Bubble Entrainment by Breaking Waves and their Effects on the Inherent Optical Properties of the Upper Ocean

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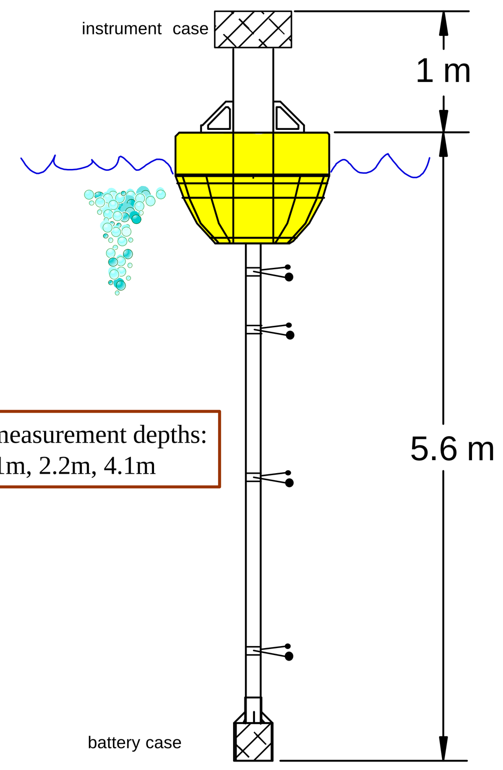
INTRODUCTION.

Breaking waves at the ocean's surface inject bubbles and turbulence into the water column. During periods of rough weather, the scales of wave breaking tend to increase with increasing sea states, resulting in mixing of the surface waters and the turbulent transport of bubbles to depth. Bubbles can significantly change the optical properties of water depending on their concentrations and size distribution, introducing potentially significant errors in retrieval of remotely-sensed hyperspectral data products.

The development of acoustic bubble measurement techniques now allows for oceanic bubble size distributions to be resolved across a wide range of radii with high temporal resolution. Field measurements of bubbles are presented and their effect on the inherent optical properties are estimated using Mie scattering calculations.

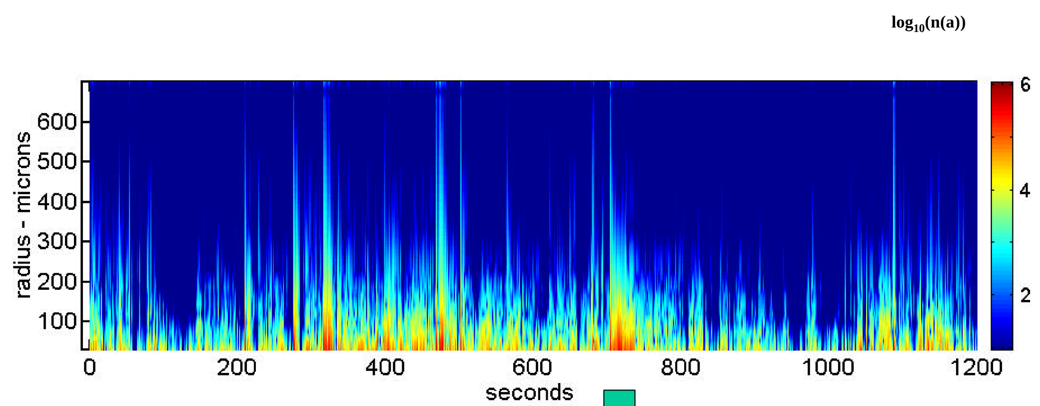
FIELD MEASUREMENTS OF BUBBLE SIZE DISTRIBUTIONS

Broadband acoustic techniques are used on a lightweight buoy package and can be deployed in both moored or freely drifting modes. Data is shown from an experiment which took place off Point Conception, California in June, 1997. Bubble size distributions were measured at 2 Hz while the buoy freely drifted. Bubble densities were found to vary several orders of magnitude as a result of the instrument drifting into bubble clouds formed by breaking waves.

