SCATTERING AND DEPOLARIZATION BY ROUGH TERRAIN AND SEA
A UNIFIED FULL WAVE APPROACH

FINAL REPORT

EZEKIEL BAHAR
PRINCIPAL INVESTIGATOR

JULY 31, 1990

U. S. ARMY RESEARCH OFFICE

CONTRACT/GRANT NUMBER
DAAL03-87-K-0085

PERIOD COVERED
BY REPORT
1 JULY 1987-30 JUNE 1990

UNIVERSITY OF NEBRASKA-LINCOLN

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16. SUPPLEMENTARY NOTATION

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17. COSATI CODES

Field Group Sub-Group

19. ABSTRACT

During the period of this contract (July 1, 1987-June 30, 1990) the principal investigator presented twenty-four (24) papers at scientific/technical meetings (see Item 7.1a) and five (5) additional papers have been accepted/submitted for presentation at International Conferences during the next few months (see Item 7.1b). Twenty-six (26) papers were submitted to Journal Editors for review (see Item (7.2)) and eighteen (18) were accepted for publication (see Item (7.3)). Twenty-two (22) papers were published in journals and conference proceedings (see Item (7.4)) and reprints of these papers have been submitted along with the six (6) semiannual progress reports. One (1) Interim Report and three (3) M.S. Theses have been completed during this reporting period (see Item (7.5)), copies were submitted with the Progress Reports. Two (2) Ph.D. Dissertations based on the research conducted under this contract will be completed by the end of next year (see Section 4). Details of the research results are provided in the reprints submitted with the Semiannual Progress Reports and the preprints of manuscripts sent directly to the Project Monitor. (continued on back)
The principal results are summarized here.

1. Two separate approaches have been developed to account for multiple scatter from rough surfaces. This first approach involves a second order iterative solution. The second approach involves the numerical solution of the generalized telegraphists' equations for the scattered wave amplitudes.

2. In the high frequency limit shadowing is accounted for by limiting the angles of incidence and scatter to less than 90°. This is referred to as self shadow. In addition shadowing is due to obstruction by distant topographical features. In the low frequency limit it is only necessary to account for self shadow.

3. The random rough surfaces are usually characterized by Gaussian surface height and slope probability density functions. In this work a broad family of non Gaussian probability density functions are considered. These are based on the gamma functions of order K. Methods based on the examination of the tilt modulation of the scattering cross sections are suggested to remotely determine the appropriate statistical characterization of the surface under observation.

4. To determine the rough surface cross sections, the random rough surfaces need to be characterized by their joint characteristic functions. Both Gaussian and non Gaussian spectral density functions have been considered in this work.

5. The medium below the rough interface is characterized by its complex permittivity and permeability. Thus conduction currents and displacement currents are accounted for in the analysis.

6. To make the problem of evaluating the scattering cross sections of random rough surfaces more tractable, it is usually assumed that the rough surface heights and slopes are statistically uncorrelated. In an attempt to examine the validity of the assumption random rough surfaces are characterized by four dimensional Gaussian joint probability density functions for the surface heights and slopes at two distinct points.

7. The observed phenomena of enhanced backscatter from very rough surfaces (including particles with rough surfaces) has been examined in some detail. It is shown that at oblique angles ($\theta_0 > 90°$) single scatter is the principal contributor to the observed enhanced backscatter, while for near normal incidence the singly scattered and multiply scattered contributions to the field add constructively or destructively about the backscatter direction.

8. Investigations were conducted to determine the scattering cross sections of rough surfaces that are modified by the presence of oil slicks, ship wakes, swells and other anisotropic surface features. The motivation for this work is remote detection of these special features of the rough surface.

9. For the vector problem of electromagnetic scattering by two dimensional rough surfaces, the excitations considered are in general elliptically polarized waves. The results can be applied directly to polarimetric remote sensing.

10. As in the past several attempts have been made to obtain experimental validation of the numerical/analytical results based on the full wave approach. To this end the full wave unified and two scale solutions have been used to interpret the Apollo lunar data. The full wave solutions, with the singly and multiply (two bounce) contributions accounted for in the analyses of scattering from very rough surfaces, provide an analytical/physical interpretation of the observed enhanced backscatter at both normal and oblique incidence. The single scatter programs have been transferred to the College of Engineering VAX. The programs are in Fortran IV. A concerted effort has also been made to enhance our ability to graphically represent our data. At present the computations of the multiply scattered field are executed on the Supercomputer facility at Cornell University. This computational work is supported through an NSF supercomputer grant.
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I. INTRODUCTION - STATEMENT OF THE PROBLEM

Physical optics and perturbation theories have traditionally been used to derive the like and cross polarized scattering cross sections for composite random rough surfaces. To this end two-scale models have been adopted and the rough surfaces are regarded as small scale surface perturbations that are superimposed on large scale, filtered surfaces. Thus, the scattering cross sections are expressed as sums of two cross sections. The first accounts for specular point scattering. It is given by the physical optics cross section for the filtered surface consisting of the large scale spectral components. The second accounts for Bragg scattering. It is given by the cross section for the surface consisting of the small scale spectral components that ride on the filtered surface.

On applying the perturbed-physical optics approaches it is necessary to specify the wavenumber $k_d$ where spectral splitting is assumed to occur between the large and small scale spectral components of the rough surface. Thus, a combination of perturbation theory and physical optics was applied to obtain the scattering cross sections for perfectly conducting random rough surfaces. The spectral splitting wavenumber was specified on the basis of the characteristics of the small scale surface and/or on the characteristics of the large scale surface. In general the restrictions on both the large and small scale surfaces cannot be satisfied simultaneously and using the perturbed-physical optics approaches the evaluation of the...
scattering cross sections critically depend on the specification of the spectral splitting wavenumber.

More recently the full wave approach has been used to determine the scattering cross sections for composite random rough surfaces of finite conductivity. Since the full wave solutions account for Bragg scattering and specular point scattering in a self-consistent manner, it is not necessary to decompose the surface into two surfaces with small and large roughness scales. However, when such a decomposition is implemented, the full wave solutions for the scattering cross sections is expressed in terms of a weighted sum of two cross sections. Thus, on adopting a two-scale model, the full wave solution resolves the discrepancies between solutions mostly based on physical considerations. In an attempt to draw more definite conclusions regarding the choice of $k_d$, it was varied over a wide range of values. It was shown that while, as expected, the cross sections associated with the individual large and small scale surfaces critically depend upon the choice of $k_d$, the weighted sum of the like polarized cross sections remain practically insensitive to variations in $k_d$ for $2.0 > \beta > 1.0$. Thus, provided that the large scale surface satisfies the radii of curvature criteria (associated with the Kirchhoff approximations) the full wave solutions for the like polarized scattering cross sections based on the two-scale model are practically independent of the specified value of $k_d$.

On applying the full wave approach to evaluate the like and cross polarized scattering cross sections for two-scale models of composite rough surfaces, several assumptions are made to facilitate the computations.
The first assumption is that the large and small scale surfaces are statistically independent. It would seem reasonable to make such an assumption if the two surfaces are results of independent processes. For the general case, however, one cannot assume statistical independence of the large and small scale surfaces.

