Development of Analytical Techniques for Wave Propagation Over Large Rough Surfaces

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LONG TERM GOALS

The long terms goals of the project are to develop analytical or efficient numerical schemes for determining the RF signal received over a rough ocean surface and in atmospheric ducting conditions.

OBJECTIVES

The objectives of the proposed work are to develop techniques for treating radiowave propagation over an electrically large rough surface. Both analytical and numerical techniques were looked at in this project.

APPROACH

One graduate Ph.D. student, Zhiguo Lai, was fully supported through the grant to help carry out the current research work. He is expected to complete his PhD by January 2007.

Significant advances have been made in understanding the basic phenomena by means of experimental investigations of electromagnetic scattering from the ocean surface [1, 2] and in controlled wave tank experiments [3, 4]. Meanwhile a large number of publications on the theoretical treatment of the general problem are available in literature [5, 6]. However the theory is still far from completely developed as almost all the existing scattering models are only valid for small roughness and most of them are expected to fail at low grazing incidence. Rigorous numerical methods have been widely used over the past several decades to overcome the limitations of analytical theories and to provide validation for approximate scattering models [7, 8]. For one-dimensional problems, available computational resources now allow non-grazing problems to be readily solved using any of a number of standard, well established approaches. The major remaining challenge in the development of numerical methods is the low grazing angle scattering problem. For example the standard method of moment has not proven well suited for applications at low grazing angles as surfaces of increasingly large size are required for simulations when the direction of incidence approaches horizontal. Larger surfaces mean, in turn, larger matrix sizes and higher computational and storage expenses. Furthermore surfaces of finite length are used in numerical simulations leading to nonphysical edges that can introduce strong diffraction in the scattered field.

In our current work, a formulation based on full wave integral equation was developed. Our primary goal is to study the statistical properties of the scattering amplitude and the scattered fields and develop a rough surface scattering model that is especially suitable for scattering from a very rough surface at

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low grazing angles. The rough surface is assumed to be periodic over lengths much larger than the correlation length to avoid artificial edge effects. An ensemble of periodic surfaces with appropriate statistical properties was considered to generate the statistical properties of the field. The period of the surface is chosen to be large enough so that there are many peaks and valleys of the height profile within one period and the results obtained from periodic surfaces are a good predictor for the infinite-surface case of coherent/incoherent power, etc. We intend to answer questions such as ‘whether the coherent reflection coefficient is adequate to describe the scattering phenomena’ and ‘whether the coherent component continues to dominate for large roughness and low grazing angles and at what point the diffuse component takes over’ as they have not been addressed in the literature definitively.

To start we consider two-dimensional problems with Dirichlet boundary conditions where a one-dimensional periodic rough surface is illuminated by a down-propagating plane wave and the total electric field on the rough surface vanishes. The starting point in our formulation is the Helmholtz formula leading to a surface integral equation for the induced surface current. The periodic boundary condition is then analytically incorporated resulting in a surface integral over only one single period instead of over an infinite domain. The integral equation is then discretized through the method of moments and solved using the generalized conjugate residue algorithm with the help of the fast multipole method [9]. Significant progress has already been made in the development of this formulation and some preliminary results have been obtained.

Usually it is convenient to express the received signal in terms of the propagation factor, defined as the ratio of the total field to the incident field due to the direct path:

$$F = \frac{E_{\text{tot}}}{E_{\text{inc}}} = \frac{E_{\text{inc}} + E_{\text{sca}}}{E_{\text{inc}}} = 1 + \frac{E_{\text{sca}}}{E_{\text{inc}}}.$$

The propagation factor is further separated into coherent and incoherent components. The coherent component is the power of average field and is expressed as $P_{\text{C}} = \left|\langle F \rangle\right|^2$. The incoherent component is the mean of the variance of F and is expressed as $P_{\text{I}} = \left\langle \left|F - \langle F \rangle\right|^2 \right\rangle$. In these definitions, $\langle \cdot \rangle$ denotes ensemble average over many realizations.

All numerical simulation results below were performed at a frequency of 3 GHz (wavelength $\lambda = 0.1$ m). The plane wave was incident at a grazing angle of 5.0 degrees. Electric field was computed on a vertical line. Rough surfaces were generated using a zero-mean Gaussian height statistics and Pierson-Moskowitz spectrum which is a function of the wind speed U at a height of 19.5 m. The step-size along x-direction is $\lambda/8$ and the overall surface length is 2000λ (16,000 unknowns). Ensemble averages were taken over 1000 realizations.

