Sonar performance in coastal environments: suspended sediments and microbubbles

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INTRODUCTION

Research into sonar performance has traditionally focussed on long range, low frequency propagation in the deep ocean. Over the last decade or so attention has turned towards the study of sonar performance in coastal seas. Sonars operating in shallow, coastal waters are subject to many complexities of the environment which present problems for sonar performance. One such complexity is that coastal environments may be characterized by suspensions of mineral particles and populations of microbubbles which can degrade the performance of high frequency sonar systems in particular. Such systems may employ frequencies in the range tens to hundreds of kHz (wavelengths of order centimetres) in order to locate and classify relatively small targets, with propagation ranges of the order of hundreds of metres.

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. Figure 1 shows an example of a turbid coastal environment. This photograph (NASA Image STS41C-51-2422. Source: Lunar and Planetary Institute), taken from the NASA Space Shuttle, shows 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 in this image, with the Trinity River discharging a balloon-shaped sediment plume [A] through Galveston Bay, and a very high sediment load disgorging from the Atchafalaya River through Atchafalaya Bay [B]. The presence of these suspended particles may influence acoustic propagation through absorption, scattering, and changes to the sound speed.

Absorption

The principal acoustic absorption mechanisms associated with suspended particles are viscous and thermal absorption. *Viscous 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 the that of the fluid it displaces. As a result of this the oscillations which 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 due to suspended particles over the parameter range of interest for sonar performance. 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 may generally be neglected at sonar frequencies for mineral particles suspended in seawater.

Scattering

Acoustic waves incident on an inhomogeneity, such as a particle suspended in an ambient fluid, are scattered in all directions. Energy which is scattered in this way, whilst remaining part of the overall acoustic field, is effectively lost from a transmitted or reflected sonar pulse. It will, however, contribute to the volume reverberation if it propagates to the sonar receiver array. The amount of energy scattered by a particle in this way depends upon the ratio of the particle size to the acoustic wavelength. For practical sonar applications the wavelength is usually large compared to the particle size and under this regime the scattered power varies as the fourth power of this ratio. 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 by virtue of the fact that the suspended particles modify the bulk compressibility and density. This effect is small for naturally occurring suspension concentrations [1] and may therefore be neglected in sonar performance predictions.

Calculations

Over the parameter range under consideration for the sonar performance problem it may be found that the simplest, intuitive models give predictions which are in reasonable agreement with the more complete models. Urick [2] obtained an expression for the viscous 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 [3]. These models have been used to produce the result shown in Figure 2. This shows 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 due to viscous absorption, and the sharp increase in attenuation at the extremes of high frequency and large particle size is due to scattering. The black curve shows how the peak in the viscous absorption shifts to larger particle sizes as the frequency is reduced.

Laboratory measurements

In order to validate the models for viscous absorption and test their applicability to non-spherical particles, a laboratory technique for measuring ultrasonic absorption in dilute suspensions was developed [4]. 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. Consequently a novel experimental approach was required to measure these small volume absorption coefficients.

The experimental method is 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, and 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 shows a photograph of the apparatus. The test volume of around 16 litres of filtered, degassed water is contained within a thin-walled plastic membrane. This configuration was chosen to give a boundary condition approaching the idealised pressure-release boundary, ensuring that sound reflection at the interface is maximised, resulting in minimum boundary losses. The photograph shows four items penetrating the water surface. These are, from left to right, a light scattering sensor for monitoring suspended particle concentration, the two hydrophones (source and receiver) and a mechanical stirrer. A diffuse, reverberant sound field is established by exciting the volume with broadband sound. The reverberation time is then determined by switching off the source hydrophone and measuring the decay of the sound field using the receiver hydrophone. This is done first in clear water and then a known quantity of particulate matter is added and the procedure is repeated. The mechanical stirrer is used to suspend the particles and ensure that they are evenly distributed. The clear water reference measurement is also made on stirred water to ensure consistency and the stirrer is removed from the water prior to making the acoustic measurements. The additional attenuation arising from the addition of the particles is inferred from the difference in reverberation time. Initial experiments were performed using spherical glass particles, in order to compare results with the predictions of the models, which assume the particles to be spherical. 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 [4].