The second simplifying assumption that is made is that the mean square slope for the total surface was approximately equal to the mean square slope for the filtered large scale surface.

The third assumption is that the mean square height of the total rough surface is large compared to a wavelength, and the surface height characteristic function for the total surface is negligibly small compared to unity.

Finally, the physical optics approximation for the cross polarized backscatter cross section is zero. As a result, the cross polarized backscatter cross section for the filtered surface is set equal to zero when the two-scale model is used. However, for backscatter, only the specular points on the rough surface do not depolarize the incident wave.

A unified formulation has also been derived for the like and cross polarized cross sections for all angles of incidence. These solutions are compared with earlier solutions based on a two-scale model of the random rough surface. Thus, the simplifying assumptions, that are common to all the earlier solutions based on two-scale models of the rough surface, are carefully examined. It is shown that while the full wave solutions for the like polarized scattering cross sections based on the two-scale model are in reasonable agreement (within 3 db) with the unified full wave solutions, the two solutions for the cross polarized cross sections differ very significantly (about 15 db).
Using the unified full wave approach it is therefore possible to analyze more realistic models of propagation paths over the sea surface without resorting to the artificial decomposition of the irregular terrain into large and small scale surfaces.

Recent work with synthetic aperture radars has shown that the modulation of the scattering cross sections by ocean currents cannot be adequately accounted for as specular point or Bragg scattering. Thus, analyses based on the physical optics approach or on perturbation theory are in general, not valid, nor are any of the two-scale models appropriate. For example, in the case of backscatter at normal incidence, solutions based on the two-scale models cannot adequately distinguish between the vertical and horizontal like polarized cross sections. However, the full wave approach which accounts for specular point scattering and Bragg scattering in a unified self-consistent manner can properly distinguish between the two like polarized cross sections at normal incidence. This backscatter measurement at normal incidence, can provide sufficient information on wind speed and direction. Similarly, the full wave analysis has the potential to be successfully applied to problems of ship wake detection.

Several important modifications to the unified full wave solutions need to be made. The solutions are based on a second order iteration of the rigorous telegraphists' equations for the wave amplitudes. Higher order iterations need to be considered in order to account for multiple scattering by the rough surface. In addition, contributions to the scattered fields from the shadowed portions of the rough surface were ignored. The contributions from these shadow regions need to be examined. They are of particular significance for scattering near grazing incident angles $\theta$ when the Rayleigh roughness parameter $\beta = 4 k_0^2 <h^2> \cos^2 \theta$ is small ($k_0$ is the free space wavenumber and $<h^2>$ is the mean square height).
In order to derive the mean values for the like and cross polarized scattering cross sections, it is necessary to ascertain the two point joint probability density functions for the rough surface height $h$ and slopes $\tilde{n}$. To facilitate the evaluation of the statistical average, it is usually assumed that the rough surface height and slopes are statistically independent and $p(\tilde{n}, \tilde{n}') = p(\tilde{n})\delta(\tilde{n}-\tilde{n}')$ ($\delta$ is the Dirac delta function). The impact of these assumptions need to be examined. Furthermore, it is usually assumed that the surface height and slope statistics are Gaussian. It is necessary to examine the effects of non-Gaussian surface statistics. Anisotropic models of the rough surfaces (such as surfaces with swells and ship wakes) need to be considered. The rough surface autocorrelation function is not necessarily assumed to be Gaussian in this work. Rather, it is derived from realistic models of rough surfaces. The effects of different surface height autocorrelation functions or their Fourier transforms the surface height spectral density functions need to be examined.

The full wave approach can be used to evaluate the bistatic scattering cross sections for all incident and scattered wave directions. In this work, backscatter is emphasized. Recent work on scattering from rough surfaces and particles with irregular shapes indicates that the full wave approach correctly predicts backscatter enhancement from surfaces with different roughness scales.

In this work, the rough surfaces are characterized by a complex permittivity to account for its finite conductivity. This has an important impact upon both single scattering and multiple scattering by rough surfaces.

A documented computer code for the evaluation of the like and cross polarized cross sections will be developed. These codes will be no more difficult to implement than those based on the hybrid, perturbed-physical optics approach.
Finally, a concerted effort will be made to obtain experimental validation of the analytical/numerical results.
2. SUMMARY OF RESULTS

During the period of this contract (July 1, 1987 - June 30, 1990) the principal investigator presented twenty-four (24) papers at scientific/ technical meetings (see Item 7.1a) and five (5) additional papers have been accepted/submitted for presentation at International Conferences during the next few months (see Item 7.1b). Twenty-six (26) papers were submitted to Journal Editors for review (see Item 7.2), and eighteen (18) were accepted for publication (see Item 7.3). Twenty-two (22) papers were published in journals and conference proceedings (see Item 7.4) and reprints of these papers have been submitted along with the six (6) semiannual progress reports. One (1) Interim Report and three (3) M.S. Theses have been completed during this reporting period (see Item 7.5), copies were submitted with the Progress Reports. Two (2) Ph.D. Theses based on the research conducted under this contract will be completed by the end of next year (see Section 7). Details of the research results are provided in the reprints submitted with the Semi Annual Progress Reports and the preprints of manuscripts sent directly to the project monitor.

The principal results are summarized here.

1. Two separate approaches have been developed to account for multiple scatter from rough surfaces. The first approach involves a second order iterative solution. In the high frequency limit it is shown that these results correspond to one bounce (single scatter) and two bounces (multiple scatter) of the incident wave from the surface. The second approach involves the numerical solution of the generalized telegraphists' equations for the scattered wave amplitudes. To this end the radiation wave spectrum is discretized and the resulting set of first order coupled differential equations are solved numerically. This work is currently in
progress and only preliminary results have been obtained. This numerical solution contains the total field (the single and the multiple bounce contributions). Only one dimensionally rough surfaces are considered when this numerical approach is used.

2. In the high frequency limit shadowing is accounted for by limiting the local angles of incidence and scatter to less than $90^\circ$. Thus if $\bar{n}$ and $\bar{n}'$ are unit vectors normal to the surface and in the direction of propagation respectively, then this condition is satisfied if $-\bar{n} \cdot \bar{n} > 0$. This is referred to as self-shadow. In addition, it is assumed in the high frequency limit, that the fields vanish below the local tangent planes at the points where $\bar{n} \cdot \bar{n} = 0$. This shadowing is due to obstruction by distant topographical features. In the low frequency limit it is only necessary to account for self shadow since the field below this local tangent plane cannot be ignored (see Item (7.2),xxv).

3. The random rough surfaces are usually characterized by Gaussian surface height and slope probability density functions. In this work, a broad family of non-Gaussian probability density functions are considered. These are based on the Gamma functions of order $K$. For $K = 1$, the marginals of the joint probability density function of the surface height is exponential while for $K \to \infty$ (for all practical purposes $K > 25$) the marginals reduce to the Gaussian probability density function. Methods based on the examination of the tilt modulation of the scattering cross sections are suggested to remotely determine the appropriate probability density function (order $K$) that most closely represents the statistical characterization of the surface under observation.

