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Re: NASA Grant NGR 05-020-348

Gentlemen,

This letter constitutes Part I of the Final Report on Bistatic Radar Studies of the Moon. Part II of this report is bound separately and accompanies the letter. This report describes work carried out between June 1, 1969 and November 31, 1970 at the Center for Radar Astronomy, Stanford University, under National Aeronautics and Space Administration grant number NGR 05-020-348.

The principal goal of this work was the analysis and understanding of previously acquired lunar bistatic-radar data obtained in conjunction with Lunar Orbiters I and III and Explorer 35 spacecraft. At the beginning of this study the first systematic bistatic-radar observations had just been carried out with Explorer 35. In addition, a limited set of observations from the Lunar Orbiters also existed. It was clear that the data were reliable and in agreement with the first order predictions regarding bistatic radar echoes.[1] However, there had been no opportunity to examine the data in detail or to take more than the most preliminary steps towards using it to derive inferences as to the nature of the lunar surface. Several obvious theoretical questions required answers. Among these, two of particular importance were, what is the precise (as opposed to first order) relationship between the surface scattering law and the bistatic-radar spectra for arbitrary scattering laws, and how likely are conclusions based on simplified models to be corrupted by the diffuse component of the scattering? Others were related to the bistatic technique and the assumptions used in the analysis: can the quasi-specular and diffuse components of the bistatic radar spectrum be separated, and if so is the bistatic echo primary quasi-specular; can monochromatic bistatic radar data be interpreted unambiguously? It was possible during the course of this study to find answers to these original questions. New insights were obtained and new questions have arisen.

The visible, completed output of this work appears in three scientific publications[2,3,4] and two reports[5,6]

Bistatic radar measurements of topographic variations in lunar surface slopes with Explorer 35 (Tyler, G. L. and R. A. Simpson, Radio Science)

Lunar slope distributions: a comparison of bistatic radar and photographic results (Tyler, G. L., R. A. Simpson and H. J. Moore, JGR)

Functional dependences of bistatic radar frequency spectra on lunar scattering laws (Tyler, G. L. and D. H. H. Ingalls, submitted, JGR)

Estimation of polarization with arbitrary antennas (Tyler, G. L., Stanford Technical Report)

Bistatic-radar studies of the moon with Explorer 35 - Final Report: Part 2 (Tyler, G. L. and R. A. Simpson, Stanford Technical Report)

There are also two additional papers[7,8] in early stages of preparation that are based on the results obtained.

There have been a number of less tangible results. In order to attack the problems mentioned above, it was necessary to develop several new computational techniques for manipulating data in the form peculiar to the bistatic radar experiments. The spectral decomposition of echo polarization is the prime example. The use of the galactic background for calibration of percentage polarization is novel. Study of the data has led to advances in the hardware and data reduction system that will be used for bistatic-radar experiments on Apollo.

There has been considerable interaction with geologists working on lunar problems. The paper "Lunar Slope Distributions: A Comparison of Bistatic Radar and Photographic Results", by Tyler, Simpson and Moore, is a product of this cooperation. As a result, we now have an improved understanding of the type of information, both quantitative and qualitative, useful to geology, and our collaborators are better able to understand the potentialities and the limitations of radar.

The remainder of this report contains a brief description of the several problem areas studied, the work carried out, and our conclusions.

## A. SCIENTIFIC CONSIDERATIONS

### 1. Lunar Surface Slope Distributions

The determination of root mean square lunar slopes was one of the first scientific results of radar astronomy. Values of 4 to 5 degrees were obtained in the meter wavelength range with the use of ground based techniques. With time, as the theory was improved, this value rose steadily to the 10 degree range. Ground based values apply to a limited region near the center of the lunar disk. Although the effects of variations in slope distributions are apparent in ground based range-Doppler maps of regions remote from the sub-radar point, no quantitative assessment of these variations in terms of root mean square slope distributions has been reported.

