Space, Telecommunications And Radioscience Laboratory

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Dear Frank and Dennis,

This letter is the final report on ONR contract N00014-89-J-3223, entitled, "New Methods for Wave Scattering from Rough Surfaces." This contract began in the Autumn of 1989 and ended in the Summer of 1993 after a no cost extension. Below we review the objectives and approach of the research, how the objectives were met, research results produced and the applications these results are finding in current research at other institutions. The bulk of the final results are to be contained in Glenn Jensen's Ph. D. thesis which is now nearing completion. A list of presentations and publications is attached.

The major goals of this research can be summarized as follows:

1. Investigate new methods for modeling the radar backscatter cross section (σ°) of the ocean surface as a function of observational parameters and environmental conditions

2. Act as a theoretical component for the SAXON-FPN program that also included many radar and air-sea interaction observations.

A key element in our approach was to work with investigators of the SAXON-FPN team and others with expertise in ocean surface dynamics. In particular we worked with Dr. Roman Glazman of the Jet Propulsion Laboratory who has excellent knowledge of the statistical geometry of the ocean surface. A new method for estimating the radar cross section of the ocean (σ°) was developed and compared with current models. We attempted to make use of ocean surface topography data collected by stereo photography during SAXON-FPN, but the data were too coarse in spatial resolution to be truly useful and contained regions where no topography estimate was produced.

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Our achievements during this research can be summarized under three headings, as follows:

1. Investigations of the knowledge of ocean surface geometry required for accurate estimates of ocean surface σ°
2. Investigation of a new method for estimating σ° for the ocean
3. Comparison of model results (others, as well as ours) with a comprehensive compilation of observational data sets giving σ° for a wide variety of observational and air-sea environmental parameters.

The following paragraphs discuss each of these achievements in more detail.

Required knowledge of ocean surface geometry: One of the oceanographic advances of the World War II era was the statistical characterization of the ocean surface using the wave height spectrum. The wave height spectrum (or Fourier power spectrum of ocean surface height variance), extending to very high wavenumbers, has since been used to predict the radar cross section of the ocean using the two-scale or composite surface model. We have shown that the autocorrelation function (or equivalently the power spectrum) of surface roughness is <u>not in general</u> sufficient to characterize the surface geometry for purposes of estimating the radar scattering properties of the surface. This was done using a computational experiment shown in Fig. 1 below.

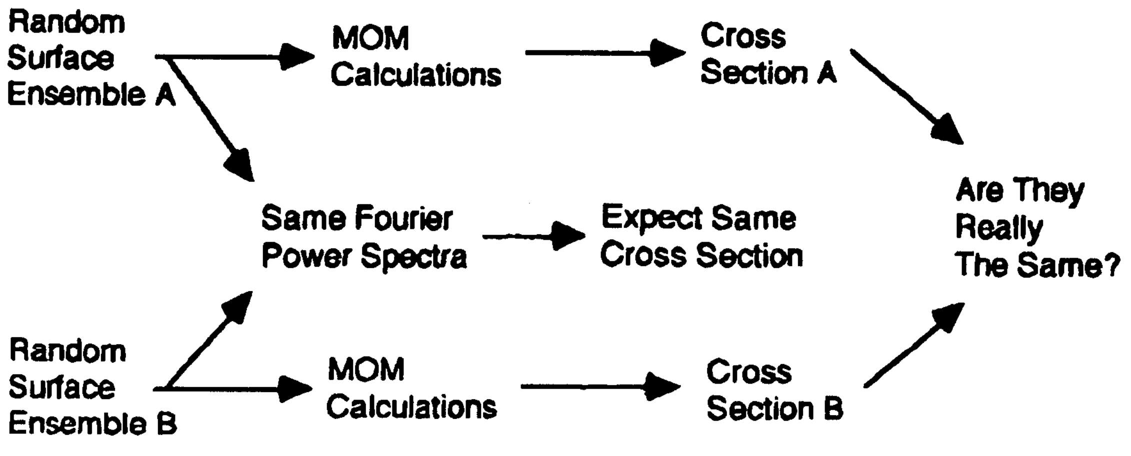

Fig. 1. Computational Experiment Concept. Given two different statistically rough surfaces that share a common autocorrelation function (or equivalently a common Fourier power spectrum), calculate the radar cross section of each using the method of moments (MOM) numerical electromagnetic technique and compare.

