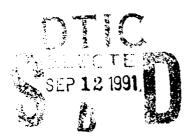# Naval Research Laboratory

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A Survey of Scattering, Attenuation, and Size Spectra Studies of Bubble Layers and Plumes Beneath the Air-Sea Interface

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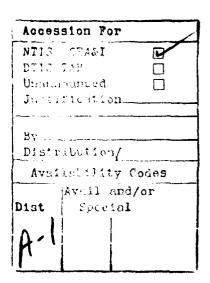
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13. ABSTRACT *(Maximum 200 words)*

Previous and ongoing research relating to acoustic scattering and attenuation by sub-surface oceanic bubble layers and clouds is surveyed within the context of sea-surface scattering and the parameters relevant to numerical modeling. Bubble concentration and size spectra measurements are addressed, as are theoretical and numerical studies of bubble cloud ("plume") generation processes and scattering mechanisms. Related studies of oceanic processes such as Langmuir circulation, wavebreak plume injection, and the biological bubble component are discussed. Conclusions are drawn regarding the current understanding of phenomena and the availability of sufficient data.

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CONTENTS

A SURVEY OF SCATTERING, ATTENUATION, AND SIZE SPECTRA STUDIES OF BUBBLE LAYERS AND PLUMES BENEATH THE AIR-SEA INTERFACE

1 INTRODUCTION

It is clear that the role of bubble layers and clouds in ocean acoustics is an important one. That there has been a historical discrepancy between theoretical interface scattering predictions and experimental observation has probably been the dominant driver for motivating a continuing investigation of bubble scattering phenomena, once considered incidental to acoustic propagation. With the refinement and maturation of competing interface scattering theories it became necessary to closely examine the other factors at work.

This report is a survey of some representative studies relevant to current knowledge of ocean sub-surface bubble populations and the cloud-like structures protruding down from the bubble layer, known as plumes. Since the literature on sub-surface bubbles and their acoustic phenomenology is extensive, it has been impractical to attempt to discuss all articles on the subject. Some works are discussed at length, while others are only briefly summarized (usually from abstracts of presentations); where possible an attempt has been made to go into detail with regard to descriptions of research. The purpose has been to provide summaries of work useful for determination of bubble-related propagation, scattering, and reverberation issues of importance to modeling, as well as to provide a guide to the literature on the subject.

Where possible a phenomenological focus is maintained, with the desire to highlight the available experimental information of importance to the underwater acoustics modeling community. There has been an effort to discuss most works in the context of other pertinent research, and to cross-reference related studies. It was decided to group the studies chronologically, but within three categories: one for those articles addressing measurements or interpretation of data taken at sea, another for laboratory studies, and the third to discuss theoretical or numerical work. While there obviously is some overlap, this division seems instructive.

In all cases the units of the authors have been retained in the discussions. Attention to the authors' text is especially recommended with regard to environmental parameters. For example, a general caveat is that the instantaneous wind speed (whether referenced to 10 m or to 19.5 m) is not always an accurate descriptor of the sea conditions ("sea state"); the wind

history is important for not-fully-developed seas. Since occasionally such measurements are not mentioned, or possibly an author may assume there to be a fully-developed sea state, attention should be given these matters in comparing results.

The following section provides a list of the papers discussed.

2 LIST OF PAPERS DISCUSSED

Measurements at Sea

Laboratory Studies

Theoretical and Numerical Studies

3 MEASUREMENTS AT SEA

While the experimental situation at sea is one in which it is difficult to separate the effects of pure interface (rough surface) scatter from those of the bubble layer and plumes, only bubble-oriented studies are examined here. Studies of rough surface scattering per se are not considered, although some important papers have been included in the references. With a few exceptions [48] research on the bubble layer's ambient sound field is not addressed. The subject of the dynamical effects of wavebreaks in the upper ocean is not considered, although the interested reader may read [74] as well as a number of the titles included in the references. Those desiring to review the related work on electromagnetic scattering from foam plumes above the interface may pursue [199] and [82].

Historically, measurements and interpretation of bubble concentrations and spectra at sea date back over several decades. In the seventies the measurements of Medwin and others provided a basis for assessing bubble phenomena in the air-sea interface and planning for ensuing experiments. The 1979 Johnson and Cooke study [81] provided corroborative optical determinations of bubble size spectra. Wu's 1981 analysis [206] addressed the differences in observed size spectra measured in warm, open sea regions versus those measured in cold, coastal areas, comparing the results of available measurements at the time. Thorpe's work [175], [176] in the mid-eighties was a serious attempt to show Langmuir flow to be a viable mechanism for deep plume generation from the background of bubbles presumed supplied by wavebreaks. (While the detailed dynamics of this process remain unclear, its importance as a contributing mechanism is now taken very seriously). The works of Farmer and Lemon [47] and Crawford and Farmer [30] provided further acoustical determinations of bubble/plume populations.

While variations in size distributions may not strongly affect systems at most frequencies of interest, the concentrations are important. The overall environmental variations in plume spatial and temporal occurrence are critical to scattering analysis. For many years these were not well characterized due to sparse data and due to the very limited simultaneous measurements of surface scattering and environmental bubble data.

Prior to 1987 much of the available data was taken by various researchers working near Monterey Bay, California. There was a critical need not only for more measurements, but in a variety of locations and environmental conditions. Walsh and Mulhearn conducted photographic measurements in the Tasman Sea [192], and with the completion of the LA PEROUSE (British Columbia) and Frontal Air/Sea Interaction Experiment (FASINEX) measurements [48] south and west of Bermuda, and the previous works at the North Sea platform NORDSEE [72], [97] the geographic and environmental database improved sig-

nificantly. During the OCEAN STORMS (1987-1988) experiment Langmuir circulation velocities were studied during severe storms. More recent experiments such as the Surface Wave Processes Program (SWAPP), conducted with the FLIP platform about 800 kilometers west of Los Angeles, and the Surface Wave Dynamics Experiment (SWADE), which was located about 200 kilometers southeast of Norfolk, Virginia, offer valuable additions to the available empirical information.

The SWAPP experiment was completed in the winter of 1990 and preliminary results have provided data on the initiation, evolution, and dissipation of Langmuir circulation under different wind and wave conditions. In particular, the Langmuir process was observed under light wind conditions, lending further credence to a threshold near 3 m/s. For the SWAPP measurement individual wavebreak events were detected and tracked using a 3-dimensional hydrophone array. This has resulted in some unique data on the dynamical interactions of wavebreaks, bubble clouds, and Langmuir flow.

1. **"Langmuir Circulation Observed by Sonar," S.A. Thorpe, J. Acoust. Soc. Am. Suppl. 1., Vol. 88, Fall 1990 (120th meeting, November 1990, San Diego, California).**

Results are shown for upward-pointing HF sonars used to examine the ocean surface boundary layer structure. Pulsed 90 and 250 kHz upward tilted sidescan sonar data reveals linear bands of scatterers aligned toward the wind direction and typically 10 m apart. Appearing to be clouds of bubbles organized into linear "streets" by the presence of Langmuir circulation, the features appear whenever breaking waves are present, and are more clearly visible in heavy rain.

The experiments reveal two distinct scales of bands: the shorter being carried by the circulation of the larger, and the larger formed by the collective locus of the smaller. Circulation speeds depend on wind speed and it was observed that the larger bands appear to migrate cross-wind. The observed repetition of wave-breaking in groups of waves is also discussed.

2. **"Whitecaps and Bubble Clouds: Average and Individual Characteristics," J. Wu, J. Acoust. Soc. Am. Suppl. 1., Vol. 88, Fall 1990 (120th meeting, November 1990, San Diego, California).**

Previous parameterizations (Wu, 1988) of spatially averaged results on white cap coverage are discussed. Noting that both the whitecap coverage and the bubble population at the sea surface are found to vary with the cube of the wind velocity, the author observes that the vertical distributions of bubble populations are found to be exponential. The reported data of individual whitecaps (Snyder et al., 1983 [163]; Bortkovskii, 1987 [10]) are analyzed according to the scaling of breaking waves reported by Hwang et al. [76].

Individual characteristics are then used along with global descriptions to estimate the spatial density of whitecaps on the sea surface. The influence of water temperature on production of whitecaps and bubbles is discussed. Different distributions and coverages are proposed for bubbles and whitecaps in cold and warm waters. The vertical distribution of volumetric concentrations dispersed bubbles is thereby obtained from that of numerical concentrations. Results of whitecaps and bubbles are compared with respect to physical processes of their production by the wind.

3. **"Generation and Decay of the Acoustically Significant Sub-Surface Bubble Plumes," E. Monahan, J. Acoust. Soc. Am. Suppl. 1., Vol. 88, Fall 1990 (120th**

meeting, November 1990, San Diego, California).

The author provides an explicit model relating the flux of bubbles into the sea to the fraction of the sea surface covered by whitecaps. The model is framed by the conceptual basis of there being two stages of whitecaps and three stages of plumes. The spilling wave crests are termed Stage A whitecaps, and the decay of the initial, acoustically radiating α plumes into β plumes (with their accompanying Stage B white caps), and then into γ plumes is discussed.

The dispersion of bubbles in these diffuse plumes into the background bubble layer is described, and bubble spectra corresponding to each stage of plume evolution are addressed. The near-surface concentration of large bubbles (> 100 μm radius) inferred from this model for the 11-13 m/s wind speed range is in general agreement with measured field observations.

4. "Open Ocean Bubble Measurements from Multi-frequency Acoustic Scatter," Svein Vagle, J. Acoust. Soc. Am. Sup 1., Vol. 88, Fall 1990 (120th meeting, November 1990, San Diego, California).

Size distributions of sub-surface ocean bubbles are shown from the results of the Surface Wave Processes Program (SWAPP) and Critical Sea Test (CST) experiments. A six-frequency acoustic backscatter technique is presented. Variability in the bubble size spectra is related to the "age" of the bubble clouds as well as the presence of coherent flows in the ocean, including Langmuir circulation.

5. "Low Frequency Noise From Breaking Waves," W. Carey, J. Fitzgerald, and D. Browning, Naval Underwater Systems Center Technical Document 8783, October 1990 (also presented at the Conference on Natural Physical Sources of Underwater Sound, University of Cambridge, England, July 1990).

This paper is a review of low frequency ambient sound measurements in the 30 to 500 Hz region. The wind speed dependency and its relation to noise characteristics are discussed. Noise production by breaking waves and the generation of bubble plumes and clouds is evaluated. A calculation is made for a cloud of bubbles initially compressed by a wave breaking event and it is concluded that sound levels may be adequate for this to be a candidate mechanism. This paper provides a good review of the experimental situation with respect to the most recent studies at the time of its writing. (Also see the related paper in reference [14]).

**6. "On the Losses Due to Storm Bubbles in Oceanic Sound Transmission,"
D.E. Weston, J. Acoust. Soc. Am. 86(4), 1546 (1989).**

This study considers several major effects of bubbles on acoustic propagation not addressed elsewhere. With a 1-4 kHz, wind-effect oriented shallow water experiment as a background [198] the author addresses the scattering versus absorptive loss contributions, surface decoupling (coherence) effects, ray refraction in the bubble layer at low and high frequencies, and realistic implications for modeling of bubble layers. The above factors are explicitly related to the Perranporth shallow water experiment and in this context conclusions are drawn concerning the probable relative contributions of bubbles, fish, and surface waves to the surface loss. Weston provides a fresh and relevant perspective of the problem and this paper deals with physical effects too often ignored.

**7. "Waveguide Propagation of Ambient Sound in the Ocean Surface Bubble
Layer," D. Farmer and S. Vagle, J. Acoust. Soc. Am. 86(5), 1897-1908 (1989).**

In this work the authors cast an intriguing light on observational aspects of the subsurface bubble layer and its spectrum. The LA PEROUSE (British Columbia) and FASINEX (southwest of Bermuda) experiments were conducted with the purpose of relating the observed fine structure in the wavebreak-induced ambient field to the measured bubble-size spectra. Ambient sound measurements ranging from 40 to 20,000 Hz demonstrated a robust structure in the spectral peaks which was found to be rather independent of wavebreak occurrence (but not of sea state).

