High frequency sonar performance predictions for littoral operations - the effects of suspended sediments and micro-bubbles

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Abstract
Sonar performance models were traditionally developed for open oceans. Littoral waters may contain relatively high levels of suspended mineral particles and micro-bubbles that can significantly affect the propagation of sound, particularly at frequencies of tens of kHz and above, and therefore influence the performance of high frequency naval sonars and other high frequency acoustic sensors. The primary effect of suspended particulate matter is to increase the volume attenuation coefficient as a result of visco-inertial absorption and scattering. Account of this effect has now been taken in a minehunting sonar performance model. Similarly, micro-bubbles contribute to the volume attenuation through visco-inertial and thermal absorption and scattering, and also modify the sound speed. Both effects have been included in the same sonar model. Results from the enhanced sonar performance model demonstrate that the effects of both suspended particles and micro-bubbles on the performance of high frequency sonars in littoral waters can be significant.

1 INTRODUCTION

Research into naval sonar performance has traditionally focused on anti-submarine warfare involving long range, low frequency propagation in the deep ocean. Since the end of the Cold War, attention has turned towards the study of sonar performance in coastal seas. Sonars operating in shallow coastal waters are subject to many environmental complexities that affect performance: one such is that coastal waters may contain suspensions of mineral particles and populations of micro-bubbles that can degrade the performance of high frequency systems, such as minehunting sonars in particular. Such systems use frequencies of tens to hundreds of kHz (wavelengths of the order of centimetres) to achieve the spatial resolution required to locate and classify relatively small targets (of the order of a metre) such as naval mines at ranges of hundreds of metres.

We describe the physical effects of suspended particles and micro-bubbles, and then turn to expected sonar performance. Results show that performance is reduced and that account of such suspensions must be taken when modelling sonar performance.

2 SUSPENDED PARTICLES

High concentrations of suspended mineral particles may be found in coastal waters as a result of rivers discharging their sediment load, wind- and tide-generated currents stirring up bottom sediments, and human activity including dredging of navigation channels and underwater explosions. Figure 1 shows an example of a turbid coastal environment. This photograph, taken from the NASA Space Shuttle, shows a synoptic oblique view of the Texas and Louisiana coastline of the Gulf of Mexico, extending from Houston at the bottom left of the frame to the Mississippi Delta at the top right. High levels of coastal turbidity may clearly be seen all along the coastline, with the Trinity River discharging a balloon-shaped sediment plume through Galveston Bay, and a very high sediment load disgorging from the Atchafalaya River through Atchafalaya Bay. The presence of these suspended particles may influence acoustic propagation at minehunting and torpedo sonar frequencies through absorption, scattering and changes to the sound speed.

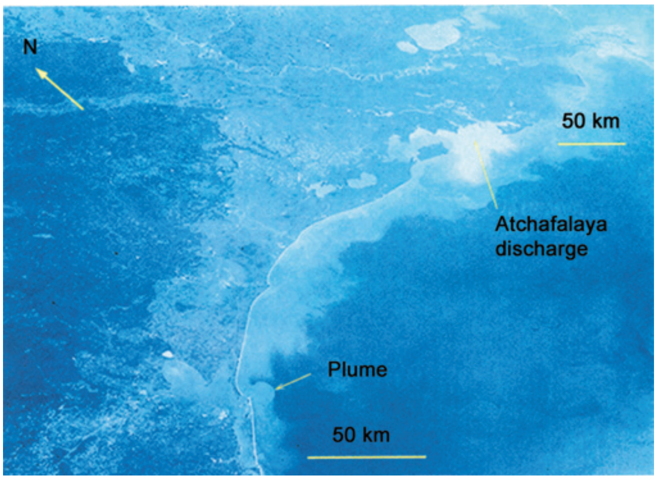

Fig 1. Photograph showing evidence of coastal turbidity along the Louisiana and Texas Gulf Coast. The scale and orientation indicators are approximate. The two different scale bars indicate the perspective arising from the oblique viewing angle. [NASA Image STS41C-51-2422. Source: Lunar and Planetary Institute]

