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ACOUSTICALLY OBSERVED BUBBLE CLOUD EVOLUTION UNDER DEEP-WATER BREAKING WAVES

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Abstract: *A novel multi-beam system was deployed in an uplooking configuration to probe into the crests of breaking waves. The deployment was in 4000 m water depth, with typical winds of 10 to 15 m/s. Several breaking events were captured, and one is examined in detail. The breaking wave displays a phase lag with depth that is not seen in non-breaking waves. The bubbles injected mix to several meters depth within a few wave periods. The bottom boundary of the bubble layer is fairly sharp.*

Keywords: *Bubbles, wave breaking, turbulence, air-sea exchange, gas flux*

1. INTRODUCTION.

One of the greatest challenges in the study of the air-sea interface is presented by breaking waves. Entrainment of gases and the expulsion of droplets and particles by breaking waves are of primary importance to gas fluxes in particular and air/sea exchanges in general [1-3]. The surface roughness and turbulence near the surface are key to understanding the kinematics and dynamics of this elusive interface. Unfortunately, it is nearly impossible to obtain measurements closer than a meter or two below actively breaking wave crests, although many promising techniques are being developed [4-10]

High-resolution ultrasound measurements from an up-looking phased-array system are presented. The system provides digitally beamformed measurements over "pies" about 22 degrees wide by 16 m maximum range, with resolutions of about 1.5 degrees by 5 cm. The instrument was mounted 13.5 m below the mean surface, so the cell size near the surface is about 5 cm (vertical) by 30 cm (along-wind). Sequences of intensity images form a “movie” that can be analyzed for motion as well as for relative scatterer (bubble) density.

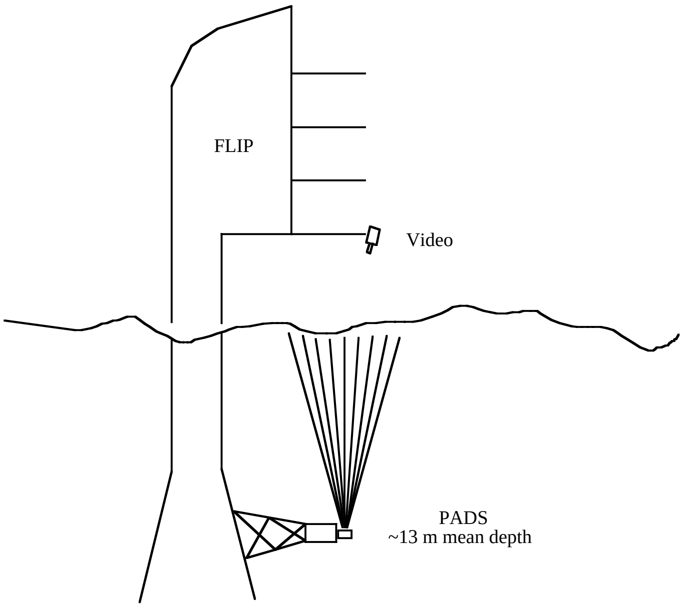

Fig. 1: Schematic of the deployment on FLIP. The experimental site was some 200 West of San Diego, in 4 km water depth.

