Chapter 4

METHODS OF BUBBLE MEASUREMENTS

As the size distribution is the most important characteristics of the oceanic bubble population necessary to be measured, much effort was directed toward designing a reliable, simple, and wide-range bubble spectrometer.

4.1 Early Methods

Early attempts to measure bubble population involved methods based on bubble traps, acoustics and photography (§3.5) . At this time those were effective, though they faced some limitations. For example, the 60 cm length of the trap used by Kolovayev (1976) provided a means of capturing the bubbles, however each measurement started after some delay time necessary for the smallest bubbles to rise to the upper side. This raises questions about the effects of bubble dissolution, growth and coalescence, since according the Stokes law a bubble 25 μm in radius requires 8 minutes to travel along the 60-cm tube, while the same bubble requires only 3 minutes to dissolve at 10 cm depth in air-saturated water (Scott, 1986) . The acoustic device used by Medwin (1977a) brought some difficulties in the data interpretation as large bubble concentrations were observed at light winds. The only explanation was that these bubbles were produced by biological processes. However, it raises the question about the acoustic response of bubbles covered with an organic layer. These restrictions prompted the development of the photographic method used by Johnson and Cooke (1979), which employed three strobe lights and identified each bubble as a group of three bright spots corresponding to the specular reflection of each strobe impulse from the bubble. The same method was successfully used later by Walsh and Mulhearn (1987) .

4.2 Principles of the Available Methods

Three measuring techniques, among others, have been widely accepted throughout the years: optic, photographic and acoustic. As it can be expected, a single ideal technique for measurements in both laboratory and field is not found to provide an adequate size range, a large sampling volume, a large spatial area and depth coverage, and amenable automatic data analysis (Su et al., 1994) .

4.2.1 Optical Method

The optical technique is based on either the light-blocking principle (Wu, 1977) or dark-field specular reflection (Su et al., 1994) . A laser beam is sent into the liquid and a photodetector, usually a photomultiplier, is used to measure the reflected and refracted light from a gas bubble (suitable for solid particle too) as it passes through a small control volume. The pulses from the photodetector are amplified and sorted according to their height and length by a pulse height analyzer. The bubble size must be larger than the wavelength of the light. The method is continuous, but looks at only a small portion of the flow. Devices using this principle possess the following possibilities: size range at small-size side: usually 10 - 200 μm up to 800 μm; small sampling volume; small spatial coverage; suited for automatic data analysis. Optical methods such as holography (O'Hearn et al., 1988) and microscope methods are usually employed for sizing the cavitation nuclei.

4.2.2 Photographic Method

The photographic imaging system consists of a camera with suitable lighting, packed in waterproof housing. The size range covered is 50 - 500 μm. The sampling volume and spatial coverage are bigger than those of the optical system, but should be kept small so as not to lose resolution. The most serious drawback of the photographic system is the tedious analysis – usually data from still pictures are processed manually. This problem has been overcome by using a video camera instead of a still picture camera and a sophisticated image processing software. However, the resolution is aggravated compared to that of the still photographs. The standard video cameras can be used with confidence only for large bubbles with diameters of 600 μm and up. At the present state of technology high resolution cameras are available only at very high prices.

4.2.3 Acoustic Method

Bubble sizes can be determined acoustically on the basis of three types of measurements: scattering or excessive attenuation of the acoustic wave and the changes in sound velocity. As these are frequency dependent phenomena, two kinds of acoustic resonance can be used (Su et al., 1994): resonance at low frequencies (50 - 1000 Hz) at which bubble plumes resonate collectively; resonance at high frequencies (10 - 400 kHz) at which a single-bubble is registered. Medwin (1977b) points out the advantages of the acoustic method as: 1) the bubble resonance frequency is inversely proportional to its radius, b) at resonance, the scattering and the extinction cross-sections of a bubble are about 1000 times greater than its geometrical cross-section and 3) the bubbly liquids are dispersive, i.e., they add a complex compressibility to the real compressibility of a pure liquid and the sound speed becomes a function of the frequency. The range of bubble size can be chosen by changing the sonar frequency. A size range of 34 - 1200 μm is typically covered; it can be extended in both directions to 8 μm and 2.5 mm. The sampling volume and spatial coverage are much more larger than for the two previous systems; the data processing is highly amenable to automatic performance.

4.2.4 Others

Commonly used in bubble size measurements (also for any other particles) is the Coulter counter (Young, 1989) . The particles are suspended in an electrically conductive liquid and flow through a small aperture, that has an emersed electrode on either side, one by one. Each particle displaces electrolyte when passing through the aperture and momentarily changes the resistance between the electrodes, producing a voltage pulse with a magnitude proportional to the particle volume. The resultant series of pulses is amplified and counted. The device may cover a range of size from 0.5 to 500 μm.

Doppler bubble detectors, bubble detectors based on second harmonic or on the non-linear mixing of two frequencies, and pressure pulse methods are reported (Young, 1989) . Generally, these are devices based on the usage of acoustic frequencies.

A new optical method based on the Kerr effect has the potential to be applicable to bubble-size measurements.

4.3 Comparison of the Available Methods

The comparison of three particular systems performed in laboratory (Su et al., 1994) is summarized in Table 4.1.

Table 4.1

System name	Range of meas. radius (μm)	Sampling volume (cm^{3})	Processing abilities
Light Scattering Bubble Counter	10 - 150	0.012	automatic analysis
Photographic Bubble-Imaging system	50 - 500	330	tedious analysis
Acoustic resonator array	34 - 1200 (8 - 2500)	1250	highly automated

The results unequivocally favor the acoustic one, since it covers the widest size range and the largest sampling volume, and is the easiest to perform automatic data analysis. It seems to be most suitable method for measuring the bubble density in the field, especially for the long-term monitoring (Melville et al., 1995) . The other two systems are more suitable for laboratory experiments. Considering the size range, the optical system is often preferred. Undoubtedly, the photographic technique will become more popular as computers grow faster and cheaper, cameras continue to develop toward state-of-art in both speed and resolution, and refined image processing software become available.

