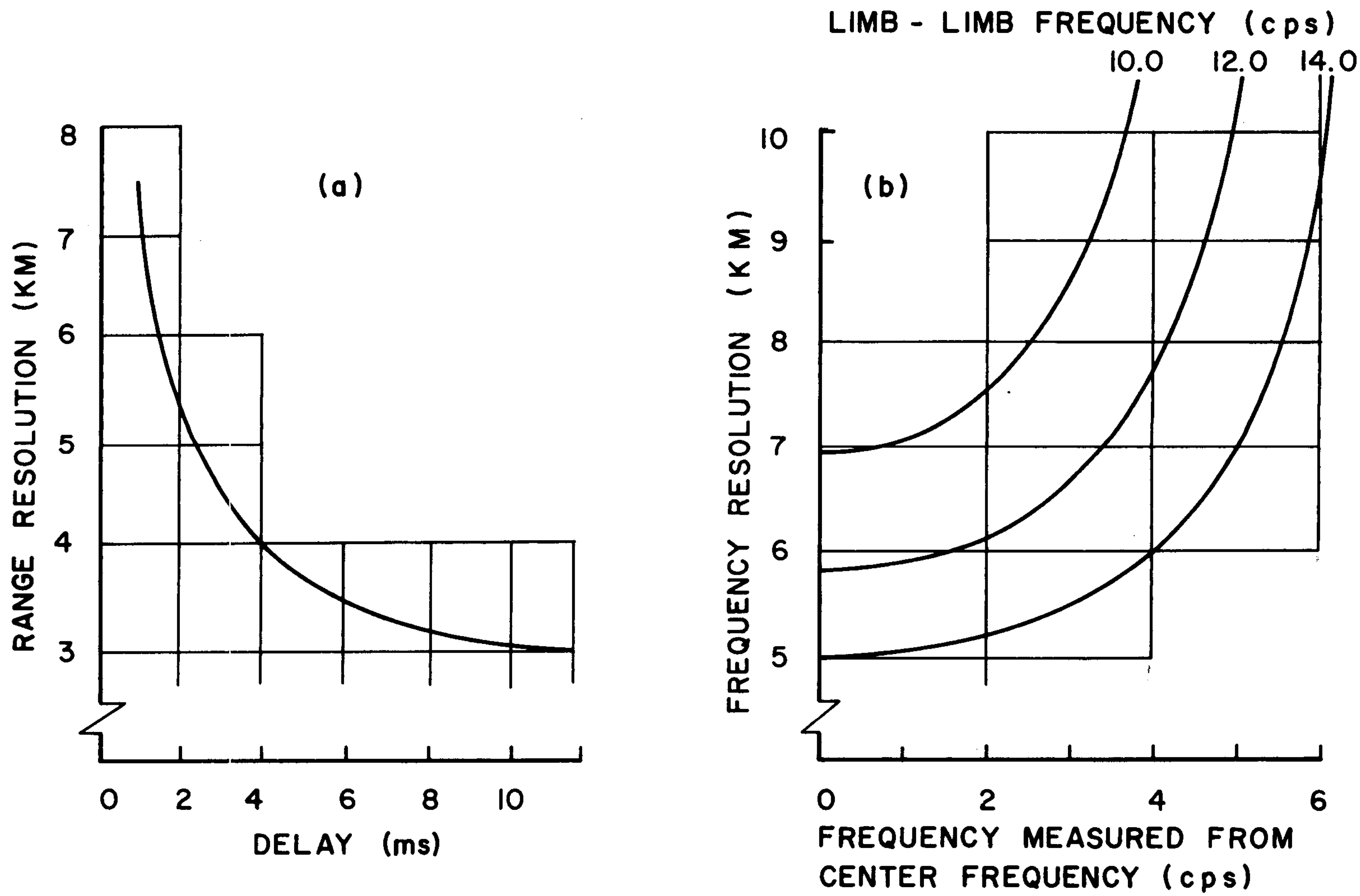


FIGURE 6. (a) Range Resolution for Transmitter Pulse Length of 20 μs, (b) Frequency Resolution for Bandwidth of 0.02 c/s and for Typical Libration Conditions at A.I.O.