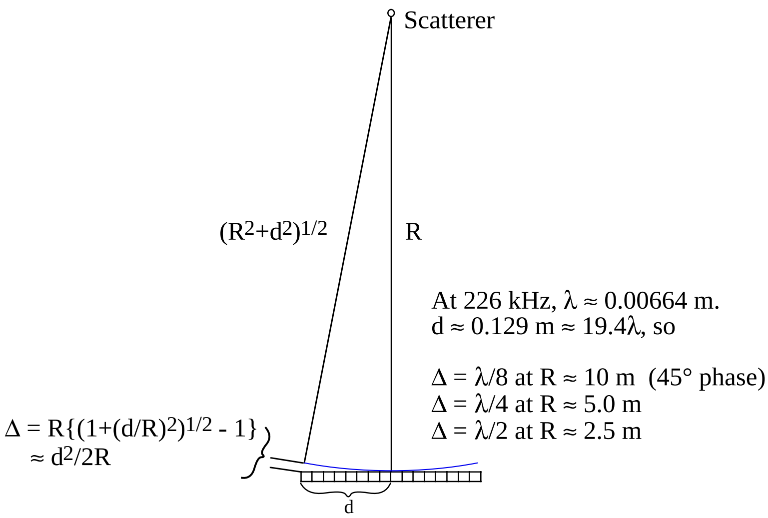

Fig. 2 The need for focus. In practice, the 5 m cutoff (90° phase criterion) appears the most appropriate; beyond this the images produced with and without focusing adjustments are hard to distintuish.

2. EXPERIMENTAL SETUP

The objective was to get high-resolution, high sample-rate acoustic measurements over a two-dimensional vertical “slice” of water extending right up into the crests of breaking and non-breaking waves. A 225 kHz “Phased-Array Doppler Sonar” (PADS) was mounted on an external strut about 6 m from the hull of FLIP (Fig. 1). The PADS was configured to provide

16 beams, formed digitally from a linear array, covering a 22° wide pie-shaped wedge (1.4° resolution). The thickness of the "pie" is about 3.6°. With a usable bandwidth of up to 25 kHz, range resolution to ~3 cm was possible. At a nominal depth of 13 m, sound can be projected to the surface and back over 50 times per second, providing the desired high sample rate. To minimize the interference from previous pings, the delay between pings was staggered between two values (thanks to Tim Stanton, NPGS, for this idea). The two delays also provide the potential to help unwrap the phase-change from one sample to the next; although Doppler processing of this particular data has not yet been attempted. For this experiment, the PADS was operated in a simple intensity-measuring mode. Over these short ranges, focusing can be required (Fig. 2). For ranges beyond a meter or two, focusing can be achieved with a simple range-dependent phase adjustment prior to beamforming. For the beamforming parameters here (pulses more than 10 cycles long; Nyquist wavenumber-angle corresponds to only 8 cycles across the array), simple FFT beamforming is suitable.

To provide visual verification of breaking, and video analysis potential, a video camera was mounted looking down on the surface covering an area of the surface above the vertical "slice" probed by the PADS.

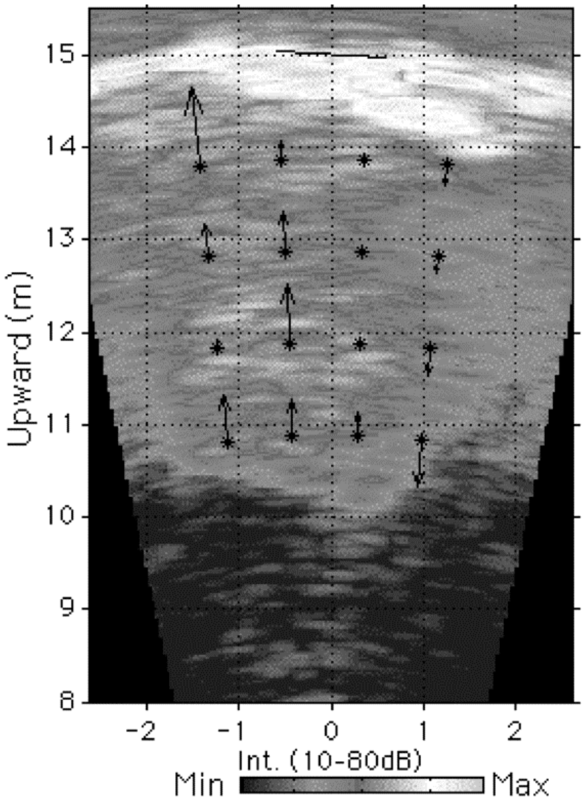

Fig. 3. One frame from a time series of vertical-slice images under a breaking wave. The wave is propagating from right to left. The upper edge of the region of highest backscatter (light) provides an estimate of the surface location, illustrated by the line segment crossing x=0, y=15 m. The wedge extending down and to the right from the highest point on the surface is produced by a cloud of bubbles being actively injected by the breaking wave. Over time this bubble cloud penetrates between 2 and 3 m below the surface. A time-delayed correlation technique (PIV) was used to track the mean motion of 2 m squares in the vertical. A set of 16 squares were tracked, centered on the locations indicated by asterisks (*). Arrows indicate estimated vertical velocities of each square at the time of the picture.