The measurement instrument incorporated a digital broadband hydrophone, a four-frequency vertically oriented echo sounder (28, 50, 88, and 200 kHz), and (optionally) a video camera and sidescan sonar. The instrument was deployed in the open ocean as a drifter suspended from a surface float by a rubber cord, which presumably provided some decoupling from the effects of waves.

In a treatment analogous to that of optical propagation in crystals with refractive indices modified near the surface (integrated optics), a waveguide modal propagation model was constructed and the cutoff frequencies for active modes determined. Examination of theory reveals that for a given modal amplitude the signal at a fixed depth in the exponential part of the eigenfunction will be proportionately greater as the cutoff frequency is approached. Hence a hydrophone placed beneath the bubble-perturbed profile will register spectral peaks corresponding to the cutoff frequencies. The strength of these peaks should decay with depth.

Comparison of theory with the two measurements is generally good. The LA PEROUSE measurement used a hydrophone depth of 14 m and showed stronger spectral peaks than the FASINEX case with a phone depth of 24 m. The FASINEX conditions involved higher measured bubble concentrations than LA PEROUSE and supported many more modes. In the FASINEX data set the calculated cutoff frequencies for the first eight modes corresponded to spectral peaks. In the LA PEROUSE data the first five predicted mode cutoffs showed good agreement.

The authors suggest the possibility of solving the inverse problem: that of determining the bubble size spectrum from a measurement of ambient spectral peaks. It is stated that two hydrophones at different depths might be used to evaluate both the e-folding depth and the sound speed anomaly. Implications of this possibility are discussed in the context of remote sensing, and the determination of the vertical diffusivity (as in [174]).

8. "The Influence of Bubbles on Acoustic Propagation and Scattering," H. Herwig and B. Nutzel, Proceedings of NATO Advanced Study Institute on Underwater Acoustic Data Processing, Kingston, Ontario, Canada, July, 1988.

Two types of shallow water (30 m.) experiments conducted in the North Sea are described. In the first type the attenuation along a 2.4 meter fixed acoustic path was measured at different depths within the surface bubble layer. In the second experiment the vertical and 30 degree grazing backscatter from the surface was measured using a high-resolution parametric array mounted atop a tower 22.5 m below the sea surface.

In the variable depth attenuation experiment the fixed path apparatus was situated at depths ranging from 1.5 to 12 m below the surface and measurements are taken at 5, 10, 30, 50, and 100 kHz. Each data set consisted of 2048 transmissions of a 1 msec pulse at a repetition rate of 120 msec. Twenty data plots were taken over an eighty minute period during which the environmental conditions were stable. Predictably the higher values of attenuation occurred for the high-frequency measurements. Time histories of the measured attenuation are shown for different frequencies and sensor depths at a wind speed of 17.5 m/s. Probability distribution functions of the attenuation are shown for the five different frequencies and for wind speeds of 10 and 22 m/s.

The backscattering experiment's parametric array had a center frequency of 39 kHz. Scattering measurements were made at frequencies of 3,5,10, and 18 kHz using the array as a conventional receiver against the two grazing angles. Each measurement set consisted of 750 pings of 4 msec pulses at a repetition rate of 400 msec. The cumulative bubble volume and surface backscattering from 750 returns (measuring time of 5 minutes) are shown for separate stable wind speed conditions corresponding to wave heights of 0.5, 2.2, 3.3, and 3.8

m for a frequency of 18 kHz and a pulse length of 4 msec. In the 0.5 m wave height data no wavebreaks were yet observed and a pure surface reflected signal can be seen (note the steep slope of the initial echo). At the higher sea states, echoes from the bubble clouds precede those of the surface and the increased attenuation results in a net reduction in backscatter and a surface screening affect.

Several factors should be noted in this work. The attenuation is described as showing short-term fluctuations of more than 30 dB per meter, but this is over the horizontal path and may not compare well with the variation (in magnitude or period) over the paths in the scattering experiment. The 30 dB fluctuations do not appear to correlate with swell or wavebreak occurrence since fluctuations are intermittent from tens of seconds to over a minute in separation.

The attenuation and scattering experiments were apparently not simultaneous. The spatial location of the parametric array is described as being in the vicinity of the research platform (NORDSEE), and the backscattered signal does indeed drop with increase in wind speed, presumably due to the growth of the bubble population. However, although the bubbles' screening effect on the scattering strength can be inferred, its existence is somewhat indirectly supported by this measurement.

Further information on this experiment can be found in [138].

9. "Photographic Measurements of Bubble Populations from Breaking Wind Waves at Sea," A. Walsh and P. Mulhearn, J. Geophy. Res. 92 (C13), 14553-14565 (1987).

This work utilizes essentially the same photographic technique as employed by Johnson and Cooke (1979) [81]. The measurements were taken in predominantly open ocean, deep water conditions in the Tasman Sea. A triplet of bright spots on a single bubble were photographed to determine the bubble radius (and presence) using a towed camera system. The system operated at depths of 0.5 - 2.0 m in wind speeds of 2 - 14 m/s. Bubble populations were sampled and showed measurable variability with time. Bubble density varied with wind speed (W) as $W^{3.3}$. Total air volume entrained by bubbles was found to increase as $W^{4.9}$ and bubble size spectra varied with radius (r) as r^{-4}.

This paper raises some important questions regarding errors associated with this type of measurement. In particular there is a discussion of the practical resolution of the system, which was taken to be 50 μ bubble radius, despite the Rayleigh limit being found to be 20 μ. The authors provide an optical error analysis and comment on the fact that Johnson and Cooke apparently obtained a resolution of 17 μ.

10. "Study of Micro-Bubbles in the North Sea," S.C. Ling and H.P. Pao, Proceedings of the NATO Advanced Research Workshop, 1987, Italy.

This experimental work employed a optical darkfield specular reflection measurement system, originally developed by Ling in 1982, to determine the relative contributions of zooplankton and breaking waves to the bubble spectrum in the ocean. To this end, three sites were selected for measurements of optical bubble spectra: a constantly filtered pool, a small glacial lake, and the platform NORDSEE of Germany in the North Sea.

The Ling measurement system utilizes several effects to discriminate bubbles from non-bubbles. Knowing the dependency of the incident light angle on the surface reflectance of gas bubbles and plankton respectively, a forward scattering angle of (nominally) 125 degrees is used to detect passage of a bubble through the instruments field of view. At this angle the surface reflectance of zooplankton is negligible due to the change in the index of refraction at the water-plankton interface, and since non-bubble scatters are non-spherical the probability of a surface reflection at the detection angle small. Additionally, non-bubbles are discriminated from bubbles through the signal-pulse-height to pulse-width ratio. The authors state that living organisms less than 500 μ in size can be differentiated from bubbles larger than 17 μ (detection threshold) by the difference in pulse amplitudes, while organisms larger than 500 μ can be determined by their larger signal pulse width to pulse height ratios.

Since two photomultiplier tubes are used for detection in successive regions of the vertical plane, the system can measure vertical bubble velocity, and thus bubble size through the Stokes-Oseen equation. Also, since the signal intensity is proportional to the surface area of the bubble, the square root of the signal provides a value proportional to the diameter of the bubble. These system features are used in the calibration as well as the data analysis.

Measurements of the bubble population in the filtered pool revealed a relatively small concentration of bubbles at all diameters. Bubbles larger than 200 μ diameter were rare. The total bubble concentration for bubbles in the diameter range 25 to 200 μ was found to be over 100 times less than that of natural waters. The authors take this as support for the conclusion that a persistent high bubble concentration is largely caused by biological activities. One possible factor not addressed is the effect of the cited "chemically treated water" on bubble life history. The pool measurement was done to provide a controlled case wherein neither biological sources nor breaking wave sources were present. While the chemical treatment of the water may eliminate the biological sources, it could have other effects.

Measurements in the glacial lake showed a peak in the bubble spectra near 50 μ in diameter with maximum concentration at a depth of 25 m, which corresponded to the lower

boundary of the mixed layer. Water temperature in this layer was near 15 degrees C, while below into the 300 meter depths the temperature approached 4 degrees Centigrade. The authors apparently undertook some microscopic studies of zooplankton and note that there is found a substantial presence of micro-bubbles under the inside carapace of the creature. The bubbles were typically 20 μ diameter and larger, and it was noted that the zooplankton consume some 0.5 cubic millimeters of CO_2 per hour, occasionally discharging a cloud of mucous substance containing digested food particles and micro-bubbles.

Due to the limited fetch of the lake only small breaking waves, 0.6 m in height were observed at wind speeds of 10 to 15 m/s. Bubble measurements at 5 m depth, for diameters in the range 30 to 100 μ, showed only five per cent increase in concentration above the quiescent state. The authors make no statement regarding the duration of the change in the wind speed, and it is hard to conclude much from this particular observation.

Oceanic measurements at the NORDSEE platform are the principal focus of this paper, with the other measurements providing a general background for experimental reference. The experiment was conducted in the month of November when high sea states prevail. The North Sea with its approximate depth of 31 m is a completely mixed layer with uniform temperature to within 0.1 degrees Centigrade. During the experiment there was a period of very high wind velocity (18 m/s) for four days, followed by a sudden drop-off to calm conditions for 1.5 days, thus providing an opportunity for observing bubble population decay characteristics.

A variety of dependencies were examined during the NORDSEE measurements. The growth and decay times of large and small bubbles were measured for both temporal and spatial variation. There was found some interesting correlation of local large bubble (greater than 100 μ) concentrations with wind row spacings. The authors' analysis indicates that breaking waves do not directly contribute to the population of smaller bubbles. The large bubble population was found to have a fast rise time under increasing wind conditions, whereas those bubbles smaller than 100 μ evolved in concentration very slowly. As the wind subsided the small bubble population showed robustness in decay also, perhaps, as the authors cite, due to the contributions from the more rapid decay of large bubbles.

Three major conclusions were ultimately drawn by the authors. First, that the persistent presence of a micro-bubble population component with diameters less than 100 μ is biological in origin. The larger and transitory population component, greater than 200 μ in diameter, is closely associated with the breaking waves. Finally, there is the observation that the smaller bubble component is robust in concentration, exhibiting a very long time constant for either increase or decrease over time. The opposite is true for the large bubbles. There is much speculation regarding possible mechanisms for inter-populational dynamics in this paper and the authors make a strong case for their conclusions. The spectra shown are

consistent with those of other observations. Some of the speculation prompts pursuit of theoretical mechanisms for spectral dynamics.

11. "On the Spatial Distribution of Ocean Bubbles," G. Crawford and D. Farmer, Jour. Geophy. Res. 92(C8), 8231-82 . (1987).

This often cited study of bubble concentrations utilized an upward pointing acoustic transducer operating at 119 kHz, mounted on the deck of the submarine USS Dolphin in a series of operations 10 km off the coast of Monterey, California. The single-frequency measurements inferred the bubble concentrations from the backscattered signal, the sonar equation, and classical scattering calculations using a simplified model for the size distributions. The vertical and horizontal distribution of bubble clouds were considered in terms of wave-break injection, the temperature differential ΔT for the air/sea interface, and various subsurface motions. The mean concentrations of bubbles were found to decrease roughly exponentially with depth (e-folds ranged 0.7-1.5 m). The mean bubble concentration at the surface N_0 was found to depend on the cube of the wind speed, measured ten meters above the surface (within 10 percent). No surface observations of wave breaking or wind rows were made during the scattering measurements.

Bubble concentrations were calculated to range from approximately $10^5/m^3$ at 1 meter depth to under $10^2/m^3$ at ten meters depth (for a wind speed of 11 m/s). Lower wind speeds resulted in respectively lower concentrations. The authors cite several potential sources of error. The approximations of their scattering calculations may lead to an over-prediction of transmission loss below 5-m depth. This is said not to affect the concentration estimates greatly since only a small portion of the bubbles were found below this depth. The authors repeatedly refer to the presence of a near surface (1 meter and above) scattering layer. They state that since its effects were not removed from the concentration calculations there may be room for misinterpretation of distributions.

Bubble plume spacing was observed to be quite variable although the plume structures themselves were considered distinct. The authors follow Thorpe and Hall (1983) [178] in estimating the lifetime of the bubble plumes to be about one minute. Data collected at low wind speeds of 2-3 m/s show few identifiable bubble plumes, as would be expected if the wave breaks characteristic of higher wind speeds are the main plume generation mechanism. Some of the measurements were taken during rain, and bubble concentrations are substantially reduced during this period. (Rain is known to quench wave motion and provide a more uniform entrainment of bubbles).

