LOW FREQUENCY RESONANCE BACKSCATTER FROM NEAR-SURFACE BUBBLE CLOUDS

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Abstract

When active sonar systems are used to insonate the sea surface, anomalous scattering is observed in the form of enhanced backscatter, and more importantly, in the form of discrete, bright echoes. The most plausible explanation for these effects is the increased scattering resulting from the presence of bubble plumes and clouds, produced near the surface by breaking waves. This paper describes some preliminary calculations of the backscattered target strengths expected on the basis of resonance scattering from bubble clouds.

I. Introduction

In tests of low frequency active sonar systems, false targets have arisen when insonation of the sea surface is attempted, especially in circumstances of high sea state [Gauss *et al.*, 1992]. The origin of these false targets is still unclear, although the most likely candidates are assemblages of gas bubbles in an acoustically compact form. Bubble clouds are a common occurrence in the near surface of the ocean when breaking waves are present; these clouds are likely to result from bubble entrainment during wave breaking. Collections of bubbles in diffuse concentrations in the form of plumes have been observed at depths of several meters [Monahan, 1971; Thorpe, 1982; Farmer and Vagle, 1988], presumably drawn to these depths as a result of convective flows such as Langmuir circulation and thermal mixing [Thorpe, 1982]. Significant acoustic backscattering from the sea surface can result either from these small, relatively dense clouds that are near the surface, or from the larger, relatively diffuse plumes that can extend to greater depths.

It has been shown that the available surface scattering data [Chapman-Harris, 1962; Ogden and Erskine, 1992] can be accounted for in terms of either weak scattering (the well-known Born Approximation) from deep, diffuse bubble plumes generated by Langmuir circulation [MacDonald, 1991; Henyey, 1991], or by resonance scattering from higher void fraction clouds near the surface [Prosperetti and Sarkar, 1992]; it is the contention in this paper that the observed large target strength false echoes result principally from detatched bubble clouds; furthermore, we present in this paper the range of bubble cloud and environmental parameters that are likely to result in these bright targets.

2. Background

The attempts to characterize acoustic scattering from the ocean surface in the absence of bubble clouds, due to Bragg Scattering alone, have resulted in significant disagreement between the calculations [McDaniel, 1987] and the experimental data [Chapman and Harris, 1962; Ogden and Erskine, 1992]. Consequently, MacDonald [1991] and Henyey [1991] have used weak scattering theory (Born approximation) to obtain the surface backscatter in the presence of "tenuous" (void fractions less than, say, 10^{-3} %) bubble plumes of various configurations and orientations. Their calculations assume that the clouds are sufficiently diffuse so that multiple scattering can be ignored; consequently, the scattered sound energy is mostly specular. Their results indicate that if one wishes only to account for the average surface backscatter, then the tenuous bubble plumes generated by Langmuir circulation are sufficient. However, it is not yet clear whether these approaches can account for the presence of the "bright echoes" or "hot spots" observed in the critical sea tests and described by Gauss *et al.*, [1992]. Thorsos [1992] has examined the effect of a rough surface and noted that focusing from appropriate contours can significantly enhance the calculated backscatter from tenuous clouds. However, we shall follow a different approach and assume that there are concentrations of bubbles in the form of clouds that are of sufficient void fraction to lead to a resonance oscillation of the cloud itself, thus resulting in high target strengths at low frequencies.

These cloud oscillations are called "collective oscillations" and represent a type of acoustic backscatter that is fundamentally different from that described by Born-approximation, weak-scattering theory. Collective effects occur when the acoustic wavelength is considerably larger than the dimensions of the cloud and the resonance frequency of the individual bubbles comprising the cloud is much higher than the insonation frequency; thus, all the bubbles oscillate essentially in phase. Because the compressibility of the cloud is similar to that for a single gas bubble while the induced mass is associated with that of the entire cloud, the oscillation frequency can be quite low, and particularly, much lower than that of an individual gas bubble. An alternative but equivalent explanation is that because the phase speed in the bubbly mixture is greatly reduced (sometimes even below that for a pure gas), the oscillation frequency is correspondingly reduced.

2.1 Collective Oscillations

Carey and Browning, [1988] and Prosperetti [1988] independently suggested that bubble clouds whose geometrical dimensions were small with respect to a wavelength could behave as a compact scatterers. Evidence for the existence of collective oscillations have been firmly established by laboratory work [Yoon, *et al.*, 1991; Nicholas, *et al.*, 1992; Lu, *et al.*, 1991], and also by field experiments in a large fresh water lake [Roy, et al., 1992]. Furthermore, recent data by Farmer and Ding, [1992] on sources of ambient noise in the ocean provide strong support for the existence of low frequency emissions indicative of collective oscillations. If these clouds are observed to radiate at low frequencies by collective effects then it is likely that they would also act as effective scatterers of low frequency sound.