A determination of root mean square slopes was also an initial result of this work. However, we find values for the slopes which are factors of 2 to 10 lower than those obtained with the earlier techniques. Furthermore, we observe wide variation in the slopes with lunar topography. Considerable effort was devoted to understanding the reasons for this discrepancy between the monostatic (ground based) and bistatic results. We now believe that it arises from the difficulties in accurately probing the quasi-specular portion of the scattering from very gently undulating surfaces. The pulse lengths required by present systems are sufficiently long to wash out the details of the scattering law in this region. It is not clear at present whether or not these problems can be overcome even with very short pulse techniques. Bistatic-radar, while limited in some other respects, is capable of accurately determining the near specular scattering law, and hence may be used to probe low r.m.s. slope surfaces effectively. It is interesting to note that the slopes based on the early monostatic work, which used long pulse techniques, are most nearly in agreement with the bistatic-radar determination.

The slope work has been closely compared with that of Henry J. Moore at the U.S. Geological Survey in Menlo Park, California. We find that these radar results are in general agreement with those from photographic techniques. We find this collaboration extremely beneficial and fully expect it to continue. Our principle interests at present are in establishing not only the root mean square slope, but the slope distribution functions as well. Apollo 14 is expected to yield considerable overlapping bistatic radar and photographic coverage. A limited set of the radar data from Apollo 14 will be obtained simultaneously at VHF and S-band.

### 2. Polarimetry

A considerable portion of our efforts was directed toward the resolution of the bistatic-radar echo into its quasi-specular and diffuse components. To accomplish this, a new data processing technique was required. Polarization measurements have been carried out previously in ground based experiments. The echos of signals transmitted from the earth are separated into their polarized and depolarized parts according to whether or not they have the same or the orthogonal polarization expected of an echo from a perfectly smooth conducting plane. In the bistatic experiment, this technique was not practical for two principle reasons: Faraday rotation in the earth's ionosphere confuses orientation of the polarization ellipse and the incident polarization is constantly changing. Hence, the echos were decomposed into their polarized and unpolarized parts, with polarization being defined in the optical sense. The polarized portion of the echo is that part which has a deterministic polarization ellipse, regardless of its shape or orientation; the depolarized portion is that part which consists of a random, time varying ellipse. In practice these two parts may be associated with the time correlated and uncorrelated components of two orthogonal polarizations. According to assumptions of scattering theory, which describe the echo in terms of quasi-specular and diffuse scattering mechanism, the polarized part is associated with the quasi-specular component of the scattered wave, while the unpolarized part is associated with the diffuse components. To our knowledge, this work represents the first time radar echos have been treated in this way. Using this technique, it is possible to determine the bistatic polar scattering diagrams of the lunar surface for the quasi-specular and diffuse components separately. This work has been carried out under this grant but is not yet published. We intend to present it in the literature in the near future.

### 3. Relations between Surface Scattering Laws and the Bistatic-Radar Echo Spectrum

As we have indicated above, the early interpretations of bistatic-radar data employed a Kirchhoff analysis for the gently undulating surface. However, it soon became clear that the data contain considerably more information than could be extracted with a simplified analysis. As an example, the early work could not account for the diffuse component, low altitude effects, and bulk shadowing. A more general relation was needed. An exact integral relation between surface scattering laws and the bistatic-radar power spectrum was found. Numerical evaluation of the expression was feasible and carried out. We now have the tools for the analysis of echoes based on arbitrary scattering laws, quasi-specular or diffuse. Furthermore, these techniques are valid for any geometry. One paper based on this technique has been submitted for publication. This capability is expected to be of considerable additional use in the future.

### 4. Polar Scattering Diagrams

The angular distribution of energy flow from a scattering surface is described by the polar scattering diagram, or scattering law, and can only be obtained through an oblique scattering experiment, such as bistatic radar. Hence, one of the principal objectives of our work has been the extraction of the polar scattering diagram from bistatic-radar data. Two approaches to this problem are available. One may attempt a direct inversion of the bistatic-radar spectra, (i.e., the data may be used to compute the scattering diagram directly) or, one may use a parametric approach. In this latter case, it is assumed that the scattering diagram is described by some particular scattering law from which the bistatic-radar spectra may be computed. The free parameters in the law are then varied to produce the best fit to the raw data.

