ANALYSIS OF RUSSIAN HYDROACOUSTIC DATA FOR CTBT VERIFICATION

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ABSTRACT

As part of a collaborative research program for the purpose of monitoring the Comprehensive Nuclear-Test-Ban Treaty (CTBT), we are in the process of examining and analyzing hydroacoustic data from underwater explosions conducted in the former Soviet Union. We are using these data as constraints on modeling the hydroacoustic source as a function of depth below the water surface. This is of interest to the CTBT because although even small explosions at depth generate signals easily observable at large distances, the hydroacoustic source amplitude decreases as the source reaches the surface. Consequently, explosions in the ocean will be more difficult to identify if they are on or near the ocean surface. We are particularly interested in records featuring various combinations of depths of explosion, and distances and depths of recording.

Unique historical Russian data sets have now become available from test explosions of 100-kg TNT cast spherical charges in a shallow reservoir (87 m length, 25 m to 55 m width, and 3 m depth) with a low-velocity air-saturated layer of sand on the bottom. A number of tests were conducted with varying water level and charge depths. Pressure measurements were taken at varying depths and horizontal distances in the water. The data available include measurements of peak pressures from all explosions and digitized pressure-time histories from some of them. A reduction of peak pressure by about 60-70% is observed in these measurements for half-immersed charges as compared with deeper explosions. In addition, several peak-pressure measurements are also available from a 1957 underwater nuclear explosion (yield < 10 KT) in the Bay of Chernaya (Novaya Zemlya).

The 100-kg TNT data were compared with model predictions. Shock wave modeling is based on spherical wave propagation and finite element calculations, constrained by empirical data from U. S. underwater chemical and nuclear tests. Modeling was performed for digitized pressure-time histories from two fully-immersed explosions and one explosion of a half-immersed charge, as well as for the peak-pressure measurements from all explosions carried out in the reservoir with water level at its maximum (3 m). Although the modeling had been calibrated to independent data sets from explosions under different conditions, the predictions match the Russian data well.

Peak-pressure measurements and pressure-time histories were simulated at 10 km distance from hypothetical 1-KT and 10-KT nuclear explosions conducted at various depths in the ocean. The ocean water was characterized by a realistic sound velocity profile featuring a velocity minimum at 700 m depth. Simulated measurements at that same depth predict about a tenfold increase in peak pressures from explosions in the SOFAR channel as compared with explosions shallower than 100 m. The observations and the modeling results were also compared with predictions calculated at the Lawrence Livermore National Laboratory using a different modeling approach. The results suggest that although the coupling is reduced for very shallow explosions, a shallow 1-KT explosion should be detectable by the IMS hydroacoustic network.

Key Words: Hydroacoustic, Russian tests, modeling, shallow underwater explosions

OBJECTIVE

The objective of this work is to analyze and model a unique historical set of Russian hydroacoustic data measured from underwater explosions. The Russian data are used as constraints on modeling the hydroacoustic source as a function of depth below the water surface. The results are expected to contribute significantly to the understanding of the difference in coupling from deep underwater explosions versus shallow and surface explosions of interest to the CTBT.

RESEARCH ACCOMPLISHED

Introduction

As part of a collaborative research program for the purpose of monitoring the Comprehensive Nuclear-Test-Ban Treaty (CTBT), we are in the process of examining and analyzing hydroacoustic data from underwater explosions conducted in the former Soviet Union. The CTBT hydroacoustic network consists of 11 stations that monitor the oceans for underwater explosions, as well as for atmospheric explosions conducted close to the ocean surface. The reason such a small network can monitor the whole world is that hydroacoustic waves propagate very efficiently in the acoustic waveguide known as the SOFAR channel. Since a significant portion of the energy from an underwater explosion couples to this channel as acoustic waves, even kilogram-sized explosions at depth generate signals easily observable at large distances. For example, Stevens et al (1999) discuss hydroacoustic signals from four-pound charges detonated off the coast of San Francisco that were recorded as far away as Wake Island, a distance of about 7,000 km.

