Ocean Surface Wave Optical Roughness – Innovative Measurement and Modeling

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LONG-TERM GOALS

We are part of a multi-institutional research team funded by the ONR-sponsored Radiance in a Dynamic Ocean (RaDyO) program. The primary research goals of the program are to (1) examine time-dependent oceanic radiance distribution in relation to dynamic surface boundary layer (SBL) processes; (2) construct a radiance-based SBL model; (3) validate the model with field observations; and (4) investigate the feasibility of inverting the model to yield SBL conditions. Our goals are to contribute innovative measurements, analyses and models of the sea surface roughness at length scales as small as a millimeter. This characterization includes microscale and whitecap breaking waves.

The members of the research team are

Michael Banner, School of Mathematics, UNSW, Sydney, Australia

Johannes Gemmrich, Physics and Astronomy, UVic, Victoria, Canada

Russel Morison, School of Mathematics, UNSW, Sydney, Australia

Howard Schultz, Computer Vision Laboratory, UMass, Dept. of Computer Science. Amherst, MA

Christopher Zappa, Lamont Doherty Earth Observatory, Palisades, NY

OBJECTIVES

Nonlinear interfacial roughness elements - sharp crested waves, breaking waves as well as the foam, subsurface bubbles and spray they produce, contribute substantially to the distortion of the optical transmission through the air-sea interface. These common surface roughness features occur on a wide range of length scales, from the dominant sea state down to capillary waves. Wave breaking signatures range from large whitecaps with their residual passive foam, down to the ubiquitous centimeter scale microscale breakers that do not entrain air. There is substantial complexity in the local wind-driven sea surface roughness microstructure, including very steep nonlinear wavelets and breakers. Traditional descriptors of sea surface roughness are scale-integrated statistical properties, such as significant wave height, mean squared slope (e.g. Cox and Munk, 1954) and breaking probability (e.g. Holthuijsen and Herbers, 1986). Subsequently, spectral characterisations of wave height, slope and curvature have been measured, providing a scale resolution into Fourier modes for these geometrical sea roughness parameters. More recently, measurements of whitecap crest length spectral density (e.g. Phillips et al,

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2001, Gemmrich et al., 2008) and microscale breaker crest length spectral density (e.g. Jessup and Phadnis, 2005) have been reported.

Our effort seeks to provide a more comprehensive description of the physical and optical roughness of the sea surface. We will achieve this through the analysis of our suite of comprehensive sea surface roughness observational measurements within the RADYO field program. These measurements are designed to provide optimal coverage of fundamental optical distortion processes associated with the air-sea interface. In our data analysis, and complementary collaborative effort with RaDyO modelers, we are investigating both spectral and phase-resolved perspectives. These will allow refining the representation of surface wave distortion in present air-sea interfacial optical transmission models.

APPROACH

We build substantially on our accumulated expertise in sea surface processes and air-sea interaction. We are working within the larger team (listed above) measuring and characterizing the surface roughness. This team is contributing the following components to the primary sea surface roughness data gathering effort in RaDyO:

- *polarization camera measurements* of the sea surface slope topography, down to capillary wave scales, of an approximately 1m x 1m patch of the sea surface (see Figure 1), captured at video rates. [Schultz, Zappa]
- *co-located and synchronous orthogonal 75 Hz linear scanning laser altimeter* data to provide spatio-temporal properties of the wave height field (resolved to O(0.5m) wavelengths) [Banner, Morison]
- *high resolution video imagery* to record whitecap data from two cameras, close range and broad field [Gemmrich]
- *fast response, infrared imagery* to quantify properties of the microscale breakers, and surface layer kinematics and vorticity [Zappa]
- *air-sea flux package including sonic anemometer* to characterize the near-surface wind speed and wind stress [Zappa]

The team's envisaged data analysis effort includes: detailed analyses of the slope field topography, including mean square slope, skewness and kurtosis; laser altimeter wave height and large scale wave slope data; statistical distributions of whitecap crest length density in different scale bands of propagation speed and similarly for the microscale breakers, as functions of the wind speed/stress and the underlying dominant sea state. Our contributions to the modeling effort will focus on using RaDyO data to refine the sea surface roughness transfer function. This includes the representation of nonlinearity and breaking surface wave effects including bubbles, passive foam, active whitecap cover and spray, as well as micro-breakers.