As shown in the diagram, we generate two random rough surfaces that share the same autocorrelation function (or equivalently the same power spectrum) and then calculate the radar cross section for each surface using the method of moments (MOM) numerical electromagnetics technique. We then compare the MOM radar cross section results for surfaces A and B. This computational experiment was completed for a variety of artificial as well as natural rough surfaces. We find that in general the two results. A & B, are different -- by as much as tens of dB depending on the choice of surfaces and observational parameters. We thus conclude that in general the power spectrum is insufficient to characterize rough surface statistical geometry for the purpose of calculating radar cross section. This is a particularly interesting result since most current ocean scattering models do, in fact, rely on the power spectrum to characterize ocean surface geometry.

Investigation of a new ocean radar cross section model: The primary objective of this research was the development of a new method for estimating the radar cross section of the ocean surface. The new method is illustrated in Fig. 2 below. It is based on scattering from sharply peaked waves. First, we estimate the size and spatial distribution of sharply peaked, near breaking, waves. Second, we model the scatter from such waves using the unified geometrical theory of

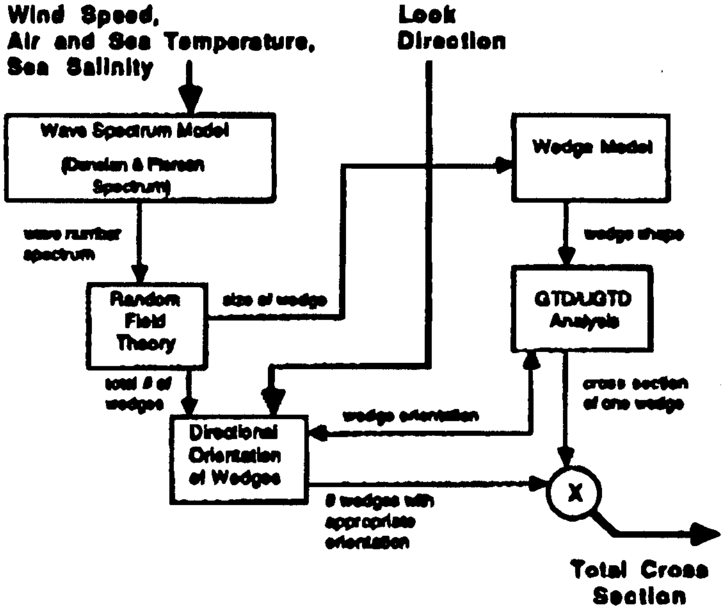

Fig. 2. Schematic diagram for the sharply-peaked-wave diffraction model for radar scattering from the ocean surface. The specified inputs, in conjunction with the various components of the wedge diffraction model result in a radar cross section estimate.

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diffraction (UGTD). Finally, we sum the scattering contributions of these sharply peaked waves over the statistical distribution of such waves to find the radar cross section.

Estimating the size and distribution of sharply peaked waves is done using the method of our collaborator Dr. Roman Glazman. In this method the theory of the statistical geometry of surfaces is applied to the ocean surface and the typical size and spatial distribution of sharply peaked waves is estimated by calculating the statistics of locations where the slope is greater that some threshold. We used a slope of 0.4 to indicate a sharply peaked wave. Our calculation uses as an input the directional waveheight spectrum, although other methods could be used. An important point here is that the calculation uses higher order moments of the waveheight spectrum, i.e. up to fourth order. In the conventional two-scale model moments of the spectrum enter in different ways so there are qualitative differences between the two models in terms of both the surface roughness characteristics used and the scattering mode.

To drive the new scattering model we did a major survey of published ocean wave spectra and wave spectrum models. In compiling this survey the spectra were converted to comparable notation so that they could be compared. To the knowledge of these investigators this collection is the most complete compilation of ocean wave spectrum models available at present.

Radar scattering from the sharply peaked wave distribution above is obtained by calculating the scattering from an ensemble of waves with the given distribution. We constructed our wavelets to have the size dictated by the above calculation and an aspect ratio of 3 to 1. A typical wavelet is shown in Fig. 3 below. The scattering from such a wavelet is calculated by the unified geometrical theory of diffraction (UGTD). This method of estimating scatter from an object is well known and we think accurate *except at near normal and near grazing incidence.* Hence the model only gives useful results between about 20 and 70° incidence. To obtain a cross section estimate we use the UGTD model and integrate over the wavelet distribution discussed above. Because UGTD gives an analytical result the integration can be done rapidly on a desktop personal computer.

