The Hurst Spit experiment: The characterisation of bubbles in the surf zone using multiple acoustic techniques

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Abstract

This paper serves only as an introduction to the three papers which follow it in this volume. Those papers describe the results of a sea trial, and the preparatory tank measurements, in which components of the separate projects of seven graduate students are brought together. This paper describes the common systems to all these studies. These student projects are at a relatively young stage, and the results outlined in the subsequent papers are all represent the first test of each system. However, once each project is mature, the data from the component tests are to be combined in a way explained in this paper, to reveal particular acoustic or oceanographic features of the surf zone environment. Such an approach, where multiple techniques not only provide independent information, but also cross-check on the limitations of each other, may be very important to surf zone acoustics: In this challenging environment, the difficult task is not that of obtaining acoustic scatter, but of interpreting that scatter rigorously in terms of oceanographic parameters.

1. Introduction

There is a wide range of acoustic techniques which have been employed to characterize bubble populations, both linear and nonlinear. Across the range, it is the reception of an acoustic signal which is the easy part of the process. The more difficult component is the conversion of that acoustic signal into rigorous descriptions of the bubble population. Yet the effort is often concentrated in the former task, and as a result, the interpretation can cause severe problems. Of even greater concern, it is often possible to get *an* interpretation of the acoustics in terms of the bubble population: the question to which more attention must be paid is: ‘How accurate is that interpretation?’.

This is the source of the problem, the ability to obtain *an* answer and the subsequent failure to criticize that answer. That criticism, in large part, must be based on our understanding of the principles of a technique, and our ability to model its operation. What must be recognized is that the degree to which we criticize should evolve as our understanding and modeling abilities develop. The assumptions employed in the pioneering days of acoustic bubble characterization were framed by the modeling abilities of that time; this does not necessarily make those assumptions valid for current use, when for example bubble populations are being measured with broadband techniques in the high void fractions of the surf zone.

For example, a problem that has become recognized in recent years has been the allowance that must be made for off-resonant contributions by bubbles. It was natural that the first interpretations of bubble signals would be in terms of resonant bubbles only, and also important that as the field evolved the off-resonant contribution be recognized for its importance, and due account taken [1, 2].

Yet the process of self-criticism of this field should continue. Even the simplest method of acoustic bubble detection, the measurement of the passive emissions generated by bubble entrainment, can be prone to errors. For example, the assumption that Minnaert’s equation may be used to relate bubble natural frequency to radius is commonly employed in reverberant environments [3-8], in which it does not strictly hold [9]. Another common technique is inversion of the propagation characteristics (attenuation and sound speed) to infer the bubble population [10]. At the heart of this [11] are the acoustic cross-sections first developed by Medwin [12-15] (in this paper termed the ‘classical’ cross-sections), which assume that the bubbles undergo linear, steady state pulsations.

That is not to say such that any inaccuracies introduced by such approximations are necessarily significant. Rather, that as we progress to more extreme environments, and to insonification regimes which tend to increase the violation of these approximations, these inaccuracies should be quantified. A salutary lesson can be learned from the acoustics of biomedical echo-contrast agents. The linear steady-state assumption inherent in the classical cross-sections, and the approximation that resonant bubbles only contribute, are common in the models of these highly damped micron-sized bubbles, which are subjected to microsecond acoustic pulses having amplitudes of the order of tens of atmospheres [16].

In acoustical oceanography, the surf zone probably represents the extreme environment where acoustics are used to characterize bubble populations. Deployment is perhaps the most difficult here, and the void fractions the greatest. Hence the Hurst Spit 2000 surf zone experiment was set up. It was aimed at gaining preliminary data for the separate projects of seven students. Since these projects are all at a relatively young stage, the expectation is that subsequent surf zone trials will lead to an experiment where the data available from the separate projects can be combined both to allow the independent and quantitative criticism of each, and to provide oceanographic information on the evolution of bubble populations. Such would not be possible with a single technique. This paper describes that overall plan, and the deployment aimed at eventually achieving it.