WORK COMPLETED

Our effort in FY09 has comprised (i) analysis of the suite of sea surface roughness measurements conducted during the Scripps Institution of Oceanography (SIO) Pier Experiment from January 6-28, 2008 and from the RaDyO field experiment in the Santa Barbara channel during September 5-27, 2008. (ii) gathering two-axis scanning lidar wave height data from FLIP, single axis scanning lidar data from the Kilo Moana and the provision of internet communication between these two vessels.

During FY09, we also refined our data gathering hardware systems and protocols and continued our analysis effort on characterizing roughness features. We also refined a framework for relating wave breaking properties and near-surface energy dissipation rates.

We carried out processing and validation of our scanning lidar data from each of the 2008 field experiments. Two scanning lidars, configured to operate in quadrature, were deployed on FLIP to measure the large scale wave geometry (height and slope components). These measurements were collocated with our partner investigators’ high resolution polarimeteric, infrared and optical imaging systems collecting the surface roughness data. We also progressed with our effort to develop a robust ‘individual wave’ decomposition capability so that local physical roughness elements can be detected and characterized along with their space-time phasing. This seeks to overcome the classical Fourier spectrum issue of bound versus free wave contributions in assessing true physical sea surface roughness.

Of major significance to our group's effort was the deployment of our polarimeter in the RaDyO observational periods from Scripps Pier, from FLIP in the Santa Barbara channel and off Hawaii. Details on progress with this development are given in the companion ONR RaDyO Annual Reports by Schultz and Zappa.

RESULTS

Figure 1 below shows the instrumentation deployed in the field measurement phase. Banner/Morison deployed two orthogonal line scanning lidars, synchronized for zero crosstalk. The lidars were positioned on the boom so that their intersection point was within the common footprint of the polarimetric (Schultz), infrared (Zappa) and visible (Gemmrich) imagery cameras which were measuring small-scale surface roughness features and breaking waves.

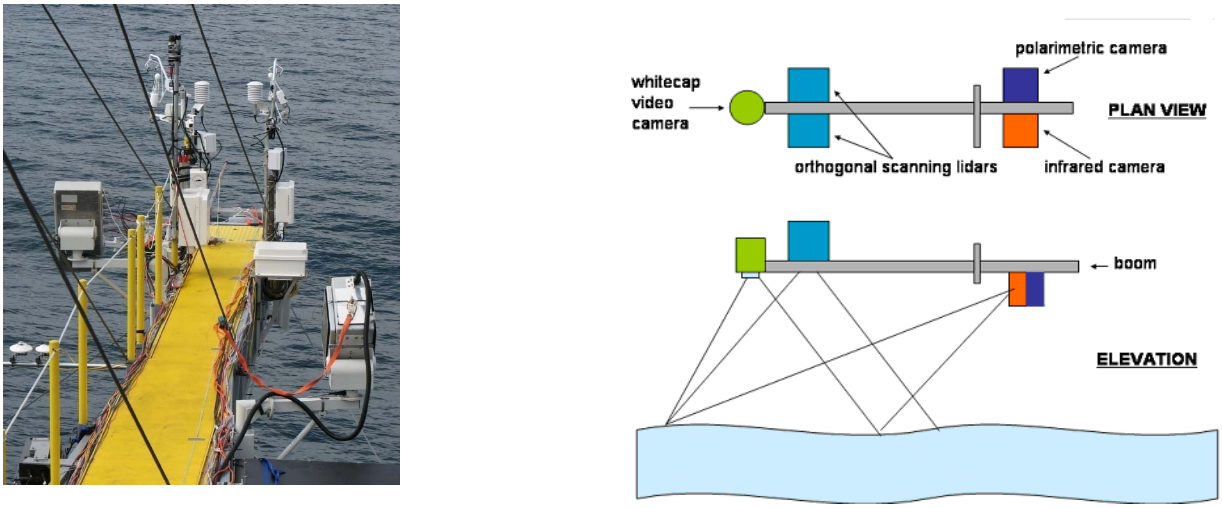

Figure 1. The left panel shows the instrumentation set-up deployed from the FLIP starboard boom. The right panel shows a schematic of instrumentation packages deployed. The end of the boom was about 8m above the mean water level. The approximate field of view of the various instruments is shown. A second wide angle whitecap video camera was mounted on FLIP well above the boom to image the larger whitecaps.

