REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

...on is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, ...leting and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this ...ducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson ...and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

2. REPORT DATE
August 13, 1993

3. REPORT TYPE AND DATES COVERED
FINAL: May 1990-June 1993

4. TITLE AND SUBTITLE
Comparative Evaluation of Kirchhoff, Perturbation, and Full Wave Methods for Rough Surface Scattering

5. FUNDING NUMBERS
No. DAAL03-90-G-0122

2

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 27911.4-GS

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. ABSTRACT *(Maximum 200 words)*

This report summarizes the principal results in three areas of investigation. The first is a new full wave method that takes two dimensional surface roughness into account and does not use the telegraphist's equations. The second study concerns scattering from a rough surface when the incident field is a gaussian beam. The third is a summary of the difficulties inherent in Bahar's extended full wave theory on which the prediction of enhanced backscatter was based. It was found that enhanced backscatter occurred only because of the invalid assumption that the heights and slopes were uncorrelated.

14. SUBJECT TERMS
Electromagnetic scattering, rough surfaces, full wave method, gaussian beam, Kirchhoff theory, cross sections.

15. NUMBER OF PAGES
15

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

COMPARATIVE EVALUATION OF KIRCHHOFF, PERTURBATION AND FULL-WAVE SOLUTIONS FOR ROUGH SURFACE SCATTERING

FINAL REPORT

R.E. COLLIN

AUGUST 13, 1993

U.S. ARMY RESEARCH OFFICE

CONTRACT NO. DAAL03-90-G-0122

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FOREWORD

Bahar's full wave theory for rough surface scattering has been the subject of considerable controversy over a period of many years. The controversy was fueled by the claim that the theory would correctly predict the observed enhanced backscatter phenomena even though it was essentially a single scatter theory.

There were difficulties in understanding the theory because the underlying assumptions were not always clearly stated and some of the approximations used were not mathematically based but seemed instead to rely on physical arguments, again not always stated.

The original development which led to what we refer to as the regular full wave theory was based on a mathematically sound local spectral expansion method. In 1980 Bahar modified the theory by replacing the angles of incidence and scatter by the angles relative to the local normal to the surface. We refer to this theory as the extended full wave theory. The work of Bahar and his colleagues in the period 1980 to 1991 is based on this extended theory. This version of the theory is the one that led to a great deal of controversy and is also the one that we investigated in detail. We found that there were a number of difficulties associated with this theory. These difficulties and the consequences are summarized in this final report.

One of the non-physical artifacts that occurred in the extended full wave theory was the existence of a pole in the scattering coefficient for vertical polarized incident waves. This pole made the theory unusable for scattering of vertically polarized waves from a perfectly conducting rough surface. Bahar has now made further modifications to his theory, the principal one having the effect of removing the pole singularity. There appears to be no mathematical basis for the latest modifications but the changes do eliminate some of the difficulties associated with the extended full wave theory. Bahar has also now included second order scattering into his theory. The ultimate utility and accuracy of the theory with the most recent modifications is still an open question since only a limited number of results have been obtained so far.

Our investigation did not examine these recent changes in the theory. Our investigation focused on the version of the extended full wave theory that was used by Bahar and his colleagues over the period 1980 to 1991 and on which the prediction of enhanced backscattering was based.

TABLE OF CONTENTS

Comparative Evaluation of Kirchhoff, Perturbation, and Full-Wave Solutions for Rough Surface Scattering.

1. Research Objectives

The objective of the research in this project was to carry out a detailed examination of Bahar's extended full wave theory and the various approximations used in implementing the theory, for the purpose of elucidating the mechanism responsible for the enhanced backscattering that was predicted. A further objective was to provide a comparison of the scattering cross sections predicted using the extended full wave theory with those predicted by the small perturbation theory and the Kirchhoff theory.

The results of this study are embodied in three papers, one which has already been published and two papers which have been accepted for publication. Thus in this final report we only provide a summary of the three papers since the full details will appear in the open literature in the near future.

2. Summary of Results

2a. Paper No. 1: R.E. Collin, Electromagnetic Scattering from Perfectly Conducting Rough Surfaces (A New Full Wave Method), IEEE Trans., Antennas and Propagat., vol. AP-40, pp. 1466-1477, Dec. 1992.

Over a period of many years Bahar has developed an approximate theory called the full wave theory for scattering from rough surfaces [1]-[5]. The basic formulation is applied to an infinite surface that is rough along one direction only. Bahar's method consists of constructing local flat surface vector basis functions that are used to provide a local expansion of the y and z components of the field. Maxwell's equations are recast in the form of telegraphist's equations that describe the propagation of waves along the preferred x direction. The field expansions involve amplitude coefficients that are unknown functions of x. After expanding the unknown fields in terms of the local vector basis functions, a set of coupled one-dimensional differential equations is obtained for the spectral components of the field amplitudes. These equations are solved by assuming that in the absence of mode coupling, the field consists of an incident plane wave and the related specular reflected field.