We have used the parametric approach to determine the general properties of the surface scattering laws, and to determine the surface parameters required to explain our observations. On the basis of this preliminary work it now appears possible to classify different lunar terrain types by their bistatic radar scattering properties.

We have also studied the problem of direct inversion and have determined the general mathematical requirements to carry out such a program. However, the additional complexity and expense of the direct inversion does not seem warranted at this time.

## B. DEVELOPMENTS

The problems and results discussed above all represent work in essentially new areas. Even though the principles of scattering analysis are well known, we know of no previous attempt to actually carry out the processes and interpretations described above with radio techniques. Consequently, in attacking these problems, we achieved some advances in the sophistication of our data processing techniques and software. Three areas in particular deserve mention.

### 1. Ratios of Polarization

Variations in the Explorer 35 antenna pattern introduced considerable difficulties in direct interpretation of the bistatic-radar data from that spacecraft. For instance, changes in the echo polarization due to changes in the polarization of the incident wave might erroneously be attributed to the lunar surface. A simple normalization procedure, based on the ratio of circular polarizations expected from a particular surface, for an arbitrary incident polarization, was developed. When combined with the known incident polarization and the data, it was possible to produce a display of the lunar surface that was corrected for spacecraft antenna properties. For instance, a contour map showing the deviation of the surface dielectric constant from any particular effective value was produced. Similar contour maps were also produced showing the variation of regolith depth. These maps have been used in preliminary joint studies with the USGS of regolith depth and surface density. Further work in this area awaits the Apollo data.

### 2. Numerical Methods of Computing Bistatic-Radar Spectra from the Surface Scattering Laws

A computer program that computes theoretical bistatic-radar spectra for arbitrary scattering laws and bistatic-radar geometries has been developed. This program is based on the analysis described in the previous section and has proved an extremely powerful tool in the data analysis and interpretation. Output from this program provides the basis for parametric studies of surface scattering laws.

### 3. Digital Polarimeters

The most powerful analysis reduction tool developed is the digital polarimeter. Inputs to this program are sets of weighted Fourier coefficients computed from sampled data. The calculation of these coefficients and their use in spectral analysis has been described at length elsewhere.[6,9,10] Our approach differs from most others in that the electromagnetic coherency matrix is computed directly from electric field measurements, rather than indirectly by electric intensity measurements of the Stokes parameters. Once the coherency matrix has been obtained, it is a computationally simple matter to perform the additional manipulation required to determine such quantities as the polarized and unpolarized parts of the echo and the percentage polarization. Furthermore, each of these quantities is obtained as a function of frequency. The final output is the spectral decomposition of the bistatic radar echo polarization. Examples of polarization spectra from Explorer 35 are given in Part II of this report.[6]

## C. CATALOGED DATA

In carrying out this work we found it convenient to combine all of the reduced data and the appropriate experimental parameters into one data set. This data set, including a description of all data manipulations, constitutes the body of Part II of this report.

Scientifically, we consider this to have been a fruitful period. We now have the tools to quantitatively describe lunar slopes and density profiles. We fully expect further progress in this work, based on the foundations laid here. Bistatic-radar data can be used to qualitatively describe rock distributions and small scale structure. From a radar theoretic point of view, we have tested the Kirchhoff approximation and found its limitations. We have extended first order theory to include arbitrary scattering laws and a considerably greater range of validity. There has been sufficient development of the data processing techniques to stimulate work on second order theory. Technically, we have extended our capabilities so as to permit the undertaking of more sophisticated experiments in the future. Specific details of our results, in addition to the summary above, may be found in the enclosed references.

Sincerely yours,

Len Tyler

G. L. Tyler
Research Engineer

GLT:lwg
Enclosures

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