Analytical and Numerical Studies of Active and Passive Microwave Ocean Remote Sensing

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LONG-TERM GOALS

The long term goals of this project involve developing improved understanding of sea surface thermal emission and scattering through the application of both analytical and efficient numerical methods for electromagnetics and hydrodynamics. New insights regarding these phenomena can then be applied to improve microwave active and passive remote sensing of the ocean surface.

OBJECTIVES

NRL's WindSat, scheduled for launch in 2002, will place a polarimetric microwave radiometer into orbit for the first time. Using WindSat measured brightness temperatures to retrieve sea surface wind speed and direction requires an understanding of the relationship between sea surface emitted microwave power and sea conditions. Analytical theories have been developed for the prediction of microwave sea surface brightness temperatures and have shown some success, but differences among the theories proposed and the limited amount of current data still make the underlying physics unclear. Project efforts in emission theory are focused on studies and extension of the analytical models to provide improved understanding of the phenomena producing emission signatures. Development of efficient numerical models for emission predictions has also been initiated, and a web-site (esl.eng.ohio-state.edu/~rstheory/windsat.html) has been created to serve as a central location for the sea emission modeling community.

A DURIP project for development of an ultra-wideband radiometric sensor is also in progress to provide experimental confirmation of project theoretical predictions.

The development of improved models for scattering from the sea surface is another focus of the project. Although standard approximate models exist for active sensing of the sea surface, several issues regarding the physical scattering mechanisms and effect of non-linear hydrodynamics remain a subject of debate. This project applies numerically exact models to avoid the limitations of approximate methods so that the influence of different scattering mechanisms can be established. Radar image formation, Doppler analysis, and detailed comparisons with standard approximate theories are used as tools to help understand the scattering process.

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14. ABSTRACT
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APPROACH

Analytical model studies of sea surface emission are focusing on the small-slope theory [1]-[4]. An extensive debate in the community is currently taking place with regard to the source of azimuthal harmonic variations of ocean brightness temperatures, particularly the relative influence of large and small scale wave structures. Uncertainties in the ocean surface directional spectrum and in long-short wave hydrodynamic modulations make this a difficult question to resolve conclusively, but studies of emission theories can reveal the extent to which asymmetry in differing length scales can contribute to observed harmonics independent of the directional spectrum model used. Insights obtained from previous project studies have shown that nadir observing, multiple frequency brightness temperature measurements offer a potential means of remote sensing the sea surface curvature spectrum; to experimentally demonstrate this concept, a DURIP project was awarded for development of an ultra-wideband radiometer. When completed, this sensor will be applied in laboratory curvature spectrum sensing tests.

The approach to the scattering problem is to apply recently developed numerical models for scattering [5] and hydrodynamic evolution [6]-[7] of both two and three dimensional rough sea surfaces. Earlier studies in the grazing angle regime have shown the importance of including non-linear hydrodynamic effects in the sea surface model, since “sea spike” like behaviors are not captured by standard linear surface models. Numerical approaches to the hydrodynamic surface evolution are therefore being applied, with scattering results compared under differing approximate hydrodynamic methods to determine the influence of these models [8]. Comparisons with analytical scattering theories, such as the small slope approximation, IEM, and composite surface model, are also being pursued to assess the performance of these techniques [9].

WORK COMPLETED

Several new developments have occurred in FY01. To clarify the relationship between the physical optics and small slope theories of sea emission, an analytical comparison was performed [4]. Because optical theories should be accurate for sea surface waves with wavelengths much larger than the electromagnetic wavelength, the comparison was limited to this region. Results showed that the third order small slope and physical optics theories yield identical predictions at least up to third order in long wave slope for zeroth, first, second, and third emission azimuthal harmonics when shadowing effects are neglected. Because the two scale emission theory [10] provides a form identical to an optical theory in this limit, the study shows that all current theories of sea emission obtain practically identical forms for long wave contributions. Initial studies of a numerical small slope theory that can provide predictions beyond third order in surface slope have also been initiated, and show that shadowing effects can be captured by a small slope theory if a sufficient number of terms in the slope series is included.

Finally, the sea emission modeling web page has been created and several test cases provided for intercomparisons of codes to ensure accurate implementations by members of the emission modeling community.

The DURIP sensor is currently under construction by Radiometrics, Inc. of Boulder, CO. A 37 channel system operating between 2 and 18 GHz is scheduled for delivery near the end of FY01. Some project efforts have been devoted to preparing the calibration procedure for the sensor and to developing an ultra-wideband antenna for use with the system.

