(NASA-CR-174577) ANALYSIS OF REGOLITH ELECTROMAGNETIC SCATTERING AS CONSTRAINED BY HIGH RESOLUTION EARTH-BASED MEASUREMENTS OF THE LUNAR MICROWAVE EMISSION Final Report (Planetary Science Inst., Tucson, Ariz.)

N84-15012

Unclas
G3/91 15211

FINAL REPORT

ANALYSIS OF REGOLITH ELECTROMAGNETIC SCATTERING AS CONSTRAINED BY HIGH RESOLUTION EARTH-BASED MEASUREMENTS OF THE LUNAR MICROWAVE EMISSION

NASW-3244
SAI 1-141-00-0374-00

July 31, 1983

Stephen J. Keihm
Principal Investigator

Planetary Science Institute
2030 E. Speedway, Suite 201
Tucson, Arizona 85719
(602) 881-0332

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE OF CONTENTS

ORIGINAL PAGE IS
OF POOR QUALITY

I. Introduction

A proposal entitled "Analysis of Regolith Electromagnetic Scattering as Constrained by High Resolution Earth-Based Measurements of Lunar Microwave Emission" was submitted to NASA's Lunar and Planetary Program on August 1, 1979. The planned research constituted a continuation of lunar regolith studies originally prposed by the Principal Investigator in 1978 while at the Lamont-Doherty Geological Observatory of Columbia University. The work described herein began in the spring of 1979 and covers a four-year period ending July 31, 1983.

The primary objectives of the proposed research were the development of theoretical models of planetary regolith scattering processes and an analysis of the effects of scattering on the interpretation of passive microwave and radar remote sensing data. Detailed results are presented in the attachments and will only be summarized within this report. In Section II, knowledge of lunar regolith properties prior to this study is reviewed, and the justification for scattering studies is presented. In Section III, results of the vertical structure modeling studies are presented and applications to the moon and Mars described. In Section IV, the volume scattering models are described, and results relevant to the intepretation of lunar remote sensing data are outlined. A summary and recommendations for future studies are presented in Section V.

II. Background

The Apollo Program provided a wealth of data relevant to the thermal and electrical properties of the lunar regolith. *In situ* experiments and laboratory measurements of returned samples yielded critical constraints on the depth and/or temperature dependence of regolith density, thermal conductivity, heat capacity, and dielectric properties. In particular, at the Apollo 15 and 17 heat flow sites, surface and subsurface temperatures were measured directly over many lunations, permitting the development of a detailed model of regolith thermophysical properties (Keihm *et al.*, 1973; Keihm and Langseth, 1973). This model was remarkably successful in matching previous earth-based observations of lunar disk center phase and eclipse variations at both infrared and microwave wavelengths (Keihm and Langseth, 1975).

This result generated confidence that the regolith properties measured at a few local sites were representative on a global scale, and that high resolution microwave measurements from a lunar orbiter could be utilized to map local variations in mineralogy and heat flow.

In the mid-1970's, however, confidence in the potential of remote microwave lunar mapping suffered a setback when a number of theoretical studies (e/g., England, 1975; Fisher and Staelin, 1977) suggested that scattering, assumed to be negligible in previous regolith models, could be significant in masking the microwave signatures of both mineralogy and heat flow. In addition, new high-resolution measurements of the phase variation of the lunar disk center brightness temperature indicated that *in situ* regolith electrical losses were larger than those measured on returned samples by a factor of 1.5 - 2.0 at centimeter wavelengths (Gary and Keihm, 1978). The additional component of electrical loss was postulated to be due to scattering and the need for a refinement of the regolith model to include a realistic treatment of scattering effects was clearly identified. For the ensuing research, two distinct scattering regimes were considered: (1) vertical variations in dielectric constant, and (2) volume scattering due to subsurface rock fragments.

III. Vertical Structure Models

Prior to this study, previous theoretical models have examined the effects of vertical dielectric structure for specific applications with limiting approximations (e.g., Gurvich *et al.*, 1973; Tsang and Kong, 1975; Tsang *et* *al.*, 1975; Fisher and Staelin, 1977). The method employed for our analysis of lunar regolith vertical structure places no restrictions on the dielectric profiles which could be treated. The analysis is based on the formulation of Stogryn (1970) who outlined a numerical approach for solution of the wave equation and derivation of the reflectivity and emission weighting function of a vertically varying half-space.