2. Method

2.1 General principles

Measurement of oceanic bubble populations was for many years restricted to sites away from the plunging breakers of the surf zone. Figure 1 shows two classes of distribution: surf zone, and examples of bubble size distributions recorded near the surface (<1.5 m) in deep water (using an oceanographic definition [17]) in high wind speeds (11-15 m/s). The latter class is illustrated by the results of Farmer and Vagle (in 1989 using the scatter at four discrete frequencies [18]; and in 1997 using a resonator technique [19]), Breitz and Medwin [20] (again, using a resonator), and Phelps and Leighton [17] (using a combination-frequency system – see below). These generally agree, but differ from the surf zone data [21-23]. That difference is only to be expected, given the dissimilar oceanographic (particularly wave-breaking) processes in these two regions, as illustrated in Figure 2.

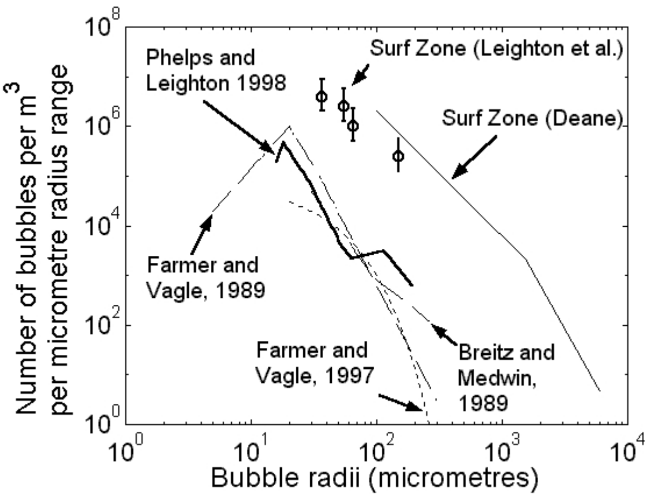

Figure 1. The number of bubbles per cubic metre per micrometer increment of radius, shown for a range of oceanic bubble populations, both in the surf zone (Leighton et al., Deane) and out of it (Farmer and Vagle, Breitz and Medwin, Phelps and Leighton).

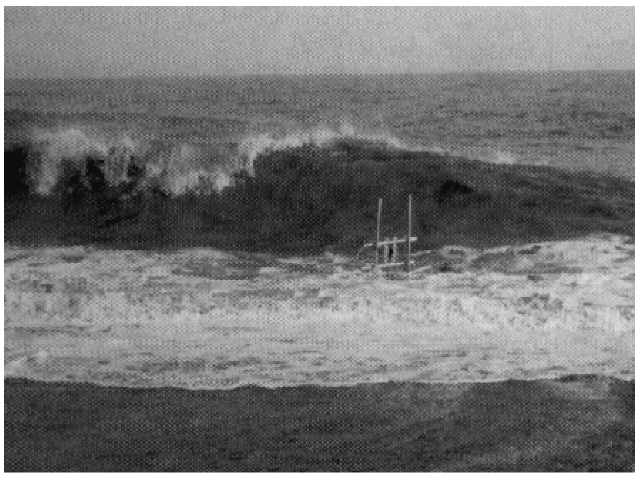

Figure 2. A photograph from the sea trial of Leighton et al. [21], illustrating why one might expect to see greater numbers of bubbles in the surf zone than in deeper water (where, in this image, few breakers are visible).