Naturally occurring marine sediment particles are not, of course, spherical. Instead they typically look more like the particles shown in Figure 5, which shows 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. The absorption was modelled assuming the particles to be spherical, with the size distribution again determined by laser diffraction analysis. The measurements were made at different concentrations, and the results normalized with respect to concentration. Clearly there is a spread in the measurements and this is largely due to uncertainties in the estimation of the water content of the sediment sample. Surprisingly, the results of the model for viscous absorption by spherical particles are in reasonable agreement with the measured absorption due to these irregular particles. Other measurements made with pure samples of highly non-spherical particles show significant departures from the spherical model, as is to be expected [5]. It is thought that, in the case of the marine sediment, 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.

MICROBUBBLES

Coastal waters may also be populated by microbubbles, not only near the surface but extending throughout the water column. Near-surface bubble populations are 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 which include a dependence on wind speed. Some models may also include the effects of a surface bubble layer in a surface loss term.

Current sonar performance models do not, however, include the effects of microbubble populations on volume attenuation. Bubbles contribute to acoustic attenuation through both absorption and scattering, as do suspended particles. Additionally gas bubbles in liquids cause the compressibility to be complex, resulting in a dispersive medium. The additional attenuation due to microbubbles, and their effect on the sound speed may be determined from the dispersion relation for bubbly water [6]. Depth dependent versions of this dispersion relation were used in this work [7].

SONAR PERFORMANCE

The effects of suspended particles and microbubbles may be particularly significant for the performance of high frequency sonars, operating in the frequency 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 applying the active sonar equation. The model uses direct paths only, assumes a flat, homogeneous seabed and employs a single sound speed profile.

The additional attenuation due to viscous 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 within the model (transmitted and reflected signals; reverberation terms; propagating noise terms). The viscosity and the density of the seawater must be known in order to calculate the additional attenuation terms, and viscosity and density profiles are therefore computed within the model. 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 [8]. The effects of suspended particles on the sound speed are considered to be negligible and have not been included in the model.

The depth-dependent dispersion relation for bubbly water is computed within 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 contribute significantly to the volume reverberation and this contribution has not yet been incorporated into the model.

EXAMPLE RESULTS

Figure 7 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 monodisperse 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 [9] of microbubbles with radii in the range 10-200 μm was used, with coefficients chosen to approximate at-sea bubble density measurements [10,11]. 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.

SUMMARY

Populations of suspended solid particles and microbubbles are just one of the many complexities which 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 predictive modelling of sonar performance.

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Figure 1: Photograph showing coastal turbidity along the Texas and Louisiana Gulf coast. Galveston Bay is shown at the bottom of the picture, with the Mississippi Delta at the top right. [Source: Lunar and Planetary Institute]