Understanding the effects of underwater explosions is largely based on measurements and modeling of shock waves. The coupled energy is the energy transferred from the source to the water, manifested as a point-source explosion generating an initially spherically divergent underwater shock wave. The amount of energy coupled to the water depends strongly on the explosion depth. Of interest to the CTBT are shallow and surface sources, as the explosion energy from such tests would be significantly decoupled from the ocean. In light of the above, we are particularly interested in records featuring various combinations of depths of explosion, and distances and depths of recording. Historical Russian hydroacoustic data have become available recently that consist of a number of such measurements. The usefulness of these data lies in the possibility of understanding better the coupling for shallow and surface explosions, and how they differ from deeper, fully coupled explosions. Thus we are using these data as constraints on modeling the hydroacoustic source as a function of depth below the water surface.

The focus in this work is on analyzing and modeling uniquely comprehensive hydroacoustic data from relatively small-scale explosions in a shallow reservoir. The available measurements feature shock-wave parameters (peak pressure, duration and impulse) and pressure-time histories. This data clearly demonstrates that underwater shock waves from explosions at or near the water surface depend strongly on the amount of energy coupled to the water in the source region and peak pressures are significantly diminished by comparison with deeper explosions (by 60-70%). Several measurements from an underwater nuclear explosion in shallow water are also examined. Scaling rules can be applied to relate smaller HE explosions to the nuclear explosions of interest to the CTBT. Additional hydroacoustic data from Russian nuclear underwater explosions are becoming available at time of writing, to be analyzed in a future work.

The modeling in the present work uses a numerical code known as REFMS (Britt et al., 1991; Britt, 1985; Britt, 1999 – personal communication) that models surface reflections, bottom reflections and refraction due to sound velocity gradients. Many of the measurements in the Russian experiments are predicted remarkably well, given that the REFMS code had been previously validated on the basis of U. S. data only. REFMS was also used here to simulate pressure-time histories and maximum peak pressures from 1-KT and 10-KT nuclear sources detonated in the ocean, using a realistic sound-velocity profile.

Data

Unique historical Russian data have become available recently, among them a variety of hydroacoustic measurements. These include data from 100-kg TNT explosions in a shallow reservoir, explosions of 136-kg bombs

in the deep waters of the Sea of Okhotsk, detonation of a 500-m long cord at depth 1 m in the Black Sea, and some underwater nuclear explosions in Novaya Zemlya. The focus here is on the comprehensive data set from the 100-kg TNT explosions in shallow water. Preliminary modeling of data from an underwater nuclear explosion is also discussed.

100-kg TNT Explosions in Shallow Water

Twenty nine explosion experiments were conducted in a shallow reservoir in the former Soviet Union (Kozachenko and Khristoforov, 1970; Korobeinikov and Khristoforov, 1976). The radius of the 100-kg TNT cast spherical charges was about 0.25 m. Charge depth varied from surface (0 m, or half-immersed) to 2.75 m (charge on the bottom) and water level from 0.25 m to 3 m. The bottom of the reservoir consisted of 1-m thick layer of air-saturated sand with a very low sound velocity of 270 m/s. Figure 1 schematically represents the dimensions of the reservoir and the experimental setup of the explosions.