The first surf zone measurements [17, 22] were taken by the student generation prior to the one currently co-authoring this paper, and the subsequent three, in this volume. A form of the combination frequency technique was used, where one frequency (the pump) excites the resonance of the bubble, the pulsation of which modulates the scatter of the other frequency (the imaging). (This 'modulation' technique is different to the combination-frequency technique described in an earlier paper in the volume [24], where the difference between the frequencies of two fields is equal to the bubble resonance which is to be investigated.) Key to the accurate use of this technique is allowance for acoustic radiation damping of the bubble: errors of 35 dB can be incurred if it is neglected [17]. Previous laboratory [25-27] and oceanic [28] deployments of the combination frequency technique had either neglected this term, or had incorporated it only by fitting the data to historical results, compromising the independence and absolute nature of the results. However with an explicit allowance for radiation damping, this technique could be used to provide absolute measures of the bubble population in the surf zone, where the nonlinear nature of the phenomenon made it particularly appropriate for use with high void fractions. The major limitation was that the use of MHz frequency imaging beams reduced the sampling volume to millilitre order. In this respect it is inferior to techniques based on the inversion of propagation characteristics, which can readily give measurements over larger volumes. However, as outlined above, such inversions rely on the assumption of linear steady-state bubble oscillations, and these may not occur in the surf zone where amplitudes at the sources must be high to cope with attenuation losses of 40 dB/m, and where temporal resolution is often achieved by the use of short pulses, of the order 50 – 500 μs duration.

Hence one of the eventual goals of the planned series of surf zone trials, of which Hurst Spit 2000 was the first, is to provide an inversion process which allows for time-dependent, nonlinear bubble oscillations. Two components are key to this. The first is the use of the absolute bubble population measured over a small volume, as provided by the nonlinear combination frequency technique, to assist in the inversion. How this fits into the overall scheme by which the data is used, is described in section 2.1.2. Before this, the second component is discussed, specifically the development of the nonlinear, time-dependent form of the acoustic scattering cross-sections of a bubble.

2.1.1 Range dependent, time-dependent, nonlinear model for acoustic propagation through a bubble cloud of given shape and dimension.

The acoustic scatter and extinction cross-sections of single bubbles have proven to be very useful in recent decades. They are defined, respectively, as the ratio of the time averaged power scattered by a bubble, or the time-averaged power loss from an incident beam, to the intensity of an incident plane wave which drives the bubble into pulsation. Hence the concepts already have the inbuilt assumption that the field which insonifies the bubble is plane wave. Further assumptions follow from the manner in which analytical expressions are obtained for these cross-sections. The scattering is assumed to be monopole (i.e. $kR_0 \ll 1$, where k is the wavenumber of the incident plane wave, and R_0 is the equilibrium bubble radius); and the bubbles are assumed to undergo linear pulsations only in the free-field, and to be in the steady state regime. With these assumptions, the analytical forms of the cross-sections can readily be obtained [12, 29]. In part the usefulness of these classical cross-sections lies in the fact that, because of key assumptions in their derivation, they are additive: the cross-section of a group of bubbles in a given volume element equals the sum of the individual bubble cross-sections. Those key assumptions are: the bubbles scatter incoherently; the attenuation in the element is assumed to be negligible; all bubbles in the element are subjected to the same plane wave intensity. As such the classical cross-sections can be used to estimate the scatter and attenuation resulting from insonification. It must be born in mind, however, that the assumptions are ever-present, and inversions based on this analysis will also incorporate them. It is not sufficient to undertake such inversions without quantitatively checking the effect on the result of the degree to which these assumptions were violated when the acoustic data were gathered.

For this reason, and for the purposes outlined in Section 2.1.2, a new form of the single-bubble cross-sections (which include nonlinear bubble oscillations and is not restricted to the steady state) was developed [30]. The bubble wall motion is described by the Herring-Keller equation of motion, and is therefore nonlinear (indeed, the Gilmore-Akulichev equation has been used with this model [30]). The acoustic scatter cross-section is fully nonlinear, but the extinction cross-section retains an element of the linear approximation, in that it uses the bubble damping parameters derived by Prosperetti [31], and these rely on a linearised theory. Whilst these cross-sections can readily be extended to predict the time-dependent scattering and attenuation from a cloud of bubbles at fixed range if the assumptions of incoherent scatter and plane wave insonification are enforced [30], for the purposes of this work it was necessary to develop a more sophisticated model. The time-dependency is vital to the model to enable the effect of pulse length to be incorporated; to include 'ring-up', 'ring-down' and transient effects in the bubble response; to incorporate reverberation; and to allow for the effect of having a cloud of finite size. Indeed, time-dependency must be included in the model if the bubble population is range-dependent. For example, depth-dependency at least will occur because of the 'filtering' of bubble size which occurs as a result of turbulence, buoyancy etc. [32, 33].