4. To determine the rough surface cross sections, the random rough surfaces need to be characterized by their joint characteristic functions for the surface heights at two separate points. To this end it is also necessary to know the surface height spectral density function. Both
Gaussian and non-Gaussian spectral density functions have been considered in this work.

5. The medium below the rough interface is characterized by its complex permittivity and permeability. Thus conduction currents and displacement currents are accounted for in the analysis. In limiting cases, both perfect conductors and perfect dielectrics can be considered for the reflection as well as the transmission scattering problems.

6. To make the problem of evaluating the scattering cross sections of random rough surfaces more tractable, it is usually assumed that the rough surface height and slopes are statistically uncorrelated. In an attempt to examine the validity of this assumption random rough surfaces that vary in height, only in one dimension, are examined in detail. In order to simplify the analytical expressions for the scattered fields, the surface is also assumed to be perfectly conducting. Thus these random rough surfaces are characterized by four-dimensional Gaussian joint probability density functions for the surface heights and slopes at two distinct points. The surfaces are also assumed to be slightly rough in order to determine the conditions for the coalescence of the full wave solutions with the small perturbation and specular point solutions. A preprint of this paper has been sent to the project monitor.

7. The observed phenomena of enhanced backscatter from very rough surfaces (including particles with rough surfaces) has been examined in some detail. The effects of varying the angles of incidence, the material below the interface, the surface mean square slope and height and the rough surface correlation lengths are considered. It is shown that at oblique angles ($\theta_0 > 20^\circ$) single scatter is the principal contributor to the observed enhanced backscatter, while for near normal incidence the single scattered and multiply scattered contributions to the field add constructively or
destructively about the backscatter direction.

8. During this reporting period several investigations were conducted to determine the scattering cross sections of rough surfaces that are modified by the presence of oil slicks naturally occurring or due to deliberate or accidental oil spills, ship wakes, swells, and other anisotropic surface features. The motivation for this work is remote detection of these special features of the rough surface.

9. For the vector problem of electromagnetic scattering by two dimensional rough surfaces, the excitations considered are in general elliptically polarized waves, including the special cases; vertically, horizontally, right and left circular polarized waves. Thus, these results can be applied directly to polarimetric remote sensing.

10. As in the past, several attempts have been made to obtain experimental validation of the numerical/analytical results based on the full wave approach.

The University of Nebraska is currently in the process of setting up an optical scatterometer and Scanning Tunnelling Microscope facility (with a 75 micrometer dual scan for the STM and the Atomic Force Microscope for conducting and non-conducting surfaces). Therefore, current attempts at experimental validation are restricted to comparison with data obtained from external sources. To this end, the full wave unified and two scale solutions have been used to interpret the Apollo lunar data. This data represents quasi specular reflection (from Apollo 14 through 16) off the moon surface to the earth at angles of incidence from about 10° to 85°. The full wave solution properly accounts for the significant rise in the normalized scattering cross section at around 80° just before rough surface shadowing needs to be accounted for in the analysis.
The full wave solutions, with the singly and multiply (two bounce) contributions accounted for in the analysis of scattering from very rough surfaces, provide an analytical/physical interpretation of the observed enhanced backscatter at both normal and oblique incidence (see Item #7, Section 2).

The single scatter programs that were executed previously on the CDC computers at the University have been transferred to the College of Engineering VAX. The programs are in Fortran IV and batch jobs are usually executed within 24 hours. Smaller jobs can be executed practically in real time. A concerted effort has also been made to enhance our ability to graphically represent our data. Thus, for instance, the enhanced backscatter phenomena can be viewed in three dimensions as surfaces whose distances from the origin are proportional to the bistatic cross sections $(\sigma^{PP} + \sigma^{QP})_{P,Q = V (vertical), H (horizontal) polarizations}$. Illustrations of these data are shown in Figures (9.1) and (9.2).

At present the computations of the multiply (two bounce) scattered field are executed on the Supercomputer facility at Cornell University. This computational work is supported through an NSF supercomputer grant. Magda El-Shenawee (Ph.D. student) has taken two short courses at Cornell University on the efficient use of Supercomputers.
3. DESCRIPTION OF RESEARCH

Detailed description of the analytical and numerical techniques used in these investigations and their applications to engineering and technology are given in the reprints and preprints of the scientific manuscripts submitted with the six (6) Semi Annual Progress Reports (See List of Publications, Section 7 and Appendix).
4. PERSONNEL SUPPORTED BY THIS CONTRACT

In addition to the principal investigator, Ezekiel Bahar, the main contributors to this research project are Mary Ann Fitzwater (Research Associate through 1988), and five (5) Graduate Research Assistants.

During this reporting period the following students received their M.S. degrees in Electrical Engineering. Copies of their theses were submitted with the Semi Annual Progress Reports (see Item #(7.5)).

(i) Robert D. Kubik
(ii) Yan-Feng Li
(iii) Guorong Huang

The Ph.D. dissertation of Magda El-Shenawee and Xiaochuan Shi should be completed by the end of next year.
5. ACKNOWLEDGMENTS

The author wishes to thank Walter Flood, (ARO Durham, North Carolina), for his encouragement, suggestions and continued interest in these investigations.

The author also wishes to acknowledge the support he received from the University of Nebraska-Lincoln for use of its computing facilities. He is especially indebted to the National Science Foundation for the Engineering Supercomputer Grants he was awarded in order to use the University of Cornell's Supercomputer facility.

This manuscript was prepared by Eunice Everett.
6. CONCLUDING REMARKS

The research group at the University of Nebraska-Lincoln has over the three year duration of the ARO contract, satisfied all the research objectives in the original proposal. Several new objectives need to be considered for future work in this field. They include the evaluation of the scattering cross sections of foliage covered terrain. To exploit recent advances in polarimetric radar techniques, it is also necessary to evaluate all the sixteen (16) Mueller matrix elements (not only the scattering cross sections). For slightly rough surfaces it is necessary to evaluate both the coherent and incoherent scattering cross sections. This would significantly contribute to resolving some of the questions raised recently on the validity of the small perturbation and Kirchhoff approaches to rough surface scattering. In addition, excitation by real sources rather than uniform plane wave should be considered.

Suggested topics for future consideration by the researchers at the University of Nebraska are listed below.

1. Use rigorous mathematical/physical models of pertinent engineering/scientific problems and employ a judicious combination of theoretical, applied and computational mathematics to solve them. These solutions should be applicable to a very broad class of rough surfaces and to ultra wideband radars. No artificial scaling parameters or "effective" median parameters should be used in this work.

2. Determine the full wave like and cross polarized incoherent diffuse scattered intensities for finitely conducting leaves characterized by their rough surface height autocorrelation functions (or surface height spectral density functions).
3. Determine the full wave like and cross polarized incoherent diffuse scattered intensities for finitely conducting stems modeled as cylinders with random rough surfaces.

4. Determine the full wave like and cross polarized incoherent diffuse scattered intensities for finitely conducting random rough terrain characterized by realistic surface height autocorrelation functions.