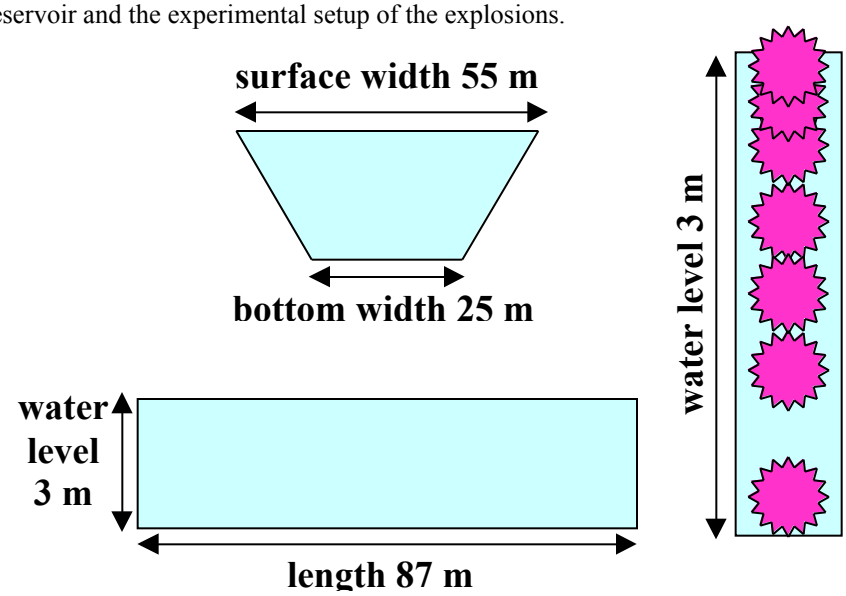


Figure 1. Schematic representation of the reservoir and the experiments with underwater explosions. Left – cross-sections of the reservoir (dimensions not to scale). Right - explosions were carried out featuring various combinations of water levels (0.25 m to 3 m) and charge depths (0 m to 2.75 m). Charge radius is 0.25 m.

Measurements from these explosions were made with piezoelectric gauges suspended at various distances (7.5 m to 30 m) and depths (0.25 m to 2.75 m) in the water. 26 digitized pressure records (pressure-time histories) from two fully immersed explosions (1-m charge depth, 3-m water level) and 14 such records from one half-immersed charge (0-m charge depth, 3-m water level) are now available. In addition, peak-pressure measurements are available from all 100-kg TNT explosions. Figure 2 below shows pressure-time histories from the fully immersed charges along with modeling results to be discussed in the next section. The available pressure-time histories from the half-immersed charges are shown in Eneva et al. (1999). The peak pressures measured at depth of 1.5 m from half-immersed charges are reduced by 60% at a distance of 15 m and 70% at 30 m by comparison with the fully immersed explosions. Peak pressures measured at sensor depth of 1.5 m (mid-pool) in this comparison can be assumed to be least affected by surface and bottom reflections.

Underwater Nuclear Explosion in Novaya Zemlya

Three underwater nuclear explosions were carried out in the Bay of Chernaya, Novaya Zemlya (70.70^{0}N, 54.67^{0}E) in the period 1955-1961 (*USSR Nuclear Weapons Tests and Peaceful Nuclear Explosions 1949 through 1990*, 1996). These explosions were conducted in shallow water, as the bottom in the Bay of Chernaya is 60 m to 100 m deep. The purpose was to test torpedo launches with various nuclear charges and to study their effects on military equipment, such as ships, submarines, and buildings on the coast.

The hydroacoustic data available at present consist of seven peak-pressure measurements (see Eneva et al., 1999) at a distance of 235 m from the second of the three underwater tests, conducted on October 10, 1957. The reported yield of this explosion is 10 KT, but the modeling performed below indicates a lower yield.