4.4 The Peak in Bubble Size Distribution: Physical or Technical Problem?

The presence of a peak in the bubble size distribution has been debated in the "bubble community" for years (Medwin and Breitz, 1989) . It rose from the discrepancies between measurements performed with optical (including photographic) and acoustical systems. These discrepancies were first discussed by Wu (1981) . Acoustically estimated bubble size spectra usually show continuously increasing values toward the small-side of bubble diameters without a characteristic peak. Furthermore, bubble concentration falls off slowly or remains almost invariant with depth. In contrast, optically determined bubble spectra show a peak around 75 μm and bubble concentration falls off rapidly with depth (see again Figures 3.1 and 3.2, and Figure 4.1) . Wu (1981) attributed these differences to different mechanisms of bubble production and this was fairly true for the comparison between Medwin's results (1970) obtained in quiescent coastal waters and those of

Figure 4.1 Compilation of bubble size distributions obtained by different authors with different measuring techniques: optical technique – dashed lines; acoustical technique – solid lines. The abbreviations are: Ga = Gavrilov (1969); M0 = Medwin (1970); M7 = Medwin (1977); BW = Blanchard and Woodcock (1957); G = Glotov et al. (1962); K = Kolovayev (1976); JC = Johnson and Cooke (1982) (from MacIntyre, 1986) .

Kolovayev (1976) and Johnson and Cooke (1979) under various wind conditions. Meanwhile, most of the later optical and acoustical measurements consistently revealed the same features: presence of peak and rapid fall-off for optical measurements, and missing of the peak and slow fall-off for acoustical ones. There are some exceptions (Table 3.1) . For example, Blanchard and Woodcock (1957) with a bubble trap, O'Hearn et al. (1988) with holographic system and Baldy (1988) and Hwang et al. (1990) with laser employing systems are optical techniques which do not show a peak. However, Valge and Farmer (1992) with an acoustical technique measured a peak. It is born in mind that the reason for the discrepancies are more complex than just technical capabilities of the systems. MacIntyre (1986) considered the possible reasons for that phenomenon. First, he makes a strict analysis of the three mechanisms for attenuating the sound (§2.4) . Referring to Figure 2.5, for large bubbles (> 6.5 mm in diameter) the re-radiation, δ_r, is the main process for attenuation. Below this bubble size down to 6.5 μm, the attenuation is due mostly to the thermal damping, δ_T. Beyond this size the attenuating is dominated by the viscous term, μ_L, in the total sound damping coefficient δ. This last process, usually omitted in the classical acoustical considerations, introduces important overestimates of the number of bubbles at small diameters. The correction of this omission shifts the acoustical results closer to the optical ones. But this can account only for 10% of the discrepancies. Therefore, the second consideration that McIntyre (1986) makes is the correction in optical results. There are three important features to be noted when an optical device detects small bubbles: 1) all neutrally buoyant bubbles, which do not rise across the beam, are not detected; 2) only specular objects, reflecting the sensing beam, are detected; 3) the very small bubbles, say 1 μm, are seen as bright spots broadened by diffraction and scattering. The tentative conclusion from these two considerations is that optical and acoustical techniques count fundamentally different objects. Optical methods detect buoyant specular objects and usually miss the smaller bubbles; acoustical methods detect anything that contains gas, including neutrally buoyant non-specular (covered with active monolayer) “remains” of true bubbles and overestimate small bubbles. For the air-sea interaction studies these last objects are not of interest since they do not rise to the surface and produce drops.

It is believed that the size spectrum of the bubbles of air-sea interaction interest (buoyant specular bubbles) must be characterized with this specific peak. There are two arguments for this statement. First, there is a physical reason. Immediately after the initial air entrainment, two processes start to act on the bubbles until an equilibrium is reached: the quick dissolution of the small bubbles and the fast surfacing of the large bubbles (Wu, 1981). Only the bubbles with size for which the surface tension and buoyant forces, governing respectively the dissolution and the rising, are equal, survive. Thus the initial size spectrum narrows from both, the small-size and large-size, sides. As depth increases both effects, dissolution and penetration, become stronger from the both sides of the spectrum and overall the total number of bubbles is reduced and confined only in a band of sizes around a peak. Unfortunately, this peak, observed in the range of 40 - 80 μm, often coincides with the resolution limitation of the optical devices and its exact position is difficult to be determined confidently. Second, in our opinion, the reducing of the total number of buoyant specular bubbles on the small-size side is actually well revealed in acoustically obtained spectra. They usually observe a plateau, or at least a considerable change of the spectrum slope, at the place where optically obtained spectra have a peak, Figure 4.2 reproducing Figures 1 and 6 from Medwin and Breitz (1989) results. Obviously, at this place the acoustical technique stops to detect the buoyant specular bubbles and starts to detect all other small gas-containing resonant objects. The differences in the place of this peak (for the optical techniques) or a plateau (for the acoustical techniques) can be attributed solely to the different conditions of data obtaining by different investigators.

Figure 4.2 Reproduction of figures 1 and 6 from Medwin and Breitz (1989): a) the plateau or slope change in bubble distributions measured by different authors with acoustical technique are evident. The abbreviations are: MN and MD = Medwin (1970); HZN and HZD = Huffman and Zveare (1974); N and D refer to day and night data; OH2, OH3, OH5 = O`Hern et al. (1988) at different stations (2, 3, and 5) .