Three types of vertical variations, appropriate to the lunar regolith structure, were considered: (1) A two-layer model, composed of solid rock overlain by a mantle of fine soil; (2) A multi-layer structure composed of centimeter-scale strata of coarse and fine-grained soils with moderate dielectric contrasts between adjacent layers; (3) A continuous variation of dielectric constant with depth. Models were analyzed in terms of their effects on the zeroth and first harmonic (phase variation) of the lunar disk center brightness temperature. Detailed results are presented in Keihm and Cutts (1981; Attachment 2) and can be summarized as follows:

- Large impedance contrasts (bedrock overlain by a soil mantle) will cause no significant spectral variation over the wavelength range 3-30 cm unless interfaces occur within 3 m of the surface. Rock substrates occurring at depth ≲1 m could produce a negative spectral gradient comparable in magnitude to the effect of a heat flow gradient. However, such shallow bedrock occurrence is believed to be rare for the lunar frontside.

- Lunation variations in microwave brightness temperatures are not affected by a rock substrate that is deeper than 10 cm.

- The occurrence of multiple soil-strata layers of moderate dielectric contrast (as suggested by Apollo core tube studies) is not likely to affect either the absolute level or lunation variation of centimeter-wave brightness temperatures due to lateral variations in layer thicknesses and depths.

•Models of the rapid increase in soil density, believed to be characteristic of the lunar regolith's upper 10 cm, predict a brightness temperature decrease of 2-10°K over the wavelength range 3-30 cm. The onset of the spectral decrease occurs at a wavelength of 3-15 cm, dependent on the thickness of the porous regolith surface layer (~1-2 cm). The magnitude and slope of the spectral decrease depend, respectively, on the contrast and thickness of the density transition layer.

•Plausible continuous density variations do not significantly effect the amplitude of diurnal brightness temperature variations or subsequent inferences of electrical loss properties.

The two-layer models have also been utilized to examine the feasibility of reported (Zisk and Mouginis-Mark, 1980) seasonal variations in the radar reflectivity of the Sinai Planum region of Mars. We have proposed an eolian explanation for the reflectivity variation, postulating a seasonal stripping and recoating of near surface rock strata by local transport of dust. Details are presented in Cutts and Keihm, 1983 (Attachment 5).

IV. Volume Scattering Models

Prior to this study, England (1975) applied radiative transfer theory, using the Rayleigh approximation, to the problem of lunar regolith fragment scattering. Assuming a single effective particle size, he concluded that spectral brightness temperature variations of tens of degrees could occur at centimeter wavelengths, completely masking the spectral signatures of mineralogy and heat flow. The method applied for the present study also utilizes the radiative transfer formulation, but employs Mie scattering phase functions and allows for a continuous distribution of particle sizes. Model results and implications for lunar remote sensing interpretation are presented in Keihm (1982; Attachment 3) and can be summarized as follows:

- For subsurface fragment size populations representative of Surveyor mare sites, emission darkening of 1-4°K is predicted. For freshly cratered regions, such as Tycho, brightness temperature decreases of up to 7°K, relative to the non-scattering case, are predicted.

- Spectral signature due to fragment scattering depends on the relative distribution of particle sizes. For mare sites, a small increase in brightness temperature, approximately 30% of that due to heat flow, is predicted over the wavelength range 3-30 cm. Regions with a high fraction of larger size (≥10 cm) fragments, such as Tycho, can produce negative spectral gradients, comparable in magnitude to the heat flow signature.

- The amplitude of lunation variations in brightness temperature can be affected by fragment populations in the upper 10 cm surface layer. If mare-type populations exist in this layer, scattering losses will be comparable to absorption losses; and purely absorptive properties, such as the electrical loss tangent, can be seriously overestimated from remote measurements if scattering is not taken into account. Comparison of laboratory and remote inferences of electrical loss suggest that scattering effects may be particularly significant at wavelengths of 6-13 cm for the lunar disk center.

- The featurelessness of microwave brightness temperature maps of the lunar frontside indicates that the scattering properties of the upper 10 cm of regolith are remarkably uniform on a 250 km scale.