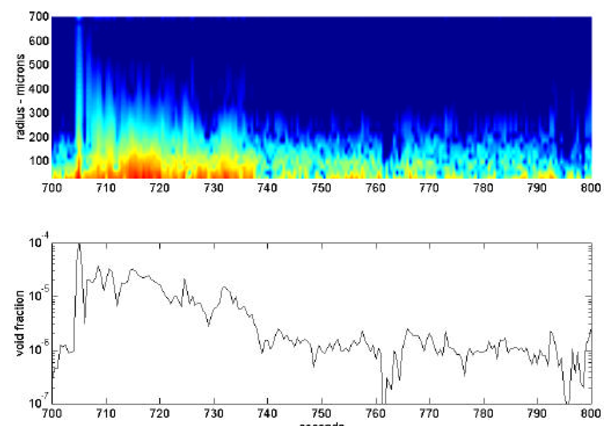


Bubble measurement depths: 0.7m, 1.1m, 2.2m, 4.1m

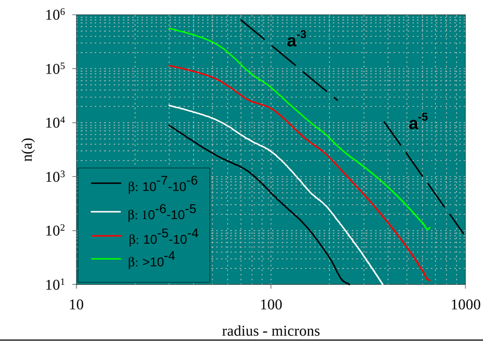
A 20 minute time series of the bubble size distribution measured at a depth of 0.7 m in wind speeds of 15 m/s and significant wave heights of 3.2 m. The logarithm of the bubble density, in units of number bubbles/m³/µm increment, is mapped to the color scheme shown. The bubble densities are highly variable due to intermittent wave breaking.



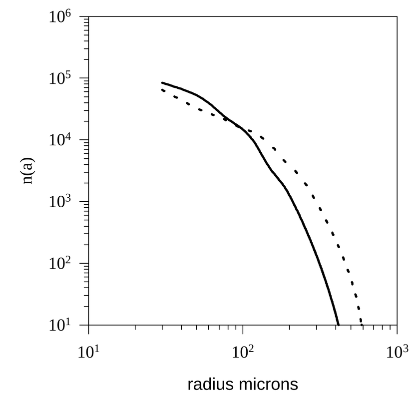
An expanded view of the bubble size distribution for the event that begins near t = 700 seconds. Shown below is the void fraction of the bubbly mixture. The plot shows the variability in the bubble field - the void fraction varies by approximately 3 orders of magnitude for the 100 second period.



