The Influence of Breaking at the Ocean Surface on Oceanic Radiance and Imaging

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LONG-TERM GOALS

The long-term goals of the work are to measure the influence of surface wave breaking on imaging across the surface and develop measurements and models of breaking statistics as input to the interpretation and modeling of oceanic radiance measurements.

OBJECTIVES

Image transmission across breaking surfaces will be measured in both the laboratory and the field. Field measurements of breaking and breaking statistics will be used to quantify the degradation and recovery of image fidelity by surface and subsurface processes associated with breaking, including surface turbulence and bubble entrainment. The PI will collaborate with other PIs in the use of breaking measurements and models to interpret measurements and develop models of oceanic radiance.

APPROACH

The transmission of light across the ocean surface, whether downwelling or upwelling, depends strongly on refraction across the air-sea interface. Models of refractive effects depend on the structure of the surface; ideally, the surface displacement and all its spatial and temporal derivatives. However, measuring the surface and its derivatives at all relevant scales is technically not possible at present as the spatial scales range from millimeters to kilometers, and the temporal scales from milliseconds to hours. The task is simplified if the temporal and spatial scales can be related through the dispersion relationship for linear surface waves, $\sigma = \sigma(k)$, where σ is the radian frequency, and $k = |\mathbf{k}|$ is the magnitude of the wavenumber vector; but this only works if the wave slope, $ak << 1$ (linear waves), whereas more generally $\sigma = \sigma(k; ak)$. The most important departures from the linear assumption occur in the neighborhood of breaking waves of all scales, from long large gravity waves, to the much smaller, but just as steep, gravity-capillary waves. In the context of ocean optics, the fact that breaking occurs near the crests of the larger waves gives combinations of large surface displacements and large slopes, which can lead to significant departures from the simplest horizontal planar-surface assumption that leads to a simple Snell's cone. Breaking also leads to surface turbulence, which does not have a dispersion relationship, and therefore no explicit deterministic relationship between the length and time scales of the surface. At the larger scales, breaking also leads to significant air entrainment and the

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attenuation and scattering of light by bubbles. For all these reasons, a better understanding of the occurrence (statistics) and scales of breaking in the context of light transmission across the ocean surface, will lead to improved forward and inverse models of the oceanic radiance distribution. Figure 1 shows a schematic of the major components that will be deployed as part of the RaDyO field deployments off the coast of California. The centerpiece of the planned experiments will be the direct measurement of imaging through the surface using a subsurface display to generate test patterns and a color video camera above the surface. Additional and concurrent measurements include surface displacement (at various scales) as well as occurrence of breaking and air entrainment using Lidar, acoustic technologies, and underwater stereo-imagery.