2.2 Preliminary Results

We have performed some preliminary experiments of the low frequency scattering characteristics of bubble clouds. The test plan and some initial results are described in a previous SACLANT Symposium report [Carey and Roy, 1993], and in a more widely distributed publication [Roy, et al., 1992]; they are shown for completeness in Fig. 1.

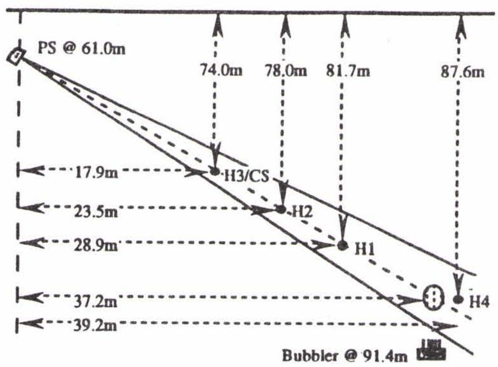

Fig. 1a. Test Plan for Seneca Lake scattering experiment.

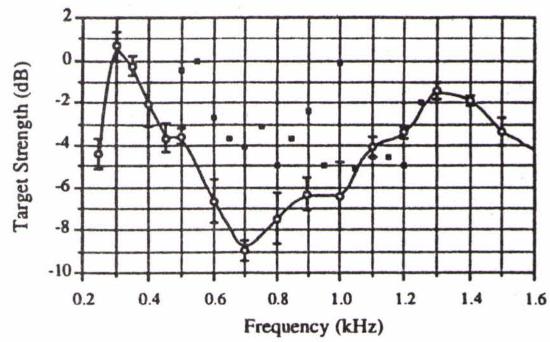

Fig. 1b. Low-frequency backscattering results.

The principal results of this experimental study can be summarized as follows:

- Artificially generated bubble clouds of ellipsoidal geometry and about 0.5 meter in diameter and 1.0 meter in length were created at a depth of about 90 meters in a fresh water lake. The clouds were insonified with both a directed beam (parametric array) and an omnidirectional conventional source over a frequency range from 200 Hz to approximately 14 kHz.

- Measurements of the target strength (TS) as a function of frequency show relative maxima at approximately 0.3 and 1.3 kHz, as well as several other (higher) frequencies. The amplitude of these peaks is quite large and indicative of resonance effects.

- The resonance frequencies of the individual bubbles comprising the clouds are on the order of 2-3 kHz, and are so much larger than the low frequency maximum that these low frequency peaks are most likely due to collective oscillation resonances. If the cloud is treated as an acoustically compact object with a velocity of sound significantly different than that of water, then the fundamental (monopole) resonance frequency depends solely upon its volume, and its effective acoustic impedance. Using a modified Minnaert formula, a calculated resonance frequency of about 324 Hz can be obtained for the lowest peak; this value compares favorably with the measured resonance of 310 Hz [Roy, et al., 1992; Carey and Roy, 1993].

- The target strength of these clouds insonified near resonance is on the order of 0 db. Thus, they represent bright targets and compact scatterers. Calculations of the target strength based on resonance scattering [Roy, et al., 1992; Carey and Roy, 1993] suggest values on this order.

The success of these preliminary studies has emboldened us to attempt a more systematic and detailed analysis of low frequency resonance scattering from near-surface bubble clouds; our progress along these lines is described in the sections to follow.

3. Approach

We follow the approach of Morse and Ingard [1968] in which we assume a plane wave incident on a compliant sphere of radius a_c surrounded by a continuous medium of density and sound speed ρ and c respectively. Likewise, we consider the sphere to be a homogeneous medium of density and sound speed ρ_ℓ and c_ℓ respectively. (It should be noted that the subscript "ℓ" refers to the bubbly mixture, not the pure liquid.) We shall assume that the target is illuminated by plane waves and that it radiates a spherically outgoing acoustic wave.

We shall also assume that the sphere (bubble cloud) is composed of many bubbles; thus, the medium is dispersive with effective density and wave number given by,

$$\rho_\ell = \beta\rho_{air} + (1-\beta)\rho$$
$$k_\ell^2 = k^2 + \frac{4\pi\omega^2 a\eta}{\omega_o^2 - \omega^2 + 2ib\omega}, \qquad (1)$$

where $k = \omega / c$ is the wave number in the liquid, a is the radius of individual bubbles (considered to monodispersed in size), η is the number of bubbles per unit volume, ω_o is the resonance frequency of the bubbles, $\beta = 4\pi\eta a^3 / 3$ is the void fraction, and b is the damping constant [Commander and Prosperetti, 1989; Lu, *et al*, 1990]. For $\omega << \omega_o$, one can show that the real portion of the complex phase speed in the mixture is given by,

$$c_\ell^2 = \frac{\gamma P_\infty}{\frac{\gamma P_\infty}{c^2} + \beta\rho}. \qquad (2)$$