5. Determine the full wave like and cross polarized incoherent diffuse scattered intensities for propagation paths involving vegetation (leaves and stems) as well as rough terrain.

6. Develop techniques to discriminate between clutter due to vegetation and vegetation covered terrain and radar signatures from specific targets. In particular special consideration should be given to the existence of transmission windows in either the frequency domain or the spacial (angular) domain.

7. Full wave solutions for the (4 x 4) Mueller matrix elements should be used to evaluate polarimetric radar techniques for target/clutter discrimination.

8. Analytical and numerical determination of the like and cross polarized multiple scatter contributions to the total scattered field from one and two dimensionally rough surfaces.

9. Consider the effects of rough surface height and slope correlations on the evaluation of the like and cross polarized scattering cross sections of one and two dimensionally rough surfaces. Thus the random rough surface is characterized in general by a six dimensional joint probability density function for heights and slopes at two points.
10. Consider the impact of self shadow (due to restrictions on local angles of incidence and scatter) and the impact of shadowing due to neighboring surface obtrusions, on the scattered field.

11. Determine the transmission scattering cross sections for rough surfaces. Thus the like and cross polarized intensities diffusely scattered across irregular boundaries need to be evaluated.

12. For slightly rough surfaces, both the coherent and incoherent scattering cross sections should be evaluated.

13. Excitation by real sources rather than uniform plane waves should be considered.

14. A major effort can now be made to compare the analytical/numerical results with both in situ measurements (over the earth's surface) as well as controlled laboratory experiments. To this end the Electrical Engineering Department is setting up an optical scatterometer, microwave anechoic chamber and tunnelling microscope facility in conjunction with the Center for Electro-Optics in the College of Engineering and Technology.

The Principal Investigator has had wide experience in constructing laboratory models (earth-ionosphere waveguide) to experimentally examine the validity of analytical/numerical solutions. He has compared the predictions based on the full wave analysis with in situ experimental data over the earth's surface as well as with controlled laboratory experiments. He has interest and experience to conduct research in analytical, numerical and experimental areas listed above.
7. LIST OF PUBLICATIONS BY THE PRINCIPAL INVESTIGATOR
   DURING PERIOD OF ARMY CONTRACT
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1a) Papers Presented at Technical Meetings


(xx) First Los Alamos Symposium on Ultra-Wideband Radar, Los Alamos National Laboratory, March 5-8, 1990, "Rough Surface Scattering Cross Sections for Ultra-Wideband Radars."

(xxi) IEEE AP-S International Symposium and URSI Radio Science Meeting, May 7-11, 1990, Dallas, Texas, "Full Wave Multiple Scattering from Rough Surfaces with M. El-Shenawee.


(7.Ib) Papers Accepted for Presentation at Technical Meetings


Papers Submitted to Journal Editors for Review

(i) "Full Wave - Co-Polarized Nonspecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater.


(iii) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater.

(iv) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater.

(v) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater.

(vi) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M. A. Fitzwater.

(vii) "Non-Specular Scattering by Irregular Layered Media - Full Wave Approach.


(ix) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland.


(xiii) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths.

(xiv) "Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces."

(xv) "Conditions for the Coalescence of the Full Wave Solutions for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions.

(xvi) "Unified and Two Scale Full Wave Solutions to Interpret Apollo Lunar Surface Data," with M. Haugland.


(xix) "Electromagnetic Scattering and Depolarization Across Rough Surfaces - Full Wave Solutions," with G. Huang.


(xxi) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Models of Non-Gaussian Rough Surfaces: Unified Full Wave Approach."

(xxiii) "Full Wave Multiple Scattering from Rough Surfaces," with M. El-Shenawee.

(xxiv) "Acoustic Scattering by Two-Dimensionally Rough Interfaces Between Dissipative Acoustic Media - Full Wave, Physical Acoustics and Perturbation Solutions."

(xxv) "Conditions for the Coalescence of the Full Wave Solutions for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions." Revised.

(7.3) Papers Accepted for Publication


(ii) "Full Wave - Co-Polarized Non Specular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America, A.


(vi) "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," Journal of Geophysical Research - Ocean.


(viii) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater, Journal of the Optical Society of America, A.


(xi) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland, Proceedings of the IGARSS '89 Conference on Remote Sensing.

(xii) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths," Proceedings of Progress in Electromagnetic Research Symposium.

(xiii) "Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces, Proceedings of Progress in Electromagnetic Research Symposium.


(xvii) "Full Wave Solutions for the Scattering of Acoustic Waves Excited by Arbitrary Source Distributions in Irregular Layered Media," Wave Motion.

(xviii) "Full Wave Multiple Scattering from Rough Surfaces," with M. El-Shenawee, Proceedings of the IEEE AP-S International Symposium and URSI Radio Science Meeting.
(7.4) Papers Published in the Technical Literature and Submitted with the six (6) Semi-Annual Reports


(7.5) Interim Reports and M.S. Thesis Completed During This Reporting Period


(iii) "Scattering and Depolarization of Electromagnetic Waves from Random Rough Surfaces with Non-Gaussian Statistics - Full Wave Solution by Yan-Feng Li.

(iv) "Transmission Scattering and Depolarization of Electromagnetic Waves Across Rough Interfaces, Full Wave Approach," by Guorong Huang.
8. APPENDIX

SEMI-ANNUAL PROGRESS REPORTS NUMBERS 1-6
PROGRESS REPORT #1

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 25130-GS

2. PERIOD COVERED BY REPORT: 1 July 1987 - 31 December 1987

3. TITLE OF PROPOSAL: Scattering and Depolarization by Rough Terrain and Sea-A Unified Full Wave Approach

4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: Ezekiel Bahar

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator

Ezekiel Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NE 68508
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS
THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1) Papers Presented at Technical Meetings

(i) XXIInd General Assembly of the International Union of Radio Science,
Tel Aviv, Israel, August 24-September 21, 1987, Paper Presented "Radar
Cross Sections of Rough Terrain and Vegetation Covered Terrain," Member of

(7.2) Papers Submitted to Journal Editors for Review

(i) "Full Wave - Co-Polarized Nonspecular Transmission and Reflection Scattering

(ii) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified

(iii) "Depolarization and Backscatter Enhancement in Light Scattering from Random
Rough Surfaces - Theory and Experiment," with M. A. Fitzwater, submitted
for review.

(7.3) Papers Accepted for Publication

(i) "Enhancement of the Backscattered Diffuse Specific Intensities from Random
Distributions of Finitely Conducting Particles with Rough Surfaces," with

(7.4) Papers Published in the Technical Literature and Submitted with this Report

(i) "Full Wave Theory and Controlled Optical Experiments for Enhanced
Scattering and Depolarization by Random Rough Surfaces," with M. A. Fitzwater,
OUTLINE OF RESEARCH FINDINGS

During the reporting period (July 1–December 31, 1987), the principal investigator presented an invited paper at the XXIIInd General Assembly of the International Union of Radio Science (see Item (7.1)(i)). He also attended the URSI General Assembly as an official U.S. Delegate appointed by the U. S. National Research Council. Three technical/scientific manuscripts were prepared and submitted for publication (see Items (7.2)(i)–(iii), preprint of Item (7.2)(iii) also submitted to contract monitor). One paper was accepted for publication by the Journal of the Optical of America (see Item (7.3)(i) and one paper was published in Optics Communications (see Item (7.4)(i)).