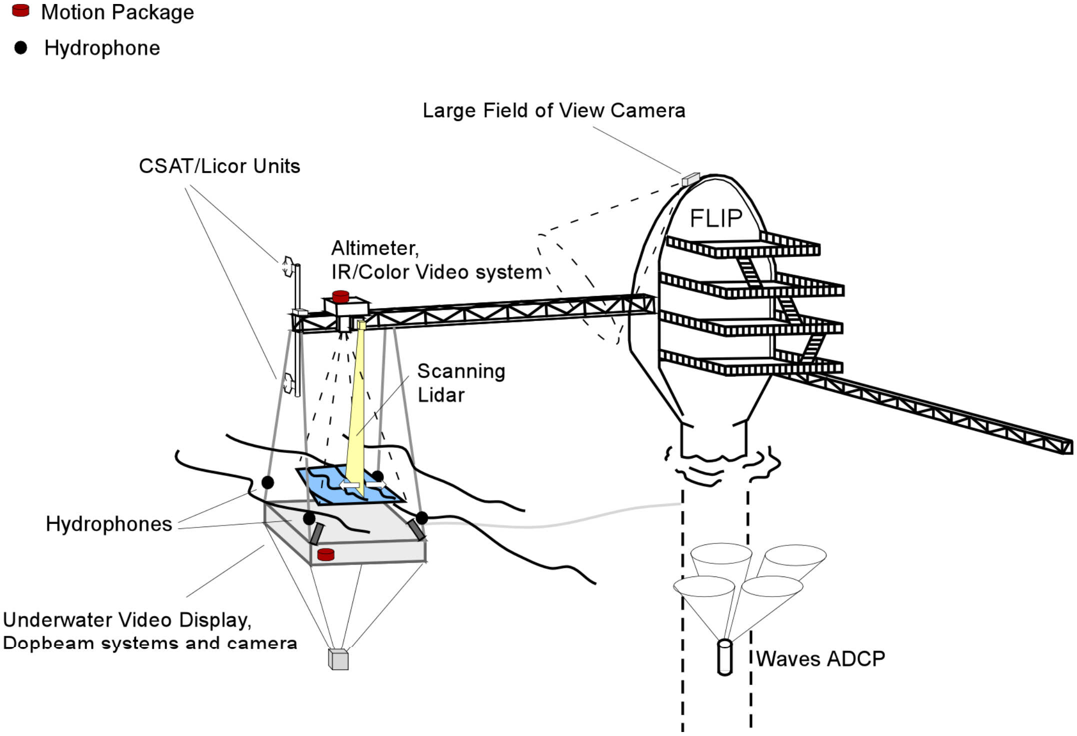

Figure 1. Schematic of the FLIP-based experiments showing the major components of the instrumentation and their deployment.

For imaging through the surface, one of the primary questions concerns the characterization of the fraction of time during which the turbulence and bubbles due to breaking will make any imaging impractical. This requires a statistical description of the probability of breaking over different length and time scales; the characterization of the time scales between breaking at a point; the distance between breaking events at a particular time, and the time scale for the disturbance (turbulence and bubble clouds) to decay to acceptable levels for imaging.

In a seminal paper, Phillips (1985) introduced, $\Lambda(\vec{c})d\vec{c}$, the average length of breaking fronts traveling with velocities in the range $(\vec{c}, \vec{c} + d\vec{c})$. The first moment of the corresponding scalar distribution, $c\Lambda(c)dc$, gives the area per unit area of ocean surface per unit time swept out by breakers traveling in the same speed range. Therefore, $\int_0^\infty c\Lambda(c)dc$ gives the area per unit area per unit time swept out by *all* breakers. If we assume that imaging is impractical during active breaking at a point, this gives a lower estimate of the probability of breaking interfering with imaging during any time interval. Using simple arguments, based on Froude scaling (that the length and time scales are related through the dispersion relationship) it may be shown that the whitecap coverage, the fraction of surface covered by breaking waves, is proportional to the second moment, $\int_0^\infty c^2\Lambda(c)dc$. Similar arguments applied to the depth to which breaking mixes the surface water (and also the small optically-significant bubbles) result in the volume of fluid mixed down by breaking per unit area per unit time being proportional to the third moment, $\int_0^\infty c^3\Lambda(c)dc$. Thus measurements of breaking are fundamental to a determination of the effects of breaking on the transmission of light through the ocean surface and the ability to image through the surface.

WORK COMPLETED

Laboratory Experiments

During this year we have completed a series of laboratory experiments designed to simulate the effects of wave breaking, entrained ar and gravity-capillary waves on the attenuation, scattering and refraction of light transmitted from the atmosphere.

Fall 2006 was devoted to the expansion of the current laboratory studies underway at the Hydraulics Laboratory, Scripps Institution of Oceanography. New measurements were performed using a 5W Argon - Ion laser continuously generating a vertical light sheet perpendicular to a wavy surface comprised of gravity-capillary waves generated using a fan mounted on the glass wave channel channel. Two high resolution cameras (TM4100CL Pulnix 4 Megapixels monochrome cameras, 25Hz sampling rate) provided detailed surface slope information as well as the simultaneous light distribution below the surface, enhanced by fluorescent dye (Fluorescein). The schematic layout is shown in Figure 1 and a photo of the setup is in Figure 2.