Here, γ is the ratio of specific heats of the gas. It should be noted that for β not too small or P_∞ not too large, the low frequency phase speed in Eq. (2) reduces to the more familiar expression,

$$c_\ell = \sqrt{\frac{\gamma P_\infty}{\beta\rho}}. \qquad (3)$$

For the scattering problem in an infinite medium we solve the Helmholtz equation subject to the boundary conditions of continuous pressure and normal velocity across the surface of the sphere.

$$\nabla^2 p_\omega + k^2 p_\omega = -f_\omega(\bar{r}). \qquad (4)$$

We take the solution to be a superposition of incident plane wave and scattered waves:

$$p_\omega = p_i + p_s \quad \text{where } p_i = Ae^{-i\bar{k}\cdot\bar{r}}. \qquad (5)$$

Morse and Ingard used an integral Green's function method to demonstrate that the solution for the exterior scattered wave in spherical coordinates is represented by an expansion in Legendre polynomials and spherical Hankel functions with appropriate coefficients,

$$
\begin{aligned}
p_s(r) &= -\frac{1}{2} A \sum_{m=0}^{\infty} i^m (2m+1)(1+R_m) P_m(\cos\theta) h_m(kr) \\
&\underset{r\to\infty}{\to} i \frac{A}{2k} \frac{e^{ikr}}{r} \sum_{m=0}^{\infty} (2m+1)(1+R_m) P_m(\cos\theta)
\end{aligned}
\tag{6}
$$

where the asymptotic form is given in the far field. The coefficient R_m satisfies the boundary conditions and describes the reflectivity of the sphere where,

$(1+R_m) = 2\dfrac{j_m'(ka_c)+i\beta_m j_m(ka_c)}{h_m'(ka_c)+i\beta_m h_m(ka_c)}$, and $\beta_m = i\dfrac{\rho c}{\rho_\ell c_\ell}\left[\dfrac{j_m'(k_\ell a_c)}{j_m(k_\ell a_c)}\right]$ is the specific admittance of the surface. In this study we make use of the limiting form of c_ℓ given in Eq. (2) which is not a complex phase speed and hence does not take into account damping from the bubbles within the cloud.

We are primarily interested in the backscattering; hence, we take $\theta = \pi$. In the free-field, the TS is given by [Urick,1967],

$$
TS_{ff} = 20\log\left|\frac{p_s}{p_i}\right|_{r=1m} = 10\log\left(\frac{I_s}{I_i}\right)_{r=1m}
\tag{7}
$$

Carey and Roy [1993] have shown that for small ka_c, the monopole term in Eq. (6) can be approximated by

$$
\frac{p_s}{p_i} \approx i\frac{k^2a^3}{3r}\frac{\left(1-\frac{\rho c^2}{\rho_\ell c_\ell^2}\right)}{\left(1-\frac{\rho c^2}{\rho_\ell c_\ell^2}\frac{(ka_c)^2}{3}\right) - i\left(\frac{\rho c^2}{\rho_\ell c_\ell^2}\frac{(ka_c)^3}{3}\right)}.
\tag{8}
$$

At resonance, this leads to

$$
\omega_c \approx \frac{1}{a_c}\sqrt{\frac{3\gamma P_\infty}{\beta\rho}},
\tag{9}
$$

which is a modified form of Minnaert's equation for bubble resonance.

The above equations allow us to make some observations concerning the interdependence of some of the more important parameters, viz,

- The effective phase speed in the bubbly mixture increases with depth, for a fixed volume fraction β; likewise, for fixed a_c, the resonance frequency of the cloud, ω_c, also increases with depth.

- As β decreases/increases, both ω_c and c_ℓ increases/decreases (other parameters held fixed).

• As a_c decreases/increases, ω_c increases/decreases (other parameters held fixed).

Furthermore, we can also deduce how changes in some of these parameters affect the TS? At resonance, Eq(8) reduces to

$$\left|\frac{p_s}{p_i}\right|_{r=1m} \rightarrow \frac{c}{\omega_c}\left(\frac{\rho_\ell c_\ell^2}{\rho c^2}-1\right). \tag{10}$$

Thus, as the resonance frequency decreases, or the void fraction becomes larger, or the size of the cloud increases, the TS increases.

We now turn to a determination of the TS for a variety of environmental and acoustic conditions. In our calculations, we choose to obtain the resonance frequencies by numerical methods. We will approximate Eq. (6) by truncating the series at the $m=0$ monopole term, since for the frequencies of interest in this paper, the wavelength of sound is many times greater than the bubble cloud radius and the higher order terms do not contribute to the lowest resonance.

To solve the problem of scattering from targets near the ocean surface we make use of the method of images; in Fig 2 below a diagram is shown of our approach.