Variability in the bubble size distributions

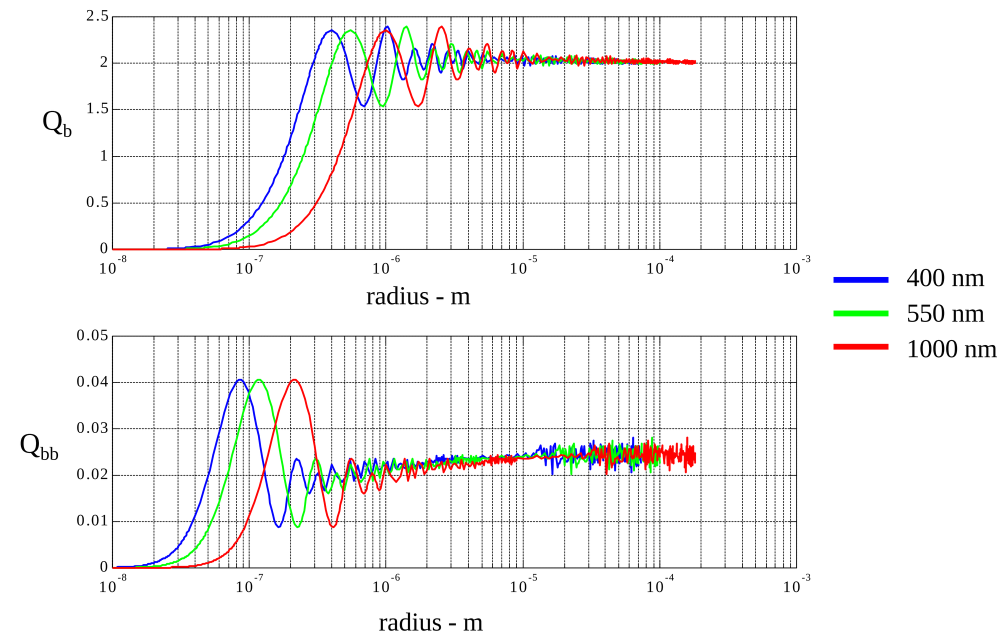


Averaging the bubble size distributions according to their void fraction highlights the variability that can exist in oceanic bubble populations (above). Variability will also be present due to Langmuir circulations (see below).



Comparison of the bubble size distributions measured outside the convergent zone of a Langmuir cell (solid line) and inside the convergent zone (dashed line) at a depth of 0.7 m. More larger bubbles tend to exist inside the convergent zones as resulting of the downwelling.

OPTICAL PROPERTIES OF BUBBLES

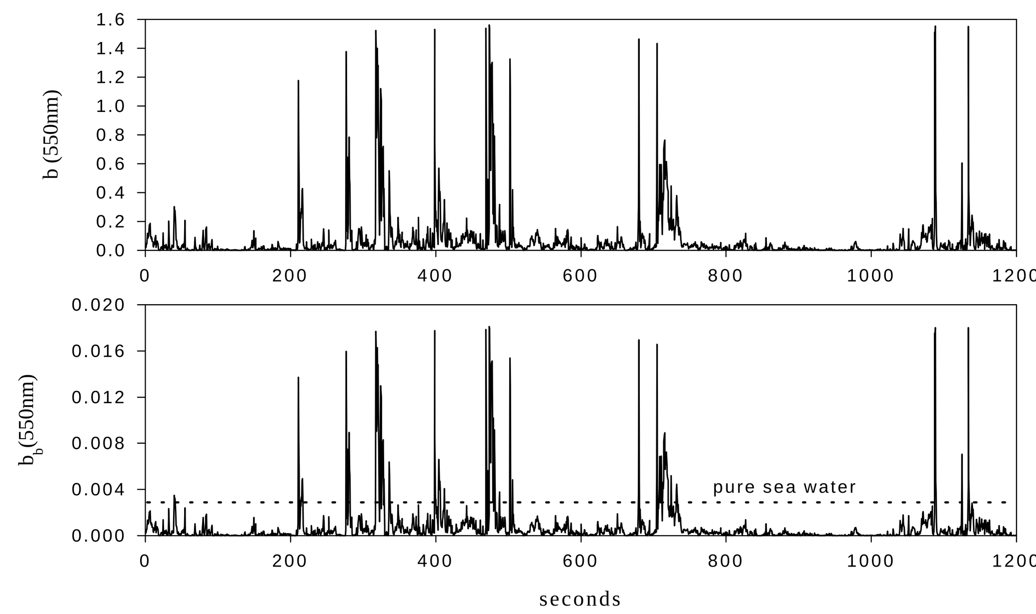


The scattering efficiency factor, Q_b, and the backscattering efficiency factor, Q_{bb}, can be determined for different light wavelengths and bubble radii using Mie scattering calculations (Bohren & Huffman, 1983). The contribution of a given bubble size distribution to the bulk inherent optical properties can be calculated by treating the bubbly water as a mixture of random scattering particles, whereby the bulk properties are a sum of the contributions by the individual bubbles (Stramski 1994, Mobley 1994). The bulk scattering coefficient and backscattering coefficients for a given bubble size distribution is typically found through numerical integration over the range of radii present using 1 micron increments.