On December 9-10, 1987, the contract monitor Dr. W. A. (Bud) Flood visited the University of Nebraska-Lincoln (UNL) and discussed with the principal investigator and his research associates the progress made in the investigations of the UNL group during this reporting period. During his visit, Dr. Flood also received a series of plots he requested of the like and cross polarized scattering cross sections for rough surfaces with complex permitivities and surface height statistics specified by him. As per his request during the meeting, a set of computer print-outs and plots were also mailed to Dr. Flood on December 23, 1987. Data was provided for both the bistatic scattering cross sections as functions of scatter angle in the plane of incidence as well as the backscatter cross sections as functions of the angle of incidence.

The observed like and cross polarized backscatter enhancement was predicted as a first order effect on the basis of an iterative-closed form solution to the full wave-telegraphists' equations. This approximation
of the full wave solution therefore does not account for multiple scattering by the rough surface. At present the principal investigators has also derived analytical expressions for the second order multiply scattered field and this work, in its two dimensional version (one dimensional rough surface) has been given to a graduate student for the purpose of preparing a computer code to calculate the second order multiply scattered fields. The information derived from this phase of the research project is to be used to generate criteria regarding the cases for which multiple scatter significantly modifies the first order results and to determine the major impact of multiple scatter on the total scattered field—whether it is a very diffuse contribution or whether (as some conjecture), it contributes to the observed enhanced backscatter.

The full wave solutions for the horizontally polarized bistatic scattering cross sections of one dimensional perfectly conducting surfaces were also compared with the computed data obtained with a Monte Carlo technique by E. I. Thorsos and A. Ishimaru (at the University of Washington at Seattle, Washington). Since the mean square slopes of the surfaces examined were very small compared to unity and since the correlation between the surface heights and slopes is proportioned to the mean square slopes, this correlation was ignored in these full wave computations. It is shown that for all the cases provided to Dr. Flood by Thorsos and Ishimaru, these full wave solutions were in very good agreement with their results. At present the full wave computer code is being modified to account for all the correlations between the slopes and heights at two points on the rough surface. This phase of the research project which may have to be executed
on a supercomputer, should shed light on the different conclusions reached
by the researchers at UNL and UW at Seattle. It should be noted that for
the purposes of the full wave analysis, the excitation is assumed to be an
obliquely incident uniform plane wave, however the results provided by
the UW researchers are for an obliquely incident "wave" with a Gaussian
"taper"—not transverse to the direction of the incident wave but transverse
to the mean reference plane of the rough surface—such a "tapered wave"
does not satisfy Maxwell's equations.
PROGRESS REPORT #2

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 25130-GS

2. PERIOD COVERED BY REPORT: 1 January 1988 - 30 June 1988

3. TITLE OF PROPOSAL: Scattering and Depolarization by Rough Terrain and Sea-A Unified Full Wave Approach

4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: Ezekiel Bahar

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:
   
   See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:
   
   Professor Ezekiel Bahar - Principal Investigator
   Dr. M. A. Fitzwater - Research Associate
   Graduate Research Assistants

   Ezekiel Bahar
   Department of Electrical Engineering
   University of Nebraska
   Lincoln, NE 68508
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1a) Papers Presented at Technical Meetings


(7.1b) Papers Accepted for Presentation at Technical Meetings


(7.2) Papers Submitted to Journal Editors for Review


(ii) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity" with M. A. Fitzwater, Journal of Wave-Material Interaction


(7.3) Papers Accepted for Publication


(7.4) Papers Published in the Technical Literature and Submitted with This Report

OUTLINE OF RESEARCH FINDINGS

During the reporting period (1 January–June 30, 1988), the principal investigator presented three papers at scientific/technical meetings (see Item (7.1a)) and he has been invited to present two papers at the International Working Group Meeting on Wave Propagation in Random Media (see Item (7.1b)). Three technical/scientific manuscripts were prepared and submitted for publication (see Item (7.2)). Three papers were accepted for publication (see Item (7.3)) and one paper was published in the Journal of the Optical Society of America A (see Item (7.4)) and reprints have been submitted with this Report.

The principal investigator visited with the contract monitor, Dr. W. A. (Bud) Flood, while attending the IEEE AP-S International Symposium and URSI Radio Science Meeting at the University of Syracuse, Syracuse, New York, June 6-11, 1988. An oral report was presented on the research conducted by the UNL group.

In order to evaluate the mean values of the scattering cross sections for random rough surfaces, it is necessary to characterize the surfaces by their height and slope joint characteristic function $\chi_2(h(\mathbf{r}),h(\mathbf{r}'),\bar{n}(\mathbf{r}),\bar{n}(\mathbf{r}'))$ at points $\mathbf{r}$ and $\mathbf{r}'$ on the rough surface ($h$ is the height and $\bar{n}$ is the normal to the surface) or its Fourier transform the joint probability density function, $p(h(\mathbf{r}),h(\mathbf{r}'),\bar{n}(\mathbf{r}),\bar{n}(\mathbf{r}'))$. Thus, for isotropic, homogeneous two dimensionally rough surfaces it is necessary to evaluate five dimensional integrals. These integrals account for all the correlations between the random surface height and slopes at two neighboring points on the rough surface. If it is assumed that the surface does not vary in the direction normal to the scattering plane, the scattering problem can be reduced to two uncoupled problems for the vertically and horizontally polarized waves since the scattered waves are not
In view of the fact that for this phase of our work the computations are very time-consuming even for one-dimensionally rough surfaces, one of the graduate research assistants associated with our investigations is attending a two-week workshop sponsored by the National Science Foundation at the Super Computer facility at Cornell University this summer. We expect to have access to the Super Computer facility at the CRDEC, Aberdeen, Maryland. Access to Super Computers (NSF or DOD) would facilitate the extension of this phase of our investigations to two dimensional models of rough surfaces.
PROGRESS REPORT #3
TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 25130-GS

2. PERIOD COVERED BY REPORT: 1 July 1988 - 31 December 1988

3. TITLE OF PROPOSAL: Scattering and Depolarization by Rough Terrain and Sea-A Unified Full Wave Approach

4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: Ezekiel Bahar

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   See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

   Professor Ezekiel Bahar - Principal Investigator
   Dr. M. A. Fitzwater - Research Associate
   Graduate Research Assistants

Ezekiel Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NB 68508
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1a) Papers Presented at Technical Meetings


(7.1b) Papers Accepted for Presentation at Technical Meetings


(7.2) Papers Submitted to Journal Editors for Review


(7.3) Papers Accepted for Publication


(7.3) continued


(7.4) Papers Published in the Technical Literature and Submitted with This Report


(7.5) Interim Reports

Outline of Research Findings

During the reporting period (1 July 1988 - 31 December, 1988), the principal investigator presented three papers at Scientific/Technical meetings (see Item (7.1a)) and seven papers have been accepted for presentation in the next few months (see Item (7.1b)). One paper was submitted for publication (see Item 7.2) and four papers were accepted for publication (see Item 7.3). Six papers were published (see Item 7.4) and reprints of these papers have been submitted with this report. An interim report on synthetic aperture radar images was submitted to the project monitor (see Item 7.5).