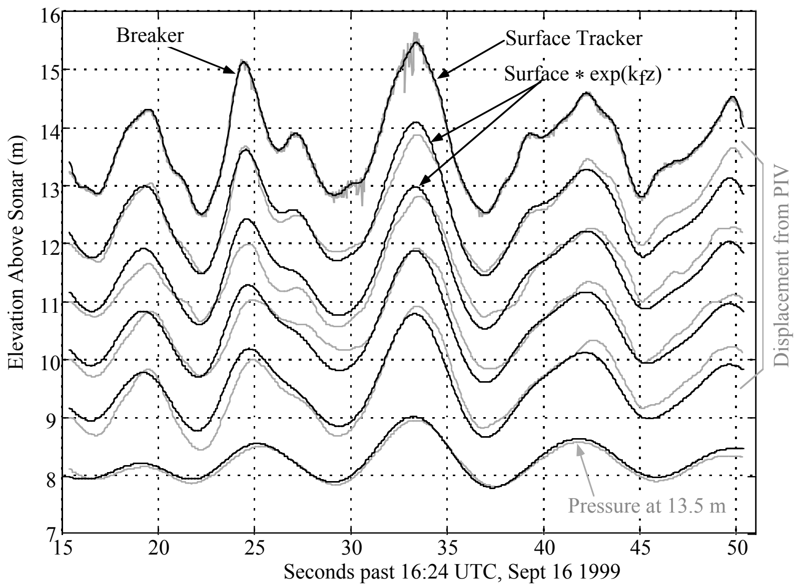

Fig. 4. Time-series of (equivalent) vertical displacements at and below the surface. The uppermost trace is from a "surface finder" threshold-based routine. Intense bubble clouds can cause dropouts (jagged gray line), so that de-spiking is needed to produce a more reasonable surface estimate (superimposed black line). This trace is characterized by motions near 8 and 5 second periods. Time-delay correlations produce velocity estimates from the heterogeneous intensity fields; these were integrated to synthesize equivalent displacements versus location below the surface ("Displacement from PIV", gray lines). The pressure at 13 m mean depth was also recorded (lowest gray line). For comparison, an equivalent trace at each depth is computed from the surface track (black lines) using exponential decay versus frequency computed from linear dispersion. Breaking occurs for the second peak, near T = 24.5 s.

3. RESULTS

The data show breaking and bubble cloud evolution in several events. About a dozen breaking events were documented. One event was selected as being particularly "clean," in the sense that the interference due to the nearby hull of FLIP was minimal for the particular wave direction. The data presented were obtained as a wave of about 2.5 m height crest to trough passed through the field of view while breaking (one of several breakers captured over a two-week deployment from R/P FLIP). Figure 3 shows a frame from a PADS movie of acoustic intensity, from data taken at 16:24:24.41 UTC, 9/16/1999 (9:24 am local time) on the open ocean (~4000 m deep) about 200 km west of San Diego, CA.

By tracking features in time and space over the 2D sample area, the background velocity field can be estimated (Figure 8). One significant feature is the surface. However, by its nature only the vertical velocity can be estimated there. The surface is located in each frame as follows: Beamforming is over-resolved, producing 31 beams from the 16 receivers (the Nyquist wavenumber is not processed). Analysis is restricted to the centre 13 beams, ranges 8 to 16 m. Along each beam, the nearest range after the maximum that falls 13 dB below the maximum is identified. The 3 farthest outliers from the median of the 13 values are rejected. A line is fitted to the remaining points, providing the surface location and slope directly above the sonar. Finally, the time series of height and slope are de-spiked (median filtered using 15 points). Dropouts introduced by dense bubble clouds are an issue, and this procedure was developed to minimize the effect.