In this model a different bubble population can be specified in any of the 3-D spatial elements into which the cloud is divided. The waveform by which each element is driven is fully controllable in the model (in processing the Hurst Spit data, pulses of variable center frequency and duration were used, and although ring up and down *of the driving pulse* may be incorporated, it was for simplicity omitted here). Its features can be adjusted for each element, and in the Hurst Spit experiment its energy was adjusted to account for the attenuation of the insonifiying wave by preceding elements. For each bubble size modeled (typically 1-500 μm in 1μm increments) the time dependent individual bubble response is determined using the method described above. Integrating over the whole bubble population within an element gives the attenuation or scatter resulting from that element. This is incorporated into propagation models to calculate the total sound field (due to the driving field and the effect of the bubble cloud) at any given point.

From this description of the model, it is clear that the concept of an acoustic cross-section has had to be abandoned altogether. It is important to understand why. Simple physics would lead us to expect that the degree to which the nonlinear cross-section of a single bubble, even in steady state, differs from the value predicted by the classical formulation, increases as the driving amplitude increases. Example calculations demonstrate this [30]. However the implications of the requirement to incorporate time-dependency in the calculations has farther-reaching consequences. One immediate problem, which undermines the entire concept of the cross-section, is that it becomes indefinitely large during ring-down. However this does not stop calculation of the scattered pressure, which can be calculated either by classical or nonlinear methods.

But if this is done, then the degree of nonlinearity still needs addressing. If the driving amplitude were sufficiently high that the linear calculation was inaccurate in the steady-state value it predicted, then clearly the full nonlinear calculation should be used. This can be tested using the published method [30]. However suppose that the driving amplitude were low. The one might suppose that the 'classical' formulation [12, 14] would be adequate. However the lower the driving amplitude, the longer the ring-up time [30]. Therefore in the low-amplitude case, *unless the sonar pulse was much longer than the resonant bubble ring up time (or unless the numbers of resonant bubbles present was insignificant),* then the actual scatter attained by the bubble during the pulse would be less than the steady state. In such circumstances, use of the linear theory would lead to over estimation of the scatter (unless the energy emitted during the ring-down were enough to compensate). This is shown in Figure 3, which schematically shows scattered power from a single bubble, as predicted by the time-depend nonlinear calculation (solid line) and by the classical steady-state linear calculation (dashed line). Two features are assumed to give the 'best-case' scenario. First, the classical cross-section takes a value which equals that achieved by the nonlinear calculation in steady-state). Second, the scattered power can be calculated from the 'classical' cross-section by artificially setting it to zero once the insonifiying pulse ceases (at which point the cross-section in reality becomes undefined). In the three parts of Figure 3, the bubble is assumed to have the same inherent ring-up and ring-down tendencies, but the length of the driving pulse is varied. Consider Figure 3a. The energy scattered by the bubble into the reverberant field is given by the area under the solid curve. However the energy scattered by the bubble as predicted by classical theory [12, 14] is given by the area shaded under the dashed line. If the pulse duration were very much longer than the bubble ring-up, the discrepancy would be small (Figure 3b). But if it were less, then the classical theory will overestimate the volume reverberation (Figure 3c). Hence the formulations introduced in this paper must be used to test to what extent the classical theory is valid, and whether the insonification conditions of the test lie in the compromise region where the driving amplitude is not so great as to make classical theory severely overestimate the steady state value of the scatter, but still sufficiently high so that the bubble ring-up time is fore-shortened.