Active sea remote sensing studies in FY01 have emphasized radar image studies of the sea surface, including radar image studies for simulated breaking waves [11]-[12]. Breaking wave images directly illustrate multipath scattering contributions, and show that the high polarization ratios obtained (i.e. "sea-spike" scattering behaviors) with simulated breaking waves are due primarily to polarization effects of direct backscattering from the crest region. Development and testing of numerical hydrodynamic models for broad sea spectra have also continued in FY01 using the Watson-West [6] and Vortex-sheet [7] methods. A detailed comparison of these hydrodynamic methods with a single frequency "pressure-ramp" input showed the more efficient, but more approximate, Watson-West method to perform well. Current efforts are working to develop methods for suppressing small scale wave steepening effects in the Watson-West algorithm, because these features can cause the simulation to become unstable and terminate even if the overall hydrodynamic effect of these features is unimportant.

RESULTS

Figure 1 illustrates a comparison of small slope theory and physical optics theory first, second, and third emission azimuthal harmonic long wave "weighting functions" versus polar observation angle for the third emission Stokes parameter U and for a sea water rough surface at 19.35 GHz. These weighting functions apply for "long wave" contributions (i.e. from sea waves with wavelengths much greater than the electromagnetic wavelength) and are multiplied by appropriate sea surface slope moments and the sea surface temperature to obtain the predicted corresponding emission brightness harmonic. Results show that identical predictions are obtained from the small slope and physical optics theories when shadowing effects in the physical optics theory are neglected. Results also show first and third azimuthal harmonics to be generally increasing functions of observation angle, while the second harmonic demonstrates a sign change in the range of 50 to 60 degrees. Such behaviors are consistent with aircraft measured data, although resonant contributions from shorter waves are needed to provide an improved match with aircraft measurements [2].

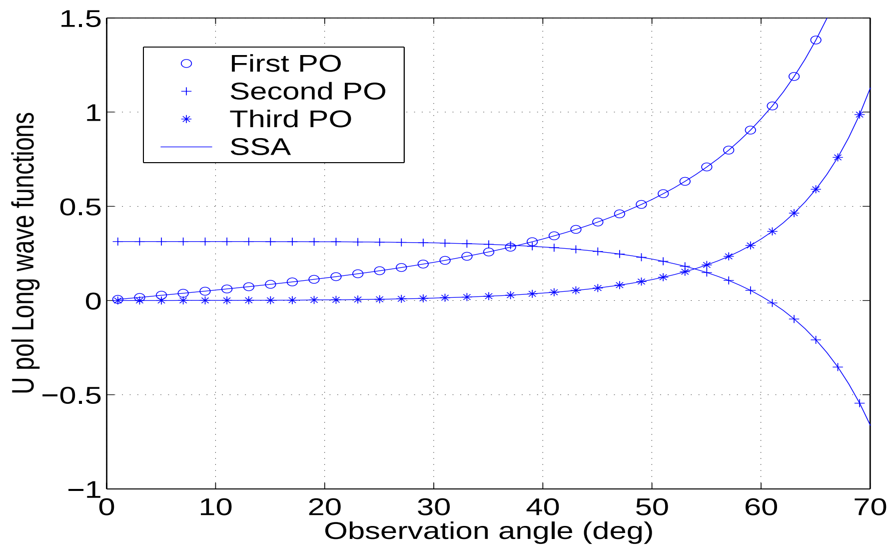

Figure 1: Small slope and physical optics theory emission long wave weighting functions for the third Stokes parameter; results show the curves to be identical

Figure 2 illustrates an initial result from a numerical small slope emission model that is capable of providing predictions up to an arbitrary order in the small slope theory. Predictions were obtained for a bi-sinusoidal surface (i.e., sin(x)sin(y)) with period 50 wavelengths in both the x and y directions and a peak-to-peak amplitude of 3 wavelengths. A dielectric constant of 3 for the surface medium was used in this initial test. A much more computationally extensive numerically exact emission model was used to provide results for comparison; Figure 2 plots the level of error from the small slope theory versus observation angle as the order of the slope expansion is increased from second to twelfth order. For this surface, the onset of possible multiple scattering effects occurs around 70 degrees observation angle. Figure 2 demonstrates an increase in the number of terms required for accuracy at 70 degrees, but an accurate result (within 0.4K of the exact model at 12^{th} order) is obtained as the number of terms is increased. This result demonstrates that the small slope theory is capable of capturing multiple scattering and shadowing effects if a sufficient number of terms is included, and motivates further development of and tests with the numerical small slope theory.