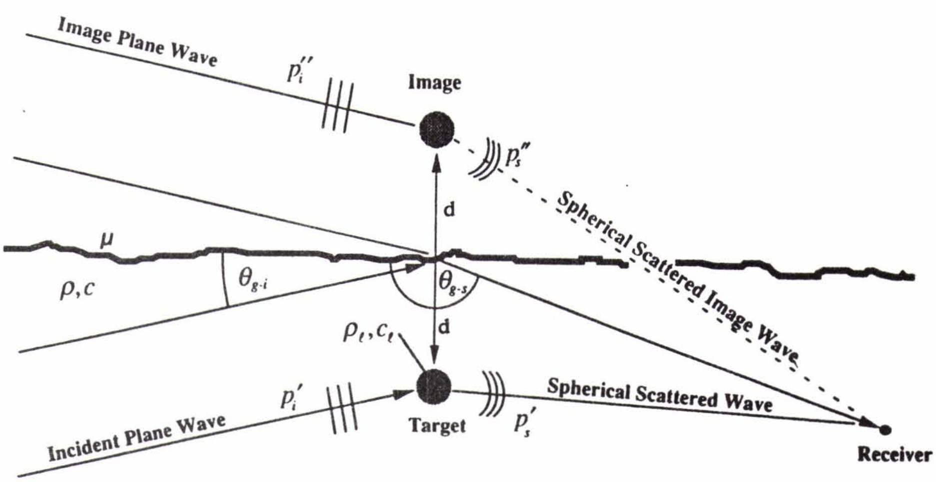

Fig. 2. Diagram of the theoretical model used in the determination of the scattered target strengths.

Here we treat the target as a point scatterer a distance d below a pressure release surface with reflectivity coefficient μ ($-1< \mu <0$). The reflection coefficient describes the roughness of the sea surface where $\mu = -1$ corresponds to a smooth pressure release surface and $\mu = 0$ corresponds to an extremely rough surface (effectively equivalent to an infinite medium); realistic sea states fall somewhere in between. Rather than relate μ to the frequency and wave-height, we have chosen to evaluate the TS at fixed values of μ in order to generalize the analysis. Using the method of images one obtains,

$$p_i = p_i' + p_i'' = p_i\left[e^{i(kx\cos\theta_g + kd\sin\theta_g)} + \mu e^{i(kx\cos\theta_g - kd\sin\theta_g)}\right] \tag{11a}$$

$$p_s = p_s' + p_s'' = \frac{p_s}{r}\left[e^{i(kx\cos\theta_g + kd\sin\theta_g)} + \mu e^{i(kx\cos\theta_g - kd\sin\theta_g)}\right], \tag{11b}$$

where θ_g is the surface grazing angle, and p_i and p_s are the magnitudes of the incident and scattered fields in the free-field. The single-primes indicate the fields neglecting the surface, the double-primes denote the image fields, and $|p_s|_2^2 = |P_i|^2 f^2$ is the response of the cloud to the incident plane wave, where $TS_{ff} = 10\log f^2$ is the target strength computed in a free field. After some algebra, we find that the TS for a bubble cloud near the sea surface is given by

$$TS = 20\log\left|\frac{p_s}{p_i}\right|_{r=1m} = TS_{ff} + 10\log\left\{1 + \mu^2 + 2\mu - 4\mu\sin^2\left(kd\sin\theta_g\right)\right\}^2 . \tag{12}$$

Clearly, when $\mu = 0$ the expression for TS yields the free-field target strength; for $\mu = -1$, and the source close to the surface, phase cancellation occurs, and the source behaves like a dipole.

If one considers the limiting from of Eq. (12), for kd<<1, one observes a dipole characteristic to the scattered field in which the scattered pressure scales with $(d/\lambda)^4 \sin^4\theta$, where λ is the acoustic wavelength. This equation suggests a complex acoustical behavior which can be briefly summarized as follows. High void-fraction clouds which generate significant TS's in the free field may not be acoustically important because these clouds tend to reside near the surface, and thus are subject to the mitigating effect of surface dipole cancellation. This effect is exacerbated by the fact that these large TS clouds tend to resonate at low frequencies (i.e. long wavelengths), and the proximity of the cloud to the surface is defined relative to the acoustic wavelength.

If one considers deeper scatterers, then one is necessarily limited (by oceanographic constraints) to the consideration of lower void-fraction clouds that will not have as pronounced a resonance scattering characteristic. Indeed, clouds in the deepest portion of the bubble layer, (order 10 m) are very tenuous and probably do not resonate at all. It seems likely that there are optimum combinations of cloud depth, cloud characteristics and frequency that produces significant backscatter target strengths (larger than, say -10 db). In the next section, using the equations determined above, we have explored a variety of conditions that could give rise to significant scattering TS's.

4. Results

We have generated a series of multidimensional figures to display the calculated target strengths of these bubble assemblages as a function of several relevant parameters. These figures are quite complex and require studious attention in order to fully grasp the principal implications of the data. The parameters shown in these figures with brief comments where appropriate are as follows: TS--the target strength, defined as in Eq. 12 above; β--the void fraction, defined above; d--the depth of the center of the bubble cloud below the ocean surface; θ_g--the grazing angle of the incident sound beam; a_c--bubble cloud radius; μ--a measure of the reflectivity of the surface: for $\mu = -1$, the surface is perfectly reflecting, for $\mu = 0$, the surface is at infinity and there is no reflection from the surface.