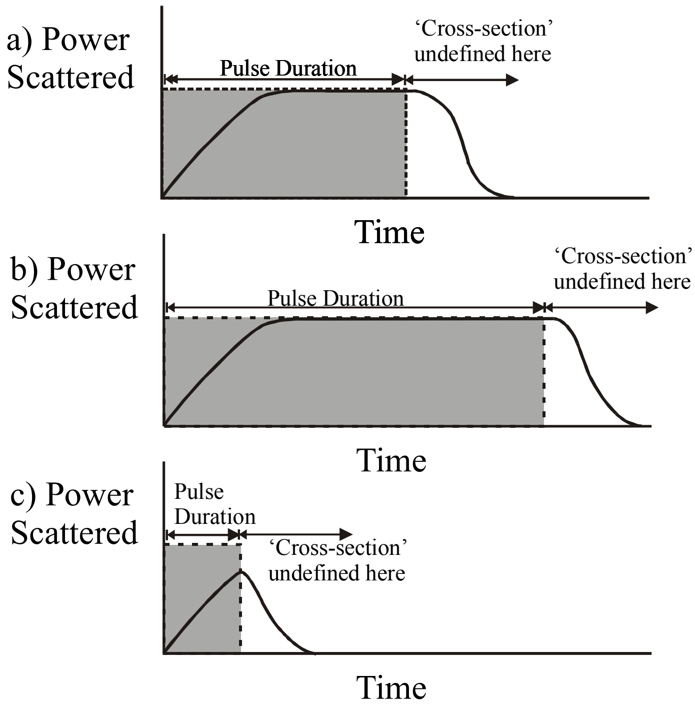

Figure 3. Three schematic plots of the time history of power scattered by a single bubble, comparing the results of the classical scatter cross-section (dashed line, the scattered energy being represented by the shaded area under this) with those of the exact nonlinear solution (solid curve). The three cases (a, b, and c) demonstrate the discrepancies that can occur for various ratios of driving pulse length to bubble ring-up and ring-down times. Note that best-case conditions area assumed: the value of the classical cross-section equals the steady-state value of the nonlinear calculation; and the scattered power is artificially set to equal zero when the classical cross-section becomes undefined.

2.1.2 Scheme for the eventual use of the data

Figure 4 shows the intended use of the data from this series of surf zone trials (of which Hurst Spit 2000 is the first). Roman numeral are used in the figure and in the following text to identify key facets of the test. First, the ambient noise (I) is used to measure the population generated by the bubbles on entrainment [34] (II). Comparison of this 'entrainment' population with the 'ambient' population (III) (measured by active techniques – see below) will reveal differences (IV). These differences tell us about the oceanographic processes which cause the bubble population to evolve. Those processes include turbulence, circulation, bubble fragmentation/coalescence/dissolution, and variations in static pressure resulting from changes in bubble depth. To separate out the mass flux (V) contribution to this difference, electrochemistry is used [35] (VI).

First however, it is very important to understand that the 'entrainment' population is not directly measured from the passive emissions from bubbles. Passive emissions can be used to infer the bubble population using either inversion [36] or signature [34] techniques. These, however, do not measure the 'entrainment' population, an entity which can be compared on a like-for-like basis with the ambient population to identify the oceanographic processes which cause them to differ. Rather, they measure the 'ringing' population, and it is important to appreciate that the statistics of these two populations differ for a given oceanographic situation. They must not be equated or used interchangeably. They differ by a weighting factor, which can be estimated from the ratio of the time for which each bubble emits, to the lifetime of that bubble.

Once account has been taken from this, the 'ringing' population (obtained, for example, using the techniques of [34, 36]) can be converted into the 'entrainment' population, and from the difference between this and the 'ambient' population, together with the electrochemical data [35], the contribution to atmosphere/ocean mass flux from each bubble size can be estimated.