Absorption

The principal acoustic absorption mechanisms associated with suspended particles are visco-inertial and thermal absorption. Visco-inertial absorption occurs as a result of the density contrast between the particles and the suspending water. Unless the particle is neutrally buoyant, its inertia will differ from that of the fluid it displaces. As a result, the oscillations that the particles undergo in response to an acoustic field will have a phase lag relative to the oscillations of the ambient fluid. This phase lag leads to a boundary layer at the surface of the particle, in which there is a velocity gradient. As a consequence of internal friction (viscosity), this velocity gradient results in conversion of energy to heat, and hence a loss of energy from the acoustic field. This represents the dominant energy loss mechanism caused by suspended particles over the parameter range of interest for sonar performance. In addition, thermal waves may be generated as a result of the adiabatic compression and rarefaction associated with the passage of the acoustic wave. Phase differences between the thermal waves in the solid and fluid lead to thermal absorption, although this effect for mineral particles suspended in seawater may generally be neglected at sonar frequencies.

Scattering

Acoustic waves incident on an inhomogeneity, such as a particle suspended in an ambient fluid, are scattered in all directions. Scattered energy, whilst remaining part of the overall acoustic field, is effectively lost from a transmitted or reflected sonar pulse. It will, however, also contribute to the volume reverberation if it propagates to the sonar receiver array. The amount of energy scattered by a particle depends upon the ratio of the particle size to the acoustic wavelength. For practical sonar applications, the wavelength is usually large compared with the particle size, and under this so-called Rayleigh regime the scattered power varies as the fourth power of this ratio (Rayleigh scattering). As a result, scattering is usually a small contribution to the absorption, becoming important only at the upper extremes of frequency and particle size.

Sound speed

The speed of sound in a suspension may differ from that in the suspending fluid because the suspended particles modify the bulk compressibility and density. This effect is small for naturally occurring suspension concentrations [1], except in the boundary layer near the water-sediment interface, and may therefore be neglected in sonar performance predictions.

Calculations

A complete mathematical description of visco-inertial absorption, thermal absorption and scattering by a thermally conducting, viscous or elastic sphere suspended in a thermally conducting, viscous fluid is provided by the Allegra-Hawley model [2]. The theoretical approach in this model is to formulate partial-wave expansions of the solutions of the Helmholtz equations for the six waves generated when plane waves are incident on a spherical inhomogeneity (compression, thermal and shear waves in both the solid and fluid phases). These equations may be solved by using six boundary conditions at the fluid-solid interface - continuity of: radial velocity, tangential velocity, temperature, heat flux, radial stress and tangential stress. The solution of the resulting matrix equation is computationally challenging, since the 6 x 6 matrix is often ill-conditioned and near-singular, and many of the terms involve spherical Bessel and Hankel functions of complex arguments, together with their first and second derivatives, that must be computed with care.

Simpler formulations for visco-inertial absorption and scattering exist and, over the frequency range for high frequency sonar performance problems (tens to hundreds of kHz), these can give predictions that are in reasonable agreement with the more complete, rigorous model. Urick [3] obtained an expression for the visco-inertial absorption coefficient based on energy-balancing arguments for a solid sphere oscillating in a viscous fluid. The scattering attenuation coefficient may be estimated using a simple polynomial fit to the scattering form function [4]. These models have been used to produce the result shown in figure 2 for the normalized attenuation coefficient in water containing a suspension of spherical particles with physical properties representative of typical mineral particles. The main peak dominating much of the parameter range is the contribution of visco-inertial absorption, and the sharp increase in attenuation at the extremes of high frequency and large particle size is caused by scattering. The black curve shows how the peak in the visco-inertial absorption shifts to larger particle sizes as the frequency is reduced.

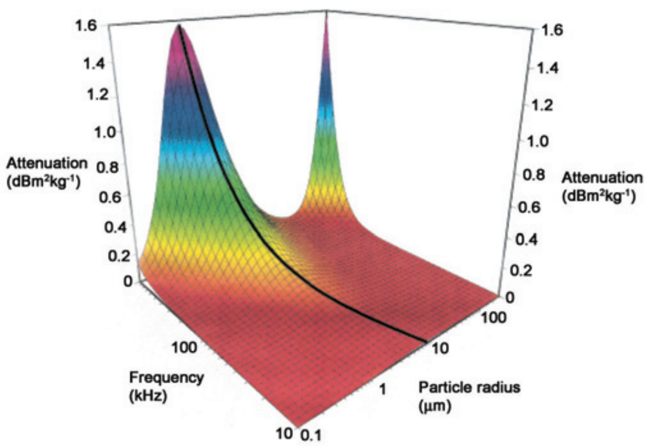

Fig 2. The attenuation coefficient from visco-inertial absorption and scattering by quartz-like spheres suspended in water. The black curve shows the peak in the visco-inertial term.