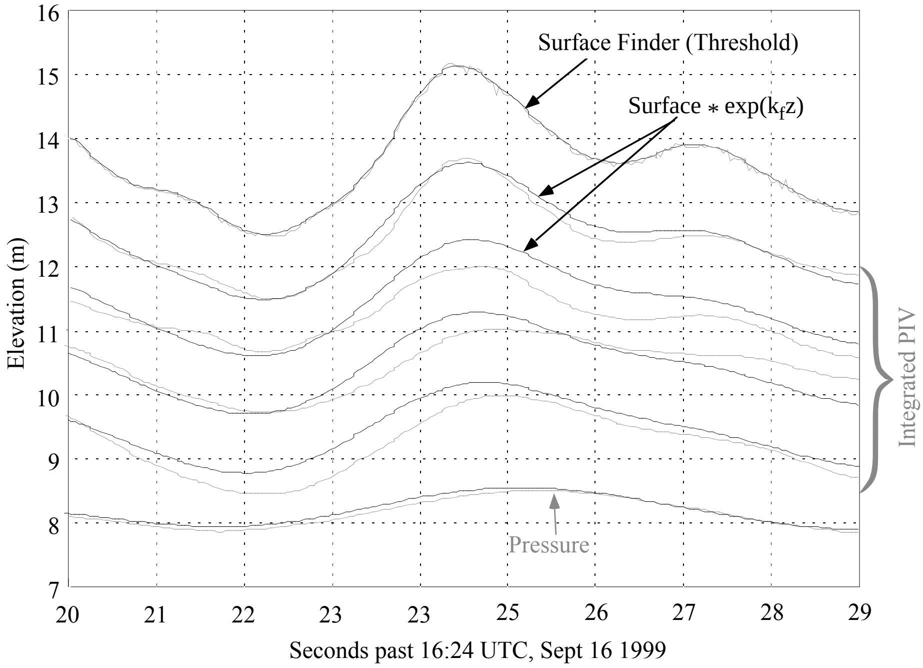

Fig. 5. Closup of the estimated displacements vs. depth under the breaking crest. Otherwise as in Fig. 4

This prototype crest-penetrating deployment shows promise, and performance could be improved significantly with a few modest adjustments: (1) A transmitter with much narrower beampattern in the cross-pie direction is needed, to bring that dimension of the sample area into line with the other two spatial dimensions. (2) A position closer to the surface would both reduce the along-wave cell size and increase the permissible sample rate. For example, from 5 m below the surface horizontal resolution at the surface becomes 10 cm, and sample rates up to 150 frames per second are possible. At these rates, coherent phase changes from one ping to the next could be used to refine vertical velocity estimates (actually radial velocity from the sonar) after an initial estimate from feature tracking. The ambiguity velocity would be around 30 cm/s for 200 kHz sound. (3) More receivers would also help to refine the angular resolution; doubling the number and reducing the range to 5 m would result in 5 cm resolution in both vertical and horizontal. It would appear that much could be learned about the velocity and turbulence structure under breaking waves by this approach.

4. CONCLUSIONS

- Sound can be used to probe into the crests of breaking waves

- Surface tracking requires many beams to provide a robust estimate of surface location (e.g., a median), due to random blocking by dense bubble clouds

- Particle imaging velocities (PIV) appear sensible, and might be used to unwrap coherent (pulse-to-pulse) phase estimates for Doppler velocities.

• Vertical displacement vs. depth from integrated PIV appears sensible. Of note: deeper displacements lag the shallow in time.

• Dynamics of the near-surface shear layer (about one wave amplitude thick) should be re-examined. In particular: wave-shear interactions and resulting excess strain of the layer.

• Dissipation might be estimated from time-lagged coherences. But coherences must be averaged in a frame that tracks the scatterers as they move with the wave orbital motion.

5. ACKNOWLEDGEMENTS

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