ELECTROMAGNETIC SCATTERING

A Remote Sensing Perspective

Yang DU

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Remote sensing is a fast-growing field with many important applications as demonstrated in the numerous scientific missions of the Earth Observation System (EOS) worldwide. Given the inter-disciplinary nature of remote sensing technologies, the fulfillment of these scientific goals calls for, among other things, a fundamental understanding of the complex interaction between electromagnetic waves and the targets of interest.

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Using a systematic treatment, Electromagnetic Scattering: A Remote Sensing Perspective presents some of the recently advanced methods in electromagnetic scattering, as well as updates on the current progress on several important aspects of such an interaction. The book covers topics including scattering from random rough surfaces of both terranean and oceanic natures, scattering from typical man-made targets or important canonical constituents of natural scenes, such as a dielectric finite cylinder or dielectric thin disk, the characterization of a natural scene as a whole represented as a random medium, and the extraction of target features with a polarimetric radar.

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PREFACE

Remote sensing has been increasingly playing an indispensable role in the monitoring and exploration of the earth system, and in the enabling and maintaining of the welfare and prosperity of the society at large. In the development of remote sensing theories and technologies, one of the cornerstones is to have a good understanding of the interaction between the electromagnetic wave and the complex terrain, ocean surfaces, man-made targets, and the like.

Tremendous efforts have been put into the development of analytical models and numerical approaches of electromagnetic scattering from the earlier mentioned complexes, and significant relevant knowledge has been accumulated, as reflected by the numerous excellent technical books, journal papers, and conference proceedings on this aspect. Yet one feels that we are only midway in our quest to reach to the ultimate goal of establishing a unified scattering model that at least works well in the microwave region for a specific target. Take for example, the current scattering models for rough surfaces, or for the even simpler mundane target of a thin dielectric disk. Adding to our current indecisiveness is the complex nature of terrain and man-made targets, the interaction of the mesoscopic scale and the microscopic scale as the dimensions of the objects and mean free path of the random medium measured against the sensing wavelength at microwave range, and the very random nature of the observed scenes.

This book is the product of a wish to provide some updates on the current progress toward the ultimate goal. The topics covered are far from comprehensive, yet we believe they possess sufficient degree of diversity to be of interest to a large readership. We hope that the reader may find the material contained in the book illuminating.

The importance of understanding the scattering of electromagnetic wave from rough surfaces has been well recognized. Either the accurate retrieval of geophysical parameters of interest, such as soil moisture and sea surface salinity, undertaken by current scientific missions such as Soil Moisture Active Passive (SMAP) and Soil Moisture and Ocean Salinity (SMOS), or the detection of target above or beneath the surface requires such knowledge to ensure a reasonably good performance. There have been long-standing efforts in pursuing a unified model capable of bridging the conventional analytical models of Kirchhoff approximation (KA) at the one end and the small perturbation method (SPM) at the other end. Such efforts have been reflected and recorded in many excellent reference books and thus will not be repeated here. The integral equation method (IEM) has become one of the most popular analytical models in electromagnetic scattering from terrain because of its ability to provide good predictions for forward and backward scattering coefficients. Refinements to IEM have led to the more advanced models, such as the improved IEM (I-IEM), the advanced IEM (AIEM), the IEM for the second-order multiple, scattering (IEM2M), and the extended AIEM (EAIEM) models. Professor K. S. Chen is one of the three inventors of the original IEM model and the key figure behind the AIEM model whose insights on the ins and outs of IEM and its variants are tremendously impressive. In Chapter I, he describes new refinement to the IEM and AIEM models to improve the accuracy as well as to extend the applicability of the models.