Figures 1 to 4 show the coherent/incoherent power for $U = 2, 5, 10, 15$ m/s, respectively. It is seen that the difference between the coherent and incoherent parts decreases as the surface becomes rougher. Figures 5 to 8 show the histograms of the propagation factor (real part, imaginary part and magnitude) superimposed by analytical Gaussian PDFs at a fixed height ($z = 5$ m) for $U = 2, 5, 10, 15$ m/s, respectively. The scattered field closely follows a complex Gaussian random process with independent real and imaginary parts. The correlation coefficients between the real part and imaginary part are 0.036, 0.063, 0.001, and 0.082, respectively.

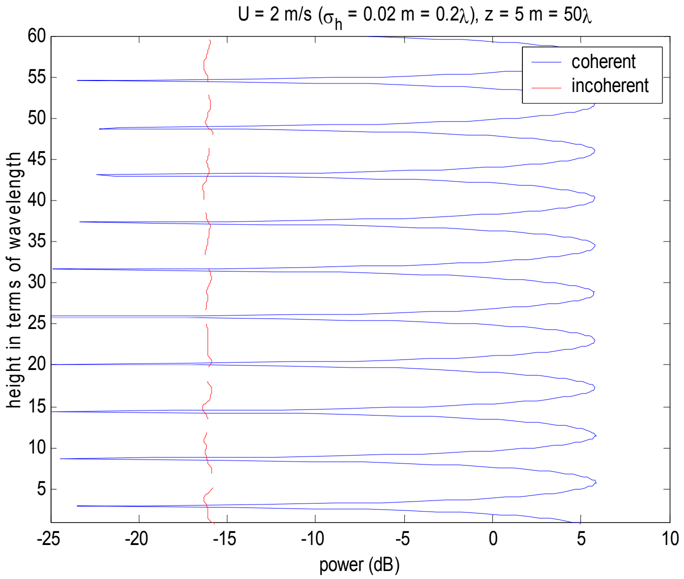

Figure 1. Coherent and incoherent power for U = 2 m/s.

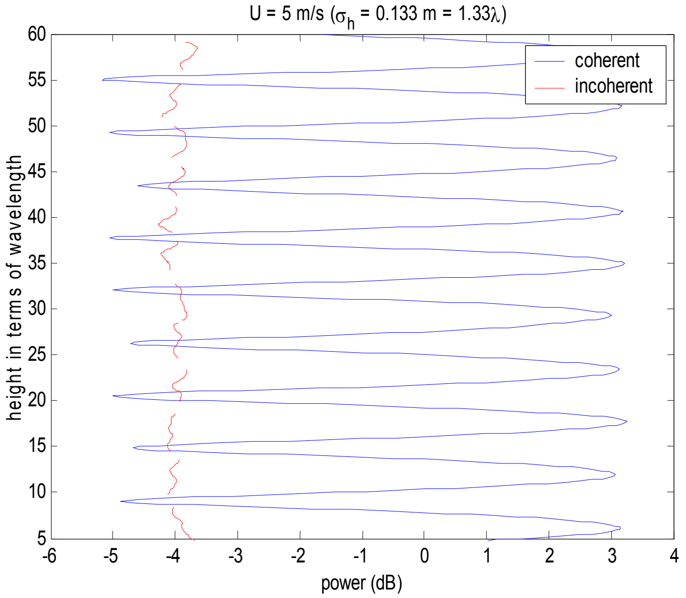

Figure 2. Coherent and incoherent power for U = 5 m/s.

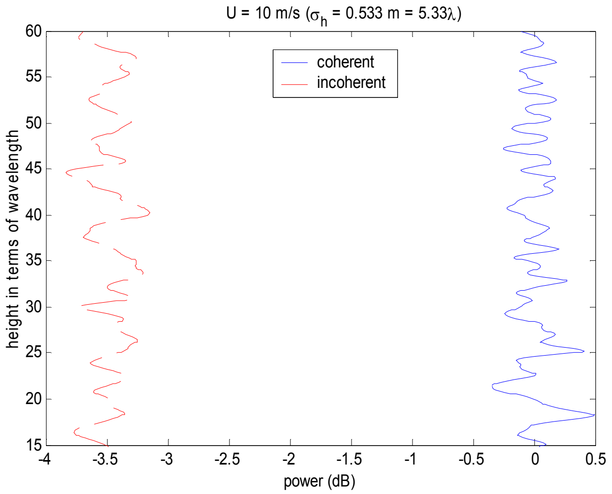

Figure 3. Coherent and incoherent power for U = 10 m/s.