The contractor monitor Dr. W. A. (Bud) Flood visited the research group at the University of Nebraska-Lincoln in November, 1988. He was presented an oral report by the principal investigator and the graduate students involved with this project.

The full wave analytical and computational work on the horizontally and vertically polarized incoherent bistatic cross sections for one-dimensionally rough perfectly conducting surfaces is near completion. In this work, the random rough surface is characterized by a four-dimensional Gaussian probability density function for the surface heights and slopes at two points on the surface. It is also assumed that the surface height spectral density functions (and their Fourier transforms the surface height autocorrelation functions) are also Gaussian. Thus, all the correlations between the surface heights and slopes at two points on the rough surface are accounted for in the analysis.

In this work the corresponding physical optics and small perturbation solutions are also evaluated. It is shown that when the rough surface slopes are assumed to be negligibly small (as in the analysis of Rice (1951)), the full wave analysis reduces to the small perturbation results. However, when it is assumed that the major contributions to the scattered field come from
the neighborhoods of the stationary phase points, the full wave solutions are in
agreement with the physical optics solutions. In general there is good agreement
between the full wave, small perturbation and physical optics solutions for scattering
in the near specular directions when the mean square slopes are very small compared
to unity and mean square heights are very small compared to the wavelength of the
electromagnetic excitations. However, for backscatter, this is not the case.

Since the full wave scattering coefficients involve expressions for the sine and
cosines of the local angles of incidence and scatter, shadowing is intrinsically
accounted for in the analysis. It is shown that where shadowing is deliberately
ignored, all the integrals for the specular cross sections (and the horizontally
polarized backscatter cross section) can be evaluated analytically. This work
has shown that shadowing effects are very significant.

Surfaces characterized by different spectral density functions, but with the
same mean square heights and correlation lengths are shown to have significantly
different bistatic cross sections.

Progress has also been made involving the evaluations of the like and cross
polarized cross sections for two dimensionally random rough surfaces. The medium below
the rough interface is characterized by complex relative permittivities $\varepsilon_r = \varepsilon' - i\varepsilon''$
with a positive or a negative real part ($\varepsilon'$) and a negative imaginary part ($\varepsilon'' > 0$
accounts for dissipation). The like and cross polarized scattering cross sections
for vertically and horizontally polarized excitations can be evaluated for any
direction in the upper half space and not just in the plane of incidence.
Methods for presenting these new three dimensional data are presently under study.

The computer codes for scattering by two dimensionally rough surfaces have
been generalized to account for both (vertical and horizontal) linearly polarized
excitations as well as (right and left) circularly polarized excitations.
Thus in addition to the four like and cross polarized cross sections
\(\sigma_{VV}, \sigma_{HH}, \sigma_{HV}, \sigma_{VH}\) (V-vertical, H-horizontal) four new cross sections \(\sigma_{RR}, \sigma_{LL}, \sigma_{LR}, \sigma_{RL}\) (R-right circular, L-left circular) can now be evaluated. These new results will be used to shed additional light on the interpretation of the experimental data.

Two approaches (by different students) are currently being investigated in order to account for multiple scattering. At this time only one dimensionally rough surfaces are considered for this phase of our work. In one approach we seek numerical solutions to the (full wave) generalized telegraphists' equations. A major difficulty with this approach involves the singular nature of these integro differential equations. The second approach involves the evaluation of a third order iterative solution to the telegraphists' equations. It is shown that in the high frequency limit (using stationary phase integration techniques) these third order iterative solutions correspond to incident waves that are specularly scattered twice by the rough surface. (The first and second order iterative solutions are the primary and single scatter solutions respectively). The principal problem with the evaluation of the third order iterative solutions involves the very large amount of computer time needed even for super computers.

The principal investigator has been informed that he has been awarded 95 hours of computational time on the NSF supported Super Computer Center at Cornell University. This supercomputer Grant will facilitate progress in this phase of our research.

Progress has been made on the efficient evaluation of the radar cross sections for rough surfaces with arbitrarily oriented mean planes (with respect to the plane of incidence). The modulations of the scattering cross sections characterized by two angles; the tilt of the mean plane measured "in" the plane of incidence and the tilt of the mean plane measured "perpendicular" to the plane of incidence. This will facilitate the rapid evaluation of the scattering cross sections for rough surfaces that are tilt modulated by very large scale
terrain features. (These very large scale terrain features are assumed to be much larger than the dimensions of the surface area illuminated by the radar).

Progress has also been made on the evaluation of the scattering cross sections for surfaces with non-Gaussian height and slopes statistics using the unified full wave approach instead of the earlier solutions based on the two scale approach. Consideration is being given to practical ways that can be used to determine the rough surface statistics using these analytical studies.

References

PROGRESS REPORT #4
TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 25130-GS

2. PERIOD COVERED BY REPORT: 1 January 1989 - 30 June 1989

3. TITLE OF PROPOSAL: Scattering and Depolarization by Rough Terrain and Sea - A Unified Full Wave Approach

4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: Ezekiel Bahar

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

   See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

   Professor Ezekiel Bahar - Principal Investigator
   Graduate Research Assistants

Ezekiel Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NB 68508
LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES.

(7.1a) Papers Presented at Technical Meetings


(7.1b) Papers Accepted for Presentation at Technical Meetings


(7.2) Papers Submitted to Journal Editors for Review


(ii) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland, Proceedings of the IGARSS '89 Conference on Remote Sensing, Vancouver, Canada.


-48-
(7.2) continued


(v) "Electromagnetic Wave Scattering by Randomly Rough Boundaries," Invited paper on Review of Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel, Proceedings of the National Science Foundation Workshop on Future Directions in Electromagnetic Research, Boston, Massachusetts.

(vi) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts.

(vii) "Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts.

(7.3) Papers Accepted for Publication


(iii) "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland, Proceedings of the IGARSS "89 Conference on Remote Sensing, July 4-10, 1989, Vancouver, Canada, in press.

(iv) "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, in press.

(v) "Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces," Proceedings of Progress in Electromagnetic Research Symposium, Boston, Massachusetts, in press.

(7.4) Papers Published in the Technical Literature and Submitted with This Report


(7.5) M.S. Thesis Completed During this Reporting Period

Outline of Research Findings

During the reporting period (1 January 1989 - 30 June 1989), the principal investigator presented three papers at Scientific/Technical meetings (see Item (7.1a)) and eight papers have been accepted for presentation in the next few months (see Item (7.1b)). Seven papers were submitted for publication (see Item (7.2)) and five papers were accepted for publication (see Item (7.3)). Two papers were published (see Item (7.4)) and reprints of these papers have been submitted with this report. The M.S. Thesis by R.D. Kubik was accepted. (see Item (7.5)).