Figure 3 shows a waterfall plot (upper panel) of the surface profiles over a horizontal extent of approximately 9 cm for wind-generated waves. The lower panel shows the image of the surface profile at time t_o and sequential images at t_o - 0.04 and t_o - 0.08 seconds. Note the parasitic capillary waves on the forward face of the longer gravity-capillary waves, a ubiquitous feature of wind-driven water surfaces. The impact of these parasitic capillary waves is to strongly modulate the subsurface light intensity.

This is demonstrated in Figure 4, where we show in the upper and middle panels simultaneous images of the surface and the subsurface. Note the strong modulation and caustics in the subsurface image. The lowest panel is a computation of the subsurface image using geometrical optics and the measured surface (shown as a red profile) in the middle panel. Note the good agreement between the measured and computed subsurface image, especially the location of the caustics.

Preparation for the RaDyO SIO Pier Experiment

As hosts for the RaDyO SIO pier experiment in January 2008, a significant effort has been made to prepare for this three-week experiment. The most visible aspect of this preparation so far has been the design, construction and installation of a new instrument boom on the NW corner of the pier, which is shown in Figure 5. Along with the original boom on the SW corner of the pier, this will provide RaDyo PIs with unprecedented access to incident wind and wave fields from the west. Other aspects of preparation for the pier experiment that are still in progress include the installation of two new lab spaces on the pier and the provision of trailer/office space just east of the entrance to the pier.

Preparation for Field Experiments

A: For the RaDyO Community

The PI organized and hosted a planning workshop for the RaDyO program at Scripps June 6-8, 2007. As part of that workshop a visit to R/P FLIP at SIO's MARFAC facility on San Diego harbor was arranged to familiarize the RaDyO PIs with FLIP and its capabilities. As a result of that visit it was decided that the port boom of FLIP did not have the capacity to support all PIs needing unimpeded boom access. It was agreed that a second boom on the starboard side would be needed to accommodate the required space. The PI arranged for Eric Slater, a retired SIO engineer with many decades experience on FLIP to design and cost a second boom. Submission of the proposal to ONR for construction of this boom is imminent.

B: For the PI's Program

Work has proceeded to design and build the subsurface light panel (LED array) for optical transmission and imaging through the ocean surface, along with the above surface imaging system and the related supporting measurements. This system will be tested during the SIO pier experiment in January 2008.

RESULTS

The primary technical result in the last year has been the demonstration of the value of the laboratory experiments in demonstrating our ability to measure the fine-scale structure of a wind-driven water surface down to the scale of capillary waves (mm) and use the measured surface to predict the refraction of the incident light from above the surface into the water column.

IMPACT/APPLICATIONS

It is too soon for there to be any impact or applications of this work beyond the RaDyO program.

TRANSITIONS

None

RELATED PROJECTS

None

REFERENCES

Phillips, O.M. Spectral and statistical properties of the equilibrium range in wind-generated gravity waves. *J. Fluid Mech.*,156, 505-31, 1985.