Radar returns from and Doppler spectra of time-evolving sea surface at microwave frequencies with a target has always been an attractive topic. Yet the analysis is a challenging one. Even in the absence of the target, for one thing, each of the available analytical models (KA, SPM, target setting model [TSM], small slope approximation [SSA], weighted curvature approximation [WCA], IEM, etc.) demonstrates a difficulty in covering a reasonably large range of sea states, looking angles, or sensing frequencies. Due to the multiscale nature of the ocean surface, any attempt of a numerical analysis to fully describe the contributions due to the gravity wave (large-scale wave and intermediate-scale wave) as well as the interaction among waves of different scales calls for a very small cut-off wave number, which translates to very large illuminated area. Challenges for any such attempt include a rapid increase in memory requirement and the difficulty in designing a computationally efficient algorithm, which in the framework of method of moment (MoM) refers to the difficult in approximating the Green's function in the impedance matrix, a difficulty stemming from the much increased roughness associated with the inclusion of intermediate wave and even certain part of gravity waves. In Chapter II, Professor M. Zhang and his colleagues show how they circumvent the obstacles by working with a facet-based asymptotical model, which has demonstrated higher accuracy and computing efficiency. With the added complexity of the presence of a target on the ocean surface, the motion of ship is represented with six degrees of freedom and the multiple scattering between the object and the sea surface is accounted for by the specular reflection weighted four-path model. Good tractability of the total simulation scheme for the dynamic composite ship-ocean scene is numerically demonstrated.

The problems of multiple dielectric objects above conducting rough surfaces, dielectric objects beneath and above dielectric rough surfaces for two-dimensional scattering, as well as dielectric objects above conducting rough surfaces for three-dimensional scattering have been discussed in detail by Professor L. Guo and his colleague in Chapter III. In their approach, the appealing features of the finite element method (FEM) capable of handling inhomogeneous materials and of the boundary integral method (BIM) leading to reduced unknowns and solving time are combined to extend the conventional applicability of BIM and to alleviate the strict requirement of FEM on the disposition of the approximate absorbing boundaries. They illustrate the efficiency of their approach with several numerical examples.

In Chapter IV, Professor M. S. Tong considers electromagnetic scattering by penetrable objects, which is an important topic since such objects appear in many remote sensing applications. Since the treatment of inhomogeneous penetratable objects is more involved than the homogeneous ones, in developing the volume integral equation solvers, he describes why the choice of the IEM is preferable to that of finite difference time domain (FDTD) and FEM, and then introduces two primary numerical methods for the solution. Several numerical results are presented to demonstrate the effectiveness of the fast algorithms.

In Chapter V, Professor J. Hu and his colleagues choose to analyze the scattering from multiple bodies of revolution (BoRs). A theoretical evaluation of the electromagnetic scattering from a BoR has attracted considerable attention over more than half a century due to its significance in radar techniques. Here a numerical analysis is presented, starting from the analysis of a single BoR, where by symmetry the IEM can be reduced to a 2.5-dimensional problem, thus the associated unknowns can be greatly reduced. The authors then move to the more challenging analysis of multiple BoRs, where they describe two fast solvers for such task. Numerical results are presented to demonstrate the effectiveness of the fast algorithms.

The vegetation constituents are represented by simple geometries. For instance, tree trunks, branches, and crop stalks and stems, branches are modeled as dielectric circular cylinders of finite length, whereas leaves are represented by circular or elliptical thin dielectric disks. Therefore, the accurate modeling of the scattering behavior of these canonical geometries is of utmost importance. In Chapter VI, Professor I.-S. Koh describes two approaches according to the electric size of these geometries. In dealing, with dielectric circular cylinders of finite length, he describes at low frequency, how certain modification can be made to the Rayleigh–Gans (RG) approximation so as to extend its validity region; at intermediate frequency, the eigen-series formalism can be applied so long as the assumption about the surface currents approximated by the infinite cylinder remains valid; and at high frequency, the physical optics (PO) approximation is a good candidate, though its accuracy can be improved by combining it with the uniform theory of diffraction (UTD). He further treats dielectric disks along the same line by considering the case of low, intermediate, and high frequency separately. The treatment is validated by the good agreement between theory and MoM simulations.