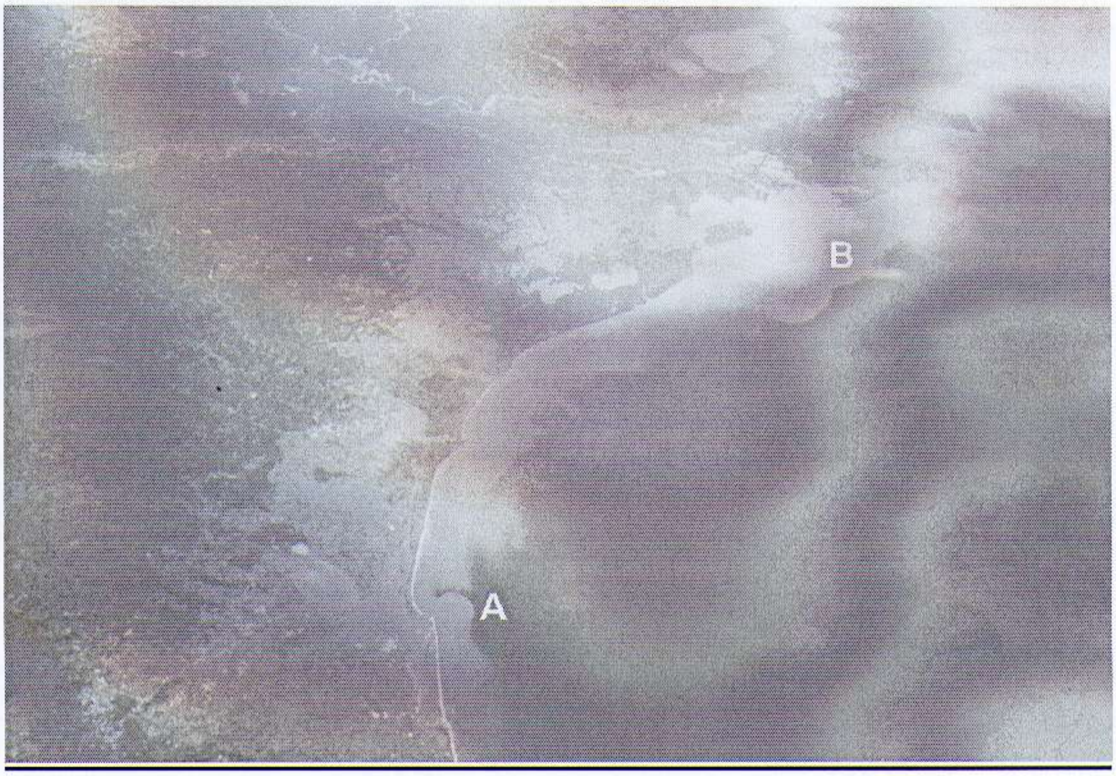

Figure 2: Attenuation coefficient for a suspension of quartz-like spheres