Laboratory measurements

To validate the models for visco-inertial absorption and test their applicability to non-spherical particles, a laboratory technique for measuring ultrasonic absorption in dilute suspensions was developed [5]. Whilst the absorption by dilute suspensions can be significant over propagation ranges of hundreds of metres, it is a challenging quantity to measure in a laboratory tank as the losses at the walls of the tank are much greater than the volume losses under investigation.

Consequently, a novel experimental approach was required to measure these small volume absorption coefficients.

The experimental method was based on measuring the reverberation time of an enclosure, defined as the time taken for the sound pressure level to fall by 60 dB after the sound source is switched off. The reverberation time depends on the total acoustic attenuation in the system; by measuring changes in the reverberation time, changes in the attenuation may be inferred. This technique measures only the absorption, as scattering merely contributes to the reverberation and does not therefore represent a loss of acoustic energy from the system. Figure 3 shows the measurement system schematically and figure 4 a photograph of the apparatus.

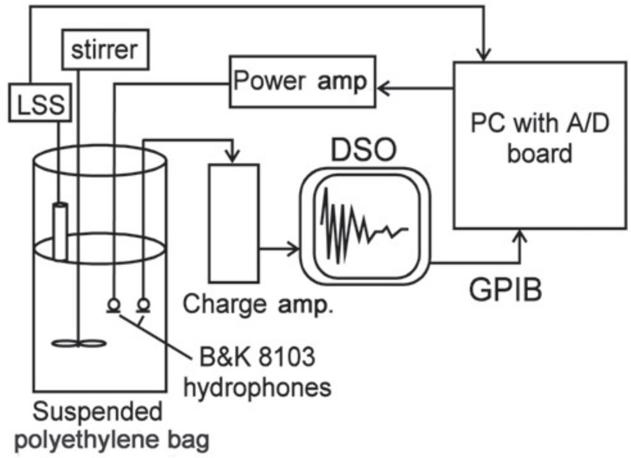

Fig 3. Schematic drawing of the apparatus used for measuring ultrasonic absorption in dilute suspensions

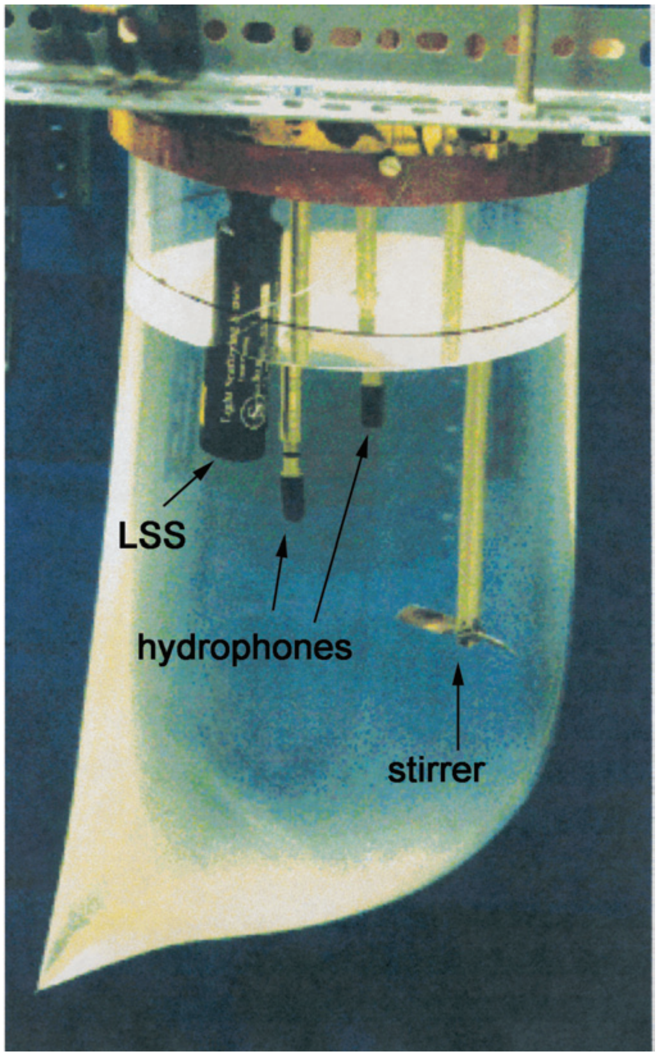

Fig 4. The apparatus used for measuring ultrasonic absorption in dilute suspensions