PUBLICATIONS

None

PATENTS

None

HONORS/AWARDS/PRIZES

None

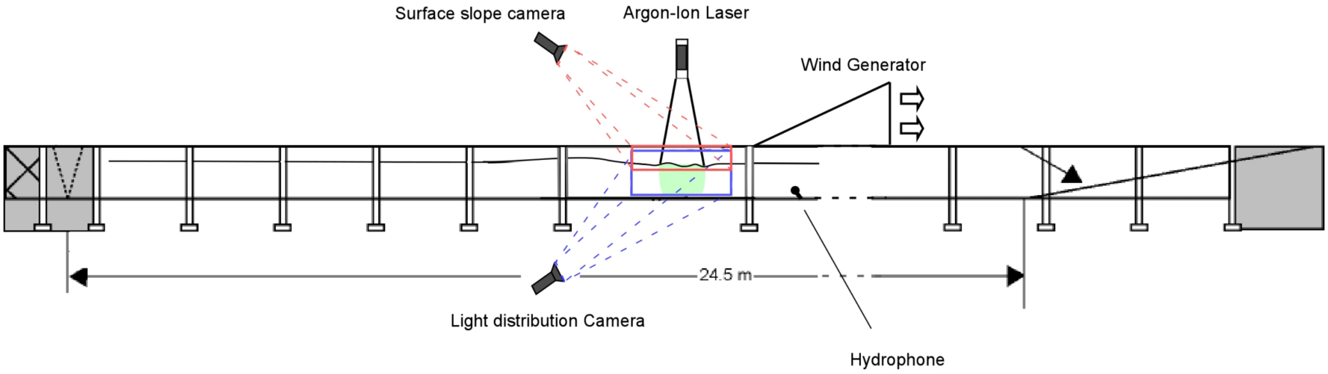

Figure 1: Schematic of the laboratory experiment in the glass wave channel in the SIO Hydraulics Laboratory. Two high resolution cameras are used to measure detailed surface slope and its effect on subsurface light distribution.

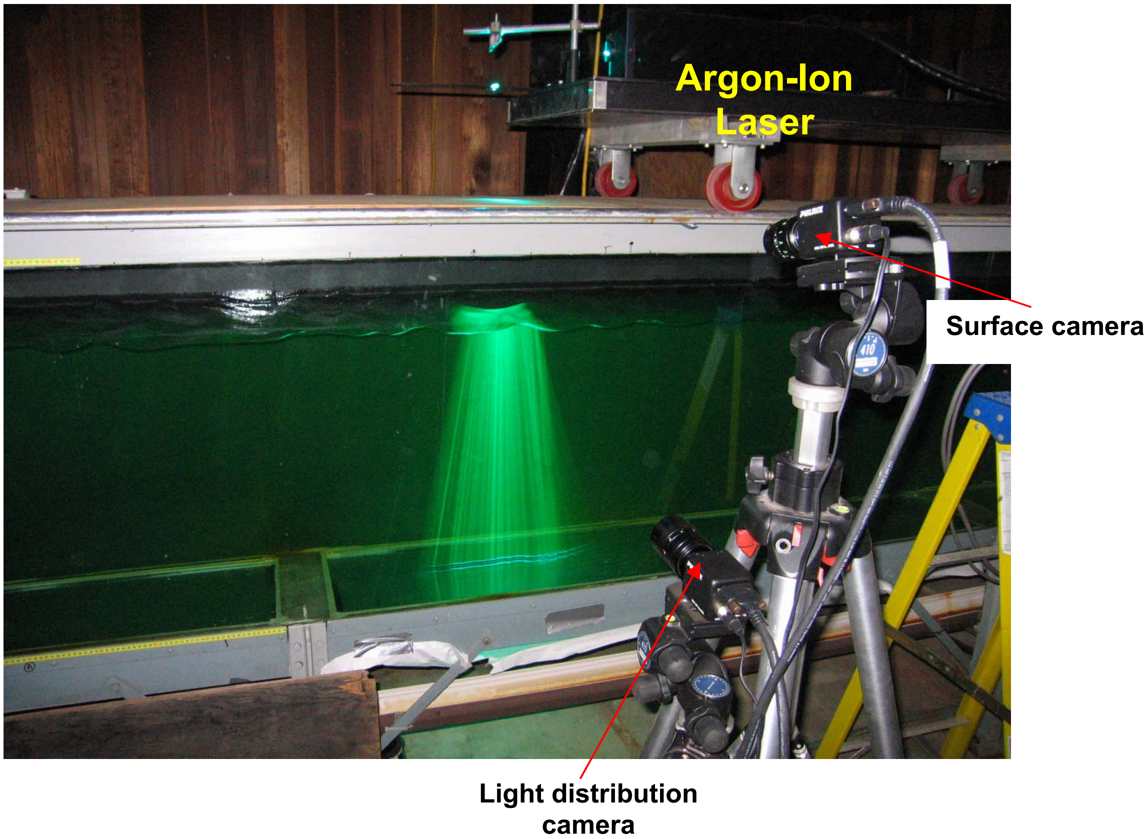

Figure 2: Laboratory Setup.