Zappa deployed his infrared/visible camera system and his environmental monitoring system (sonic anemometer, water vapor sensor, relative humidity/temperature probe, motion package, pyranometer and pyrgeometer). Gemmrich deployed 2 video visible imagery cameras. One camera was mounted on the main boom next to our other instrumentation packages, the second camera was mounted higher up to view larger scale breaking events. Schultz deployed an instrument package located on the boom that includes a polarimetric camera imaging the very small-scale waves. The individual data acquisition systems were synchronized to GPS accuracy which allowed the various data sets to be interrelated to within 0.1 seconds.

Imaging Polarimeter Results

We began processing the Santa Barbara Benign Wind Conditions polarimetric data. We encountered several problems which required an algorithm development effort, including 1) correcting for fixed pattern noise, and correcting for variable gain between sensors. We were able to recover surface slopes with the new N-IPol instrument and synchronize the Infrared and N-IPol instruments. Figure 2

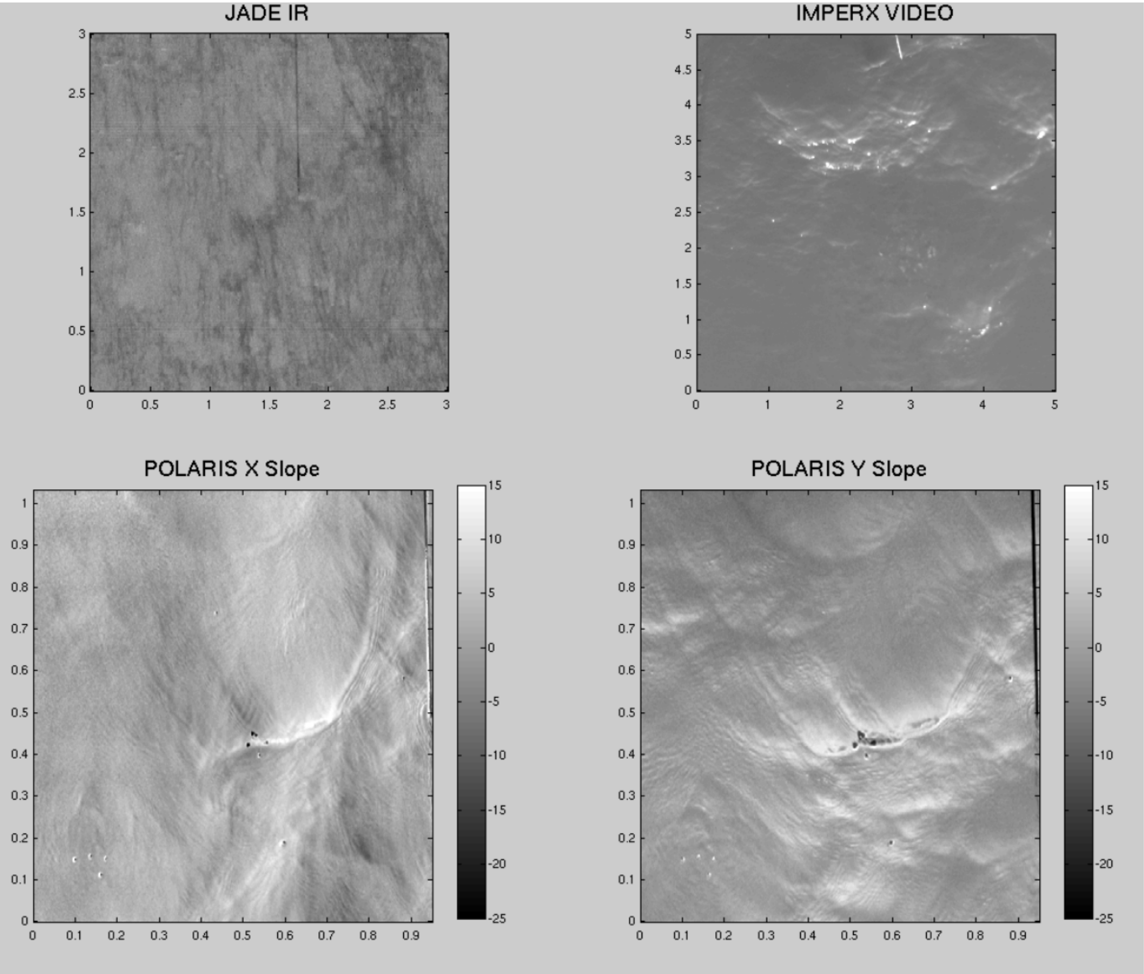

Figure 2. A typical co-located data snapshot show the infrared image, a high-resolution video image and the X and Y Slope image.