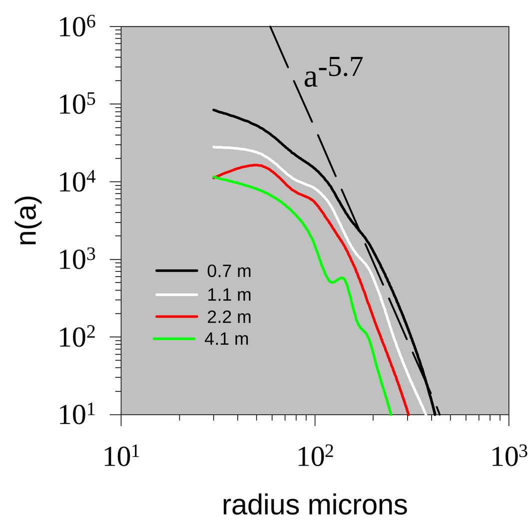
$$b(bubbles) = \int Q_b \pi a^2 n(a) da$$

$$b_b(bubbles) = \int Q_{bb} \pi a^2 n(a) da$$

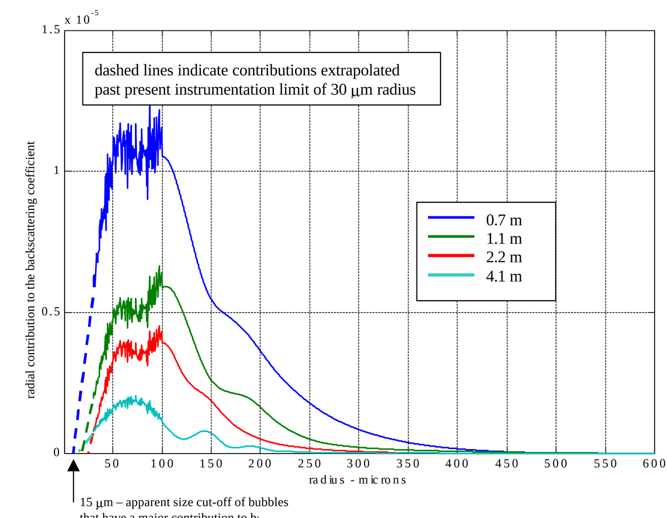
GENERATE TIME SERIES OF THE BUBBLE SCATTERING COEFFICIENTS (550nm) FROM FIELD MEASUREMENTS



Twenty minute time series of the total scattering, b, and backscattering coefficients, b_b, (light wavelength of 550nm) calculated from the bubble data obtained off Point Conception, California at a depth of 0.7m. Note the episodic nature of the scattering coefficients due to the variable nature of the bubble densities.

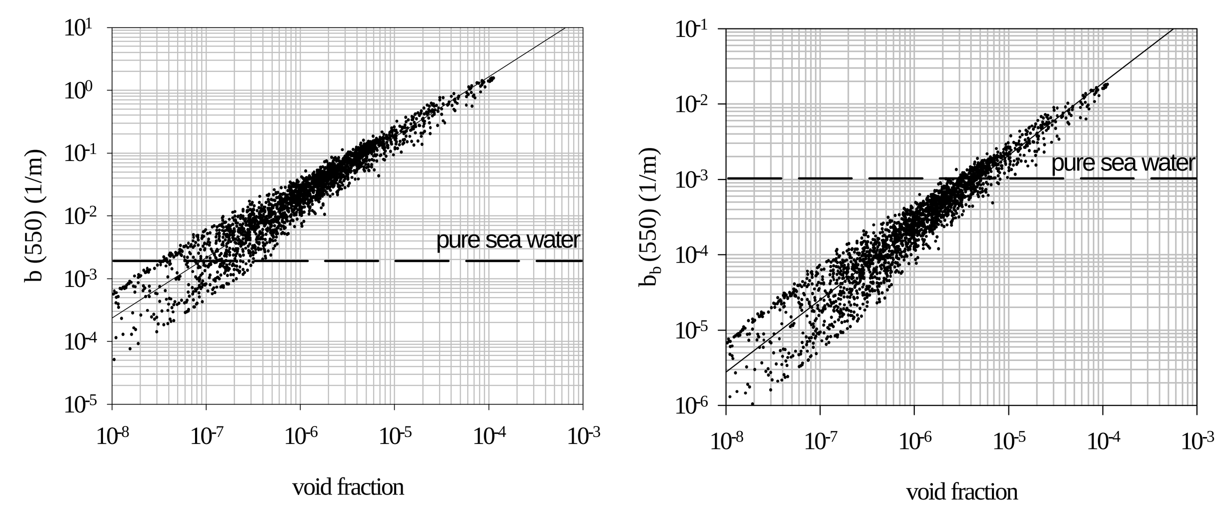


The mean bubble size distributions measured at four different depths. The distributions appear to follow a power law for radii greater than 100µm.