Assessment of the new model: To assess our new scattering model we compiled a comprehensive data base of ocean radar cross section experiment data. This data set spans results over decades and a wide variety of radar observational and environmental conditions. These data were put into a digital data base with common notation.

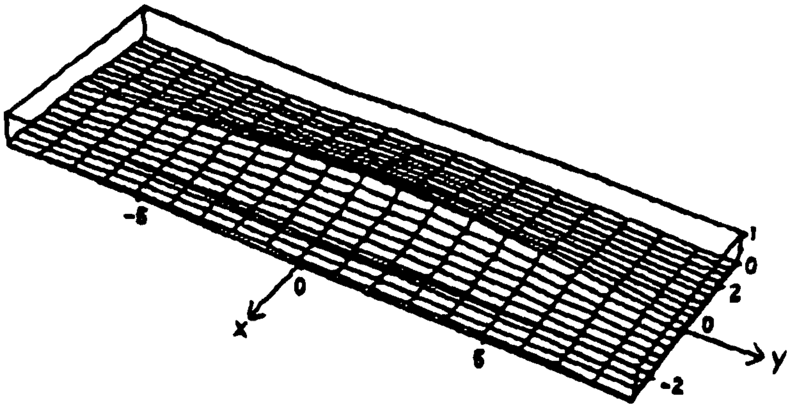

Fig. 3. Typical sharply peaked wavelet used in the wave diffraction, ocean scattering model. Dimensions are in centimeters.

Observations were compared with model results for all of these data sets and the results plotted. We found that the differences between the model and the data were approximately the same as the differences between different experiments for supposedly the same observational and environmental conditions. An example of such a comparison in given in Fig. 4. We also compared our wavelet diffraction model results and other two scale model results with the aforementioned data sets. We found that for the angles of incidence over which our model is valid (≈ 20 to 70°) the wavelet diffraction model agreed with the experimental data as well as the other scattering models. The free parameters in our model are the form of the wavelet and the threshold slope for a peaked wave, aside from the free parameters in the waveheight spectrum we used, i.e. the spectrum of Donelan and Pierson, which we left unchanged. The size and density of the wavelets are computed from the spectrum model and are not free parameters. In the results above we have not 'tuned' our model to produce results, i.e. it contains the same wavelet form and slope threshold with which we started.

The thesis of Stanford graduate student Glenn Jensen will contain the bulk of the results of this work. The thesis was supported by this grant. It is now being completed.

In summary we have gathered inspiration from the work of Roman Glazman on the statistical geometry of the real ocean surface and earlier work on scattering from wedge shaped waves by Lou Wetzel and Dave Lyzenga. We have advanced this type of ocean scattering model in two important ways:

- Determination of wavelet characteristics from a realistic model for the statistical geometry of the ocean surface that is dependent on environmental parameters

- The use of a wavelet that is both finite and much like a real ocean wavelet.