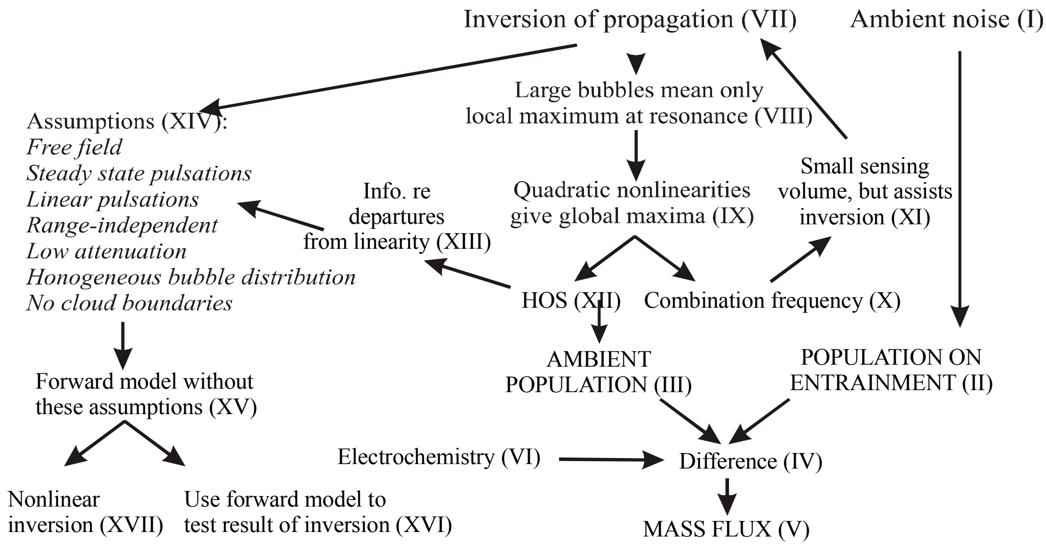

Figure 4. Schematic showing the use to which the data is to be put in the sea trial series.

However, as emphasised at the start of this paper, it is no simple matter to obtain an estimate for the ambient bubble population in high void fractions using techniques such as inversion of propagation measures (VII). The scatter from resonant bubbles needs to be separated from that of off-resonance bubbles. Even if fixed-frequency scattering from single bubbles is plotted as a function of the bubble size, the effect of very large bubbles is to make that scatter only a local maximum at resonance (VIII) [12, 29, 32]. However quadratic nonlinearities do give a global maximum at resonance (IX). One result of the quadratic nonlinearity is the production of combination frequencies (X). These give accurate and absolute measures of the bubble population even at high void fractions, which can be used to assist the inversion (XI). They cannot readily replace it, because of the complexity of the technique, and because of its typically small sensing volumes.

Another signal produced by the quadratic nonlinearity is the second harmonic of the bubble resonance. The production of this, and higher harmonics, can be diagnosed using HOS, Higher Order Spectra [37] (XII). This tells us about the departures from linearity which occur (XIII). It can therefore be used to diagnose the validity of the assumptions inherent in the process of inverting the propagation characteristics to obtain the ambient bubble population (XIV). Having assessed these, the forward model described in the preceding section (XV) can be used to quantify their effect on the estimation of the bubble population (XVI). There is even the possibility of using it to perform nonlinear inversions (XVII).

2.2 Sea trial arrangement

The surf-zone sea trial was conducted on a beach at Hurst Spit, Milford on Sea in Hampshire from 5^{th}-16^{th} November, 2000. Constructed in 1997 from 125,000 tonnes of boulders and 300,000 m^3 shingle (which needs to be regularly replaced), its southerly beach is exposed, with a shingle and sand composition and a significant amount of sediment transport (marker poles showed, for example, 50 cm vertical bed movement in 20 minutes during calm conditions). After several storm events observed during the two week period, during which the on-beach winds attained a sustained 50 mph, the depth of shingle on the beach changed by several feet and the beach profile changed. This profile was stepped, the position of the step changing after a storm event, resulting in a form of reef brake which generated plunging breakers in all but the calmest of conditions. The position of the wave breaking was a function of water depth, owing to the tide, and the position of the step in the beach and was a significant factor in the deployment of the equipment.