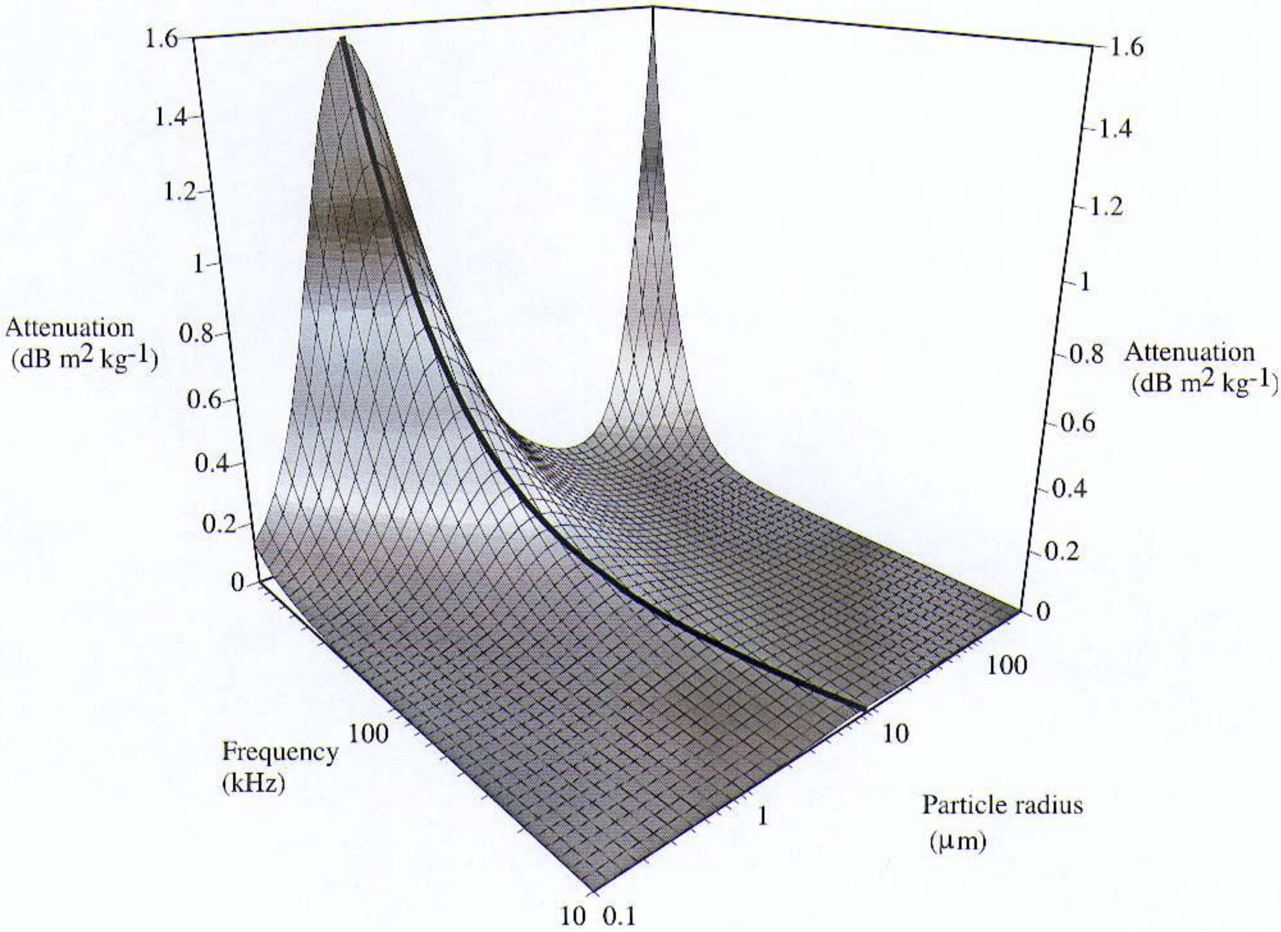

Figure 3: Schematic of experimental apparatus for measuring ultrasonic absorption in dilute suspensions