shows a sample intensity JADE IR image, a high resolution Imperx video image, and x- and y-slope images from the Polaris N-IPol. There were a few N-IPol calibration issues related to determining the registration and relative sensitivity of the four internal CCD images. These calibration issues were resolved and incorporated in to the Santa Barbara channel experimental procedures. We produced time lapsed video of the X and Y Slope images which were shown at the RaDyO science meeting held in Honolulu, HI August 2009.

FLIP scanning lidar wave topography

Our scanning lidars were field-deployed from FLIP and the Kilo Moana during the first intensive observational experiment during September 2008 in the Santa Barbara channel. A wide range of conditions prevailed where the wind speed U_{10} ranged from light and variable, up to 25 knots. Figure 3 below shows typical scanning lidar data measured during reasonably strong winds.

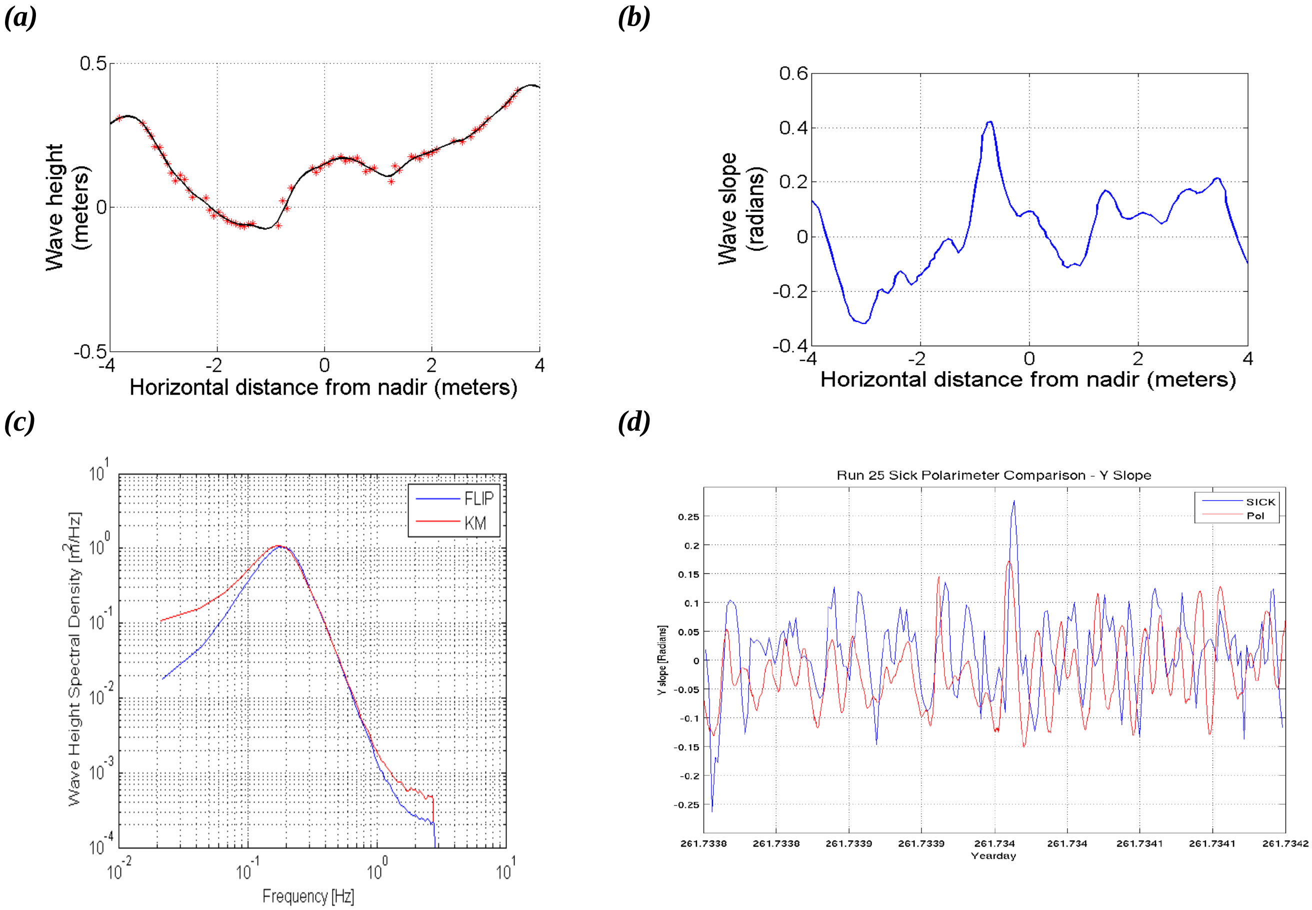

Figure 3. (a) Example of the measured wave height along a 4meter footprint track in the wind direction from the new starboard boom on FLIP, using a 75 Hz scanning lidar. The red asterisks indicate the lidar data and the black line is the smoothed profile. (b) wave slope derived from the smoothed wave height profile in panel (a). (c) Wave frequency spectra measured from FLIP and from the Kilo Moana (d) initial comparison of the local wave slope over a 1 meter baseline determined from the polarimeter and scanning lidar data. These data were taken during approximately 15 knot winds in the Santa Barbara channel on 23 September, 2008.

The lidars operated continuously throughout the field experiments. This instrumentation has provided useful data on the height and local directional slope of the gravity waves, and the initial 1-meter baseline slope intercomparison with the polarimeter slope shown in Figure 2(d) shows a high (0.8) coherence level. In addition, the lidar data characterizes the background environment experienced by the very short wind waves that comprise the sea surface microstructure. This information allows accurate phasing of the polarimetric camera imagery of the sea surface microstructure with respect to the underlying dominant wind waves.

IMPACT/APPLICATIONS

Emerging optical remote sensing techniques based on polarimetry have the potential to provide high spatial and temporal resolution topographic information about ocean surface waves. Our recent work within the RaDyO program and the DURIP award “Equipment in Support for Polarimetric Imaging” (N00014-07-1-0731) has developed an imaging polarimeter that successfully recovers two-dimensional slope fields at up to 60 Hz frame rates of very short gravity wind waves down to capillary waves.