Consider Fig. 3, which is a four-dimensional plot of the target strength as a function of void fraction, cloud depth, and cloud resonance frequency. For this case, the grazing angle is shallow--10°--and the cloud radius is relatively large--0.5 m. We anticipate that this case would correspond to the insonation of a "bubble plume", formed from the convection of entrained gas bubbles to a considerable depth; however, this plume will be treated as a resonant, compact scatterer. We presume that the large bubbles have risen by gravitational forces to the surface, and that consequently the remaining bubbles, and particularly the void fraction, are both relatively small. The data shown in the lower right-hand-corner of Fig. 3 correspond to $\mu = -1$, which presumes a perfectly reflecting surface. Note that there is little scattering for small depths; in this case the cloud acts as a dipole scatterer, and thus for small grazing angles, the TS is very low. However, as the depth increases to a few meters, even for void fractions as low as 10^{-5}, relatively large TS's are observed. For example, at a depth of 5 m, and for a void fraction of 10^{-4}, the observed target strength is on the order of 0 db for an insonation frequency of 300 Hz.

With a value of $\mu = -1$, it is assumed that the surface is perfectly reflecting, a situation unlikely to be realized in a rough sea. The data shown in the upper left hand corner of this figure corresponds to value of $\mu = 0$, or for a surface so rough that no coherent energy is reflected. Note that in this case, there is little depth dependence--no phase cancellation from the reflecting surface--and this cloud is a high TS scatterer for all "depths". Perhaps a more reasonable representation of the surface effect is presented in the lower left-hand-corner, calculated for a value of $\mu = -0.5$, which thus corresponds to the intermediate case. It is seen from this figure, that TS's on the order of 0 db should be observed for plumes with void fractions above 10^{-4}, at depths between 2-6 m, and at insonation frequencies on the order of 300 Hz. As the void fraction falls below 10^{-5}, the backscattered intensity rapidly falls in magnitude.

Let us now compare and contrast these results for a relatively large, low void-fraction plume with the case shown in the next figure. Shown in Fig. 4 are plots for a bubble cloud of radius 0.1 m, and a grazing angle of 10° (as in Fig. 3). Consider again first the case for a perfect reflecting surface, as shown the lower right-hand-corner. This cloud is relatively small; thus, the monopole resonance frequency is rather high (of order 400 Hz near the surface). Consequently, it can produce a large backscattered TS even when it is within a few meters of the surface. Since we can presume that for such a small cloud, it is not unreasonable to expect a large void fraction, we shall consider values of β as high as 10^{-3}. Note that for the surface conditions of $\mu = -1$, TS's of 0 db can be expected only for clouds 3-4 meters below the surface.

Consider next, however, the conditions demonstrated in the upper left-hand-corner, in which the surface condition corresponds to a very rough surface--a more likely occurrence for large void fraction clouds. For this case, TS's of 0 db can be observed at any depth for a range of frequencies near 400 Hz. Again, if the more realistic case of $\mu = -0.5$ is considered (lower left), a TS of 0 db can be expected to occur for a cloud with a void fraction of 10^{-3}, a radius of 0.1 m, a frequency of 400 Hz, and at a depth of about 4 m.

Finally, let us consider Fig. 5, which summarizes the principal features of this report. Our field measurements at Lake Seneca [Roy, et al., 1992; Carey and Roy, 1993] demonstrated that TS's of approximately 0 db could be achieved for resonance oscillations of a bubble cloud, far removed from the surface, with a void fraction of about 10^{-3}, a radius of about 0.25 m and at an insonation frequency of about 300 Hz. Furthermore, Prosperetti and his students [Prosperetti, et al., 1993; Sarkar and Prosperetti, 1993] have demonstrated that bubble clouds of similar size and void fraction, when located very near the surface, could account for the Chapman-Harris, Ogden-Erskine surface acoustic backscatter when