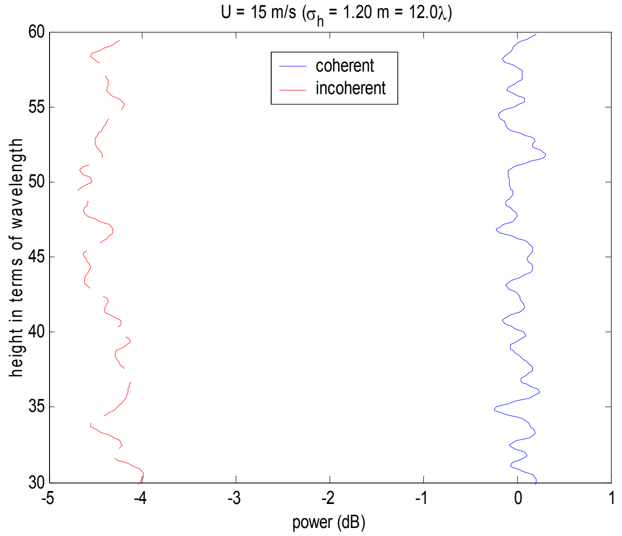

Figure 4. Coherent and incoherent power for U = 15 m/s.

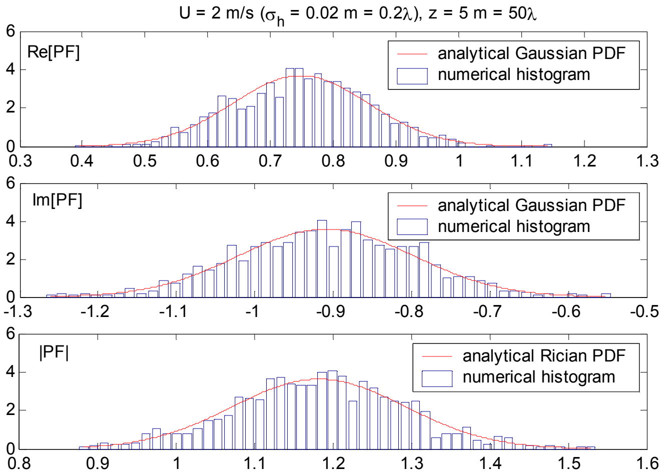

Figure 5. Histograms (PDFs) of the propagation factor at z = 5 m for U = 2 m/s.

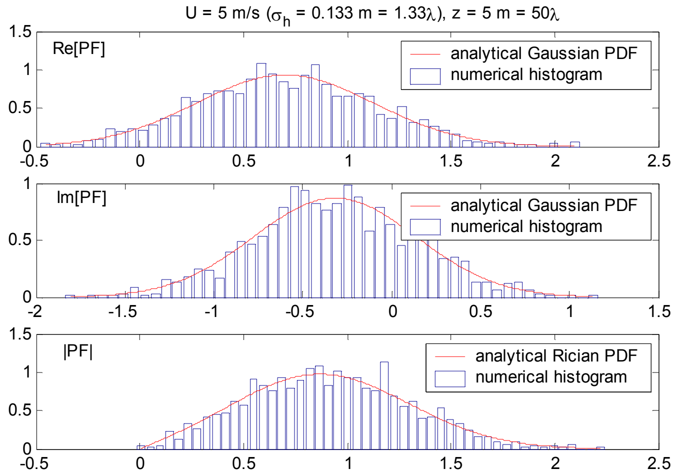

Figure 6. Histograms (PDFs) of the propagation factor at z = 5 m for U = 5 m/s.