The telegraphist's equations are applicable only to surfaces that are rough along one direction. For such surfaces, Bahar and Rajan have derived scattering coefficients for the co- and cross-polarized field when the incident field is a vertical or a horizontal polarized plane wave [6]. These scattering coefficients are restricted by the condition that the z component of the propagation vector for the scattered field must match the z component of the propagation vector of the incident field since the surface profile is invariant along the z direction. Explicit dependence on the slope is eliminated by an integration by parts.

In a later 1981 paper, Bahar assumes that the scattering coefficients derived for a surface with one-dimensional roughness can be applied to surfaces with two-dimensional roughness by leaving the inverse Fourier transform with respect to z uncompleted and replacing $\zeta(x)$ by $\zeta(x,z)$ in the phase term [7]. No mathematical justification for this procedure has been provided. The objective of the present investigation was to determine if a derivation of Bahar's scattering coefficients could be carried out that does not have the restrictions inherent in the use of telegraphist's equations. Our approach is based on the simple concept of reducing the three-dimensional scattering problem to a two-dimensional one by expanding Maxwell's equations in terms of local y-dependent eigen-functions so as to eliminate the dependence on y. This direct approach takes the two-dimensional surface roughness into account from the beginning. It leads to a set of transformed Maxwell equations with coupling integrals that can be interpreted as equivalent sources. The transformed field equations are functions of x and z only, and do not involve any boundary conditions except for a radiation condition. By approximating the fields in the coupling integrals by those of the incident and specular reflected plane waves, the transformed field equations are readily solved using Fourier transforms. By this means, we are able to verify the correctness of Bahar's scattering coefficients in a more rigorous way. This new full wave method provides greater physical insight into the scattering problem, and may suggest new ways to improve the accuracy of the end results.

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[7] E. Bahar, "Full wave solutions for the depolarization of the scattered radiation fields by rough surfaces of arbitrary slope," IEEE Trans. Antennas Propagat., vol. AP-29, pp. 443-454, 1981.

2b. Paper No. 2: R.E. Collin, Scattering of an Incident Gaussian Beam by a Perfectly Conducting Rough Surface, Accepted for publication in IEEE Trans., Antennas and Propagat.

In scattering experiments the incident field is a beam wave produced by a radar antenna or a lens collimated laser beam. In the numerical solution of the integral equations that govern scattering from rough surfaces it is a common practice to assume that the incident field is a gaussian beam in order to limit the area of the rough surface that is illuminated [1,2]. On the other hand, in theoretical analysis of rough surface scattering it is often assumed that the incident field is a plane wave, because of the simplification in the analysis that is obtained. The purpose of this paper is to determine the modifications required in the full wave theory for rough surface scattering when the incident field is a gaussian beam instead of a plane wave.

The full wave theory for rough surface scattering was developed by Bahar over a period of many years [3,4]. The original theory, which we will refer to as the regular full wave theory, has recently been reformulated in a simpler form for the case of scattering from perfectly conducting rough surfaces [5]. It is the modification in this regular full wave theory when the incident field is a gaussian beam that we address in this paper.

For the regular full wave theory we show that when the incident field is a gaussian beam the essential modifications in the theory that are required are a multiplication of the surface illumination function by a gaussian illumination function and a change in the normalization factor that defines the normalized scattering cross section of the surface. For conditions that normally occur in practice it is shown that the same scattering cross section as occurs for an incident plane wave is obtained.

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2c. Paper No. 3: R.E. *Collin, Full* Wave *Theories for* Rough Surface Scattering - What Works and What Doesn't Work, accepted for publication in Radio Science.

The original full wave theory, which we refer to as the regular full wave theory, was developed by Bahar in the period prior to 1980 [Bahar and Rajan, 1979]. This theory provides an improvement on the first order small perturbation theory for rough surface scattering [Collin, 1992]. The regular full wave theory is valid for surfaces with small slopes. In order to remove the small slope limitation Bahar expressed the scattering coefficients in the regular full wave theory in terms of the angles of incidence and scatter with respect to the local normal. The incident and scattered fields were also expressed as vertical and horizontal polarized fields relative to the local tangent plane. We will refer to this full wave theory as the extended full wave theory [Bahar, 1980; Bahar, 1981]. The mode coupling in the full wave theory depends on the slope of the surface. The explicit dependence on the slopes was eliminated by an integration by parts. In the early work by Bahar the integrated term was discarded as a negligible edge term [Bahar, 1972; Bahar and

Rajan, 1979]. Later on this term was retained and referred to as the diffraction field [Bajhar, 1991].

