

Ocean Surface Wave Optical Roughness – Innovative Measurement and Modeling

Michael L. Banner

School of Mathematics and Statistics, The University of New South Wales, Sydney 2052, Australia
phone: (+61-2) 9385-7071 fax: (+61-2) 9385-7123 email: m.banner@unsw.edu.au

Russel P. Morison

School of Mathematics and Statistics, The University of New South Wales, Sydney 2052, Australia;
phone: (+61-2) 9385-7064 fax: (+61-2) 9385-7123 email: r.morison@unsw.edu.au

Award Number: N00014-0610047

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, Computer Science Dept, U. Mass., Mass

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

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2009		2. REPORT TYPE		3. DATES COVERED 00-00-2009 to 00-00-2009	
4. TITLE AND SUBTITLE Ocean Surface Wave Optical Roughness - Innovative Measurement and Modeling				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The University of New South Wales,School of Mathematics and Statistics,Sydney 2052, Australia,				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 5	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

parameters. More recently, measurements of whitecap crest length spectral density (e.g. Phillips et al, 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 August 23-September 16, 2009. In FY09, we also refined our data gathering hardware systems and protocols for the Hawaii experiment, 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 polarimetric, infrared and optical imaging systems collecting the surface roughness data. We also deployed a scanning lidar from the Kilo Moana to provide local wave data for the optical measurements made from it, relocating it from the between the bows in the 2008 field experiment to a rear deck boom in the 2009 field experiment.

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.

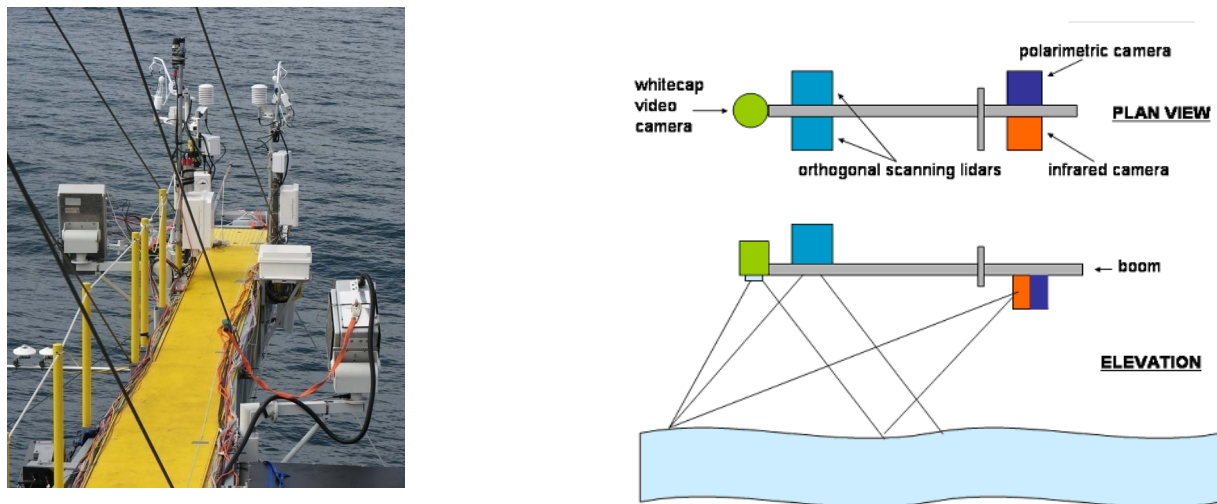


Figure 1. The left panel shows the instrumentation set-up deployed from the FLIP starboard boom. The right panel shows a schematic of instrumentation packages deployed. The end of the boom was about 8m above the mean water level. The approximate field of view of the various instruments is shown. A second 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.

(ii) 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 2 below shows typical scanning lidar data measured during reasonably strong winds.