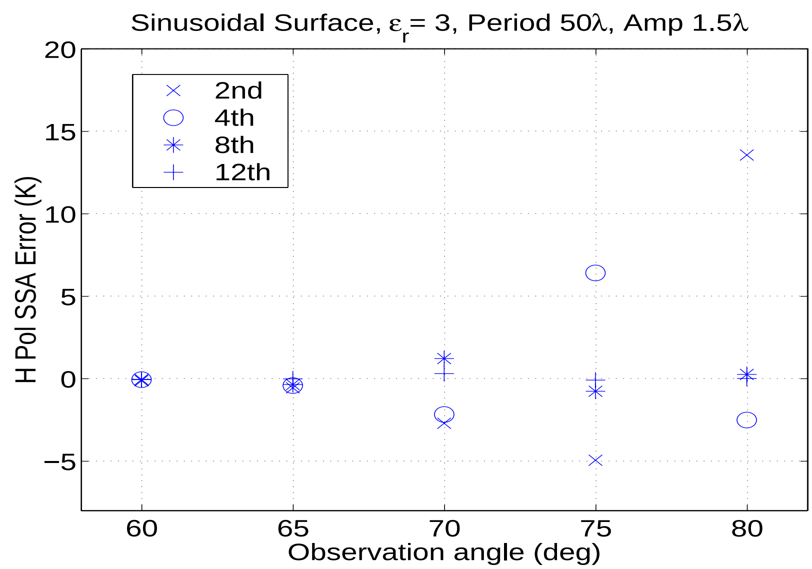

Figure 2: Error in small slope theory emission predictions versus observation angle for a bi-sinusoidal periodic surface; results show decreasing error as the order of the slope expansion is increased.

Figure 3 illustrates a radar image of a simulated breaking wave generated from 10-14 GHz HH polarization backscattered field data at incidence angles ranging from 60 to 80 degrees. Backscattered field data were generated with a numerical scattering model [5]. Results show the dominant direct backscattering from the crest region of a breaking wave, with additional scattering centers located beneath the profile. A ray tracing analysis was performed to demonstrate that these terms correspond to single and double bounce multipath scattering mechanisms as predicted by a "four-path" model [13].

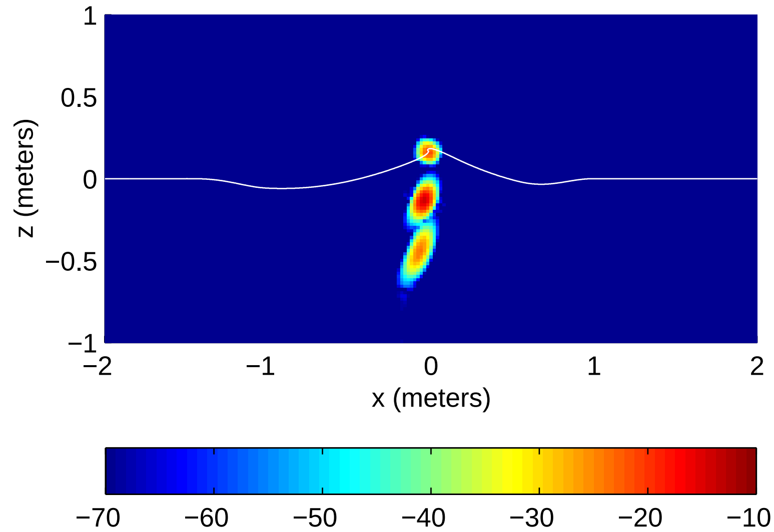

Figure 3: Radar image of a simulated breaking wave

IMPACT/APPLICATION

Insights into emission physics are expected to have impact in methods for passive remote sensing of ocean wind vectors, needed in analysis of WindSat data and in design and application of sensors for the NPOESS generation of weather satellites. If experimental results with the DURIP sensor prove successful, a new technology will exist for measurement of the sea surface curvature spectrum, which influences many areas of oceanography. New insights into sea surface scattering will allow improved clutter reduction and active sea surface sensing methods to be created.

TRANSITIONS

Results of the project have been communicated at several ONR sponsored workshops, including the ONR sponsored WindSat program workshop.

RELATED PROJECTS

Current related projects include:

1. An NSF sponsored project with Prof. Greg Baker on development of hydrodynamic models

2. A NASA sponsored project on development of digital receivers for microwave radiometry

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Eleven conference publications in FY00.