Maximum TS as a function of depth and volume fraction

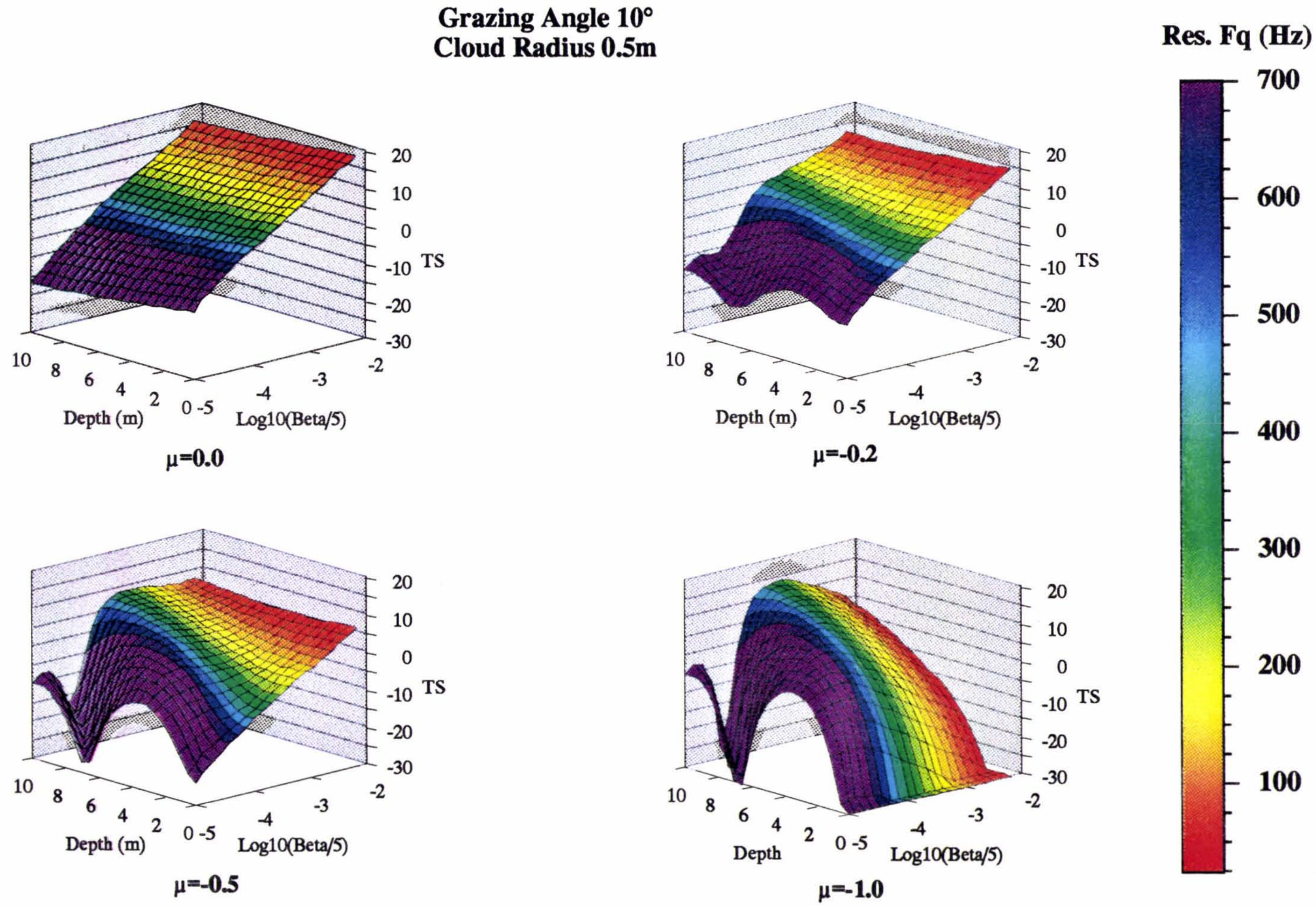

Fig. 3. Three dimensional plot of the calculated maximum target strength as a function of depth and volume fraction for a grazing angle of 10^{0} and a cloud radius of 0.5 m. The frequency of the monopole resonance is shown via the color bar to the right; this figure demonstrates that these target strengths are thus obtained for a range of frequencies. The effect of the surface is described via a reflection coefficient, μ. When μ is -1, the surface is perfectly reflecting; when μ is 0, no reflection occurs.