Wave break injection is discussed in terms of the observation that whitecaps within a wave group were found in the work of Donelan [39] to occur with a period of about twice the

period of the dominant (presumed locally forced) wind waves. This is attributed to the ratio of the group velocity and the phase velocity, which is very nearly 0.5 for deep water waves. Phillips [143] suggests that wave breaking can occur at all surface wave scales, such that small scale wave breaks might serve as injection mechanisms for the upper 1-meter surface layer observed in these measurements. If so, the authors themselves expect to see no regular spacing between bubble plumes, except in the *downwind* direction. Unfortunately, there was no means of determining the relative vessel location with respect to wind rows since there were no simultaneous surface observations during the measurements.

Thorpe's work [175] on Langmuir circulation is discussed and its consequences examined. In that article Thorpe modeled the diffusion of bubbles in the presence of such a secondary flow and found a significant increase in bubble concentrations in the convergent zones of Langmuir cells. If this is an important mechanism for plume generation then one would expect to see somewhat regular spacing of plumes when traveling *at angles* to the wind direction. If wave breaking is a large contributor then Langmuir cells would be identified by long horizontal collections of bubbles. When breaks are infrequent, as in low wind speed cases, then the bubble plumes should be discrete entities, less shaped by the Langmuir flow. In their case Crawford and Farmer state that the observed spacing gave only weak support for theories that plumes are generated by wave breaks. Nor was there strong evidence of a relationship between plume spacing and the expected scale of Langmuir flow. Plume spatial frequencies were determined by examining power spectra of the horizontal distribution of the (logarithm of) calculated concentrations at depths a few meters below the surface. These were found variously to be 28, 42, and 45 m for the data examined. While these are within the (wide) range of variability for cellular spacings, there were statistical and experimental reasons for these results not being considered especially significant by the authors.

Several qualitative features of the plumes were noted. The plumes, often appearing V-shaped in the acoustic backscatter image, sometimes exhibit a "slanting," which is attributed to local current shear. Ratios of plume length to width were found to be typically 1.4.

Crawford and Farmer suggest that wave breaks do not merely feed some driver for the plume generation, but that during wave breaks a "jet" is formed driving bubbles down to the observed depths. This is said to be strongly supported by side-scan sonar measurements [178]. Another proposed mechanism is that in the presence of a net upward heat flux convective plumes are formed to carry the bubbles upward. This is thought to be consistent with the observation [179] that bubble clouds tend to be more columnar with more negative air/sea temperature difference.

To summarize, the Crawford-Farmer paper provides important measurements of bubble concentrations, as derived from single-frequency backscatter calculations. The data on plume structures is examined in terms of the competing theoretical mechanisms for genera-

tion (local wavebreak, Langmuir circulation, turbulence, and convection), although no clear relationship is established in this article to prioritize any of the hypothetical processes as part of the overall observed phenomena

12. "The Influence of Bubbles on Ambient Noise in the Ocean at High Wind Speeds," D.M. Farmer and D.D. Lemon, J. Phys. Ocean. 14, 1762-1778 (1984).

This work establishes its principal thesis: that bubbles entrained by breaking waves provide acoustic insulation and at high wind speeds and high acoustic frequencies they account for the observed decrease in ambient noise level. The observations were carried out during the winter of 1982-83 at Queen Charlotte Sound off Canada's west coast. Using a hydrophone mounted on the sea floor (267 m depth) ambient noise levels were recorded at 4.3, 8.0, 14.5, and 25.0 kHz and plotted against anemometer-derived wind speeds at 3 m. above the sea surface. Wave height recorder data was also taken, as were (nearby) data on the profiles of temperature, salinity, and sound speed. Wind speed conditions varied from 5 to 25 m/s.

Ambient noise at 4.3 kHz displayed a logarithmic relationship with wind speed throughout the observation range, as previously reported. At the two higher frequencies there was observed a break in the slope of the curve of noise spectral level versus wind speed and for winds above 15 m/s the noise actually decreased with increasing wind.

In support of the bubble absorption thesis of the paper the authors developed a simple model of the process, assuming a bubble layer at 1-meter depth having a power law dependence for population density. Raytraces were done from the layer source to the hydrophone at 267-m bottom depth and, finding refraction negligible out to 6-km radius, a calculation of sound attenuation was developed. Distributed dipole sources were assumed and, with multiple reflection effects small, the direct path contributions were integrated over the ocean surface out to the 6 km refractive limit. Attenuation modeling was essentially following Clay and Medwin [25].

Results of the modeling basically support the data. Both the 14.5- and the 25.0-kHz plots illustrate the onset of attenuation at a wind speed of about 10 m/s, rising steeply thereafter. At 25.0 kHz the bubble attenuation rises more steeply than at 14.5 kHz and there is some scatter in the points, especially at higher wind speeds. At 8 kHz the change is more gradual.

The authors examine the exponent of the bubble population power law dependence by finding the ratio of the observed bubble attenuation factors at 14.5 and 25.0 kHz for two bubble size ranges of 30-200 and 20-400 μ. Exponent values decline from a maximum of

4.75 toward smaller values at higher wind speeds. From this is inferred an upper bubble size limit of 417 μ.

Various mechanisms for surface noise generation are discussed and limits of the calculational assumptions are pointed out. Farmer and Lemon comment that at low wind speeds the bubble layer is patchy, and hence the probability of a whitecap occurring above a bubble cloud is reduced. This is said to possibly account for the absence of noticeable attenuation at low wind speeds (< 5 m/s) even though whitecaps, and therefore bubble clouds, are known to occur. At higher wind speeds the clouds of bubbles tend to overlap, forming a continuous layer [176]. The authors suggest that even at high wind speeds the bubble layer thickness remains variable, and that this variation is reflected in the variability of the attenuation, which contributes to the scatter observed in their data. Similar scatter is said to be observed in the data of Wille and Geyer [200].

13. "Bubble Populations and Spectra in Near-Surface Ocean: Summary and Review of Field Measurements," J. Wu, J. Geophys. Res. 86(C1), 457-463 (1981).

In this paper Wu provides a summary, review, and re-analysis of prior measurements of bubble spectra. The perspective is that of examination of the variation of populational statistics with depth and wind velocity. In particular the results of Kolovayev [86], Johnson and Cooke [81], and Medwin (1970) [119] are compared.

Wu comments on the experimental errors the various measurement approaches may experience, especially at the lower end of the size distributions. It is noted that it is justifiable to count the bubble population by summing the derived bubble counts from a peaked distribution since the cutoffs at both ends of the distribution can have an insignificant effect on the total count. However, in Medwin's data the bubble counts increase continuously towards lower sizes, probably due to the particular photographic measurement technique employed [119], and Wu notes that it is unfortunately not possible to form normalized spectra from such spectra.

The author, where possible, forms the normalized size spectra from the data of various researchers and expresses the results in relative frequency of occurrence. A comment is made that the Johnson and Cooke data may have too small a sampling as evidenced by a departure from a fitted line at large radii. Wu notes that the most important difference between the results obtained by Medwin (1970) and those of Kolovayev (1976) and Johnson and Cooke (1979) is that the bubble population decreases rapidly with depth for the latter, but remains invariant with depth for the former. This difference is discussed in terms of the varying experimental conditions between the warm open sea results of Kolovayev and the

cold coastal region measurements of Johnson and Cooke.

14. "Bubble Populations and Spectra in Coastal Waters: A Photographic Approach," B.D. Johnson and R.D. Cooke, J. Geophys. Res. 84(C7), 3761-3766 (1979).

This measurement provided an optical benchmark for the growing refinement of acoustical bubble measurement techniques in the early eighties. Johnson and Cooke utilized an electronically driven 35-mm macro-camera in a photographic technique suggested by Medwin. Three small strobe lamps were equally spaced around the perimeter and slightly behind the zone of focus of the camera in order to provide illumination of three points on the spherical bubble surfaces which would be measurable on film. Bubbles therefore appeared on film as easily identifiable groups of three spots and these triangular vertices formed the basis for determination of bubble diameters.

The concentration and size spectra of bubbles having radii greater than 17 microns were determined for a water depth of 1.5-4.0 m and wind speeds of 8-13 m/s. Bubble populational dynamics is discussed in terms of bubble entrainment and dissolution by rise and surface loss. This is an intuitively and visually attractive paper which at the time was an important contributor to the growth of bubble size measurement technology.

15. "In Situ Acoustic Measurements of Microbubbles at Sea," H. Medwin, J. Acoust. Soc. Am. 82(6), 971-976 (1977).

Bubble populations are determined by Medwin with the classical resonance frequency relation to bubble radius (excess attenuation method). The Monterey Bay experiment employed a CW sawtooth of fundamental frequency 5 kHz used to find sound amplitude and phase at 32 harmonics between 5 and 160 kHz. Measurements were made over path lengths of 1-5 m at depths of 3-36 m at two sites, one of which was 40 m depth with the other being over the Monterey submarine canyon, up to 1000 m depth.

Bubble radii were found in the range of 15-300 μ at wind speeds of 6,8, and 11 knots. The 40 meter region data shows derived bubble populations as a function of radius, at two wind speeds (6 and 11 knots), taken two hours before sunset. Another measurement illustrates the size spectra of bubbles for six depths underneath wind rows at noontime. Excess sound attenuation is shown for the data taken over the canyon.

Correlations are shown illustrating dependences on season, sunset versus sunrise, wind,

and presence or absence of windrows. In general the bubble population tended to rise at sunset, corresponding to upward motion of (presumably biological) scattering layers. However, no direct biological measurements were made in this study.

This article serves to illustrate the method of excess attenuation. Other Medwin papers are perhaps better sources for explanation of technique (e.g., [118] or [119]). Fluctuation of sound speed in a bubbly surface layer is discussed in [117].

4 LABORATORY STUDIES

Laboratory studies constitute a particularly critical element in the process of understanding bubble cloud acoustic phenomena for several reasons. In addition to their traditional role in scientific methodology, laboratory studies of ocean acoustics phenomena fill the especially important needs of control and repeatability - requirements which are not truly feasible in measurements at sea. Real-world field conditions present a vast number of environmental uncertainties to the best-prepared experimenters, and there are uncertainties not only in the environment's initial state but also for the entire duration of the acoustic media/boundary interactions, occurring over finite time scales in which ocean processes may result in significant state variations. While the problem of at-sea experimental uncertainty is evident at the macroscopic level of long-range propagation measurements (practical limits on sound speed profile and bathymetry samplings, etc., as well as often unknown factors such as internal waves, fetch, local surface effects) the difficulty becomes more severe when micro-scale phenomena such as wavebreaks, bubble plumes, and Langmuir circulation are examined.

Ocean dynamical processes potentially contributing to bubble populations and structures are neither well understood nor thoroughly characterized. As a result there is considerable difficulty in determining precisely what initial conditions and functional dynamics should be emulated in a laboratory experiment. Experiments in the lab are therefore in what must be considered an early stage, and in many cases they await an improved understanding of mixed layer dynamics. It is also true that work in the lab is subject to significant limitations on the scale of processes which may be properly emulated, and researchers will usually have to address basic questions of applicability to real world conditions. For example, the Langmuir circulation process been examined in the laboratory ([43], [44], [45]) with interesting results, but there remains some debate over the significance of the findings due to scale and other considerations. Nonetheless, even vastly more complex phenomena have yielded to investigation in the laboratory, and the need for controlled simulation of phenomena observed in the field will persist.

The experiments discussed here address wavebreaks and bubble injection, their acoustic signatures, bubble excitation mechanisms, and spectral measurement techniques. A measurement of size spectra in a pool [97] can be found in the previous discussions of experiments at sea, which was the paper's main focus. Other laboratory work on bubbles and bubble plumes is reported in some of the references of this report.

1. "Variation of Bubble Density Under a Breaking Wave," Ming-Yang Su, J. Acoust. Soc. Am. Suppl. 1., Vol. 88, Fall 1990 (120th meeting, November 1990, San Diego, California).

New laboratory measurements on the variation of bubble densities in a plunging breaking wave tank are presented. Oregon State University's large-scale wave tank (12 x 15 x 350 ft) is utilized to study size spectra of waves having periods of three seconds and a maximum wave height of five feet, occurring within an unstable wave group (packet). Bubble density is measured using the acoustical resonator technique [12] covering the bubble radii from 40 to 1000 μm.