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

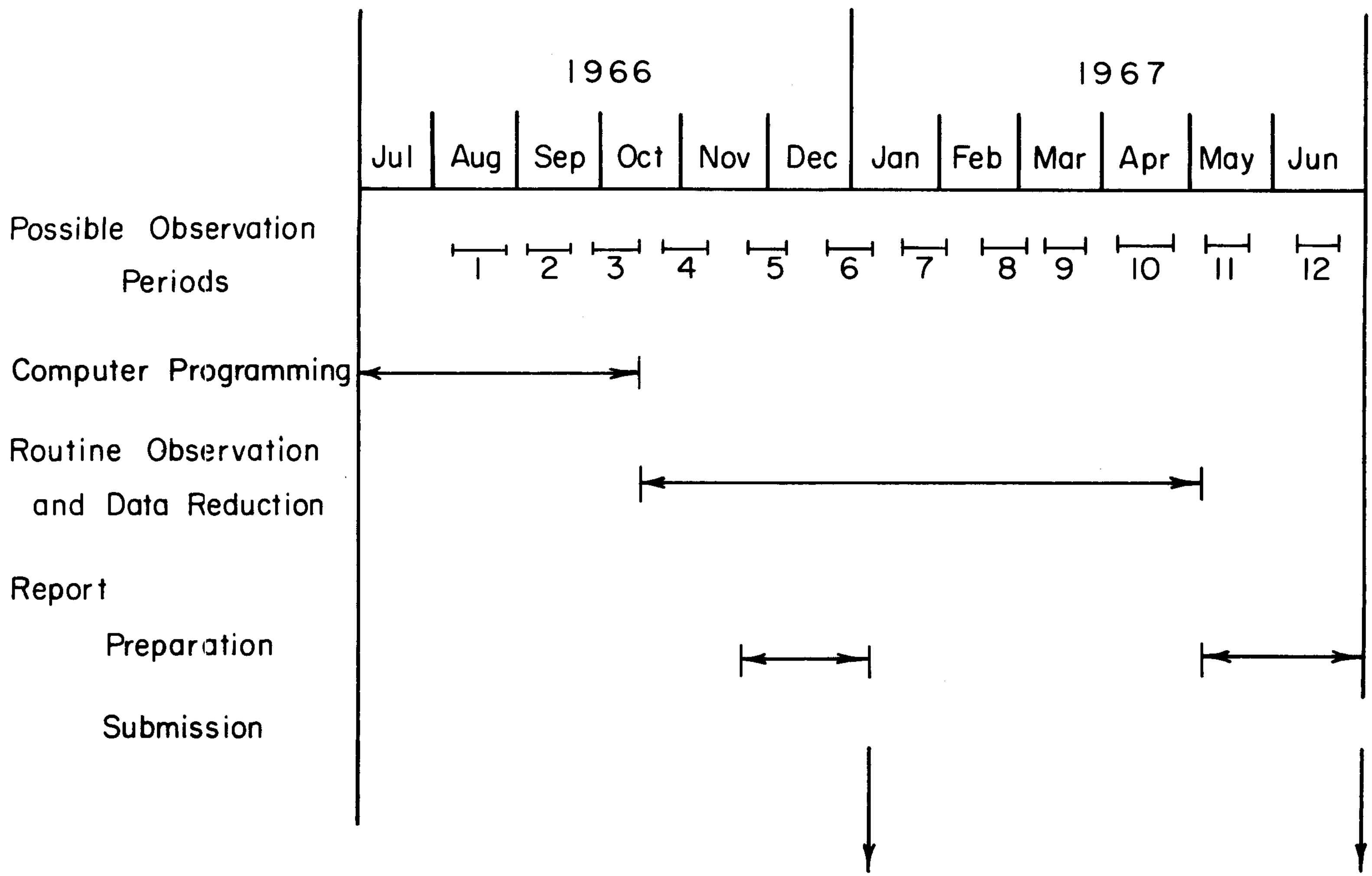
The mapping onto the LAC maps and the maps of the Orthographic Lunar Atlas Maps should yield about 40 maps in each polarization component, about 80 maps in all, in six months of observation. The moon can be observed at A.I.O. for about 2 1/2 hours for 12 days every 4 weeks. During each 2 1/2 hours, two 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:



Estimated 1 July 1966

Accomplished 1 July 1966 - 1 Dec. 1966

Projected 1 Dec. 1966 - 1 July 1967

Figure 7 - Time Schedule for Lunar Mapping

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

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

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

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

5. Mapping Program: 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

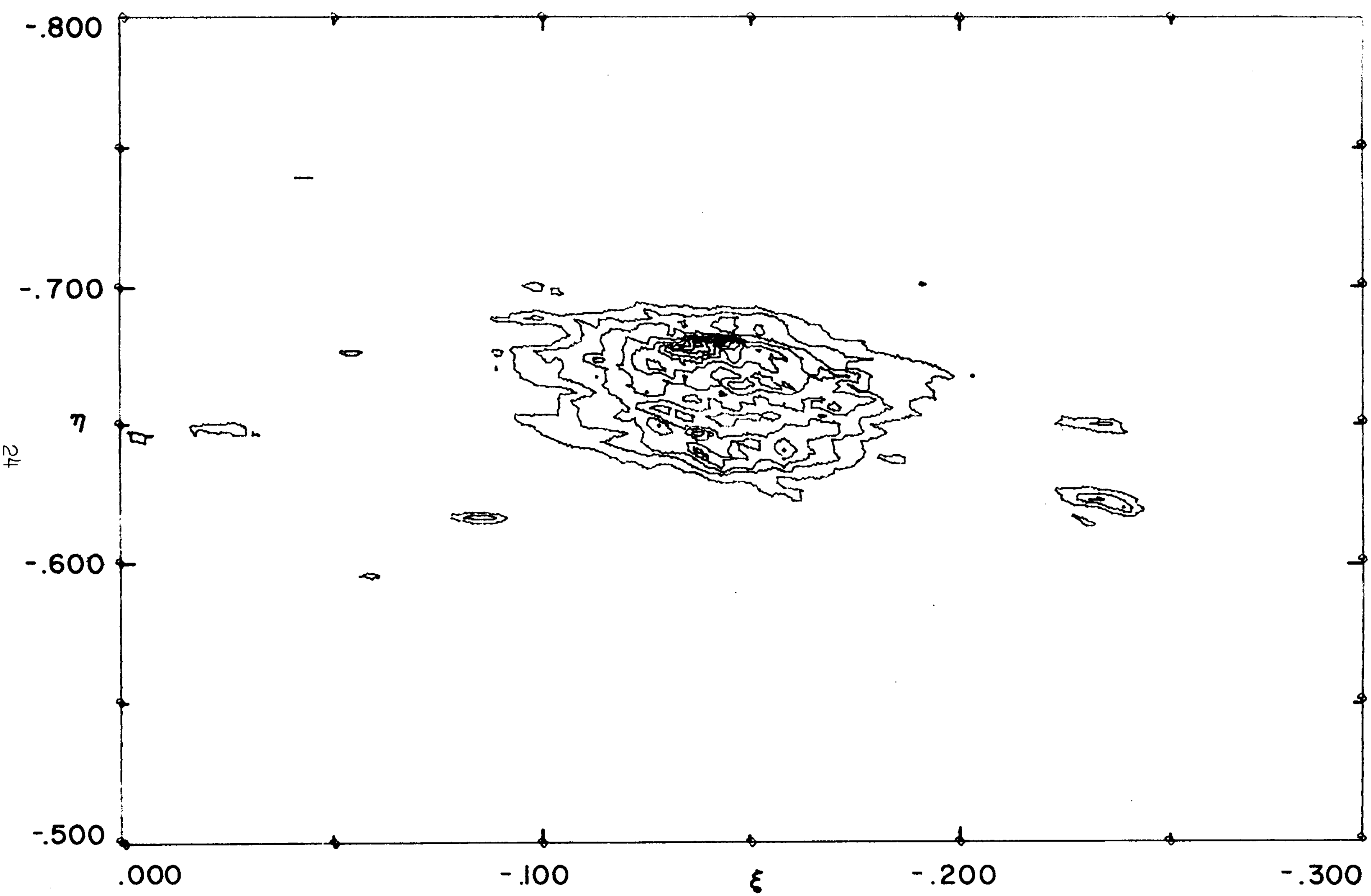


FIGURE 8. Contours of Constant Radar Reflectivity Mapped onto an Area Corresponding to Area in Plate D7a — TYCHO of Orthographic Lunar Atlas.