The test volume of around 16 litres of filtered, degassed water was contained in a thin-walled plastic membrane. This configuration gives a boundary condition approaching the idealized pressure-release boundary, ensuring that sound reflection at the interface is maximized, resulting in minimum boundary losses. The water was degassed in a vacuum chamber before testing because the presence of even a small amount of free gas in bubbles could contribute absorption to a far greater extent than the particles added in the experiments. Even leaving the water to stand and degas naturally would be insufficient, since a tiny amount of gas (stabilized, for example, against buoyancy by adhesion to the walls of the bag and released by ambient temperature fluctuations) would be sufficient to invalidate the results. The photograph shows four items penetrating the water surface. These are, from left to right, a light-scattering sensor for monitoring suspended particle concentration (in later experiments this was mounted horizontally on the outside of the transparent membrane), the two hydrophones (source and receiver) and a mechanical stirrer.

A reverberant sound field was established by exciting the volume with broadband sound. Ideally, the sound field should be diffuse, to eliminate standing-wave effects that could lead to the results being dependent on where in the volume the measurements are made. A diffuse field is one in which the energy density is the same everywhere and all propagation directions are equally probable. In the present case, the field was nearly diffuse, although some residual spatial variability was observed. This variability was included in the error analysis of the results. Measurements of the spatial uniformity of the field also revealed another interesting phenomenon: when changing the hydrophone depths, the small change in the length of submerged hydrophone cable increased the total acoustic absorption of the system sufficiently to swamp the effect due to the addition of the particles completely. This serves to illustrate the challenging nature of these measurements.

The reverberation time was determined by switching off the source hydrophone and measuring the decay of the sound field at the receiver hydrophone. This was done first in clear water; known quantities of particulate matter were then added in stages and the procedure repeated. The mechanical stirrer was used to suspend the particles and ensure that they were evenly distributed. The clear-water reference measurement was also made on stirred water to ensure consistency and the stirrer was removed from the water before making the acoustic measurements. The additional attenuation arising from the presence of the particles was inferred from the difference

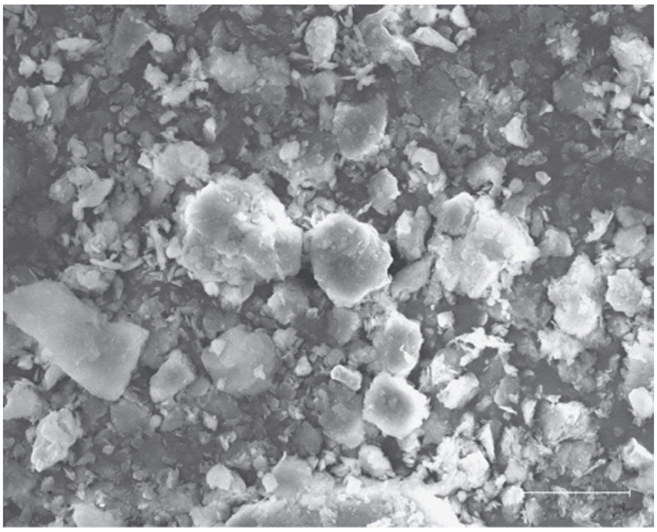

Fig 5. Scanning electron microscope image of a typical sample of fine-grained marine sediment (original instrument magnification: x 2000)