Three acoustical resonators were mounted on a free-floating support frame at three depths vertically spanning the wave height. The frame has six consecutive locations, ten feet apart, horizontally covering a wavelength of about 60 feet. The measurements are intended to constitute a continuous spatio-temporal record of bubble densities due to a breaking wave event. (See also [167]).

2. "The Acoustic Signatures of Laboratory-Generated Bubble Plumes," A. Kolaini, M. Yi, R. Roy, and L. Crum, J. Acoust. Soc. Am. Suppl. 1., Vol. 88, Fall 1990 (120th meeting, November 1990, San Diego, California).

Two laboratory experiments designed to characterize the sound field radiated by a breaking wave are described. In the first experiment progressive gravity waves were produced in a flume tank by a wedge-shaped plunger wavemaker. At the other end of the tank was placed an airfoil with a given angle of attack forcing gravity waves to break in the tank region. The second experimental series involved the introduction of a water jet, to simulate a breaking plunger, onto the plane water surface of the tank. Produced by releasing a fixed volume of water from a cylindrical container onto the surface, the jet characteristics were varied by changing the container's volume and height.

Hydrodynamic characteristics of the bubble plumes generated by these two mechanisms were measured using a high speed video camera. Underwater acoustic emissions from the entrained bubbles were measured simultaneously with the video results yielding concurrent video images and power spectra. Analysis of the data from the two experimental mechanisms showed a dominant acoustic signal occurring at frequencies lower than 200 Hz.

3. "Bubbles as Sources of Ambient Noise," H. Pumphrey and J. Ffowcs Williams, IEEE J. of Ocean Eng. 15(4), 268-274 (1990).

In this paper the authors evaluate the relative magnitudes of acoustic contributions of candidate bubble excitation mechanisms to the ambient (Knudsen) noise spectrum and compare theory with their own laboratory experiments and those of other workers. Activation mechanisms considered focus on entrainment stage events rather than bubble fission at birth (breakup). Among the entrainment processes considered are (1) Laplace and hydrostatic compression, (2) bubble surface wave shape oscillations, and (3) bubble wall velocity at formation.

The experimental portion of this paper concerns a laboratory study of high-speed flow induced bubbles generated by a stream encountering an obstacle as it enters a v. ~e trough. The whole flow apparatus was suspended in a tank in which were m ·unted a hydrophone and a high-speed rotating prism camera. Hydrophone output was photographed along side the film of the wave, producing a film with a continuous oscilloscope trace showing the acoustic pressure as a function of time, simultaneous with the wave photo sequence.

Noting that whereas a bubble may emit sound by either volume pulsations or shape variations, the sound pressure due to volume changes is likely to be 10^9 that due to shape fluctuations [165]. However, a recent new theory of surface oscillation [98] is discussed, whereby surface waves may couple to the volume mode and cause it to radiate when the volume mode has a frequency roughly twice that of the surface mode. This mechanism is evaluated and determined to be possibly significant at the low end of the papers experimental results.

Pursuing a number of mechanisms for the initial volume excitation, the authors conclude that the most likely time for excitation is when the bubbles are formed at the surface and the proto-bubbles are sheared away to become independent objects. By elimination of other mechanisms as untenable, it is concluded that the source of energy injection is the radial flow around the proto-bubble at the moment of creation.

4. "Acoustical Measurements of Bubble Production by Spilling Breakers," H. Medwin and A. Daniel, J. Acoust. Soc. Am. 88(1), 408-412 (1990).

An underlying assumption of this work is that the source of sea surface noise is the incoherent summation of the coherent radiation from individual bubbles as their shock-induced pulsation amplitudes are damped out. It is stated that the surface bubble spectral density per unit area at sea could be the same as in the laboratory, and this work determines the rate of production of the surface bubble spectral density, as well as the total volume of air encapsulated by spilling laboratory breakers (per unit area of the water surface).

This laboratory experiment was conducted in a 17 meter long water tunnel in which

surface waves of frequency 1.4 Hz were generated. Using an omnidirectional hydrophone, 24 cm below the surface, a measurement of the sound spectrum is presented and compared with the original Knudsen curves and work by Wenz (1962) [196]. By thresholding the voltage triggering against the expected intensities the source bubble radii were obtained. Bubbles studied in this experiment ranged from 50 μ to 7.4 mm, corresponding to a resonance frequency range of 81.2 kHz to 440 Hz.

In order to normalize the results, the area of coverage in the laboratory is needed. The surface area of bubble production was determined using two vertical arrays of two hydrophones each, which enabled triangulation of bubble sources to the surface. With the average area and the average spectrum the authors were able to plot the surface bubble production density (bubbles per square meter per micron radius increment). Also determined was the average number of bubbles of all radii produced, per breaker, as a function of time. The authors best-fit expression for this is $dN/dt = 3.13e^{-0.0070t}$ where t is the time in milliseconds after wavebreaking. An interesting result is that 97 per cent of the bubbles are produced in the first 500 msec after wavebreak.

Comparisons are made with other measurements of surface bubble densities by Y. Toba [182], and also a recent ocean experiment by Updegraff [188].

5. "Bubble Size Measurements Using the Nonlinear Mixing of Two Frequencies," V.L. Newhouse and P.M. Shankar, J. Acoust. Soc. Am. 75(5), 1473-1477 (1984).

The authors exploit the spatial resolution benefits of nonlinear bubble response (at the sum frequency) to the double frequency excitation by two wavelengths, one of which corresponds to resonance for the object. From derivations of bubble excitation in the spherically symmetric volume mode, expressions for the radiated pressure at different frequencies are derived assuming the bubble acts as a monopole radiator ($R_0 < \lambda$). The sum frequency (upper sideband) is distinctly sharp, providing good spatial resolution of bubble size. The derivations assume small oscillation.

The laboratory experiment utilized bubble streams from a micropipette. Three different bubble sizes were generated in separate cases. These were insonified simultaneously by a swept, relatively low, pumping frequency near their resonance and a high imaging frequency of 2.25 MHz. The bubble echo is found to consist of the imaging frequency accompanied by sidebands which consist of the imaging frequency plus or minus the resonant frequency of the bubble. With the sideband for a specific bubble therefore peaking at its resonant frequency, the sideband spectrum for a group of bubbles (when the low frequency is swept over a range) should have a shape similar to the bubble size distribution. Agreement between theory and

experiment is shown to be fairly good.

In this work the measurement volume was defined by the intersection of the beam shapes from the two transducers transmitting and receiving the imaging frequency. Because the measurement volume can be reduced to the order of the imaging frequency wavelength the spatial resolution of this method of bubble sizing is independent of the bubble resonant frequency.

5 THEORETICAL AND NUMERICAL STUDIES

Among the theoretical studies there have recently appeared several plume scattering strength calculations ([70], [110]) which utilize bubble plume parameters determined from acoustical oceanographic techniques [48]. The necessity of making a number of ad hoc assumptions in these calculations reveal much regarding the need for a still more complete description of the subsurface environment. Nonetheless, in terms of model-data comparisons these calculations offer major improvements over competing (rough surface) interface scattering theories, lending credence to the importance of bubble-layer and plume effects in ocean surface scattering.

Given the numerous candidate contributors to bubble populations (wavebreaks, Langmuir circulation, biological sources, etc.) and the complex features of plumes appearing as structures protruding from a bubble layer, there clearly are numerous pertinent variables affecting plume occurrence and characteristics. From the standpoint of surface scattering prediction there is much to consider in terms of wind-related dependencies such as (1) horizontal dependence of plume spatial occurrence, (2) the distribution of plume depths, and (3) plume lifetimes. In the determination of the relative contributions of weak, strong, and resonant scatter mechanisms to plume scattering strengths it is important that *in situ* measurements of the surface layer sound speed be conducted at the deepest depths to which Langmuir circulation may carry bubbles. This is especially significant in low-frequency plume scattering theory [110] in which cross sections are strongly sensitive to scatterer depth.

From the perspective of large-scale numerical modeling and prediction there remains the question of how to combine the available information into effective parameterizations of the surface layer and boundary. In addition to the importance of using the appropriate physics and environmental data for the frequency regimes of interest, there is the question of the geographic dependence of spectra and plume properties as determined by features of local oceanography and meteorology. The biological bubble contribution, ocean thermal states, and certain aspects of wavebreak dynamics can all be considered good candidates for site-dependent factors. Hence there is a need to develop a worldwide database on bubble layers and plumes - driven by the appropriate oceanographic and meteorological parameters. At this time it is, however, still rather difficult to determine what a complete set of these parameters would be.

The Office of Naval Research has an Acoustic Reverberation Special Research Program (ARSRP) supporting studies of the effects of bubbles and plumes on surface reverberation and this program has spawned significant work. Undoubtedly, the result of the continuing

research will be improvements in databases, environmental theory, site-specific modeling, and experimental approaches, resulting in a more complete characterization of physical parameters and a better understanding of the processes at work.

1. **"Echoes from Vertically Striated Subresonant Bubble Clouds: A Model for Ocean Surface Reverberation,"** B.E. McDonald, J. Acoust. Soc. Am. 89(2), 617-622 (1991).

In this model of bubble-cloud backscatter the author investigates mechanisms for scattering from plumes in the high-frequency (HF), but subresonant, limit (see also [109]). Plumes are modeled as elliptical cylinders of bubble regions having sound speed defect proportional to $e^{z/L}$, where z is depth and L is the e-folding depth. Arguing that while strong scattering mechanisms have been pursued by other researchers, the author presents a calculation indicating that weak scatter cannot be ignored. Using a postulated sound speed defect, the weak scatter (Born) approximation is applied to develop cross sections for the interaction.

For this case of optically-thin bubble clouds, and wavelengths large compared to the cloud dimensions, but below bubble resonance regimes (200 Hz to several kHz), McDonald calculates the Born approximation result at low and high frequency using the forms for the first J-Bessel function at small and large argument. The high-frequency expression is examined, and it is argued that the result is insensitive to the e-fold depth provided L does not exceed a few meters.

In a data comparison the phase-averaged (high-frequency) cross section is maximized with respect to horizontal orientation, with the incident wave striking the ellipse (horizontally) broadside as expected. Physical assumptions require the ellipse semi-minor axis to exceed $\lambda/4$ (where λ is the acoustic wavelength) for the HF limit. As a test case, the author chooses model parameters of L=1.5 m and acoustic frequency of 3.5 kHz.

Noting that backscatter data [106] gives the backscatter cross section for a 1 average square meter of ocean surface, the author observed that the comparable quantity from his model is $d\sigma/d\Omega$ divided by the patch area, and then normalized by an empirical factor taken to be the whitecap coverage function as expressed by Krause [87]. This function is zero for wind speeds below 3 m/s, and increases with upward curvature to 0.2 at a wind speed of 20 m/s.

The author notes that some of his simplifying assumptions may require caution, in particular the fact that the average sound-speed defect is used rather than a peak value. Other ad hoc features noted are that the horizontal dependence has been removed in maximizing the cross section at broadside, and that the surface whitecap coverage factor used for normalization will probably underestimate the subsurface area coverage of the longer-lived bubble plume remnants. Variables not considered here include horizontal spreading of bubble clouds with age (increasing area coverage), plume azimuthal orientation, and ellipticity of the plume regions. These factors were not treated primarily due to a lack of experimental observations on these effects.

Nonetheless, the approach of calibrating the assumed relationships with the whitecap coverage function, converting specific values for average sound-speed defect and peak azimuthal cross section, seems to work. The data-model comparison is shown at sound-speed defect values of 0.01 and 0.005, and the model predictions typically fall within a few dB of the data.

The author hypothesizes that most of his predicted backscatter is specular reflection from plume surfaces, rather than volume reflection. As a test, results are shown for an elliptical plume patch with a sound-speed defect which is horizontally smooth (spatially Gaussian) rather than discontinuous at the plume boundary as in the original calculation (but still retaining the same volume-integrated sound-speed defect). With this "soft surface" the backscatter is calculated and shown to be insignificant compared to the original hard surface backscatter, lending credence to the claim that specular reflection exceeds volume scatter in this frequency regime ($\lambda < 4\times$ the plume semi-minor axis). It is noted, however, that at acoustic frequencies above several kHz the comparison may be irrelevant since both specular and volume scatter may be overwhelmed by resonant scatter from a few bubbles of appropriate radii.