With the recent renewed interest in modeling of electromagnetic scattering from dielectric circular cylinders of finite length, my group is more concerned about two aspects: one associated with phase, thanks to the current trend of emphasizing coherency in canopy scattering model as well as the widespread application of interferometric synthetic aperture radar (InSAR) technology, and the other associated with the fact that neither generalized Rayleigh–Gans approximation (GRGA) nor infinite cylinder approximation (ICA) is capable of fulfilling the reciprocity principle. So we look to a semi analytical method called the T-matrix approach, which is based on the extended boundary condition method (EBCM). This approach, when applicable, has been shown to possess sufficient accuracy and to comply with the reciprocity principle. Yet the drawback of the conventional T-matrix is the difficulty in dealing with extreme geometries, and dielectric cylinder with large aspect ratio surely falls into this category and its treatment using the conventional T-matrix is out of the question. In Chapter VII, we describe how to extend the conventional T-matrix approach to handle the scattering of dielectric cylinder with arbitrary length. With its capability to cover the validity region of RG as well as that of ICA, this new method is undoubtedly a unifying model to treat scattering from dielectric cylinders.

When electromagnetic wave propagates in a dense inhomogeneous media, the mean free path (mean distance) between discrete scatterers embedded in the medium is smaller than the wavelength. On length scales of the mean free path, the so-called mesoscopic scale, the radiation transport is better described by the radiative transfer equation (RTE). However, when relating the parameters of the RTE to that of microscopic scale where the appropriate wave equation is the Maxwell's equation, different approaches can be considered. In Chapter VIII, Professor H. T. Ewe and his colleagues describe how they apply the dense medium phase and amplitude correction theory (DM-PACT) to account for coherent effects between scatterers, along with Fresnel field amplitude and phase corrections, to arrive at better phase matrices of the scatterers. They then present how this dense medium model is applied to the remote sensing of a number of important natural settings, such as sea ice, snow, and various vegetation canopies (boreal forests, rice fields, and oil palm plantations). The inversion of sea ice thickness is also provided and the effectiveness of the dense medium correction is demonstrated.

The vector nature of polarized electromagnetic waves contains important information about an object when the wave strikes it and is scattered. Polarimetric radar makes use of this fact and tries to extract target properties from the behaviors of the scattered wave. In Chapter IX, Professor J. Yang and his colleague provide a survey of feature extraction of a target, which is a key step in target detection and classification. In the process, one attempts to express the polarimetric synthetic aperture radar (SAR) data into a sum of independent elements to allow the interpretation of different physical scattering mechanisms of targets. The authors then move on to introduce the two main types of decomposition theorems.

I am grateful to all the contributors of this book for their time and devotion to the subject, their contributions to this book, and cooperation in the editing process. I would like to thank Dr. Don Mak, Commissioning Editor, for inviting me to serve as editor for this book. It has been an endeavor I have both learnt much from and enjoyed. I also appreciate the helpful suggestions and assistance of Ms. Amanda Yun, Senior Editor, and the excellent work of Ms. Ramya Gangadharan, Project Manager.

CONTENTS

CHAPTER 1

MODELING OF BISTATIC SCATTERING FROM ROUGH SURFACES — AN ADVANCED INTEGRAL EQUATION MODEL

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Abstract

This chapter deals with the modeling of bistatic scattering from a randomly rough surface. In particular, an advanced integral equation model (AIEM) is presented by giving its general framework of model developments, model expressions, and predictions of bistatic scattering under various surface conditions. Extension work to improve the model accuracy is also reported in more detail. Model performance is illustrated, demonstrated, and validated by extensive comparisons with numerical simulations and measurements. The updated AIEM remains a compact algebraic form for single scattering and substantially improves prediction accuracy in bistatic scattering that is attracting more applications in earth remote sensing.