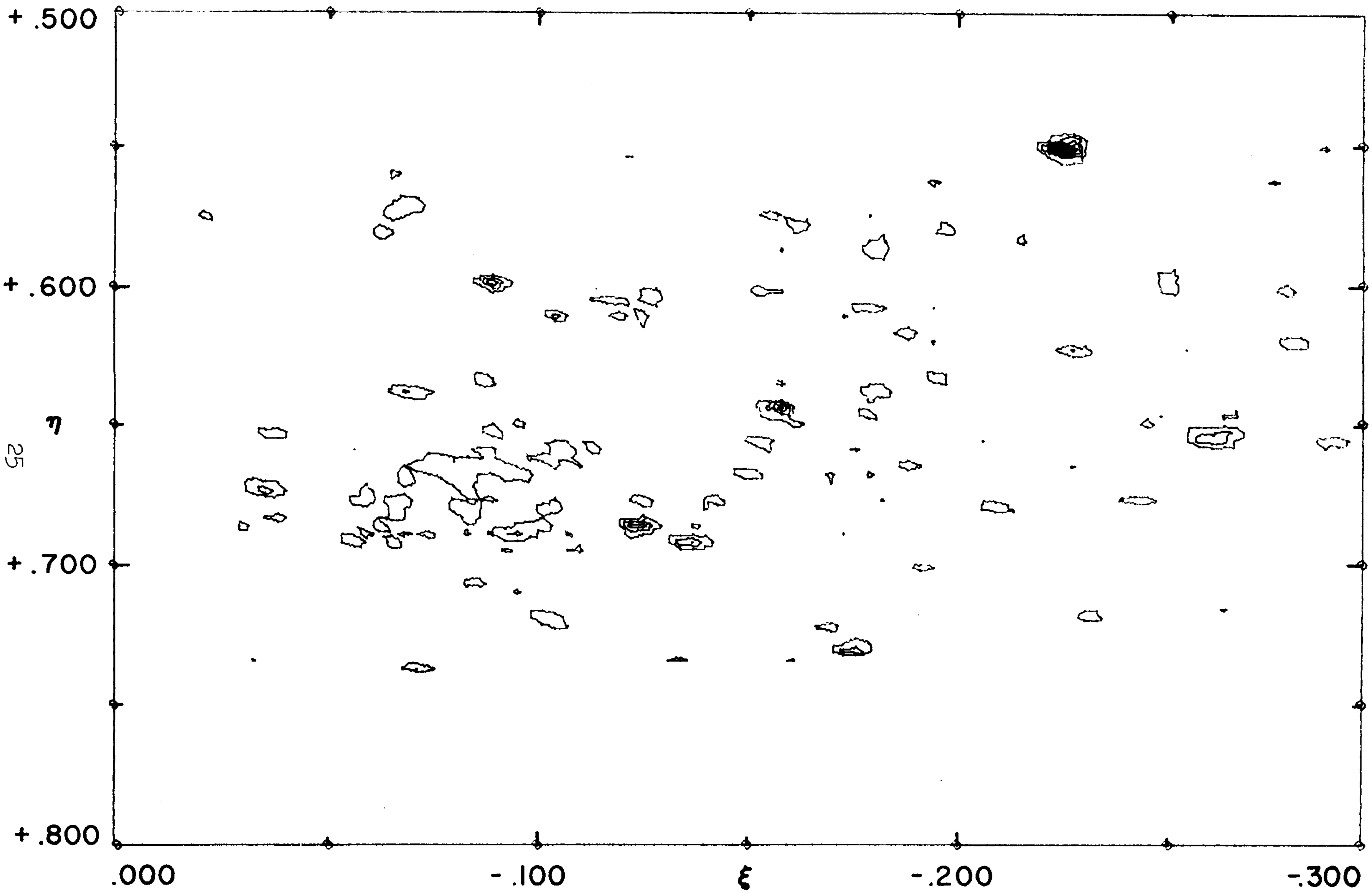


FIGURE 9. Contours of Constant Radar Reflectivity Mapped onto an Area Corresponding to Area in Plate D2a — PLATO of Orthographic Lunar Atlas.

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 (λ = 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.

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	

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