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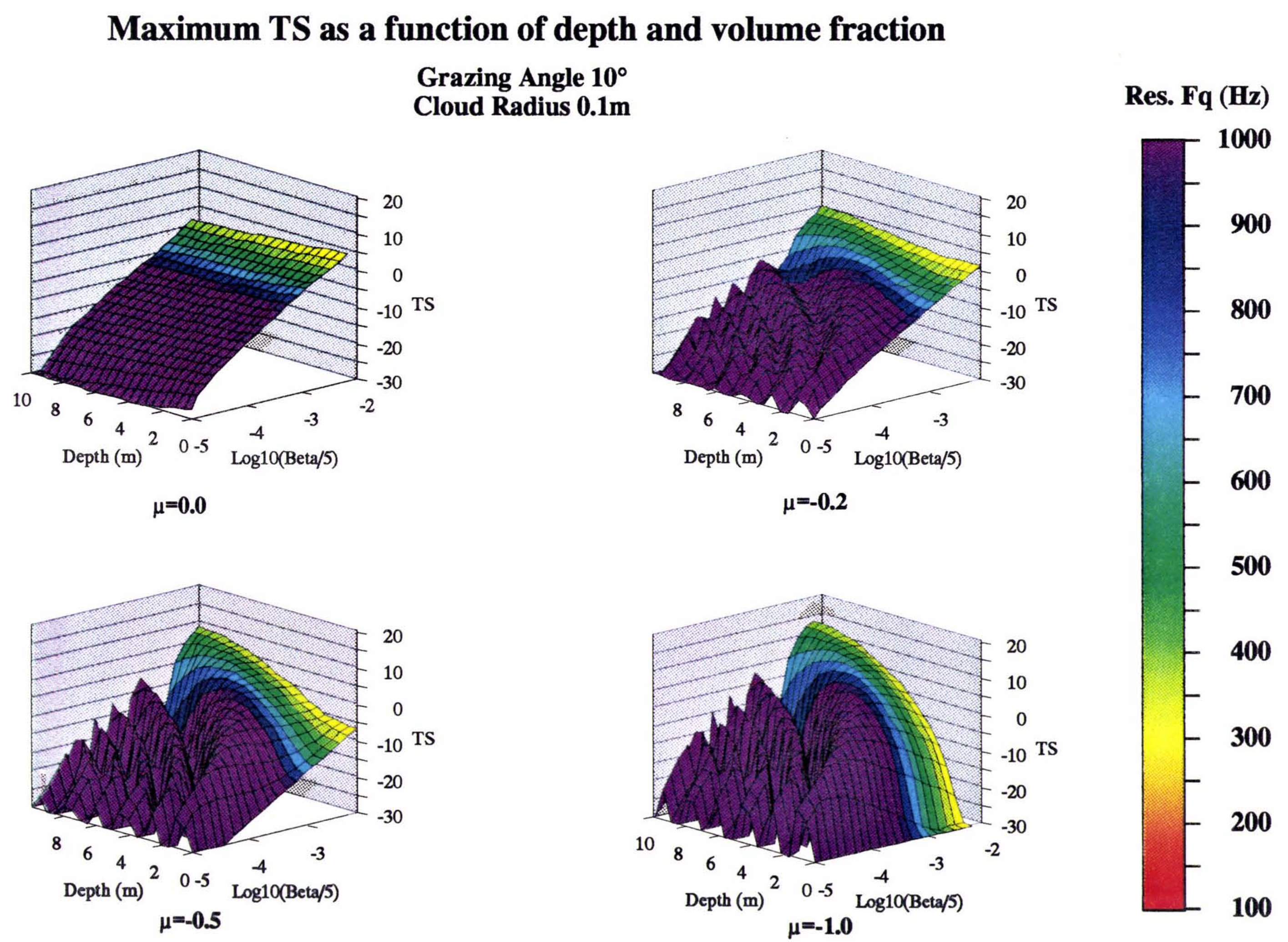

Fig. 4. Three dimensional plot of the calculated maximum target strength as a function of depth and volume fraction for a grazing angle of 10^0 and a cloud radius of 0.1 m. The frequency of the monopole resonance is shown via the color bar to the right. The effect of the surface is described via a reflection coefficient, μ. When μ is -1, the surface is perfectly reflecting; when μ is 0, no reflection occurs.

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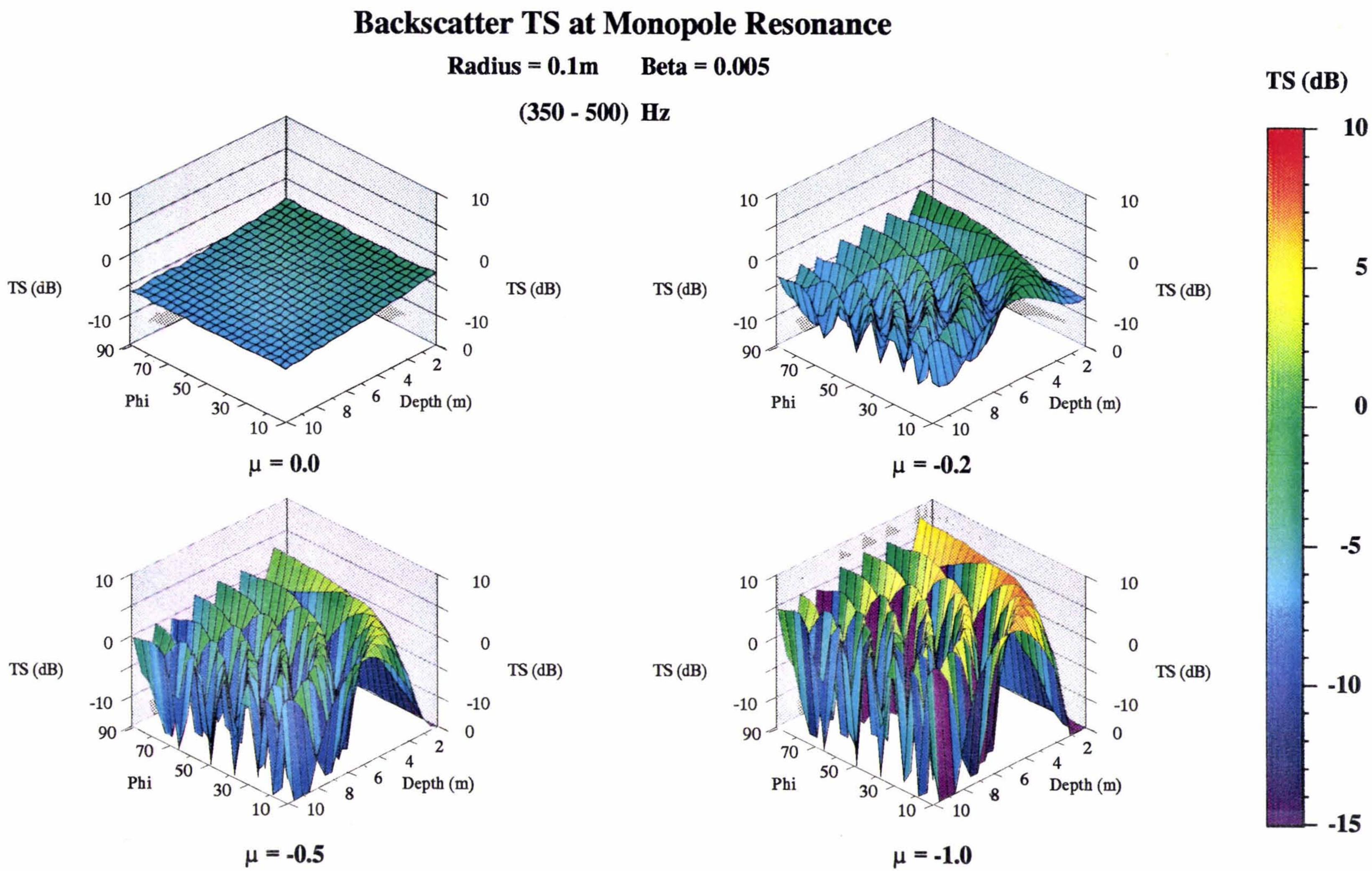