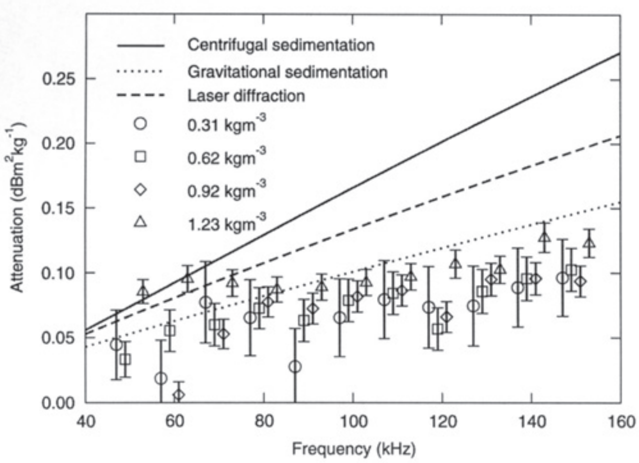

Fig 6. Measured and calculated absorption coefficients for the sediment type shown in figure 5

between reverberation times in the suspension and in clear water. To compare results with the predictions of the models, which assume the particles to be spherical, initial experiments were performed using spherical glass particles. These experiments showed very good agreement between the measurements and predictions of the model integrated over the particle size distribution, which was measured by laser diffraction analysis [5].

Naturally occurring marine sediment particles are not, of course, spherical but typically look more like those shown in figure 5, a scanning electron micrograph of a sample of fine sediment taken from the seabed. Clearly, the particles are very granular and irregular in nature. The absorption coefficients of dilute suspensions of this material were measured as before, and the results are shown in figure 6 for different concentrations, each normalized with respect to concentration. The data were processed in 10 kHz frequency bins, but the points have been offset to each side of these frequencies to show each point with its error bar. The absorption was modelled again assuming the particles to be spherical, with the size distributions determined by three different techniques: laser diffraction analysis, gravitational sedimentation and centrifugal sedimentation.

There are significant differences between the absorption spectra predicted using the size distributions obtained with the different techniques. This is because the particle size distributions yielded by the three methods are different as they measure different quantities. The laser diffraction method interprets the diffraction pattern from a suspension of particles in terms of the theoretical diffraction pattern from a collection of spheres. This technique may therefore be said to yield a distribution of effective sphere radii for optical scattering. The two sedimentation measurements are interpreted to yield the Stokes diameter, which is the diameter of a sphere that has the same density and settling velocity as the particles studied. The size distribution obtained from centrifugal sedimentation showed a bias towards smaller particle sizes compared with either the laser diffraction or gravitational sedimentation measurements. This may be owing to the break up of flocs or aggregates of particles in the centrifuge.

Of the three techniques, the gravitational sedimentation may be considered to yield a size distribution most suitable for use in the visco-inertial absorption models, since the particles are subject to the Stokes drag in the sound field, and the low acoustic power is not expected to break up the flocs. Clearly, there is a spread in the measurements of acoustic absorption and this is largely because of uncertainties in the estimation of the water content in the sediment sample.

The agreement between experiment and theory is not as good for these marine sediment particles as was found for the spherical glass particles. However, the result is encouraging considering that measurements made using highly irregular particles are being compared with a simple theory based on spherical particles. Other measurements made with pure samples of highly non-spherical particles show significant departures from the spherical model, as is to be expected [6]. It is likely that, for the marine sediment particles, the agreement between the measurements and the spherical particle theory is a result of ensemble averaging over many different particle shapes. This gives some encouragement that the simple model of viscous absorption by spherical particles may be used to estimate absorption by dilute suspensions of natural marine mineral particles.

3 MICRO-BUBBLES

Coastal waters may also be populated by micro-bubbles, not only near the surface but throughout the water column. Near-surface populations are dominated by bubbles generated by the entrainment of air through wave activity, and these populations may be taken into account implicitly in sonar performance models by empirical surface scattering algorithms that include a dependence on wind speed. Some models may also include the effects of a surface bubble layer as a surface loss term. Bubbles may also be advected further down in the water column by wave-generated turbulence, or may be generated in the seabed by biological or chemical activity and rise through the water by buoyancy. Current sonar performance models do not, however, include the effects of these water-column micro-bubble populations on either volume attenuation or phase speed. Bubbles also contribute to acoustic attenuation through both absorption and scattering, as described for suspended particles. Additionally, gas bubbles in liquids cause the compressibility to be complex, resulting in a dispersive medium. The additional attenuation due to micro-bubbles, and their effect on the sound speed, may be determined from the dispersion relation for bubbly water [7]. Depth-dependent versions of this dispersion relation were used in this work [8].