Introduction

Electromagnetic waves scattering from a randomly rough surface is of palpable importance in various fields of disciplines and bears itself in various applications spanned from surface treatment to remote sensing of terrain and sea. For example, it has been a common practice to retrieve by analyzing the sensitivity of the scattering behavior and mechanisms, the geophysical parameters of interest from the scattering, and/or emission measurements. Another example is that by knowing the backscattering patterns, one may be able to detect the presence of the undesired random roughness of a reflective surface of an antenna reflector, and thus accordingly devise a means to correct or compensate the phase errors. Therefore, it has been both theoretically and practically motivated to study the electromagnetic wave scattering from the random surfaces. Research and progress, being a long historical track, of this topic has well been documented and still been keeping updates [1–6].

To tackle the complex and sometimes intricate mathematical derivations, and yet to remain a high level of accuracy beyond conventional models, notably, Kirchhoff and small perturbation method (SPM), the IEM has been developed by Fung *et al.* [3, 7, 8] under several physical-justified assumptions. Among the assumptions, one is to use a simplified Green's function by dropping off the phase term associated with the random surface height. By doing so, it might be of more profoundly critical among all assumptions but greatly alleviates the burden of mathematical derivations, and yet unavoidably degraded the model accuracy, to a certain extent, depending on the surface property and observation geometry. Nevertheless, the IEM proves to perform very well in backscattering and offers to seamlessly bridge the gap between the Kirchhoff and SPM models.

Driven by the need of predicting bistatic scattering and microwave emissivity, much efforts have been devoted to improve the IEM accuracy [9–19] further by removing some of the assumptions that imposed for the purpose of mathematical simplicity during the course of derivation. This has been done by rederiving the expressions, though requiring excessive and tedious manipulations. Another step leap forward was the introduction of a transition function into the Fresnel reflection coefficients to take spatial dependences into account, removing the restrictions on the limits of surface roughness and permittivity [3, 11]. Though the approach is of heuristic but

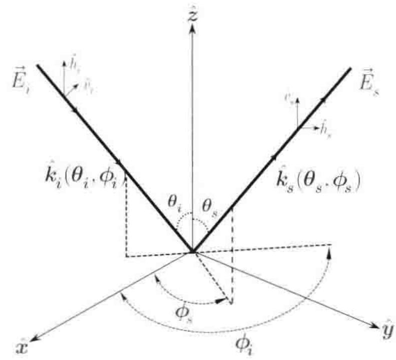

Figure 1: Wave scattering geometry.

self-consistent, it proves working perfectly for a broad range of surface dielectric and geometric parameters [6, 11, 14]. Finally, when the surface rms height is very large, an alternative form is also derived and explicitly given in Appendix B.

The Advanced Integral Equation Model

Formulation of the wave scattering from a rough surface

Referring to Fig. 1, suppose a plane wave impinges onto a dielectric rough surface that scatters waves up into the incident plane and down into the lower medium, then the electric and magnetic fields can be written as

$$\vec{E}^i = \hat{p} E_0 \exp[-j(\vec{k}_i \cdot \vec{r})] \tag{1}$$

$$\vec{H}^i = \frac{1}{\eta} \hat{k}_i \times \vec{E}^i \tag{2}$$

where $j = \sqrt{-1}$; $\hat{p}$ is the unit polarization vector; E_0 is the amplitude of the incident electric field; and η, η_t is the intrinsic impedance of the upper and lower media, respectively. The position vector and k-plane in incident and scattering directions are defined as follows:

$$\vec{r} = x\hat{x} + y\hat{y} + z\hat{z}$$
$$\vec{k}_i = k\hat{k}_i = \hat{x}k_{ix} + \hat{y}k_{iy} + \hat{z}k_{iz}; \quad k_{ix} = k\sin\theta_i\cos\phi_i,$$
$$k_{iy} = k\sin\theta_i\sin\phi_i, \quad k_{iz} = k\cos\theta_i$$