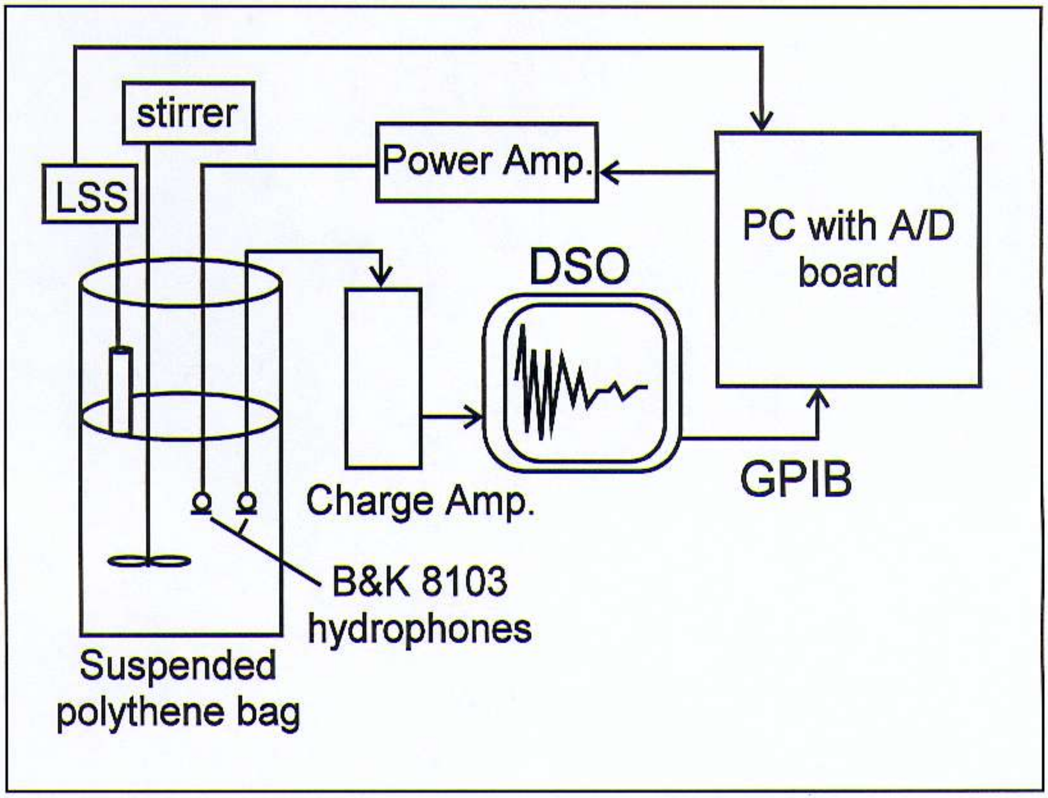

Figure 4: Photograph of experimental apparatus for measuring ultrasonic absorption in dilute suspensions