In contrast to solid particles, resonant scattering is important for gas bubbles, and the scattering cross section of a bubble at or near its resonance frequency can be very much larger than its geometric cross section. The acoustic attenuation coefficient owing to visco-inertial, thermal and radiation damping by bubbles near resonance can be very large, and the phase speed may become strongly frequency dependent in the region of the resonant frequency, departing significantly from the phase speed in the ambient water. Marine bubble populations typically contain bubbles with equilibrium radii in the range 200 μm to 10 μm. At hydrostatic pressures found under near-surface and shallow water conditions, bubbles in this size range will typically be resonant at frequencies in the range 15 kHz to 300 kHz. Thus minehunting and weapon sonars will excite bubble resonances in naturally occurring bubble populations, leading to degradation in performance.

Figure 7 shows the calculated phase speed as a function of acoustic frequency for water containing a population of micro-bubbles with a distribution of bubble sizes in the range 10 μm to 200 μm. Figure 8 shows the excess attenuation that results from the same bubble population. These curves were calculated using the dispersion relationship for linear pressure waves in bubbly liquids [7], integrated over the measured bubble population. The phase speed is obtained from the real part of the complex wavenumber and the attenuation from the imaginary part. The bubble population used in these calculations was measured, using a combination frequency technique [9], in 1997 off Southampton at 50º 46.153'N, 1º 80.911'W, at 0.5 m below the surface, in water depths ranging from 17 to 22 m and at wind speeds in the range 10 to 12 ms^{-1}.

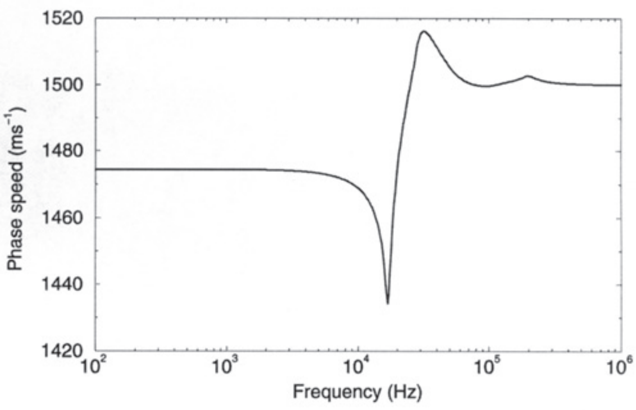

Fig 7. Calculated phase speed variation with frequency for a bubble population measured at sea (at a depth of 0.5 m in 17 to 22 m of water and a wind speed of 10 to 12 ms^{-1})

The number of bubbles at 10 distinct radii ranging between 16 μm and 192 μm were estimated. For water containing a monodisperse bubble population, there will be a rapid change in phase speed around the resonant frequency of the bubbles, with a corresponding attenuation peak resulting from the large radiation losses at resonance. Although figure 7 shows the result of integrating over a natural distribution of bubble sizes, this behaviour of the phase speed is still evident. However, this bubble population results in the bimodal attenuation spectrum shown in figure 8.

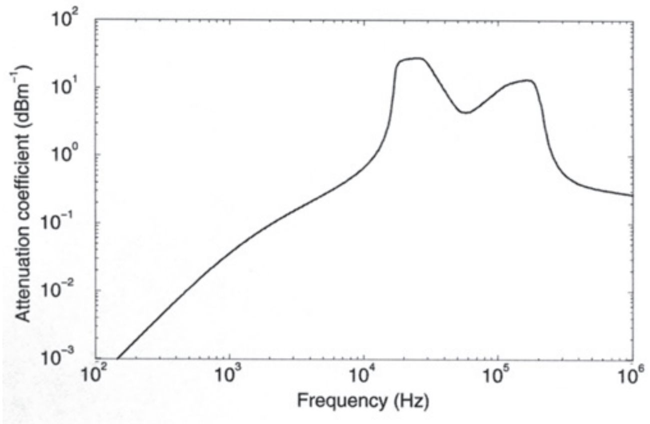

Fig 8. Calculated attenuation variation with frequency for a bubble population measured at sea (at a depth of 0.5 m in 17 to 22 m of water and a wind speed of 10 to 12 ms^{-1})

These results show that, for the population used, the presence of bubbles leads to significant variation in the phase speed, with strong dispersion over the frequency range 10 kHz to 40 kHz, and significantly different phase speeds above and below this frequency range. The results also show that large excess attenuation may be observed over a wide frequency range, with particularly high attenuation over the range 10 kHz to 300 kHz. The local minimum in the attenuation spectrum at around 60 kHz for this bubble population could be exploited to optimize acoustic sensor performance in this high attenuation band.