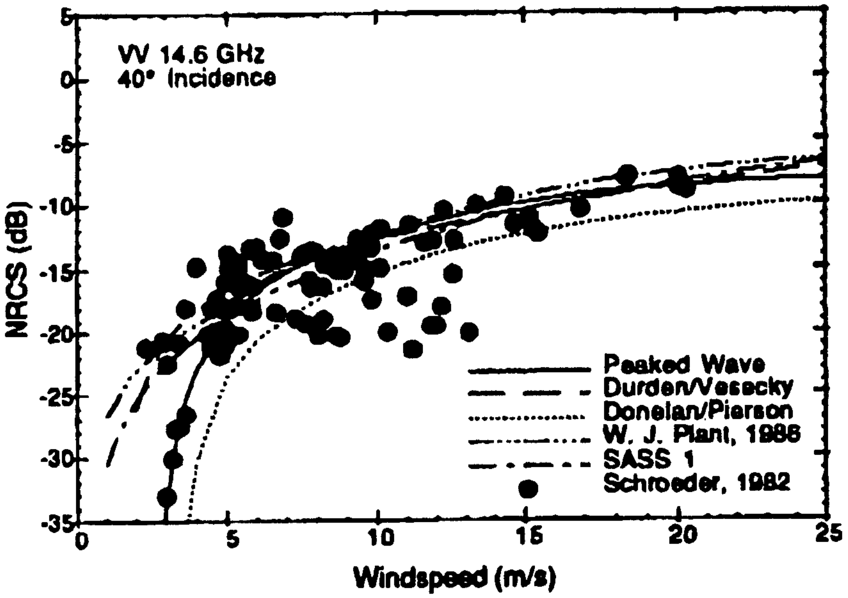

Fig. 4. Comparison of peaked wave scattering model with other models and experimental data.

The resulting model produces results as good as existing models when compared with a comprehensive set of experimental data. We anticipate that the real usefulness of this model will come in explaining the radar scatter associated with anomalous conditions on the ocean surface, such as fronts, current shears, flow over variations in bottom topography, ship wakes, regions of unstable atmospheric boundary layer and the like. We anticipate that future work in this area will be application to carefully controlled radar experiments in indoor wave tanks and extension of the model to a wider range of conditions by using the iterative Kirchhoff method in place of UGTD.

This project has been an interesting and stimulating one. We think that some useful results have been achieved and that the work will form the basis for interpretation of some features in radar images of the ocean.

Yours sincerely,

John F. Vesecky　　Glenn A. Jensen by JFV

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List of Presentations and Publications

Date	Type	Reference
3/27/90	Technical Report	Jensen, G. A., "Backscatter Radar Cross Section of an Ocean Wave," STAR Laboratory, Electrical Engineering Dept., Stanford University, Stanford CA 94305.
2/13/91	Talk	Vesecky, J. F., G. A. Jensen and R. Glazman, "Radar Scattering from a more Realistic Ocean Surface," presented at First SAXON-FPN Data Workshop, Scripps Institution of Oceanography, La Jolla CA, Feb. 13-15,1991.
4/15/91	Technical	Jensen, G. A. and J. F. Vesecky, "New Methods for Wave Scattering from Rough Surfaces," ONR Research Status Report, STAR Laboratory, Electrical Engineering Dept., Stanford University, Stanford CA 94305.
7/1/91	Talk & Abstract	Vesecky, J. F., G. A. Jensen and R. Glazman, "Simulation of Radar Backscatter from Gravity Wave Crests, PIERS '91 Proceedings, Cambridge MA, July 1-5, 1991.
8/26/91	Technical Report	Jensen, G. A., J. F. Vesecky and R. Glazman, "Diffraction from Sharply Peaked Waves as an Ocean Surface Scattering Model," distributed at the Second SAXON-FPN Data Workshop, German Aerospace Research Establishment, Oberpfaffenhofen, Germany, August 26-28, 1991.
5/26/92	Talk & Paper	Jensen, G. A., J. F. Vesecky and R. Glazman, " Diffraction from Sharply Peaked Waves as an Ocean Surface Scattering Mechanism," IGARSS '92 Proceedings, Vol. II, 1771-1773, Houston, Texas, May 26-29, 1992.

9/29/92	Talk	Jensen, G. A. and J. F. Vesecky, "Diffraction from Sharply Peaked Waves as an Ocean Surface Scattering Model," Forth SAXON-FPN Data Workshop, University of Washington, Seattle WA, Sept. 29-Oct. 2, 1993.
3/3/93	Technical Report	Jensen, G. A., "Ocean Wave Height Spectra: 40 Years of Attempting to Characterize the Ocean Surface, Mechanical Engineering Dept. 260, Stanford University, Stanford CA, March 3,1993.
7/12/93	Talk & Abstract	Jensen, G. A. and J. F. Vesecky, "Diffraction from Sharply Peaked Waves--an Alternative Theoretical Model of Ocean Surface Scattering, **PIERS '93 Proceedings**, California Institute of Technology, Pasadena CA, July 12-16,1993.
10/18/93	Talk & Paper	Jensen, G. A. and J. F. Vesecky, "Non-Fourier Spectral Characterizations of the Ocean Surface: New Theoretical Models of Ocean Surface Radar Scattering," **Oceans '93 Proceedings**, Victoria BC, Canada, October 18-21, 1993.