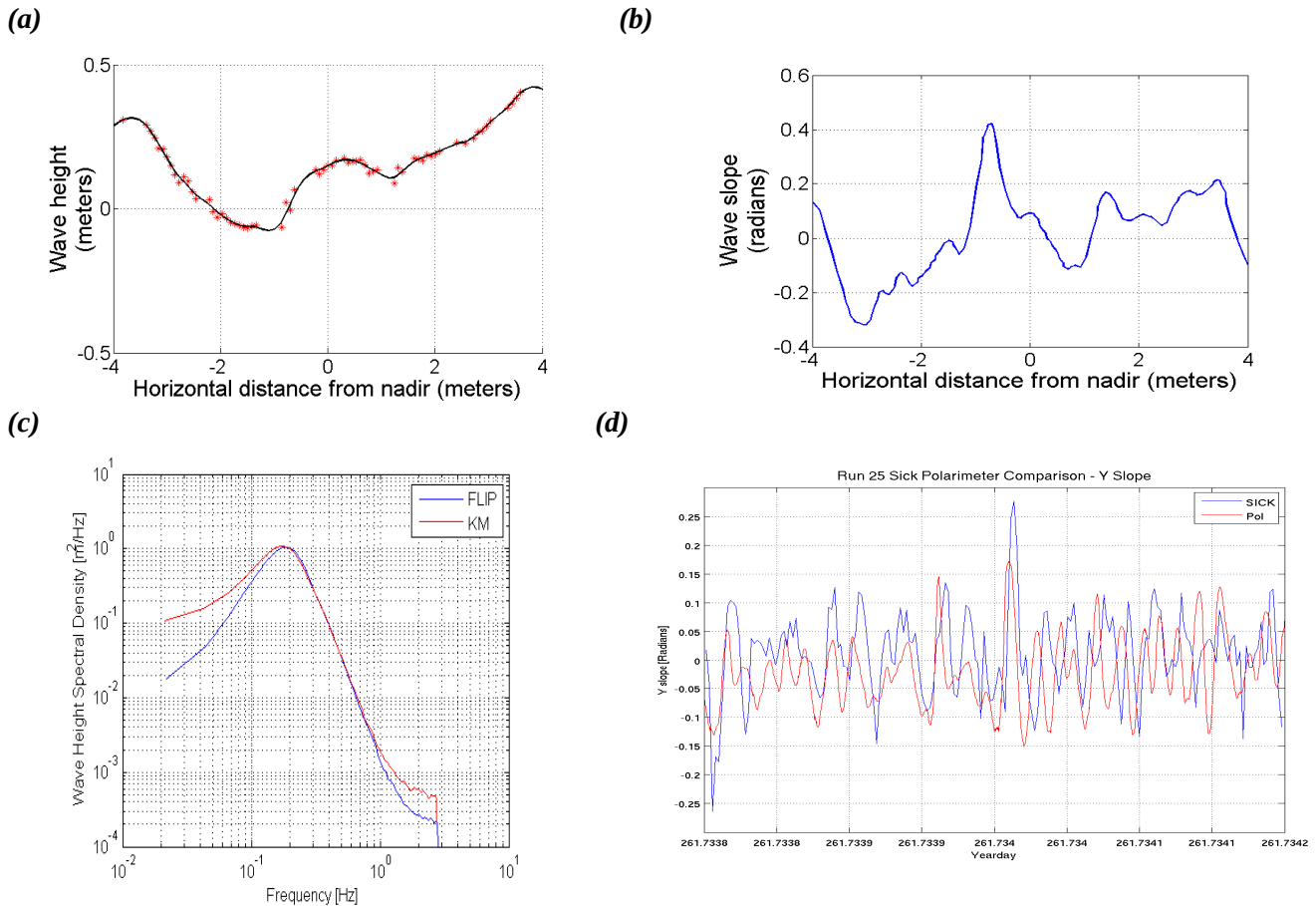


Figure 2. (a) Example of the measured wave height along an 8 meter footprint track in the wind direction from the new starboard boom on FLIP, using a 75 Hz scanning lidar. The red asterisks indicate the lidar data and the black line is the smoothed profile. (b) wave slope derived from the smoothed wave 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 in 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

This effort will provide a far more detailed characterization of the wind driven air-sea interface, including wave breaking (whitecaps and microscale breaking). This is needed to provide more complete parameterizations of these processes, which will improve the accuracy of ocean optical radiative transfer models and trans-interfacial image reconstruction techniques.

REFERENCES

- Cox, C.S. and Munk, W.H., 1954: Measurements of the roughness of the sea surface from photographs of the sun glitter. *J. Opt. Soc. Am.* 44, 838-850.
- Gemmrich, J.R., M.L. Banner and C. Garrett, 2008: Spectrally resolved energy dissipation and momentum flux of breaking waves. *J. Phys. Oceanogr.* 38, 1296-1312.
- Holthuijsen, L.H., and T.H.C. Herbers, 1986: Statistics of breaking waves observed as whitecaps in the open sea, *Journal of Physical Oceanography*, 16, 290-297.
- Jessup, A.T. and Phadnis, K.R. 2005 Measurement of the geometric and kinematic properties of microscale breaking waves from infrared imagery using a PIV algorithm. *Meas. Sci. Technol.* 16, 1961-1969.
- Phillips, O.M., Posner, F.L. and Hanson, J.P., 2001: High resolution radar measurements of the speed distribution of breaking events in wind-generated ocean waves: surface impulse and wave energy dissipation rates. *J. Phys. Oceanogr.*, 31, 450-460.

PUBLICATIONS

- Howard Schultz, Chris J. Zappa, Michael L. Banner, Andres Corrada-Emmanuel and Larry Pezzaniti (2008) "A Method for Recovering the Two-dimensional slope field of the Ocean Surface Waves Using an Imaging Polarimeter," 2008 AGU Ocean Sciences Meeting, Orlando, FL March 2-7, oral presentation. [Published]
- Zappa, C.J., M.L. Banner, H. Schultz, A. Corrada-Emmanuel, L.B. Wolff and J. Yalcin, 2008: Retrieval of Short Ocean Wave Slope Using Polarimetric Imaging. *Measurement Science and Technology*. *Measurement Science and Technology*, 19, 055503, pp 13, April 2008 [published, refereed].
- Gemmrich, J.R., M.L. Banner and C. Garrett, 2008: Spectrally resolved energy dissipation and momentum flux of breaking waves. *J. Phys. Oceanogr.* 38, 1296-1312. [published, refereed]