The role of Langmuir circulation in drawing bubbles to deeper, more effective scattering depths (see [70]) is considered in terms of the calculated Born cross section at *low* frequency (LF), which shows extremely small backscatter ($k^8 sin^4 \alpha$ dependence) at low grazing angle (2.5°). For the grazing angle factor in the expression to increase sufficiently for rising LF cross sections at 350 Hz, the incident wave must interact with vertical scale lengths larger than the 1.5 meters first considered, and the possibility of 15- and even 30-m bubble plume depths is discussed. The need for simultaneous LF backscatter data and *in situ* measurements of sound speeds at depth during Langmuir circulation events is addressed.

2. "Acoustic Scattering from Ocean Microbubble Plumes in the 100 Hz to 2 KHz Region," F. Henyey, Arete Associates Report ARS-90-023-TR, 15 November 1990, La Jolla, California (presented at Acoustical Society of America, 120th Meeting, November 1990, San Diego, California).

Assuming the 15-20 dB reverberation excess of experiment versus interface scattering theory (Dashen, Henyey, Wurmser, 1990) [36] to be due to bubbles, the author attacks the plume scattering problem by developing an azimuthally isotropic (wind-direction independent) microbubble plume model (ignoring the large wave-injected bubbles which rise rapidly). In this approach the microbubble component of air content is taken from the data of the Farmer-Vagle FASINEX experiment (1989) [48]. Using a geometrically cylindrical idealization of the plume structure (with the interior treated as an effective medium) the approach takes wind speed as a substitute for whatever environmental parameters the

bubble plume properties actually depend upon (simultaneous bubble spectra and surface scattering data being unavailable). Plume model predictions are made to fit the measured acoustic scattering strength (Chapman and Harris, 1962 [19] and Chapman and Scott, 1964 [20]) at high wind speeds.

First order perturbation theory and the distorted wave Born approximation (DWBA) are tested with corrections to the scattering amplitude (per plume) to generate an effective ocean surface scattering cross section due to bubble plumes. Single scattering is taken as dominant. In this calculation the computational convenience of a cylindrical plume geometry is taken to yield valid results for frequencies up to 2 kHz (although the DWBA is held to be otherwise adequate up to 10 kHz).

Several assumptions are critical to the analysis in this paper. The cylindrically modeled plumes are taken to have radial dimensions of 1-2 m (presumably with some distribution) in accordance with data. All the microbubbles are taken to dissolve during the downwelling precisely at some depth D, different for each plume (a stationary discrete plume for its estimated lifetime of 100 sec). Langmuir circulation is presumed responsible for the down-welling. While the author discusses wind rows and bubble curtains, the distribution of plumes beneath the ocean surface is assumed to be wind independent. This, along with the assumption that plumes are statistically independent of each other, amounts to provisionally assuming an effective horizontal isotropy of the acoustic scattering strength. In conjunction with this the author states that the only adjusted environmental parameter of the study is that of the fraction of the ocean surface containing plumes. This was taken to be 2/3.

In developing the plume scattering model this work presents several important predictions. The most critical of these is that the scattering contribution from plumes begins to exceed interface scattering (see e.g., [36]) at about 125 Hz. The model predicts plume Doppler effects to be small, with little broadening from the estimated 100 sec plume lifetime. The deeper plumes are found to be more effective scatterers than the shallower ones due to a D^2 dependence in the calculated plume scattering amplitude, with a consequent D^4 dependence in the scattering strength. The sensitivity of grazing angle dependence, shown by a 10/15 degree comparison, shows a transition at about 200 Hz, a consequence of the 5-10 meter depth extent of the dominant plumes.

This study obtains some very interesting results, subject to the validity of its rather necessary assumptions. Whether the plume statistical independence holds up for tighter spacings and is unaffected by wind direction may be worth examination. The single scatter approximation does not treat multi-plume scatter and shadowing, which at certain grazing angles and comparable scale wavelengths could be important. This may merit estimates of errors associated with these assumptions. These and other questions will undoubtedly

attract further pursuit, and this work is of considerable interest precisely because of such further investigations it may spawn. (For related works the reader should see [110], [34] and [101]).

3. "Simulation of Acoustic Backscatter from Bubble Plumes Using a Finite-Element Model and a CW Full-Field Backscatter Method," S.A. Chin-Bing, J. Acoust. Soc. Am. Suppl. 1., Vol. 88, Fall 1990 (120th meeting, November 1990, San Diego, California).

The author applies a finite element full-wave acoustic model, FOAM (Murphy and Chin-Bing, 1989) [133] and PE-FRAME, a hybrid marching version of FOAM, to a large sea-surface plume with sound speed and density corresponding to a thirty per cent volume fraction. A measure of the backscattered acoustic field caused by the object is determined with a cw differencing whereby the total full-wave acoustic field is calculated with and without the object present, and the difference in the results of the complex pressure fields in the backscattered direction is established.

The cw full-field backscatter method (cw FFBM) is benchmarked against analytical calculation of the backscattered field from a rigid plate, and other comparisons. Plume backscatter using the cw FFBM is examined for Norwegian Sea and Pacific environments, with internal wave fields introduced into the PE-FRAME and FFBM to show the combined effects of long range (one convergence zone) monostatic and bistatic backscatter from a large bubble plume in the presence of an internal wave field and the sea surface boundary.

4. "Acoustics and Hydrodynamics of Bubble Clouds," H. Oguz and A. Prosperetti, J. Acoust. Soc. Am. Suppl. 1., Vol. 88, Fall 1990 (120th meeting, November 1990, San Diego, California).

Theoretical results are reviewed concerning the active and passive acoustic behavior of bubble clouds, and are compared with experiment. In the second portion of the paper the results obtained with a simple model of the evolution of the clouds in space and time are described. The model is based on two-fluid averaged equations and describes the motion of the bubbles under the action of buoyancy and drag.

5. "Modeling Low-Frequency Scattering from a Near-Surface Bubble Cloud," R.F. Gragg and R. Pitre, Natural Physical Sources of Underwater Sound Conference, Downing College, University of Cambridge, England, July 1990.

This presentation discussed preliminary results of a Naval Research Laboratory approach to modeling of the micro-bubble plume scattering amplitude for resonant scattering. The authors investigate whether scattering strengths calculated with this approach are strong enough to account for observed discrepancies between theoretical and measured low-frequency backscatter from the ocean surface.

Utilizing the boundary integral equation method [157] for computing the scattering amplitude, the model plume is specified by arbitrary size shape and internal sound speed distribution. The integral equation of continuity across the plume surface is solved, resulting in equivalent monopole and dipole source distributions for the plume considered as a primary radiator. These distributions are then integrated over the plume's surface to yield the scattering amplitude.

This approach employs the plume's internal Green function, obtained by numerical integration in the most general case, and the Green function of the surrounding external medium. A half-space external Green function is used to invoke the pressure relief boundary condition at the nearby air-water interface. Preliminary results for the most elementary model benchmark were shown as precedence for the full model results to come.

6. "Underwater Noise Emissions from Bubble Clouds," N. Lu, A. Prosperetti, and S.W. Yoon, IEEE J. of Ocean Eng. 15(4), 275-281 (1990).

This work presents calculated results for the normal modes of (coupled) oscillation of bubble clouds in several geometrical configurations. Simple calculations for a cloud of linear dimensions of order L are discussed with regard to the case of a rigid boundary as a first approximation. The collective frequency reduction with respect to the single bubble case is shown to be an order of magnitude. Proceeding to the case of the Foldy effective equation model [52], which is accurate to volume fractions of a few per cent, the work of Commander and Prosperetti (1989) [29] is utilized in this approach.

The simplest case to which this formulation is applied is that of a layer of bubbly liquid constrained by two infinite planes a distance L apart. The complex eigenfrequencies of the layer are computed and the real and imaginary parts of the first four normal modes are shown plotted as function of the gas-volume fraction. Effects of bubble radii are shown by a comparison of the first and third modes for bubble having radii of 1 and 0.1 mm. An interesting result shown is the rapid drop of all the first three eigenmode frequencies with increasing layer thickness (frequency varies nearly inversely with thickness). This effect is apparently significant well into the frequency region dominated by ocean shipping.

The authors then treat the bubble plume modeled as a hemispherical surface cloud (1

m radius cloud with 1 mm bubbles) at a pressure release plane surface. Frequencies of oscillation of axisymmetric modes are plotted as a function of the gas volume fraction. Very low frequencies of oscillation are also observed in this case (e.g., 50 Hz for the first mode at 0.01 volume fraction).

Finally, the bubble plume is modeled as having a cylindrical surface, a configuration somewhat artificial compared to real world occurrences, but one for which there are several recent measurements using this geometry (see [187]). Brief results from this measurement are discussed and it is concluded that cloud resonances are rather easily excited, producing significant amounts of noise due to, for example, wave-break input.

In summary, this work demonstrates bubble cloud frequency reduction due to collective, normal mode oscillation for the rather idealized case of the three above cloud configurations of bubbles, all with the iso-radial spectrum. Similar treatments for these geometries, but with realistic size spectra would be of interest. For a related numerical work the reader should see [70].

7. "Acoustically Relevant Bubble Assemblages and Their Dependence on Meteorological Parameters," E. Monahan and M. Lu, IEEE J. of Ocean Eng. 15(4), 340-349 (1990).

This paper integrates current knowledge of bubble plume occurrence and characteristics into a detailed physical model of the life history of the plume with respect to its associated surface wavebreaks. The relationship between the early state of the plume and the remotely detectable whitecap coverage is addressed. Fractional coverage of the ocean surface by spilling crests versus mature whitecaps is considered in terms of wind-speed and wind-stress dependency. Expressions are developed for the estimation of near-surface bubble concentrations from remote observations of fractional whitecap coverage or from the 10-m elevation wind speed.

8. "Spectral Spreading from Surface Bubble Motion," D. McCammon and S. McDaniel, IEEE J. Ocean. Eng. 15(2), 95-100 (1990).

Decomposing bubble motion into random and deterministic components, the authors present a theoretical expression for the spectrum of low-frequency acoustic energy backscattered at shallow grazing angles from masses of bubbles created and entrained in breaking waves. The random motion of the bubbles is related to the correlation function of the motion which is obtained from the Fourier cosine transform of the surface directional wavenumber

spectrum. The deterministic motion of the scatterer is found from the Doppler shift associated with the horizontal drift of the breaking waves associated with the bubbles.

Predictions are shown for reverberation spectra for a 300 Hz signal with spectral bandwidths near 0.1 Hz at low wind speeds, increasing to 1.5 Hz for a 30 knot wind. Doppler shifts are said to range from 0.17 to 0.4 Hz over this range of wind speeds. Describing the process as very narrowband, acoustic pulse length effects are considered and conclusions are drawn that pulses shorter than 10 sec will greatly increase the measured spectral widths, especially at low wind speeds where the width can increase from 0.05 to 1.4 Hz.

The authors discuss possible improvements to the approach such as extended and dynamic plume evolution, and improved selection of oceanographic parameters relating to breaking waves.

9. "A Comprehensive Model of Wind-Generated Bubbles in the Ocean and Predictions of the Effects on Sound Propagation at Frequencies Up To 40 kHz," Marshall V. Hall, J. Acoust. Soc. Am. 86(3), 1103-1117 (1989).

In this paper the author has indeed presented a comprehensive analysis of bubble-related effects, and has applied it to a specific case of a ship mounted sonar to access the real world magnitudes of the bubble layer transmission anomaly. A new expression for the bubble population density spectrum is proposed which provides for (1) a narrowing of the radius spectrum with increasing depth (based on extrapolations from Johnson and Cooke (1987) [81], and (2) the assumption of Thorpe [176] that the surface bubble density varies as the cube of the wind speed. Expressions for the resonant bubble radius, damping coefficient, complex sound speed, attenuation, and the refraction spreading loss are presented. Accuracies of the common approximations (such as neglecting small bubbles, neglecting bubble related refraction, etc.) are evaluated. Surface duct propagation results are predicted at the 0 Hz limit, and for a 1.25 to 40 kHz range in octave steps.