The full wave analytical and computational work on the bistatic vertically and horizontally polarized scattering cross sections for one dimensionally rough perfectly conducting surfaces has been completed. A preprint of the paper, "Conditions for the Coalescence of the Full Wave Solutions for Rough Surfaces EM Scattering with Perturbation and Physical Optics Solutions" has been submitted to the sponsor. In this work, the random rough surface is characterized by a four-dimensional Gaussian joint probability density function for the surface heights and slopes at two different points on the surface. All the correlations between the surface heights and slopes at two points on the rough surface are taken into account in this analysis. For the initial illustrative examples considered, the surface height autocorrelation function and its Fourier transform, the surface height spectral density function is assumed to be Gaussian. Surfaces with other spectral density functions will also be considered in subsequent illustrative examples.

In order to compare the full wave results with other analytical results both the corresponding physical optics results (based on the Kirchhoff approximations of the surface fields) as well as Rice's small perturbation results (based on the Rayleigh approximations for the scattered field) are evaluated.

For horizontally polarized waves it is shown that the full wave results reduce to the small perturbation results only when the rough surface mean square slopes are negligibly small ($\sigma_s^2 < 0.001$). (The first order perturbation results of Rice...
of the analytical solutions are very difficult due to singularities in the coupling coefficients.

The second approach used to account for multiple (two bounce) scattering from rough surfaces is based on an iterative procedure using the full wave integral expressions for the single scattered field. Since the full wave solutions (which account for upward and downward scattering) can also be used to compute the fields near the rough surface, the single scattered field incident upon the rough surface is first computed. It is regarded as the impressed field in the full wave scattering integrals to obtain the multiply (two bounce) scattered field. A geometric optics (stationary phase) approximation of the full wave solutions show that for backscatter at normal incidence, the maximum slope of the rough surface must exceed 45° in order for multiple scattering to occur. However, the full wave expression shows that multiple scatter occurs for more moderate slopes. The intensity of the multiply scattered waves decrease significantly as the maximum slope decreases below 40°. Moreover, it is shown that for surfaces with maximum slopes, in excess of 45°, there exist several (stationary phase) ray paths. For backscatter the ray paths exist in pairs that reinforce each other. However, away from the backscatter direction these stationary phase contributions interfere with each other and the multiply scattered contributions drop sharply at about 10°-15° away from normal. It is also shown that for incident angles greater than 20°, the multiply scattered contributions become small (compared to single scatter) even for the backscatter direction. These results are consistent with experimental observation in controlled laboratory environments. The computation work has been carried out on the NSF supported Super Computer Center at Cornell University. The preliminary results on multiple scatter will be presented at an ARO workshop organized by the contract monitor, Dr. W. L. (Bud) Flood for July 28-29, 1989 at Boston University, Boston Massachusetts.

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for horizontally polarized waves, correspond to zero slope). For scattering in the near specular direction, there is general agreement between the full wave physical optics and perturbation results when the Rayleigh roughness parameter $\beta = k h^2 < 0.1$ and the mean square slopes $\sigma_s^2 < 0.002$. However, the agreement is not good in the backscatter direction.

It is also shown that shadowing plays a very important role for scattering near grazing angles even when the mean square slopes are small. The self-shadowing terms (which restrict the local angles of incidence and scatter to less than $90^\circ$) have a very significant impact on the results. Thus the physical optics approximations of the shadowing effects are not valid for near grazing angles.

The computer programs for the bistatic cross sections of three dimensionally rough surfaces have been generalized in order to evaluate the like and cross polarized scattering cross sections for any scatter direction in the half space above the rough surface and not just in the plane of incidence. New graphic programs are being utilized to present this data.

Significant advances have been made on the evaluation of multiply scattered waves from rough surfaces with large mean square slopes ($\sigma_s^2 > 1$). At this time however to make the problem more tractable, only one dimensionally rough surfaces are considered.

Using a more formal approach, the generalized telegraphists' equations which are integro (over the wave number spectra) differential (with respect to the space variable) equations, are converted into a matrix differential equation for the scattered wave amplitudes by discretizing the wave number spectra. Analytical solutions for the modified scattered wave amplitudes are derived from these matrix differential equations. These solutions account for multiple scattering in a unified self-consistent manner. However, numerical evaluations
Work on the evaluation of the scatter cross sections for rough surfaces with non-Gaussian surface height statistics is nearing completion. The complete $4 \times 4$ Mueller (Phase) matrix elements that characterize E-M scattering from rough surfaces can be computed. These computations can be used in conjunction with recent polimetric techniques for image enhancement and detection purposes.
PROGRESS REPORT #5
TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 25130-GS

2. PERIOD COVERED BY REPORT: 1 July 1989 - 31 December 1989

3. TITLE OF PROPOSAL: Scattering and Depolarization by Rough Terrain and Sea - A Unified Full Wave Approach

4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: Ezekiel Bahar

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator
Graduate Research Assistants

Ezekiel Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NB 68508
(7.1b) Papers Accepted/Submitted for Presentation at Technical Meetings


(iv) IEEE AP-S International Symposium and URSI Radio Science Meeting, May 7-11, 1990, Dallas, Texas, "Full Wave Multiple Scattering From Rough Surfaces", with M. El-Shenawee.


(vi) International Union of Radio Science Symposium on Scattering From Random Media (Joint Session B/F), Prague, Czechoslovakia, August 28 - September 5, 1990, "Like and Cross Polarized Backscatter Enhancement and Antispecular Transmission from Finitely Conducting Two Dimensionally Rough Surfaces".

(7.2) Papers Submitted to Journal Editors for Review

(i) Conditions for the Coalescence of the Full Wave Solutions for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions, submitted for review.

(ii) Unified and Two Scale Full Wave Solutions to Interpret Apollo Lunar Surface Data with M. Haugland, submitted for review.


(v) "Electromagnetic Scattering and Depolarization Across Rough Surfaces - Full Wave Solutions" with G. Huang, submitted for review.


(ix) "Full Wave Multiple Scattering From Rough Surfaces" with M. El-Shenawee, submitted for review.

(7.3) Papers Accepted for Publication


(7.4) Papers Published in the Technical Literature and Submitted with This Report


(7.5) M.S. Thesis Completed During this Reporting Period

(i) "Scattering and Depolarization of Electromagnetic Waves from Random Rough Surfaces with Non-Gaussian Statistics - Full Wave Solution by Yan-Feng Li."
Brief Outline of Research Findings

During the reporting period (1 June 1989 - 31 December 1989), the principal investigator presented eight papers at Scientific/Technical meetings (see Item # (7.1a)) and six papers have been accepted/submitted for presentation at International Conferences during the next few months (see Item # (7.1b)). Nine papers were submitted to journal editors for review (see Item # (7.2)) and three were accepted for publication (see Item # (7.3)). Six papers were published in journals and conference proceedings (see Item # (7.4)) and reprints of these papers have been submitted with this report. The M.S. thesis of Yan-Feng Li was accepted (see Item # (7.5) copy enclosed).

