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Strong Explosions at a Long Distance in the
Ocean Sound Channel by Computer Simulation**

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Investigation of the Ocean Acoustic Signatures from Strong Explosions at a Long Distance in the Ocean Sound Channel by Computer Simulation.

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Introduction

The principal objective of the non-proliferation program is to discourage clandestine testing of nuclear explosives by maintaining an effective global surveillance system. The methods of detection include underwater and atmospheric acoustics, seismology and atmospheric photometry. The goals of the underwater acoustics are the identification and location of ocean acoustic signatures. Difficulties arise primarily from the spatial and temporal variations in the conditions of the SOFAR channel¹, and from various evasive options that are available to "would-be" clandestine testers.

In this study, the path effects on the signals generated by strong explosions (1 kt) are investigated. The investigation is directed toward obtaining a quantitative correlation between the initial explosion source under various conditions and the final acoustical signatures received at a great distance for different paths. By computer simulations, we calculated the energy coupling and dissipation in the water and studied the signature patterns. The simulation process undergoes three phases, namely,

- 1- the initial explosion (coupling energy to the water),
- 2- wave propagation in the SOFAR channel,
- 3- the global ocean acoustics,

applying in series three computer programs appropriate to each regime. In this paper, we report preliminary results of the study on the signals from 1 kt explosions after the signals have propagated a significant distance in the SOFAR channel. The third step in the model has not yet been addressed.

Method of Computer Simulation

First, the explosions are simulated by a 2-D hydrodynamic computer program, CALE², which was originally developed to calculate astrophysical problems. CALE is an *Arbitrary Lagrange Eulerian* computer code written in C-language. CALE can also be operated in either the pure Eulerian mode or the pure Lagrangian mode. The two-dimensional simulations were run with a polar mesh. The energy source was modeled by an iron gas bubble with an initial density of 0.5 gm/cc and initial radius of 1 m. The calculations were run until the signal peak pressures in the water fell below 200 bars. At this point, the CALE output was linked to a hydro-acoustic computer program,

NPE Code^{3,4} (Non-linear Progressive wave-Equation Code) to analyze propagation in the SOFAR channel.

The NPE Code was developed at the Naval Research Laboratory to study ocean acoustics. The nonlinear progressive wave equation describes nonlinear propagation of compressional waves in the time domain. The wave propagation is calculated in a Cartesian frame moving at the local sound speed. The SOFAR channel is modeled by a vertical sound speed profile. Taking the CALE output from 1 kt explosions as input for NPE calculations, we then calculated the propagation of the signals over a distance of 10 km in the SOFAR channel. The current status of our research stands at this stage. The next and the final phase of calculation will be made by a global ocean acoustics code.

Validation of the Computer Codes

As a preliminary phase of the calculation, we validated the CALE computer program by simulating a real underwater experiment, WIGWAM^{5,6}. WIGWAM was a deep water nuclear explosion of 32 kt. The depth of explosion was 2000 ft in about 15000 ft of water, which eliminated interference from the ocean floor within the measurement time. The peak pressures of the passing signals were calculated at three gauge locations, slant ranges of 245, 458 and 580 m from the explosion point. The results are compared with the two sets of measurements, magnetic tape and telemeter, in Fig. 1. Agreement of the calculations with the measurements demonstrates the validity of our simulation technique. The NPE Code has also been extensively checked against various analytical solutions^{3,4}, and we have independently validated its expected fall-off for pressure as a function of range as is shown in Fig. 2.

Results of 1 kt Explosion Calculations

The energy coupling of a 1 kt source was investigated. The source was placed at water depths of 0, 5, 10, 20 and 100 m and at heights above the water of 10, 20 and 43 m, and each calculation was carried out until the signal peak pressure in the water decayed below 200 bars. Then the total kinetic energy in the water below the burst point was integrated; we call this the downward kinetic energy. Figure 3 shows the downward kinetic energy divided by the yield plotted against the depth of explosion in $\text{m}/\text{kt}^{1/3}$. The maximum coupling is achieved at about 20 m in scaled depth. As the source is lifted above the water, the coupling efficiency decreases by nearly three orders of magnitude. These results are widely recognized, and provide a "would-be" evader with an option to try and hide his test by raising it above the ocean surface.

CALE - NPE Link

The CALE output on the compressional wave gives the isobaric contours which translate to the spatial contours of overdensity, $(\rho - \rho_0)/\rho_0$, in the NPE start-up mesh. The nonlinear progressive wave equation computes the horizontal propagation of the signal with the local sound speed. A typical sound speed profile in the SOFAR channel is shown in Fig. 4. The vertical minimum in sound speed which occurs about 1 km deep causes the signals to oscillate about the sound channel axis. The NPE calculations were carried out over a distance of 10 km for five cases of 1 kt explosion, i.e. the depths of explosions at 20, 100, 250, 500 and 1000 m.

Figure 5 shows the total energies delivered to the 10 km point by the signals. The choice of a 10 km propagation was chosen because this is twice the depth of the water column in our simulations. At a 10 km range, the wave has well established cylindrical geometry. The signal from a near surface explosion (20m DOB) can deliver a mere 1 ton (0.1 %) of the original 1 kt, whereas the signal from an explosion at 1000 m deep delivers about 26 tons of energy.

Figure 6 summarizes the sample signatures that we obtained by CALE and NPE. The peak pressure in the water for the 20 m DOB case is 0.16 bar with the total energy of 1 ton, whereas the peak pressure for the 1000 m DOB case is 1.4 bars with the total energy of 26 tons. Figure 6 also reveals that the signal from the 1000 m DOB case has evolved into a "flatter" (more cylindrical) wave with a more complex structure when compared to the 20 m DOB case. In both cases, we observe bottom reflections.

Conclusion

Combining Fig. 3 (energy coupling) and Fig. 5 (energy transmitted in the SOFAR channel), it is evident that an above water explosion can decouple its energy from the SOFAR channel by an amount in excess of four orders of magnitude. More than three orders of magnitude are obtained by reducing the energy coupled to the water, and more than one order of magnitude of decoupling results from a source that is not located at the SOFAR channel depth. However, this is still a strong signal and within the detection capability of modern sensors. The signal will be detectable even if the signal is propagated to a much greater distance where the signal strength is further reduced. Difficulties that we have not addressed include discrimination and identification of the signatures. We will collaborate with others to explore these areas later along path variations using the global ocean acoustic codes such as the one developed by Howe et al⁷.

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Fig. 1 WIGWAM underwater experiment, calculation and measurements: Error bar is 2σ (15%), Calculations are within the error bars of the measured data.

Fig. 2 Signal peak pressure versus range in water
Peak pressure is the maximum over-density times the bulk modulus

Fig. 3 Downward-directed K.E. for 1 kt explosions:
The maximum coupling is achieved at a depth of 20 m.

Fig. 4 A typical sound speed profile in the SOFAR channel:
The sound speed minimum occurs at about 1 km deep.

**Fig. 5 Total energy delivered by signals from 1 kt explosions at a horizontal distance of 10 km:
Near surface explosion (20 m DOB) can deliver an order of magnitude less energy than deep water explosion (1000 m DOB).**

CALE (150 ms)

NPE (6.75 sec)

Fig. 6 Acoustical signatures, CALE-NPE calculations:

The signatures for the 1000 m DOB case has a flatter wave front, and the peak pressure and the total energy are 10 times greater than those for the 20 m DOB case.

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