The apparatus is shown schematically in Figure 5. In order to provide a stable and secure platform for mounting equipment on such a dynamic beach, four scaffolding poles were attached to feet, consisting of a meter square horizontal steel plates. A structure of poles was built around these four uprights, and to this were attached two hydrophone arrays. These were used, first, to monitor attenuation and travel times of pulses transmitted by the 'pump signal' source (20-360 kHz); and second (with the addition of an out-of-plane hydrophone to remove left/right ambiguities) to monitor ambient noise [34]. A 1 MHz transmitter and receiver provided the bistatic imaging frequency component for the combination-frequency system; the overlap of the beam patterns of these two transducers defined the 'target region for both the combination frequency system, and for the acousto-electrochemical system [35]. The pump signal source for the combination frequency, acousto-electrochemical, and array sensors, was also used in a monostatic mode across part of its frequency range (200-360 kHz). Reflections from a known target (a 50" diameter submerged buoy) were also used to assess the population [38]. The equipment was controlled from a portable cabin onshore and communicating with the equipment was via direct cable connection.

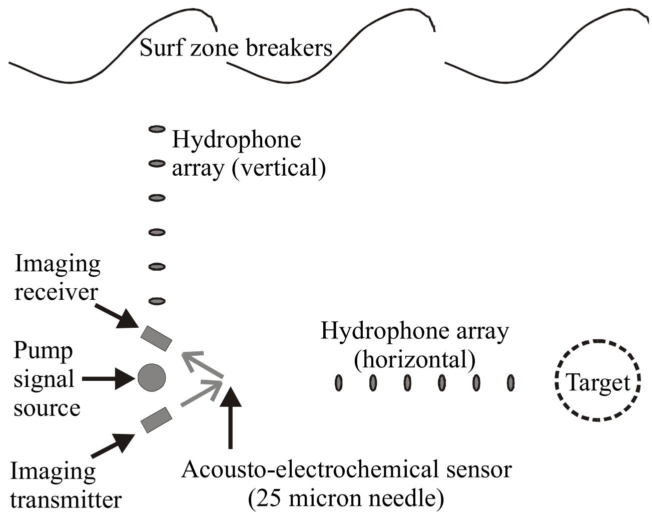

Figure 5. Schematic of apparatus deployed in surf zone (an out-of-plane hydrophone is not shown).

3. Conclusions

This paper does not contain results *per se*, but puts in context the three student papers which follow it in this volume. Those papers are based on the results processed to date from the Hurst Spit 2000 sea trial. It is hoped that this trial is the first of several, the eventual aim of which is three-fold. These are shown as the end points in Figure 4. First, identification of the extent to which assumptions (free-field, steady state, linearity etc.) that are common in the measurement of oceanic bubble populations, need to be re-assessed; and implementation of techniques to resolve these issues. Second, deployment in the ocean for the first time of a range of novel techniques (acousto-electrochemical, HOS etc.). Third, by combining novel, existing and (where necessary) modified techniques in the manner shown in Figure 4, to assess the contribution to atmosphere/ocean mass flux made by bubbles of any given size.

Hurst Spit 2000 was the first of the series of sea trials, and the preliminary testing ground for these techniques. The entire scheme of tests described in Figure 4 could not be achieved in this first trial. Indeed, the original test had been planned for summer 2000, and a less exposed beach, but became unavailable at short notice. The re-siting and re-scheduling exposed the rig and researchers to far more difficult deployment conditions (Figure 6), and removed the guarantee of a storm-free window. Given that this was the first trial of this type, and the first for these students, they were provided with a statement of the objective for each of the three facets described in the following three papers:

(i) Obtain a bubble size distribution in the surf zone for the small-bubble range (9-12 μm radius) not previously measured in the surf zone. As shown in Figure 1, this would reveal whether or not the peak in bubble numbers, observed in oceanographically deep water by Farmer and Vagle [18] and Phelps and Leighton [17], existed in the surf zone, where the oceanographic features which contribute to the reduction in bubble numbers at the smaller radii may not be so dominant [38].

(ii) Detect the diffusion of a specific dissolved gas from bubbles, and furthermore to identify the contribution to this flux made by bubbles of one specific size [35].

(iii) Identify the passive emissions ('signatures') of individual bubbles entrained within the surf zone, and so estimate the natural frequencies, and timings and locations of the emitting bubbles [34].

The degree to which these objectives were achieved are described in the following three papers.

Figure 6. Environmental conditions during deployment of rig, as illustrated by two frames from the video, a fraction of a second apart. The conditions became much rougher.

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