4 SONAR PERFORMANCE

The effects of suspended particles and micro-bubbles may be particularly significant for the performance of high frequency sonars, operating in the range tens to hundreds of kHz, and these effects have therefore been integrated into a high frequency sonar performance prediction model.

The model uses ray-tracing techniques based on the vertical sound speed gradient to determine ray paths in a horizontally stratified environment. It then calculates the signal-to-noise ratio along each ray path by calculating directivity, absorption, geometric spreading loss, surface, bottom and volume reverberation, ambient, flow and receiver noise, and by then applying the active sonar equation. The model uses direct paths only, assumes a flat, homogeneous seabed and uses a single sound-speed profile.

The additional attenuation from visco-inertial absorption and scattering by suspended particles has been added to the volume absorption algorithm, ensuring that the total attenuation coefficient is used in all propagation calculations in the model (transmitted and reflected signals, reverberation terms, propagating noise terms). The viscosity and density of the seawater must be known for calculating the additional attenuation terms, and viscosity and density profiles are therefore computed. The temperature profile is obtained from the sound-speed profile (assuming constant salinity) and this is used to determine the viscosity and density using temperature, pressure and salinity-dependent expressions [10]. The effects of suspended particles on the sound speed are considered to be negligible and have not been included in the model.

A depth-dependent dispersion relation for bubbly water [8] is computed in the model. The real part of the derived complex wavenumber is used to modify the sound-speed profile to take the effect of the bubble population into account. The imaginary part of the wavenumber is used in the volume absorption algorithm to include the bubbles' contribution to the attenuation coefficient. The bubbles may also contribute significantly to the volume reverberation and work is currently underway to incorporate this contribution into the model.

5 EXAMPLE RESULTS

Figure 9 shows the calculated signal-to-noise ratio for a typical high frequency, shallow water scenario. In this example, the water depth was 40 m, the bottom type was mud and the water column was isothermal. The horizontally-looking sonar was at a depth of 20 m and the source frequency was 80 kHz. The calculations for water containing suspended particles assume a mono-disperse population of particles with radius 2 μm, density 2600 kgm^{-3}, and a constant concentration of 0.2 kgm^{-3} throughout the water column. A depth-dependent distribution [11] of micro-bubbles with radii in the range 10-200 μm was used, with coefficients chosen to approximate to at-sea bubble density measurements [12,13]. This is appropriate for persistent background bubble populations in calm, isothermal, coastal waters and not for conditions where there is a large surface-generated bubble population.

If we assume, for the sake of argument, that a signal-to-noise ratio of 0 dB is required, shown by the horizontal line in the figure, then we can see that in this example a detection range of around 615 m is predicted for clear water. The additional attenuation due to the chosen population of suspended solid particles reduces this range to 403 m. The bubble population has an even greater effect, reducing the detection range to 243 m, whilst the combined effect of bubbles and suspended particles reduces the detection range to just 209 m.

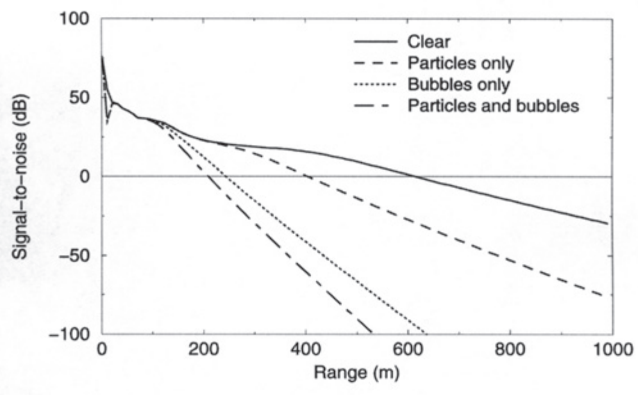

Fig 9. Calculated signal-to-noise ratio for a typical high frequency, shallow water scenario (see text) showing the effects of suspended solid particles and micro-bubbles

6 SUMMARY

Populations of suspended solid particles and micro-bubbles are just two of the many complexities that can influence the performance of sonars operating in shallow coastal waters. Such populations can significantly degrade the performance of high frequency active sonars and should therefore be taken into account in the predictive modelling of sonar performance.

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