The bubble population model is presented in the context of two important assumptions, namely that (1) the horizontal variability is independent of the dependencies on other parameters and can therefore be separated from them, and (2) that as a working hypothesis the bubble population spectrum level (PDSL) can be taken as independent of horizontal position. (The sensitivity of that matter is ultimately addressed later in the paper). The PDSL is then postulated as the product of a fitting factor, a wind-speed dependent factor, and depth (and wind-speed) dependent factor. These factors are then scrupulously proscribed by a re-evaluation of the data of Kolovayev [86], Johnson and Cooke [81] Walsh and Mulhern [192], Thorpe [176], and others.

With this bubble population model Hall constructs an acoustic model built around the sound speed perturbation $\delta C = Re(C) - C_o$ in a Snell ray analysis. The absorptive and scattering loss, refractive spreading loss, and transmission anomaly are treated in terms of the sound speed perturbation. The resulting expressions are then used in an analysis of sensitivities relating to the more important factors affecting a ship mounted sonar operating in a surface duct.

The author's investigation of the accuracy of various approximations is of particular value. The slope of the bubble spectrum at large radii has long been taken to be 4.0. Hall shows the effect of slope on (1) the perturbed surface sound speed, (2) the surface attenuation rate, and (3) the integrated path attenuation, when the slope is varied from 4.0 to 4.37. Also shown is the effect of doubling the e-folding depth constant in the expression for the population spectrum level, the effect of neglecting small bubbles, and neglecting refraction (assuming an unperturbed real part of the sound speed).

An attempt is made to quantify the effect of varying the horizontal dependence of bubble concentrations (Langmuir circulation-related, vertical bands of bubbles, parallel to wind direction, appearing in strong wind conditions). Since bubble-layer depth fluctuations are on the order of 100 sec [176], the attenuative effect of bubbles on a particular ray path is determined more by the spatial than the temporal fluctuations of the layer. Thorpe et al. [177] observed horizontal band separations on the order of ten meters. The author notes that, since the bubble-induced refractive spreading loss varies non-linearly with the bubble PDSL, the average total loss could be expected to depend on the horizontal structure at low frequencies, but become independent as frequency increases. It is noted that despite the significance of the effect, explicit descriptions of the width of the bands are not available, and indeed the data on the band separations is sparse [178]. The author notes that for transmission parallel to the wind an acoustic ray is either entirely inside or entirely outside a Langmuir band. If inside (for his particular bubble model) the attenuation excess is said to be on the order of twenty-five per cent.

The average refractive spreading loss is examined via the test case for 20 kHz propagation in a surface duct, with 15 m/s wind conditions. Hall determines that, using his bubble spectral model, to predict the spreading loss to an accuracy of 0.1 dB it would be necessary to incorporate horizontal variation (for the sonar depth of 3 m).

In general it is concluded that *at 20 kHz*, except for very high wind speeds, wind generated bubbles are confined too closely to the surface to have significant effects on surface ship sonars at conventional depths. While the bubble transmission anomaly for a sonar at surface depth is 70 dB, the value drops to 1 dB as the transducer depth is increased to 5 m.

10. "Off-Resonance Contributions to Acoustical Bubble Spectra," K. Commander and E. Moritz, J. Acoust. Soc. Am. 85(6), 2665-2669 (1989).

A computational study at 10 kHz and 100 kHz showing disagreement in experimental bubble size spectra as determined from optical techniques [102] versus those of resonant acoustical scattering and absorption theory. The acoustical methods are found to greatly overpredict the distribution of bubbles present with radii less than 50 μ. Three *a priori* size spectra (Gaussian, exponential, power law) were taken to benchmark the divergence of total scattering cross sections and attenuation via "exact" (a la Medwin [118]) and traditional acoustical scattering/absorption methods from the optical results. All void fractions studied were $3.0x10^{-5}$ percent.

The Gaussian spectrum chosen had a mean bubble radius of 60 μ and a standard deviation the same value, with the peak selected to fit void fraction. Exact backscattering strengths are computed for this spectrum for four cases with various size cutoffs (1- $\mathcal{O}$, 1-60, 15-45, and 29-32 μ ranges). At 100 kHz these yield target strengths of -27, -33, -35, and -40 dB re: 1m. This distribution was then compared with size spectra derived respectively from resonance scattering and from resonance attenuation predictions for their theoretical distributions for the same mean bubble radius. Distributions compared favorably above 50 μ, but below this figure acoustical values greatly exceeded those of the a priori Gaussian spectrum. The same calculation is shown for the 10 kHz case and the somewhat differently shaped disagreement is explained in terms of the portion of the spectrum sampled by the signal, and the relative sizes of the normalized extinction and scattering cross sections. Similar results were found when the authors considered the power law bubble distribution versus the acoustic spectra.

The authors appear to make a good case for the dangers of ignoring off-resonance portions of the bubble population in using the resonance theory approximation as opposed to the exact (full distribution) calculation. The trends in the discrepancies are described to be exactly those found by MacIntyre [102] in optical measurement comparisons to resonant acoustic determinations. It is stated that an exact full size spectrum must be obtained via the ill-posed inverse scattering problem leading to a Fredholm integral equation of the first kind. See [26], [27], and also JASA Suppl. 1, 84, S186, 1988.

11. "Inferring Bubble Populations in the Ocean from Acoustic Measurements, K.W. Commander and E. Moritz, OCEANS '89 Conference Proceedings V.4, 1181-1185, September 1989, Seattle, Washington.

An improvement over bubble population estimation with resonant attenuation of scat-

tering techniques is advanced via a heuristic numerical scheme which apparently yields a robust solution of greater accuracy at the low end of the size spectrum. Building on previous work, Commander and Moritz note that, while the classical resonance approximation for size spectra is satisfactory if the distribution follows a power law, the resonance approximation fails at the smaller end of the distribution for Gaussian and exponential distributions. It is noted that real world distributions seem to fall between the latter two cases and the authors proceed to describe their numerical scheme.

The problem of determining the size distribution from a frequency-dependent total scattering strength reduces to that of the inverse problem of the Fredholm integral equation. The problem is an ill-posed one for which small changes in the measured acoustic data result in large changes in the unknown distribution function. Starting with trial bubble spectra (Gaussian and exponential) the authors generate tables of bulk attenuations and total scattering cross sections. Candidate solution schemes are examined by deriving calculated bubble size distributions from the acoustic properties calculated from the *a priori* trial distributions The singular value decomposition method is used to solve the system of equations resulting from the scattering integral written in measured frequency dependent form. The spectrum in question is expressed as a Fourier cosine series expansion and its Fourier coefficients are then determined. The authors discuss the importance of the range of the measured frequencies and that of the bubble size spectra. The sensitivity of the numerical schemes stability to this is addressed as well as the question of the number of experimental data points required.

12. **"Numerical Simulation of Acoustic Scatter from Subsurface Bubble Clouds," C.L. Rino and H.D. Ngo, Technical Report Vista Project 1010, October, 1989 (Vista Research, Inc., Mountain View, California).**

This theoretically interesting study is an acoustic application of a spectral domain technique previously applied to electromagnetic scattering from rough surfaces. The mutual interaction method (MIM) of determining multiple scattering characteristics between two interacting objects has been described elsewhere [152]. The method is here reiterated for the EM case of cylinders near a plane impenetrable surface, and reduced to the scalar acoustic case approximating scattering from a subsurface bubble cloud. Comparisons of MIM with the method of moments (MOM) and the generalized electromagnetic code NEC are discussed, as are some of the computationally intensive aspects of implementing a numerical solution (simulations utilized a CRAY Y-MP).

While detailed discussion of multiple scattering and MIM is beyond the scope of this survey, it may suffice to make several points about the approach. First, that the method as implemented here considers a bubble cloud to be a structureless, impenetrable object

having no overlap with the sea boundary. This is possibly a serious limitation of MIM for the bubble scattering problem since plumes appear as bubbly regions extending down from, and only sometimes separating from, a near surface bubble layer at the boundary. In the MIM approach the bubble cloud boundary must be *distinct* with no transitional cushioning region. In this implementation the cloud must be at or below the depth of the deepest trough of the surface representation.

The MIM approach used here does not allow a direct dependence on sea state. While this is not a fatal feature it 's nonetheless an inconvenient one for a scattering model. A more practical problem with the mutual interaction method is the computational requirement. Although exact runtimes for MIM are not given, and it apparently does have speed advantages over MOM and NEC, nonetheless execution time would appear to be a serious problem in a full-blown implementation of a realistic sea surface with a bubble layer and plumes. While pre-sampling may possibly resolve this issue, the whole question of how MIM would be integrated into a sea surface scattering model bears further investigation.

In general an important question in this approach is whether the plume internal characteristics can be modeled adequately with MIM. This report admittedly does not pretend to do this. The bubble plume is assumed to be completely representable by a pre-calculated scattering dyadic. While this may be feasible under some circumstances, the reader is left with the impression that there are important inconsistencies between the mutual interaction method and the acoustic sea surface/bubble plume problem.

13. "Acoustical Absorption and Scattering Cross Sections of Spherical Bubble Clouds," L. d'Agostino and C.E. Brennen, J. Acoust. Soc. Am. 84(6), 2126-2134 (1988).

This is an interesting analytical study of bubble cloud dynamics and acoustic cross sections which was apparently motivated by considerations of cavitation flows. The authors presume a spherical cloud of equal radii bubbles driven by an external harmonic pressure perturbation. For simplicity the radii of all the bubbles are taken as equal at dynamical equilibrium. The bubble radii respond with nearly in-phase harmonic change under damped oscillation. The treatment allows for viscosity, heat transfer, compressibility, and relative motion of the two phases. It assumes a linearization of the velocity field (steady flow, small perturbations) and, most importantly, a linearization of the bubble dynamics, the most crucial limitation (other than that of the iso-radial size spectrum - see [88]).

Cloud response is shown in terms of reduced frequency and is dominated by a coupled, natural frequencies response. Sub-resonant, transresonant, superresonant regimes are identified in terms of the relation between the exciting frequency, the first natural cloud

frequency, and the individual bubble natural frequency. In the sub-resonant regime the bubbles have ample time to react and behave in a compliant way, with the largest bubble radius oscillation found in the interior of the cloud. In the super-resonance regime the response of a cloud tends to become stiffer and more uniform with frequency. In the trans-resonance region internal resonant-based motions complicate the response. The phase of flow parameters depends on the dominant oscillatory mode in the cloud.

Acoustic scattering and absorptive cross sections are shown as a function of void fraction. Both show two peaks corresponding to the first two natural modes. These peak frequencies decrease at higher void fractions and both the scattering and absorptive cross section maxima increase slightly with void fraction; the second resonant peaks become more pronounced due to the greater compressibility of the cloud. Unsurprisingly, the acoustical properties of a volume of dispersed phase are shown to depend strongly on the degree of dispersion of the mixture.

Some of the conclusions of the study are as follows. The natural frequencies of the cloud are always lower than that of individual bubbles. With damping, the first natural mode of cloud oscillation dominates the response. Acoustical scattering and absorptive cross sections are quite different in amplitude and frequency distribution from those of individual bubbles. The acoustical properties are strongly vapor/gas phase dispersion dependent. Increases in void fraction substantially decrease acoustic response.

The authors state that if the assumption of linear bubble dynamics were dropped then a quasi-linear analytical theory of broader applicability might be established. However, there is no discussion of the incorporation of realistic size spectra into their analysis. The iso-radial assumption causes limited applicability, but the study reveals some of the interesting physics and shows what can be done analytically with closed solutions.

14. "An Invariant Imbedding Approach to the Scattering of Sound from a Two-Phase Fluid," E.A. Skelton and W.J. Fitzgerald, J. Acoust. Soc. Am. 84(2), 742-751 (1988).

This theoretical approach applies the Carstensen-Foldy method [17] to a bubble layer with number density a function of position. Incorporating multiple scattering, but allowing no bubble interactions, it uses the invariant imbedding method for studying scattering (which avoids boundary value difficulties by appropriate selection of space and time variables to reduce all problems to the initial value type). The resulting integro-differential equation is described as well-suited for numerical studies.