ORIGINAL PAGE IS
OF POOR QUALITY

V. Summary and Recommendations for Future Work

Our understanding of the thermophysical properties which control the thermal and radiative transport of energy in the lunar regolith exceeds that of any other extraterrestrial object. Extensive evidence does exist that regolith properties are remarkably uniform on a 250 km scale. Comprehensive models now exist which could be used to generate infrared and microwave maps of the lunar frontside at all phases to be used as an absolute calibration standard. In this regard, the primary questions remaining center on the variation of emissivity and surface roughness effects with wavelength.

Our models of lunar regolith energy transport processes are now at the state for which a maximum scientific return could be realized from a lunar orbiter microwave mapping experiment. A detailed analysis, including the effects of scattering, has produced a set of nominal brightness temperature spectra for lunar equatorial regions, which could be used as a calibration reference for mapping km-scale variations in mineralogy and heat flow (Keihm, 1983; Attachment 4). A complementary radar reflectivity experiment at comparable microwave wavelengths would greatly enhance the scientific return of a passive orbital experiment.

The techniques developed for modeling the lunar regolith have broad application to the interpretation of remote sensing data of other dry, atmosphereless bodies. It is anticipated that our progress in understanding the thermal and radiative behavior of the lunar regolith will lead to investigations of other planetary surfaces which can be pursued with increased confidence and scientific output.

ORIGINAL PAGE IS
OF POOR QUALITY

References

Cutts, J.A. and Keihm, S.J. (1983). Time-variable radar reflectivity of Mars: E lian explanations, manuscript to be submitted to Icarus, October.

England, A.W. (1975). Thermal microwave emission from a scattering layer, J. Geophys. Res. 80, 4484-4496.

Fisher, A.D. and Staelin, D.H. (1977). Possible effect of subsurface inhomogeneities on the lunar microwave spectrum, Icarus 32, 98-105.

Gary, B.L. and Keihm, S.J. (1978). Interpretation of ground-based microwave measurements of the moon using a detailed regolith properties model, Proc. Lun. Planet. Sci. Conf. 9th, 2885-2900.

Gurvich, A.S., Kalinin, V.I., and Matveyev, D.T. (1983). Influence of the internal structure of glaciers on their radio emission, Atmos. Ocean Phys. 9, 712-717.

Keihm, S.J. (1982). Effects of subsurface volume scattering on the lunar microwave brightness temperature spectrum, Icarus 52, 570-584.

Keihm, S.J. (1983). Interpretation of the lunar microwave brightness temperature spectrum: Feasibility of orbital heat flow mapping, submitted to Icarus in April.

Keihm, S.J. and Cutts, J.A. (1981). Vertical-structure effects on planetary microwave brightness temperature measurements: Applications to the lunar regolith, Icarus 48, 201-229.

Keihm, S.J. and Gary, B.L. (1978). Comparison of theoretical and observed λ3.55 cm wavelength brightness temperature maps of the full moon, Proc. Lun. Planet. Sci. Conf. 10th, 2311-2319.

Keihm, S.J. and Langseth, M.G. (1973). Surface brightness temperature at the Apollo 17 heat flow site: Thermal conductivity of the upper 15 cm of regolith, Proc. Lun. Sci. Conf. 4th, 2503-2513.

ORIGINAL PAGE IS
OF POOR QUALITY

Keihm, S.J. and Langseth, M.G. (1975). Lunar microwave brightness temperature observations reevaluated in the light of Apollo program findings, Icarus 24, 211-230.

Keihm, S.J., Peters, K., Langseth, M.G., and Chute, J.L. Jr. (1973). Apollo 15 measurements of lunar surface brightness temperatures: Thermal conductivity of the upper 1 1/2 meters of regolith, Earth Planet. Sci. Lett. 19, 337-351.

Stogryn, A. (1970). The brightness temperature of a vertically structured medium, Radio Sci. 5, 1397-1406.

Tsang, L. and Kong, J.A. (1975). The brightness temperature of half-space random medium with non-uniform temperature profile, Radio Sci. 10, 1025-1033.

Tsang, L., Njoku, E., and Kong, J.A. (1975). Microwave thermal emission from a stratified medium with non-uniform temperature distribution, J. Appl. Phys. 46, 5127-5133.