When applied to oceanography and fluid mechanics problems, polarimetric imaging techniques have the potential of significantly improving the ability of investigators to study surface overturning and bubble production associated with open ocean wave breaking are the major drivers of upper ocean turbulence production and mixing, and dissipation of wave energy. In addition, breaking waves generate sea spray and droplets, and enhance microwave backscatter and underwater ambient noise generation.

In principle the Polarimetric Slope Sensing technique can be applied from vantage points above and below the water surface. In the RaDyO program the focus is on using a down looking imaging polarimeter. However, several unique applications exist for deploying a submerged, up looking, imaging polarimeter. An important facet of our long term goals is to determine the feasibility of using a submerged imaging polarimeter to recover the surface slope field. The advantages to observing the surface from below includes, reduced interference of the surface wind and wave field from the observation platform, and an increase in the amount of light energy reaching the sensor.

A submerged, up looking polarimeter, may enable imaging the surface environment from a subsurface sensor. This application is based on four-step process for removing image distortion caused by surface waves (see PATENTS below). The first step employs an imaging polarimeter to measure the polarimetric radiance of down-welling light from a vantage point below the water surface. The system then computes the 2-dimensional surface slope field from the polarization change caused by light refracting through the water surface. In the third step, Snell’s law is used to compute the change in orientation of the refracted light rays. Finally, the system uses the change in orientation to remove the image distortion cause by light refracting through the wavy air/water interface. After applying this process, the resulting images have the appearance of being taken through a flat water surface. We therefore refer to this process as optical flattening.

The optical environment associated with observing transmitted light is significantly different from observing reflected light. The methods developed for observing reflected light cannot be directly applied to an up looking configuration. Consequently, additional studies are needed to extend the Polarimetric Slope Sensing technique to an up looking configuration.

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