The invariant imbedding method, with origins in works of Ambarzumian [1] and Chan-

drasekhar [18] can be described as follows. Given a physical system, whose state at time t is specified by a state vector, consider a process that consists of a family of transformations applied to this vector. By enlarging the dimension of the original state vector by means of additional components, the state vectors are made elements of a space that is mapped into itself by a family of transformations. Using this method an invariant process is obtained by imbedding the original process within a family of processes. The functional equations governing the new process are the analytic expressions of this invariance. This type of analysis that leads to functional equations is similar to perturbation theory in which the quantity that is perturbed is an extensive variable of the medium itself rather that the more familiar intensive variable related to the physics of the situation.

This problem's approach must be read to be appreciated, but briefly the authors first describe Foldy's method of iterative series solution based on finding the average over all bubble configurations of the mean-squared pressure by replacing the water containing the bubbles by a continuous medium with effective parameters. The resulting expression is the sum of the square of the ensemble-averaged pressure plus a series of correction terms $Q_i(r)$ dependent on position. Correction terms are found by sequentially bootstraping up each Q_i from the lowest order scattered wave and calculating the term due to incoherent scattering of the average pressure wave by the bubbles, starting with the primary wave $\psi(r_0)$ in the bubble free region. Skelton and Fitzgerald then cite numerical problems with Foldy's approach and proceed with their invariant imbedding method.

The invariant imbedding method used constructs an integro-differential equation for a quantity related to the differential scattered field intensity and considers the change in this expression upon finite variation of the layer thickness δ. Multiple scattering is taken into account by identifying five distinct situations that have to be considered, and formulating an intensity term for each. An embedding variable R is chosen and a reformulated intensity expression is expanded in Taylor series and taken to the limit of an infinitesimal δ. Gaussian quadrature approximations to the integral equations are taken and integro-differential equations are found which may be solved by, e.g., Runge-Kutta methods. The method is said to be applicable to a distribution of bubble sizes.

The authors also attack the inverse problem via working back from the sound field to determine the medium's physical characteristics using the approach of quasilinearization. The interested reader is referred to the text on this matter.

In a consideration of realistic bubble populations the authors used the optical results of Johnson and Cooke [81] as well as an averaged distribution obtained by Thorpe [173]. For Thorpe's case they compare the zero order (coherent only) Foldy approximation to the invariant imbedding approach. In each case the attenuation from invariant imbedding is less than the Foldy result. This is expected since incoherent scattering is included in

the invariant imbedding estimate. The frequencies examined range from 30 to 100 kHz, spanning the resonant frequencies of the distribution. At 50 kHz many of the bubbles are at their resonance and a large amount of the removed energy is available for multiple scattering. Hence the incoherent part of the transmitted sound pressure is large and results in a marked discrepancy between the two approaches. Otherwise the agreement is rather good. The medium characteristics (inverse) problem is also solved for the Thorpe distribution and the authors end the article with several caveats regarding convergence.

15. "An Integral Equation Method for Coupled Fluid/Fluid Scattering in Three Dimensions," A. Seybert and D. Casey, J. Acoust. Soc. Am. 84(1), 379-384 (1988).

This article is concerned strictly with single bubble resonances as attacked via the boundary integral equation method (BIE). In this approach the (homogeneous) fluid/fluid boundary value problem is reformulated into a pair of integral equations, one for the exterior medium and the other for the interior medium, valid at the boundary or interface between the two media. These integral equations are then coupled together by the (unknown) boundary data corresponding to a well-posed fluid/fluid boundary value problem (continuity of acoustic pressure and particle velocity at the interface). Simultaneous solution of the (discretized) integral equations then determines the acoustic pressure and particle velocity at the interface. Velocity potential on either the interior or the exterior medium is then found by quadrature of the known boundary data. A key feature of the BIE method is to use a fundamental solution to reduce a three-dimensional problem to one involving only the two-dimensional boundary (surface) of the problem. The interested reader should see the work of Gragg and Pitre [65], described above, for an application to bubble plume scattering.

The authors discuss the known difficulties with uniqueness in the exterior acoustics problem as formulated with integral equations (not unique at all wavenumbers). The "CHIEF" method [158] is considered an effective counter to these difficulties, but in this paper the problem is circumvented by staying in a wavenumber range where the solution is unique.

Seybert and Casey treat the single bubble BIE formulation numerically for full-space and half-space resonant scattering. While the real power of BIE lies in the solution of scattering from bubbles of arbitrary shape, the authors choose the sphere for their node and element discretizations. Numerical results are shown for the backscattered velocity potential and the giant monopole is clearly visible. The second (dipole) resonance and higher resonances are not shown. An 18-node sphere discretization shows the shape of the scattered spectrum accurately, but the authors note that it incorrectly shows a shift in monopole resonance. This is corrected with a 50-node decomposition.

Since the single bubble problem has limited applicability to the collective behavior exhibited in bubble plume dynamics this article serves mainly to illustrate the BIE method. Limitations of this approach as applied to plumes due to not so much the internal dynamics as the presence of a more vaguely defined boundary in the real world. This paper offers a classic treatment of the half-plane scattering problem with BIE. Any regular solution of the wave equation can be added to the fundamental solution of the Helmholtz equation and the resulting function used in the integral equation. This approach of a modified kernel is illustrated for the scattering of a plane wave by an air bubble in water and in proximity to a hard wall. It is noted that the rigid plane affects the behavior of the giant monopole resonance even when the plane is several thousand radii from the bubble. The authors speculate that such information could possibly be exploited for the location of surfaces even at long distances underwater.

16. "Superresonant Systems of Scatterers. I.," I. Tolstoy, J. Acoust. Soc. Am. 80(1), 282-294 (1986).

Compact object (small Helmholtz number: $ka < 1$) scattering is examined in the context of simple systems of scatterers (bubbles, inflated balloons, thin shells in water) in an acoustic full space and near an elastic boundary. Such systems display resonances distinguished in nature from the single scatter intrinsic frequency resonances of isolated sources. This collective amplification is found at frequencies near or, in some cases, at the intrinsic radial frequency of the constituent bubbles. This paper deals with symmetric bubble-like objects of equal radii and is primarily concerned with relatively large bubbles and shells. A sequel paper appears in [184].

Following the work of Twersky [186] the author investigates the multiple scatter coefficient B in terms of the single scatter coefficient A. The strength B is shown to be expressible in terms of A, for pairs of scatterers (doublets) or equilateral triplets, insonified at normal incidence, as $B = A/(1 - qAF)$ where F is the three-dimensional acoustic scattering amplitude for a single source in a full space and q = 1 for the doublet and 2 for the triplet. B may have one or more poles, (i.e., resonant spacings), and frequencies. These super-resonances then will correspond to the normal modes of a system of resonant or near-resonant scatterers linked by the medium, coupled through the wave field $F(kr)$ via a process of multiple scatter. This coupling field may be either an ordinary pressure wave (e^{ikr}/ikr in a fullspace), a surface wave trapped near an elastic interface, or any combination of transmitting waves (compressional, Rayleigh, Stoneley) carrying a pressure field in a solid environment.

Three cases are examined: the infinite homogeneous acoustic fullspace, the half-space bounded by a thin plate, and the half-space bounded by a solid half-space. In the first case it is shown that at least three scatterers are required to construct a super-resonant system

(an equilateral triplet is treated). The doublet in a full space exhibits only quasi-resonances (smaller gains per scatterer). However, in the vicinity of a thin plate or an elastic wall the doublet also develops elastic resonances when its distance from the boundary is less than some limiting value. This occurs for the doublet near a wall because interaction between scatterers is assisted more efficiently by surface wave modes. Numerical results are shown and amplification factors of several orders of magnitude are found for specific conditions.

17. "A Propagator Model for Scattering of Acoustic Waves by Bubbles in Water," V.K. Varadan, V.V. Varadan, and Y. Ma, J. Acoust. Soc. Am. 78(5), 1879-1881 (1985).

A propagator model is used to study acoustic phase velocity and coherent attenuation of monochromatic plane waves propagating in an infinite fluid medium containing a random distribution of N spherical scatters with a constant number density. Lax's quasicrystalline approximation [92], (with suitable averaging techniques) and the T-matrix of a single scatterer are employed in the analysis.

Pair correlation functions that were generated by Monte Carlo simulation are employed and it is shown that this model provides the same dispersion equation as the one obtained by the authors earlier using the self-consistent multiple scattering approach [191] (see below). Numerical results for attenuation and normalized phase velocity show agreement with the laboratory experiments of Silverman [160].

For the media considered the "breathing mode" resonances of the bubbles and the resultant distinct variation of coherent attenuation and phase velocity are found. The curve of phase velocity versus wavenumber shows an oscillating behavior in the resonance region. These oscillations in the phase velocity appear even for very low concentrations (e.g., volume fraction of $6.0x10^{-4}$) between the acoustic and optical branches.

18. "Numerical Studies of the Spectrum of Low-Intensity Ultrasound Scattered by Bubbles," B. Eatock, R. Nishi, and G. Johnston, J. Acoust. Soc. Am. 77 (5), 1692-1701 (1985).

A numerical study of scattering by low intensity (10-100 mW/cm^2) ultrasound (100 kHz - 1 MHz) from nitrogen bubbles of radii in the range 1-20 microns. Solutions of the modified Rayleigh equation, including the effects of acoustic, thermal, and viscous damping, and the frequency dependence of the gas polytropic exponent are presented for various waveforms. For the selected conditions of low-to-moderate amplitude ultrasonic fields (0.01 to 1.0 bar)

it is shown that nonlinear scattering is significant only for the population of bubbles which are smaller than, or close to resonance size, and principally for those bubbles that are at half resonance size.

The Rayleigh model assumes that the wavelength of the exciting radiation is much greater than the radius of the bubble and therefore only the behavior of the bubble surface is important. Accordingly the authors solve the equation for the bubble radius in the time domain and transform it to the frequency domain to examine spectral components. In order to ascertain the relative importance of the components in the scattered wave, the bubble is modeled as a superposition of simple sources, each radiating at one of the frequencies in the autospectrum of the bubble's motion. Since the pressure radiated by a small simple source is proportional to its surface velocity and frequency [83], in the examples of bubble radii and waveforms chosen by the authors, the surface velocity, rather than displacement, is plotted as a function of equilibrium radius at specific frequencies. The overall perspective taken in the analysis is that of constraining frequency, amplitude, and pulse duration in order to determine what population of bubbles would contribute significantly to the harmonic signals.

19. "The Effect of Langmuir Circulation on the Distribution of Submerged Bubbles Caused by Breaking Wind Waves," S.A. Thorpe, J. Fluid Mech. 142, 151-170 (1984).

In 1938 Langmuir described an observation of wind rows as being generated by "helical vortices set up by the wind" [93]. Thorpe deals here with a numerical simulation of a Langmuir type circulation in an attempt to determine its effect on a given bubble distribution. An analytical model is also developed for validation. Based on Thorpe's 1982 work [176] involving a bottom-mounted, upward pointing 248-kHz sonar, this paper compares those 1982 results with sonographs [178] obtained from side-scan sonar. The bands on the sonographs have a mean separation consistent with the distance observed between wind rows, hence support for Langmuir circulation as a generator of bubble plumes. (A good tutorial and review of Langmuir theory and observations can be found in Leibovich's article [94]).

Thorpe calculates the maximum depth of bubble downdraft to be expected for a Langmuir style mechanism. Then estimations of the effective vertical diffusion coefficients K_v are found from typical vertical velocity and temperature distributions, with possible errors in the estimates of K_v admitted to be large. Langmuir circulation is then presented as a perturbation on a primarily diffusive solution to an equation describing the effects of turbulent diffusion of bubbles from a free surface, bubble rise and dissolution, and advection by circulation. This equation is solved analytically using a series expansion in which advection is assumed small relative to diffusion. The principal effects of the circulation, in particular

the distortion of the bubble field and estimates of the advective flux, are then investigated.

A numerical model is developed and later used to test a random-walk numerical simulation of turbulence which, once validated, is used to determine details of bubble motions under Langmuir circulation. An agreement is demonstrated and the numerical model is used in extending the solutions to more complex cases, which include a broad distribution of bubble sizes, and to ranges where the analytic solution is invalid. The model is used to quantify the effect of the circulation on the acoustic scattering cross-section of the bubble clouds and to compare results with earlier observations by Johnson and Cooke [81].