Fig. 5. Three dimensional plots showing calculations of the backscatter target strength at monopole resonance for a bubble cloud with a radius of 0.1 m and a void fraction of 0.5 %, as a function of cloud depth and grazing angle (phi). The range of resonance frequencies for this figure are from 350-500 Hz. The four different plots show the effect of the surface through the reflection coefficient, μ.

treated as resonant scatterers. We show now in Fig. 5 the expected individual resonance scattering characteristics of these clouds as a function of such parameters as grazing angle, depth below the surface, and surface conditions.

Shown in the lower right-hand corner of Fig. 5 is the predicted backscattered target strength for a bubble cloud at its monopole resonance (varying between 350-500 Hz), for a radius of 0.1 m, a void fraction of 0.5 %, and at a perfectly reflecting surface. Also shown in this figure are the cases for a free field (upper left) and for the intermediate case of a partially reflecting surface (lower left). Consider the plot in the lower left. This case represents our estimate of the conditions expected to give rise to false echoes in low-frequency, near-surface scattering. Note that one should expect echoes with TS's of 0 db for a wide range of grazing angles and cloud depths. Bright echoes (of order 0 db) can be expected to occur for grazing angles from 10-70^{o}, and for cloud depths from near the surface to 10 meters. This figure indicates that the ocean surface is very rich with possibilities for bright echoes from resonant bubble clouds.

The conditions that lead to the production of bubble clouds (high winds and high sea states) also favor the generation of high scattering TS's. First of all, high sea state means that the ocean surface will be rough; thus, μ=-0.5 is not an unrealistic approximation; surface cancellation won't be as important except for very low frequencies. Secondly, stormy conditions usually imply an unstable water column, which is often upward refracting. Thus, the incident angles become steeper and the $\sin^4\theta$ dependence is no longer as important. These two effects tend to make far-field-like behavior much more pronounced.

Finally, we make note of the experiments of Lamarre and Melville [1992] who obtained measurements of the void fractions of ocean-generated bubble clouds in the open ocean off the coast of Delaware during the last week of February, 1991. Their data indicate that significant numbers of clouds are produced with void fractions on the order of 0.5 %; they remark that their data are consistent with their laboratory results and are several orders of magnitude higher than the often-reported *time-averaged* values [Farmer and Vagle, 1988].

Further experiments are required, however, to determine the precise acoustic and environmental conditions that give rise to these false echoes.

5.0 Summary

False targets can occur for low frequency sound scattering from the sea surface. It is unlikely that Bragg scattering from a rough surface is the source of these echoes; rather, bubble clouds or plumes resulting from breaking waves represent a more plausible explanation. We have shown that bubble clouds or plumes can act as resonant scatterers at low frequencies and generate target strengths as large as 0 db for a wide variety of conditions that are expected to occur in rough seas with wind-driven breaking waves. Future experiments are planned to determine more precisely the measured targets strengths in terms of the environmental conditions that would generate bubbles clouds of the required size, shape and void fraction to produce these false targets.

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