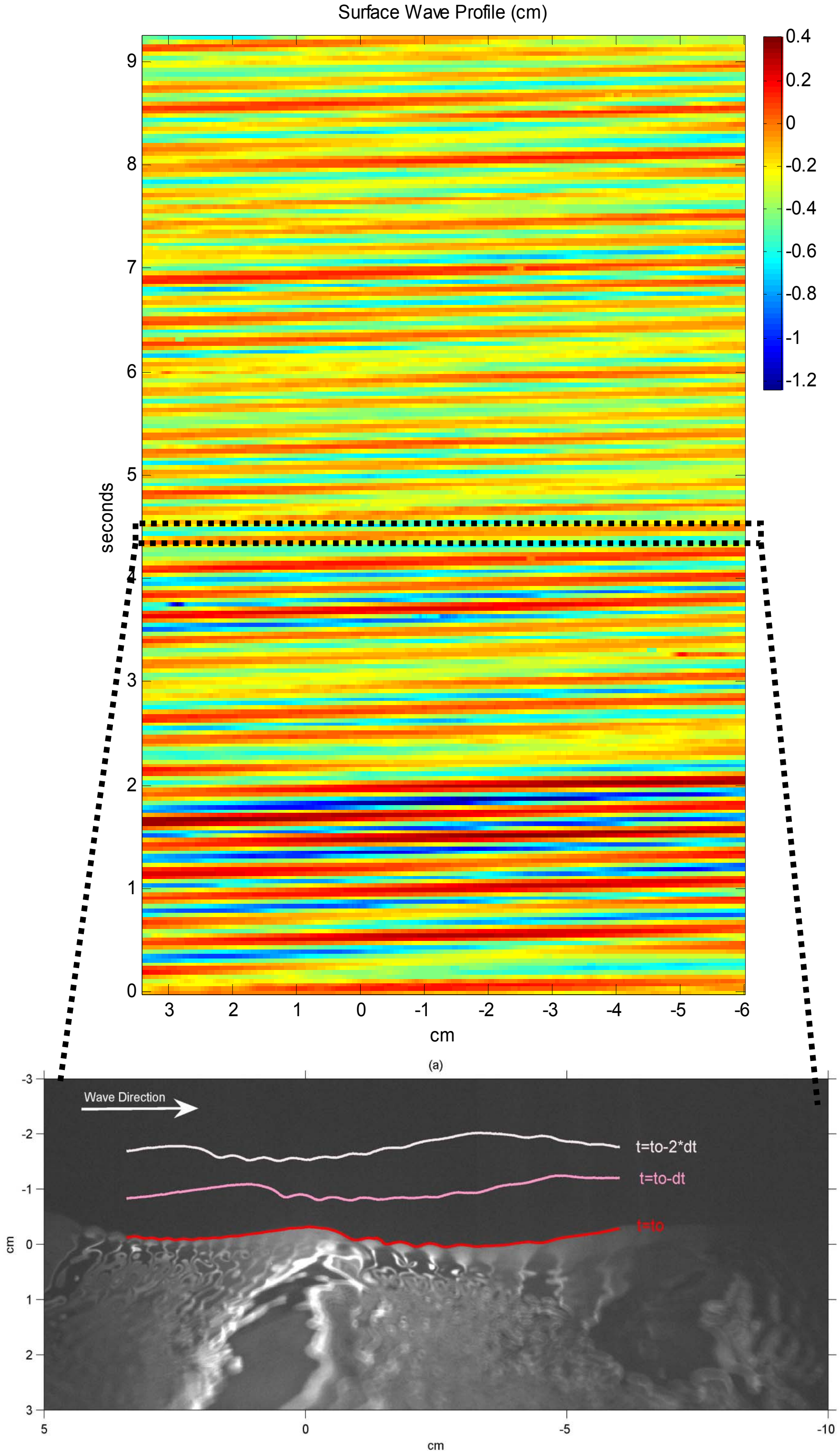

Figure 3: Surface wave profiles are detected using the upper camera. The subsequent profile is then smoothed using an 8-pixel running mean filter. (a) shows 3 sequential profiles (dt=1/25s). Image corresponds to t=to.