Thorpe notes that the analytical model does have the deficiency of failing to reproduce some features of Langmuir circulation such as the displacement of the center of the circulation towards the position of the wind row, but the main features are represented. Thorpe examines the relative values of the vertical and horizontal diffusion coefficients (K_v and K_h) and studies solution behavior under the reduction to the Stommel trapping case [164] (vanishing diffusion and bubble loss rate). Non-zero coefficients preclude permanent trapping, but still may lead to enhanced bubble concentrations (realistic conditions of course mandate that K_v be finite) under a mechanism studied by Leibovich and Lumley [96]. This suggests a perturbation about a state with zero maximum vertical speed. The series solution is therefore chosen for boundary conditions corresponding to a uniform downward diffusive flux over the ocean surface.

Subsequent examination of parameters reveals that the effect of the circulation is to increase the concentration in the vicinity of *downgoing* fluid. The solution is used to find the vertical flux associated with the circulation and the role of the effective vertical diffusion coefficient K_{ve} is discussed. K_{ve}, unlike K_v, depends on properties of the bubbles themselves (K_v depends only on the turbulent motion), and it is pointed out that it is not possible to define unambiguously an effective vertical diffusion coefficient dependent only on the turbulence and motion in the water. Consequences of this are discussed further.

The numerical model is a variation of that previously investigated by Thorpe [173]. Bubbles are represented as an oxygen-nitrogen mix and their radii evolve according to a first-order finite difference equation. The model is run with $K_v = K_h$ for turbulent diffusion. An increase in concentration is shown to be the principal effect of Langmuir circula·:on on the mean profile. Solutions for the model operating with realistic distributions are compared with observations.

Thorpe summarizes his conclusions with the statement that based on this investigation there is circumstantial evidence for the importance and significance of Langmuir circulation on the near-surface mixing layer. The primary difficulty cited lies in constructing an appropriate representation of turbulence. The simplified assumption of a diffusion coefficient

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that is independent of depth and flow is a uniformity perhaps unlikely in nature, but the real problem is that of how to select the appropriate values for K_v. The values used were selected from measurements of K_v versus wind speed, which did not distinguish between circulations and turbulence, but encompassed the effects of all processes contributing to the vertical diffusion of bubbles. The ambiguity is deeper than just a matter of needing controlled experiments. It involves the basic concepts of turbulence and circulation and suggests some uncertainty in what conclusions may be drawn regarding the role of Langmuir flow in bubble phenomena.

20. "Coherent Attenuation of Acoustic Waves by Pair-Correlated Random Distribution of Scatterers with Uniform and Gaussian Size Distributions," V.K. Varadan, V.V. Varadan, and Y. Ma, J. Acoust. Soc. Am. 73(6), 1941-1947 (1983).

The multiple scattering of acoustic waves by suspended particles (embedded rigid, fluid, or elastic bodies) is formulated using the T-matrix (Waterman, 1969) [194] to characterize the single scatter response and a configurational average over the random positions of the particles.

The method as presented results in a computational scheme that is claimed to be suitable for scatterers of arbitrary shape, orientation, dense concentration, and at wavelengths comparable to particle size. A complex, effective wavenumber in the random medium is computed as a function of frequency and it is observed that the results crucially depend on the volume fraction c; and for $c > 0.1$ the effects of the pair correlation function is especially significant for lower frequencies. As a result, improved pair correlation functions using the self-consistent approximation (SCA) were incorporated into the numerical algorithm. The SCA is a linear combination of the Percus-Yevick approximation [142] and the Hypernetted Chain approximation to the pair correlation function. This approach yielded numerical results for c near 0.35 and closed form expressions for the phase velocity and attenuation are presented in the long wavelength limit. A dispersion equation is solved numerically at higher frequency for particles with uniform and Gaussian size distributions. The interested reader should see [8] for recent work with the Percus-Yevick correlation function.

21. "Resonance Theory of Bubbly Liquids," G. Gaunaurd and H. Uberall, J. Acoust. Soc. Am. 69(2), 362-370 (1981).

This work is a rigorous application of the effective modulus technique developed by W.S. Ament [2] and Kunster and Toksoz [89]. In this approach the effective moduli of

bubbly liquids are obtained by comparing scattering amplitudes from the inclusions with the amplitude from a larger sphere containing the "effective" material. This is done in a long wavelength regime where only the lowest non-vanishing terms in the normal-mode series of the scattering amplitude are retained and the results therefore represent only the static expressions for the effective moduli (and do not demonstrate resonance effects). Whereas in many cases the resonances of inclusions are located at relatively large frequencies, in the case of gas bubbles in fluids, or air cavities in rubber, a giant monopole resonance is present in the Rayleigh (low-frequency) region and its contribution to the effective moduli must be considered.

In this study the authors treat the problem using the rigorous Ament-Kuster-Toksoz (AKT) theory, but retained those high-order terms in the long-wavelength expansion which are necessary in order to include the effects of the monopole resonance. The resulting effective moduli are therefore dynamic quantities which explicitly account for the resonances present in the scattering amplitudes. The incident waves are treated as plane waves, so that in contrast to other studies using "self-consistent" methods, the effects of the multiple scattering are not taken into account and these results hold only if the bubble concentrations are sufficiently small.

All the calculations presented are for clouds of bubbles of uniform radius, but the theoretical groundwork for use with this approach with real size distributions is also developed.

It is emphasized that the basic equations of the AKT method are obtained by equating the farfield scattering potentials for longitudinal waves of a real and a fictitious object (the equivalent sphere with an effective modulus). Equations for the effective material parameters are derived by further equating the first three coefficients of the potentials and expanding these in the long wavelength limit. Not only multiple scattering, but also the phase relationships of individual scatterers are neglected. The theory is limited to small volume concentrations in which all scatterers act independently, yet approximately in phase with each other. In the low-frequency quasistatic limit explored by Kuster and Toksoz this approach leads to generally accepted results.

6 CONCLUSIONS

Examination of the articles and presentations described here, and the large mass of literature on bubble layer and plume phenomenology, indicates that the available experimental database relating to this subject has improved greatly in recent years. However, there still remain numerous critical areas for new measurements and theoretical interpretation.

The whole question of the role of Langmuir circulation as a downwelling mechanism suggests further determination of in situ quantities such as flow rates and vertical extents as examined in the MILDEX experiment [162]. Such basic dynamical information will facilitate theoretical and modeling progress toward prediction of plume state evolution as a process. If Langmuir flow is indeed a dominant plume-sustaining mechanism, with wavebreaks providing bubble injection, then one must examine the occurrence, persistence, and hierarchy of Langmuir cells within the volatile oceanographic environment.

Uncertainties relating to the role of Langmuir circulation in bubble plume growth are many. For example, do Langmuir cells exhibit a stable spectrum of circulation scales for a particular wind speed? Are there interactions with internal waves, limiting the circulations? Do the Langmuir cells develop and recede periodically with wind speed growth or do they persist and expand? Langmuir flow is said to onset with a 3 m/s wind speed [94]. Is there a wind speed cutoff point, resulting in cell breakup at high sea states? Does the mixed layer depth represent the lowermost extent of the cells? How is the flow influenced by fronts and eddies? Is the available data now sufficient to isolate Langmuir circulation from other ocean processes such as thermal convection? What is the seasonal dependence of Langmuir flow? To what extent are diurnal factors relevant? Hopefully, a number of these issues will be addressed in the results of the SWAPP and SWADE experiments. There is also the possibility that further laboratory experiments similar to those of Faller et al ([43], [44], [45]) may be of value.

Due to the need to predict contributions from competing bubble-scattering mechanisms (weak, strong, resonant) there remains a need for more data on the variation of bubble size spectra, particularly with regard to causal environmental factors. While the moderate-to-large diameter portions of the bubble populations are clearly contributed by wavebreak-associated events, the relative contribution to the (presumably small diameter) spectrum by biological activity is not clear. Laboratory and theoretical studies will undoubtedly clarify the processes of wavebreak injection and their relation to the size spectrum, but only ocean measurements can resolve questions of the quiescent biological background in terms of locality and season.

Plankton are the most abundant form of life in the oceans, both in numbers and sheer

weight. Concentrations of them are known to vary significantly with location and season. Phytoplankton (microscopic plants) experience a "bloom" in the spring, affecting the available feed for zooplankton (microscopic animals). The growth of phytoplankton in the presence of otherwise available nutrients is known to depend on the local concentration of soluble iron in the ocean [201] - a factor which may have global ecological implications since these creatures may account for a significant removal mechanism for atmospheric carbon transfer to the ocean. Phosphate concentration is also important for plankton growth and the scarcity of it in tropical regions accounts for very low plankton populations and the crystal-clear waters. The point of such considerations for the acoustic surface scattering community is that, while the microbubble component of the spectra may indeed be robust locally [97], it may undergo geographical and seasonal variation due to biological effects. An increased interaction between the underwater acoustics and marine biology communities is thus indicated.

In general there is probably a need for better statistics on the bubble plume phenomena, with more measurements conducted on a routine basis. Plume shapes, spatial and temporal occurrences, and their wind-stress/speed dependencies need more complete characterization in a variety of environments. Plume lifetimes and extents need independent measurement and correlation with wavebreak bubble injection and the parameters associated with Langmuir circulation. The common assumption that macro-bubble plumes are strictly associated with wavebreaks, while micro-bubble plumes are associated primarily with Langmuir flow, deserves more explicit examination.

In addition to deep water studies the specific characteristics of bubble layers and plumes in shallow water need to be further determined experimentally. Shallow water effects on the surface wave spectrum have been studied by Sanders and Bruinsma [154] and Bouws et al [11] using the KNMI (Royal Netherlands Meteorological Institute) wave model in the North Sea. In this regime of bottom depths the wave-growth limitations of bottom dissipation may imply substantially different behavior of both the wavebreak bubble injection and Langmuir circulation mechanisms. Bubble concentration depth profiles and occurrences could differ significantly from those of deep water. Related effects may appear in guyot (submerged plateau) and seamount-dense environments. In these contexts the existing measurements in lakes and shallow water need follow-up work in varied locations. Whether Langmuir flow is an equally effective downwelling mechanism for plume generation in all water depths is worth consideration.

Some of the necessary simplifying assumptions of recent work ([70], [110]) suggest the need to examine several questions, notably (1) whether the spatial distribution of deep, strongly-interacting plumes can be considered independent of wind direction, (2) whether plume occurrences can be treated as statistically independent, and (3) to what extent whitecap coverage is a good indicator of subsurface plume coverage. Resolution of such questions

of horizontal dependencies will require a clearer understanding of the hydrodynamical effects at work and major efforts in the collection of in situ environmental data. The complex dynamics of the air-sea interaction present uncertainties which as yet preclude a consensus regarding correlations and indicators between subsurface conditions and the more evident meteorology transpiring above the surface. Even in acoustical regimes where the subsurface bubble layer scattering screens the rough-surface interface scattering mechanism, it will be necessary to characterize the surface spectrum in order to correlate subsurface phenomena of importance to scattering. The determination of such macroscopic, meteorologicaly-related indicators (with appropriate statistical weightings) is critical to model development and system performance prediction.

The above considerations are undoubtedly only a subset of further work that will be required to establish a sufficient knowledge base for reliable predictive model development on a global basis. To bring these things about there must be established a consensus between the acoustic and oceanographic communities as to what constitutes a minimum measurement set of environmental parameters pertinent to plume/surface scattering. This measurement set could then become part of every at-sea propagation experiment, with increased attention to oceanographic factors at the planning stage. Particularly difficult oceanographic measurements, aimed at establishing useful surface-subsurface correlators, may be impossible to routinely conduct along with every propagation experiment. Nonetheless such measurements need to be conducted under sufficient environmental variation, at enough geographic locations, and with adequate seasonal coverage to insure that sub-surface phenomena and their indicators are well correlated. While much has been accomplished towards these ends, progress will require continuing attention and coordination efforts, as well as vigorous input from the research community. Further conferences on air-sea acoustics topics will provide important opportunities for discussion and communication in the literature.

For the purposes of this report it is hoped the surveys presented here will provide some awareness to the modeling community of what is and is not understood with respect to bubble layer and plume scattering effects, and stimulate suggestions for new measurements and analyses. As in any dynamic research area where data are sparse and phenomena complex, the literature on this subject will continue to merit special attention for some time to come.

7 ACKNOWLEDGMENT

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