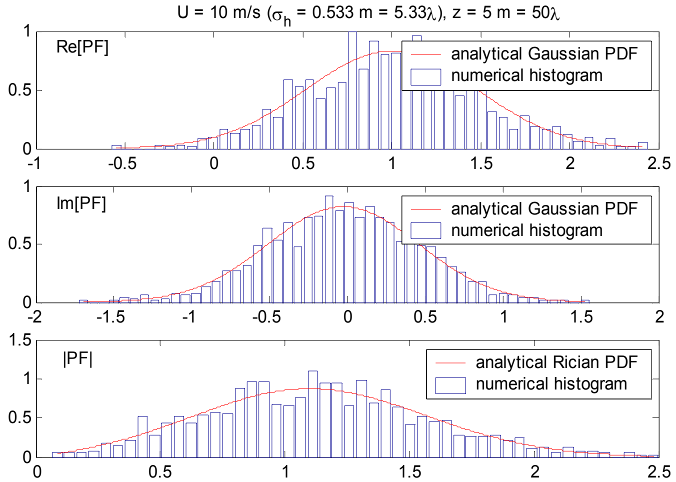

Figure 7. Histograms (PDFs) of the propagation factor at z = 5 m for U = 10 m/s.

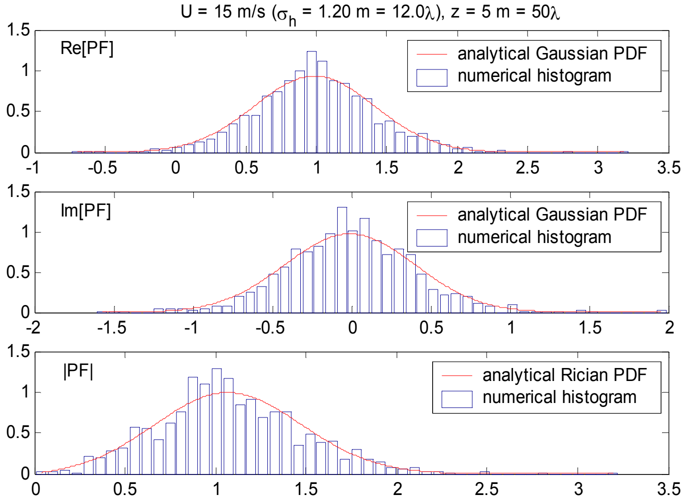

Figure 8. Histograms (PDFs) of the propagation factor at z = 5 m for U = 15 m/s.

IMPACT/APPLICATIONS

The results presented thus far and successful completion of the ongoing research should help the PE code developers in generating better operational codes for assessing the effects of ocean roughness on radar detectability and surveillance.

REFERENCES

[1] C. I. Beard, Coherent and Incoherent Scattering of Microwaves from the Ocean, *IRE Trans. Antennas Propgat*. **9**, 470-483, 1961.

[2] Y. Karasawa and T. Shiokawa, A Simple Prediction Method for L-Band Multipath-Fading in Rough Sea Conditions, *IEEE Trans. Commun*. **36**, 1098-1104, 1988.

[3] J. W. Wright, Backscattering from Capillary Waves with Application to Sea Clutter, *IEEE Trans. Antennas Propgat*. **14**, 749-754, 1966.

[4] J. R. Smith, *et. al*., Electromagnetic Forward-Scattering Measurements over a Known, Controlled Sea Surface at Grazing, *IEEE Trans. Geosci. Remote Sens*. **42**, 1731-1738, 2004.

[5] J. A. DeSanto and G. S. Brown, Analytical Techniques for Multiple Scattering from Rough Surfaces, in *Progress in Optics* **XXIII**, Edited by E. Wolf, Elsevier Science Publisher, 1-62, 1986.

[6] T. M. Elfouhaily and C. A. Guerin, A Critical Survey of Approximate Scattering Wave Theories from Random Rough Surfaces, *Waves in Random Media* **14**, R1-R40, 2004.

[7] K. F. Warnick. and W. C. Chew, Numerical Simulation Methods for Rough Surface Scattering, *Waves in Random Media* **11**, R1-R30, 2001.

[8] M. Saillard and A. Sentenac, Rigorous Solutions for Electromagnetic Scattering from Rough Surfaces, *Waves in Random Media* **11**, R103-R137, 2001.

[9] V. Rokhlin, Rapid Solution of Integral Equations of Scattering Theory in Two Dimensions, *J. Comput. Phys*. **86**, 414-439, 1990.

PUBLICATIONS

Z. Lai and R. Janaswamy, ``Specular propagation over rough surfaces: numerical assessment of Uscinski and Stanek's mean Green's function technique,'' *Waves in Random and Complex Media*, vol. 16(2), pp. 137-150, May 2006.