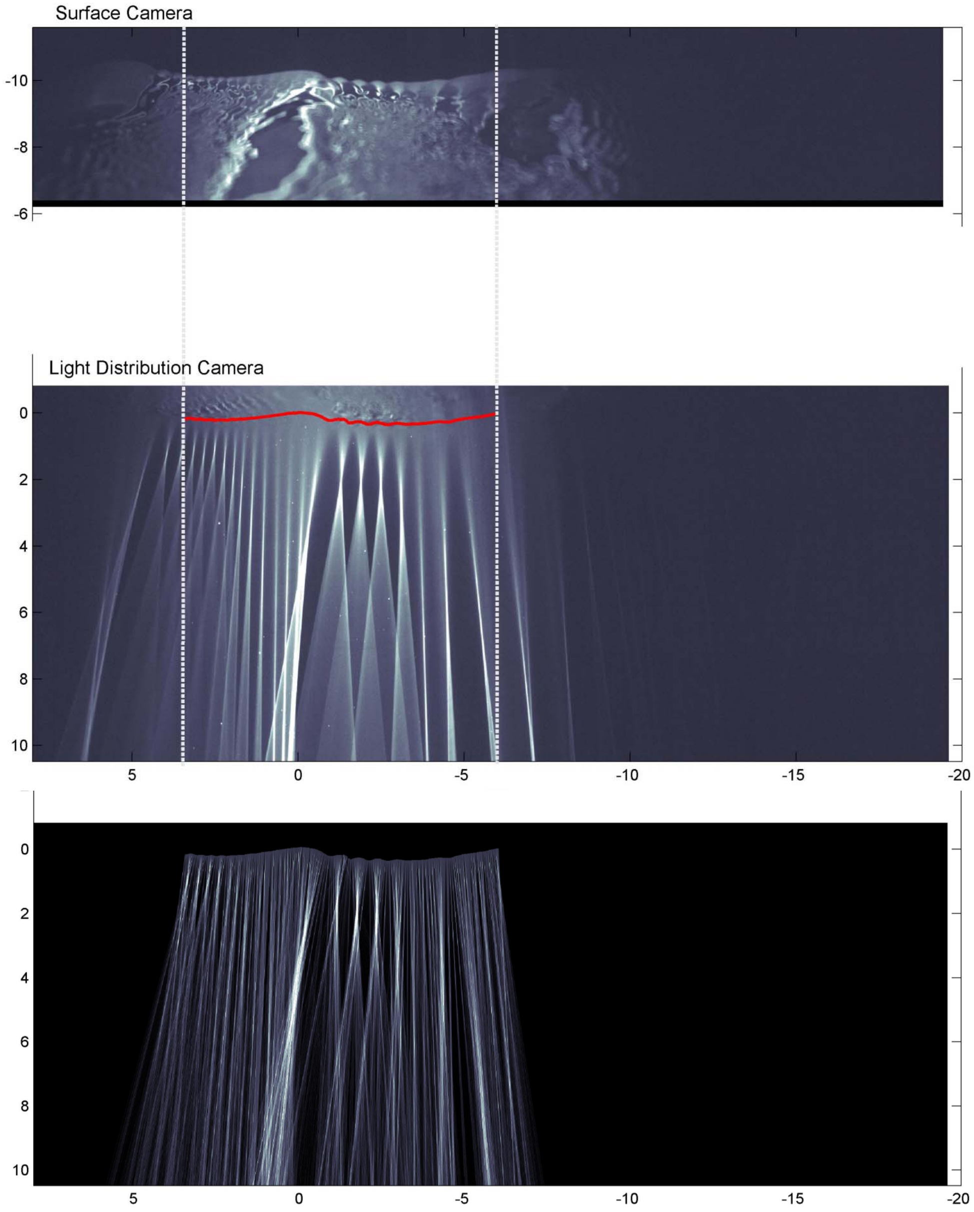

Figure 4: Upper and middle panels: Synchronized surface and subsurface images, respectively. The subsurface light distribution is modulated by the waves. The surface image is plotted with a 10cm vertical offset for display purpose. The measured surface is also shown in red in the subsurface image (arbitrary color scale units).The lowest panel shows the calculated subsurface image using geometrical optics and the measured surface profile. Note the good agreement between the middle and lowest panels.

Figure 5: SIO pier showing the new boom off the NW corner.