On July 28, 1989, the principal investigator attended an ARO/RADC sponsored workshop on "Enhanced Backscatter from Random Rough Surfaces" at Boston University, Boston, Massachusetts. The workshop was organized by the ARO contract monitor, Dr. Walter (Bud) Flood. At the workshop, an oral progress report was presented. Emphasis was given to the full-wave multiple scatter results during the principal investigator's presentation (see Item # (7.1b)(iv)). A preprint of this work was also submitted to the project monitor. In this work, the effects of varying the following parameters are investigated: angle of incidence, mean square slope, mean square height, correlation length, polarization and the complex permittivity of the scattering medium. It is shown that interference between different multiply
scattered fields can be responsible for the rapid fluctuation of the backscattered intensity (with view angle) for normal incidence. However, for oblique incidence \( (0 > 20) \) the multiple scattered intensity is smaller than the single scattered intensity. Thus the enhanced backscatter observed at oblique incidence is primarily due to the single scatter contributions. For these cases, there are no fluctuations of the backscattered field intensity (with view angle). The computation of the full-wave single and multiple scattered fields were carried out on the NSF supported super computer facility at Cornell University.

The evaluation of the scattering cross section for rough surfaces with non-Gaussian characteristics has been completed. Both real and synthetic aperture radars are considered. Methods to distinguish between surfaces with different statistical characterizations are also evaluated (see Item # (7.2)(vi) and (vii) and Thesis Item (7.5)).

Full wave analytical expressions have been derived for the scattering and depolarization of electromagnetic waves across a rough interface. Preliminary work has shown that as the surface roughness increases (large mean square slopes and small correlation lengths) the transmitted wave contains a strong non-specular component akin to the enhanced backscatterd intensity from very rough conducting surfaces.
PROGRESS REPORT #6
TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 25130-GS

2. PERIOD COVERED BY REPORT: 1 January 1990 - 30 June 1990

3. TITLE OF PROPOSAL: Scattering and Depolarization by Rough Terrain and Sea-A Unified Full Wave Approach

4. CONTRACT OR GRANT NUMBER: DAAL03-87-K-0085

5. NAME OF INSTITUTION: University of Nebraska

6. AUTHORS OF REPORT: Ezekiel Bahar

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

See Attached List

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar
Graduate Research Assistants

Ezekiel Bahar
Department of Electrical Engineering
University of Nebraska
Lincoln, NE 68588-0511
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1a) Papers Presented at Technical Meetings


(ii) First Los Alamos Symposium on Ultra-Wideband Radar, Los Alamos National Laboratory, Mar. 5-8, 1990, "Rough Surface Scattering Cross Sections for Ultra-Wideband Radars."

(iii) IEEE AP-S International Symposium and URSI Radio Science Meeting, May 7-11, 1990, Dallas, Texas, "Full Wave Multiple Scattering from Rough Surfaces with M. El-Shenawee.


(7.1b) Papers Accepted for Presentation at Technical Meetings


(7.2) Papers Submitted to Journal Editors for Review


(7.3) Papers Accepted for Publication

(i) "Full Wave Solutions for the Scattering of Acoustic Waves Excited by Arbitrary Source Distributions in Irregular Layered Media," Wave Motion, in press.


(7.4) Papers Published in the Technical Literature and Submitted with This Report


(7.5) M.S. Thesis Completed During This Reporting Period

(i) "Transmission Scattering and Depolarization of Electromagnetic Waves Across Rough Interfaces, Full Wave Approach," by Guorong Huang.
Brief Outline of Research Findings

During the reporting period (1 January 1990 - 30 June 1990), the principal investigator presented six (6) papers at Scientific/Technical Meetings (see Item #(7.1a)) and five (5) papers have been accepted/submitted for presentation at International Conferences during the next few months (see Item #(7.1b)). Three (3) papers were submitted to Journal Editors for Review (see Item #(7.2)) and two (2) were accepted for publication (see Item #(7.3)). Six (6) papers were published in journals and conference proceedings (see Item #(7.4)) and reprints of these papers have been submitted with this report. The M.S. Thesis of Guorong Huang was accepted (see Item #(7.5), copy enclosed).

At the URSI Meeting in Boulder (7.1a)(i)), the full wave solutions were presented for the scattered and depolarized waves that propagate across rough interfaces between two media. For surfaces with large mean square slopes and small correlation lengths, the transmitted fields exhibit a very strong non-specular component that is physically analogous to the enhanced backscattered intensity observed from very rough surfaces. This work was also presented as an M.S. Thesis by Guorong Haung in May 1990 ((7.5)(i), copy enclosed). The paper presented at the Los Alamos Symposium on Ultra Wideband Radar (7.1a)(ii) exploits the fact that the full wave approach can be applied to composite rough surfaces without resorting to an artificial decomposition of the surface into surfaces with small and large roughness scales. At the IEEE AP-S/URSI Meeting ((7.1a)(iii)), the singly and multiply scattered fields from one dimensional surfaces with very large slopes were presented. It is shown that the multiply (two bounce) scattered fields were primarily forward (near specularly) directed while the singly scattered fields are primarily backscattered. Thus for normal incidence the backscattered fields consist of several interfering field components.
This work is published in the Proceedings of the Symposium ((7.3)(ii), (7.4)(v)). Work is presently being conducted to extend these results to two dimensionally rough surfaces. At the URSI Commission F Meeting ((7.1a),(iv)), the results of our investigations of the radar cross sections for sea surface coated by oil slicks were presented. At the IGARSS Meeting ((7.1a),(v)), it was shown how the predictions based on the tilt modulation of the backscattered radar cross sections can be used to determine the statistical characterization of Random Rough Surfaces. This work is also published in the Conference Proceedings ((7.2),(iii)). The paper presented at the CRDEC Conference ((7.1a),(vi)), deals with multiple scattering from coated rough surfaces.

It is shown in a recent paper submitted for publication ((7.2),(ii)), that the fields scattered by slightly rough surfaces cannot be characterized solely on the basis of the mean square heights and slopes of the surfaces. When the small heights and slopes are bounded, the full wave solutions are in agreement with Rice's first order small perturbation solution. However, if the heights and slopes are characterized by an unbounded joint (four dimensional) Gaussian probability density function, specular point scattering dominates the solution (in agreement with Beckmann's results), except near grazing angles where the full wave solutions are shown to vanish. It is also shown how Rice's first order perturbation solution can be related to the full wave single scatter solution through a phase modification and a coordinate transformation.

The topics of the six papers that were published during this reporting period ((7.4), reprints enclosed), were discussed in earlier reports.
9. ILLUSTRATIONS
Fig. (9.1) Bistatic cross sections $\langle \sigma_V \rangle + \langle \sigma_{HV} \rangle$ for a vertically polarized wave incident at $\theta_i = 20^\circ$. 

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Fig. (9.2) Bistatic cross sections $\sigma^{HH} + \sigma^{VH}$ for a horizontally polarized wave incident at $\theta_0 = 50^\circ$. 