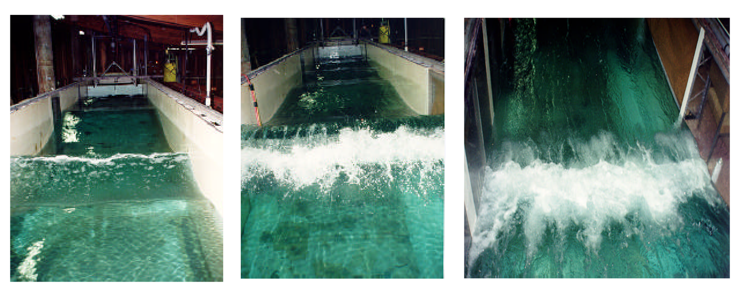
The contribution to the optical backscatter (b_b) as a function of bubble radius. The data suggests that bubbles with radii between 50-100µm contribute the most to the bubble contribution to optical backscatter while extrapolation of the data to smaller radii suggests that radii smaller than 30µm contribute less than 5% to the bubble mediated optical backscatter.

Optical scattering due to bubbles as a function of the volume of air entrained.

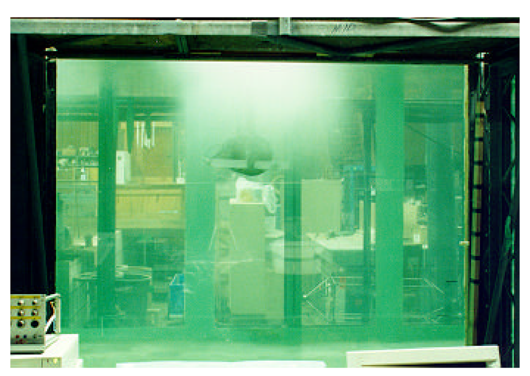


Scatter plots of b and b_b versus the void fraction of the entrained bubbles. Shown for reference are the scattering coefficients for pure sea water. The data strongly suggests that the optical effects of the bubbles on b_b, and hence the remote sensing reflectance, will be significant at void fractions above 10^{-6}.

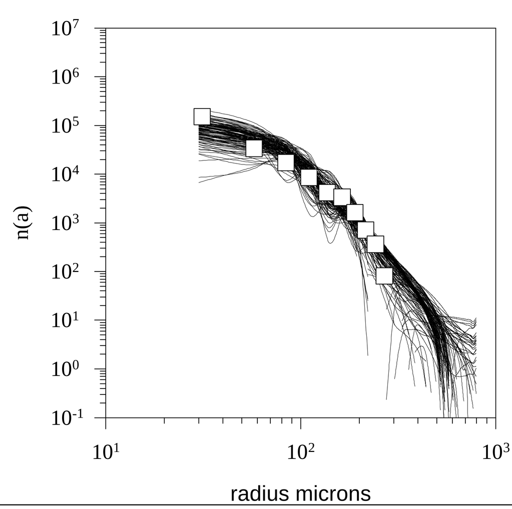
LABORATORY TESTING OF ACOUSTIC BUBBLE SIZING BENEATH BREAKING WAVES



Bubble size distributions are determined by the inversion of broadband (4kHz-100kHz) acoustic signals transmitted between a source and receiver hydrophone pair separated by a fixed pathlength (Terrill 1998, Terrill & Melville 1998). The acoustic technique has been tested beneath laboratory generated breaking waves in seawater using an independent optical bubble sizing technique(Geissler & Jahne 1997) and found to give good results.



Images of the laboratory generated breaking wave and the resulting bubble cloud.



Bubble size distributions measured at depth of 0.6m by both the acoustic technique (solid lines) and an optical bubble counting technique (hollow squares).