Bahar and Fitzwater used this theory to calculate the radar scattering cross sections for a rough surface with ϵ_r=-56.6-j21.3, a RMS height of 2.37λ_0, a RMS slope of 1.18, and a correlation length of 2.84λ_0 [Bahar and Fitzwater, 1989]. In this work it was assumed that the slopes and heights were governed by gaussian statistics but could be considered as uncorrelated. It was also assumed that the slopes could be considered to be perfectly correlated. With these assumptions it was found that the scattering cross sections were around 20 times larger than those predicted using the physical optics approximation. It was also found that the scattering cross sections had large peak values in the back scatter directions. Bahar and Fitzwater interpreted these results as showing that their full wave theory was capable of explaining the observed enhanced backscattering phenomena [Mendez and O'Donnell and Mendez, 1987].

In this paper we show that the large scattering cross sections obtained by Bahar and Fitzwater arise from the assumption that the heights and slopes are uncorrelated. When the statistical averaging is done without making any a priori assumptions the scattering cross sections obtained from the extended full wave theory can be expected to be similar to those obtained from the Kirchhoff theory and do not show any enhanced backscatter effects. In this paper we show that the field correlation function in the extended full wave theory is a highly oscillatory function and is dramatically different from the monotonically decreasing field correlation function that occurs in the Kirchhoff theory. When the slopes and heights are assumed to be uncorrelated the resultant approximation for the field correlation function gives incorrect results for the bistatic scattering cross sections. Thus in the extended full wave theory it is essential that the height-slope correlation be taken into account.

In some recent work it has been shown that for horizontal polarization the extended full wave theory does not reduce to first order small perturbation theory in the limit of small height and slope fluctuations (Thorsos and Ishimaru, 1988; Thorsos, 1989; Thorsos and Winebrenner, 1991]. In order to overcome this problem Bahar introduced the integrated term back in the integral for the scattered field before transforming to the local coordinate system [Bahar, 1991]. In this paper we show that when this version of the extended full wave theory is applied to a surface with large height and slope fluctuations, for a vertical polarized incident wave, the added term produces an addition to the scattering cross section that can be more than an order of magnitude larger than the Kirchhoff cross section. We explain why this occurs and also why this added term produces two minor lobe peaks that superficially look like enhanced backscatter effects. On the basis of a detailed study of special cases we show that retaining the integrated term produces scattering cross sections that are much too large. When the integrated term is not retained we show that the extended full wave theory for vertically polarized incident waves also does not reduce to small perturbation theory in the small height-small slope limit.

For horizontally polarized incident waves the added term is often very small but it will produce an unnatural enhancement in the specular direction for surfaces with large RMS slopes.

For the case of vertical polarization the scattering coefficient, when referred to the local coordinate system, has a pole in the backscattering direction for a perfectly conducting surface. Thus the theory cannot be used for a perfectly conducting surface. For a lossy surface the pole is suppressed but for a highly conducting surface it will produce a very large spike in the backscatter cross section at large backscattering angles. This is a non-physical artifact that is present in the theory. There are also anomalous non-physical effects associated with the shadow function in the theory. These artifacts are also discussed in the paper.

Conclusions

By means of detailed numerical evaluations for a broad range of conditions we have been able to show that there are a number of artifacts associated with the extended full wave theory, particularly for vertical polarization, that makes the theory unreliable and of questionable value. For those situations when the theory appears to give valid results the computed cross sections are almost the same as those predicted by the Kirchhoff theory. In view of the much more demanding computations it is concluded that the extended full wave theory is less useful than the Kirchhoff theory. We believe that a sufficiently large enough number of examples were examined to be able to state the following conclusions.

1. The assumption that the heights and slopes are uncorrelated is not valid. This assumption gives excessively large cross sections for vertical polarization, that violate conservation of of power.

2. For a perfectly conducting surface the scattering coefficient for vertical polarization has a non-physical pole. The pole is eliminated by assuming that the surface has a large but finite conductivity. However, for a highly conducting surface the backscatter cross section will have a large spike for large scattering angles in the backwards direction unless the RMS slope is very small. The backscatter section is very sensitive to the dielectric constant of the surface because of this pole.

3. When no approximations are made in the statistical analysis the extended full wave theory does not show any enhanced backscatter effects apart from the artifact associated with the pole for highly conducting surfaces.

4. For small heights and slopes the extended full wave theory does not reduce to first order perturbation results. For vertical polarization it also predicts large peaks in the cross sections at grazing angles because of the shadow function that is part of the theory.

5. By including the term that arises from integration by parts before transforming to the local coordinate system a version of the full wave theory that will reduce to small perturbation theory is obtained. However, this version of the extended full wave theory predicts excessively large scattering cross sections for surfaces with large roughness and is therefore not a viable version. There is no criteria available to specify when the integrated term should be retained.

6. No evidence was found that suggests that the extended full wave theory, with or without the integrated term retained, gives results that are more accurate than those given by the regular full wave theory or the Kirchhoff theory.

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3. List of Personnel

The principal investigator on this project was Professor R.E. Collin. Assistance was provided by Mr. Chungjen Hsu, a graduate student pursuing studies for the Ph.D degree.

4. Inventions

No inventions were made during this project investigation.