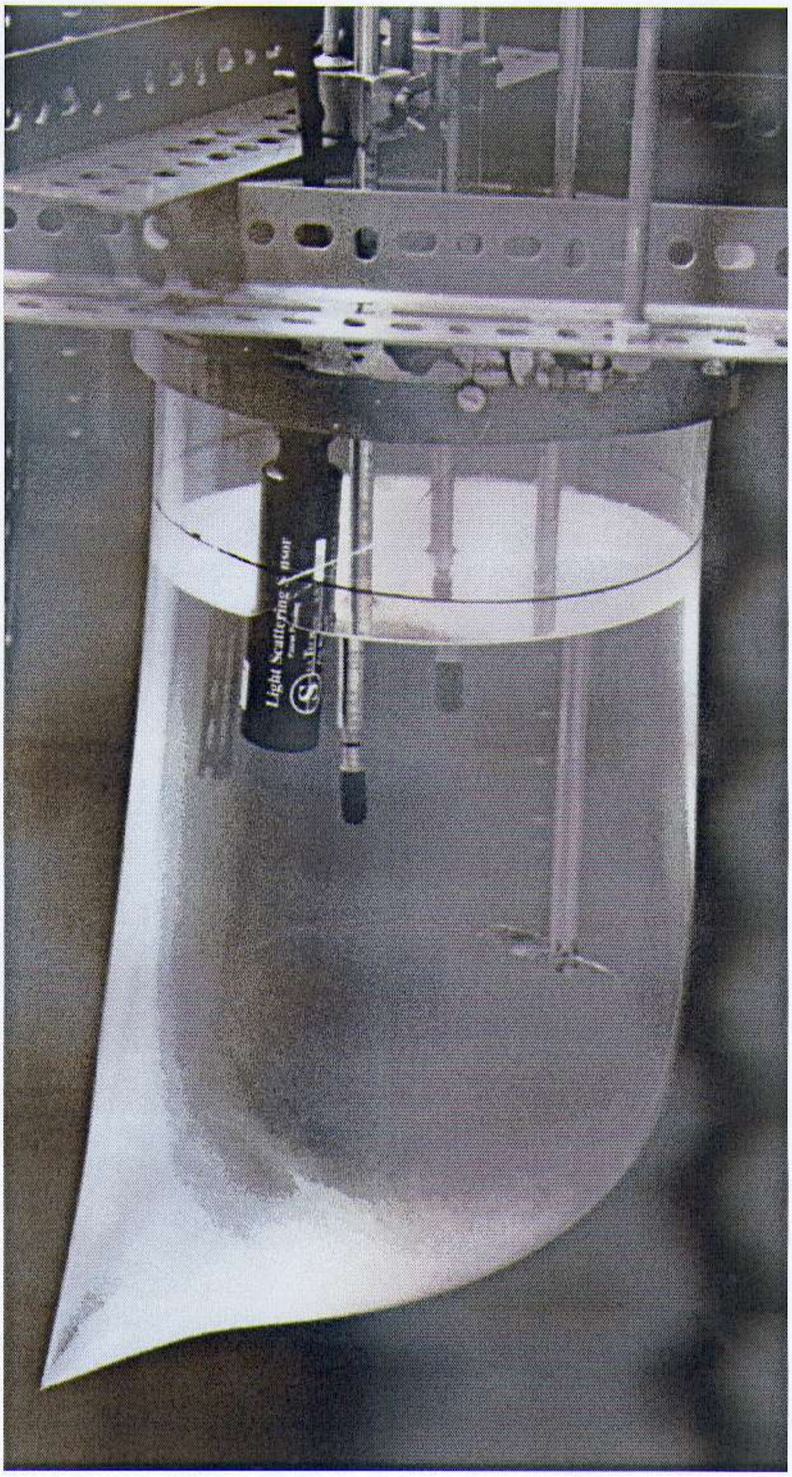

Figure 5: Scanning electron microscope image of a typical fine-grained marine sediment.

Figure 6: Measured attenuation coefficient for sediment type shown in Figure 5.

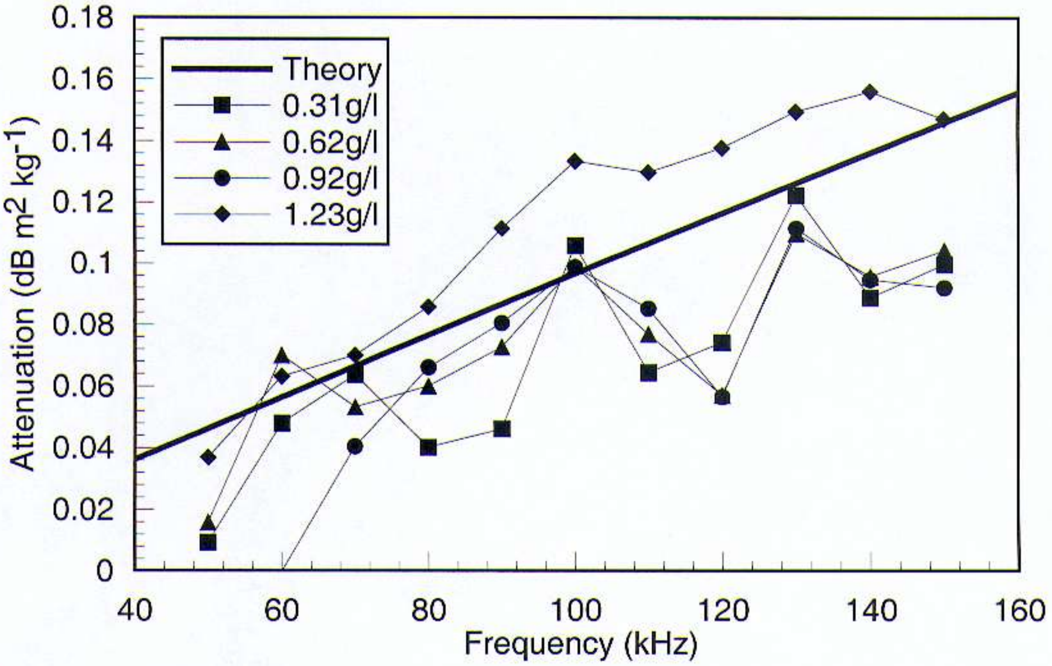

Figure 7: Calculated signal-to-noise ratio for a typical high frequency, shallow water scenario (see text), showing the effects of suspended solid particles and microbubbles.