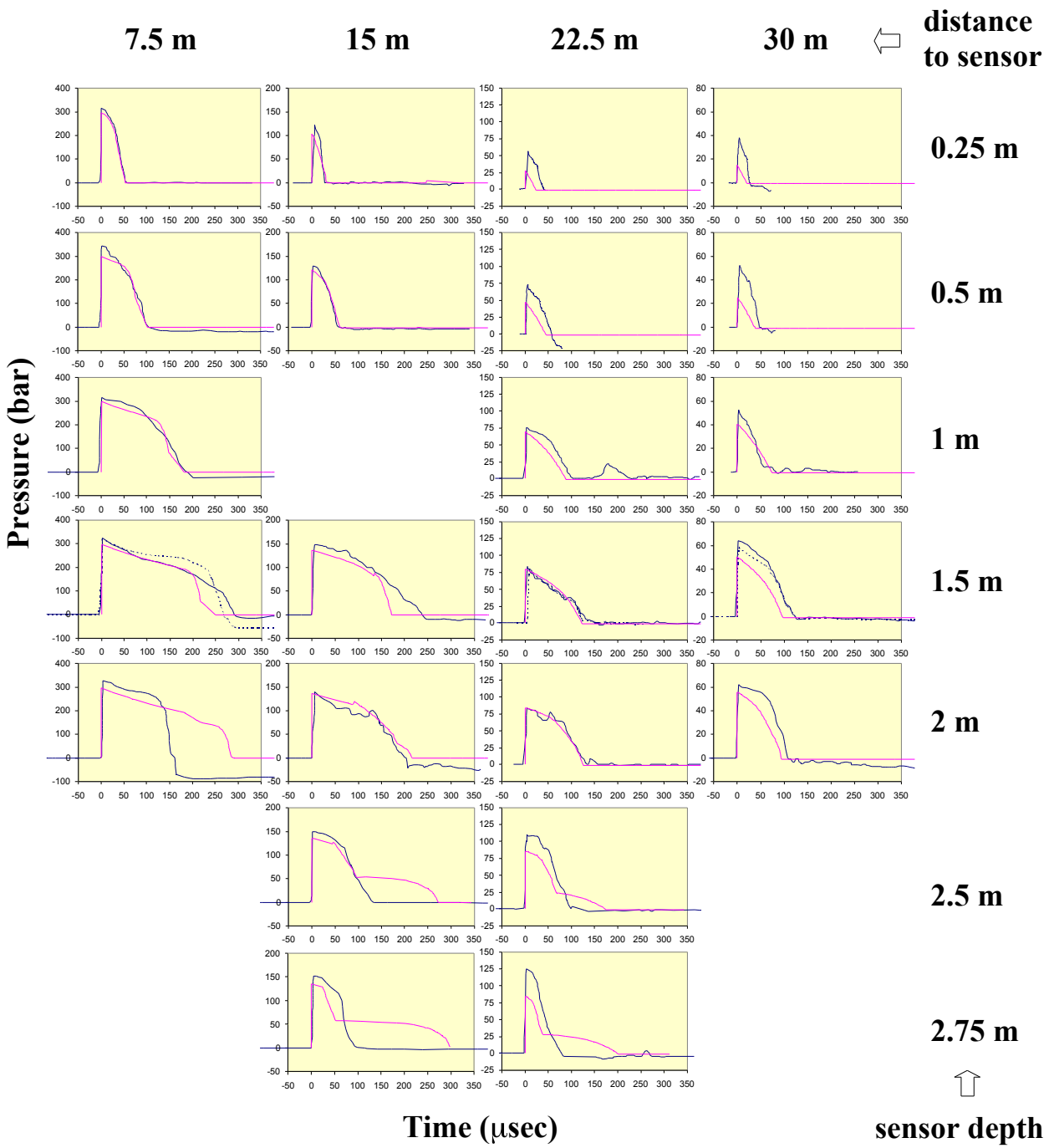


Figure 2. Observed and modeled pressure-time histories for fully immersed charges (charge depth 1 m, water level 3 m). Modeled – gray solid lines (red in color); observed – black solid lines (dark blue in color), with dashed lines indicating additional measurements at sensor depth 1.5 m.

The measurements were taken at various depths using up to six sensors at any given location. The observed peak pressure is between 300 and 320 bars, with one exception of a lower measurement (<260 bars) at 40-m depth. The pressure drop may be due to either a measurement error or a shadowing effect.

Modeling Results

The modeling of the shock waves in the present work was performed using one of the codes, Underwater_Shock, included in the so-called DNA (former Defense Nuclear Agency) Computational Aids (e.g., Stephens and Kelly, 1995). This particular computer program is a modified and simplified Windows version of the ray-tracing code, known as REFMS, that continues to undergo improvements (Britt et al., 1991; Britt, 1985; Britt, 1999 - personal communication). REFMS in turn is the newer version of a numerical code known originally as REFM (Reflection and Refraction in Multi-Layered Ocean/Ocean Bottoms).

REFMS is a computer program for predicting shock-wave parameters from underwater explosions. It includes major aspects of near-source wave propagation from underwater explosions, such as direct shock waves and in-water refraction and bottom and surface reflection. Of the reflected waves, the surface-reflected and the bottom-reflected waves are particularly important, with an effect comparable to and sometimes greater than that of the direct wave. In addition to the reflected waves, if gradients are present in the water sound velocity, the code also handles refraction calculated through the consideration of up to 150 discrete layers in the water and the bottom, each having a constant sound velocity and density. The computational tools in the REFMS modeling include two main features: (1) use of spherical wavefronts and (2) finite-element calculations taking into account deviations from acoustic propagation. The former is based on the acoustic spherical wave reflection theory formulated by Cagniard et al. (1962). The second feature is needed because finite-amplitude effects, not considered in the regular acoustic approximation, become increasingly important with increasing incident pressures and incidence angles (e.g., greater than 170 bars and 85^0, respectively).

The REFMS code has been extensively calibrated. The finite-amplitude surface reflection calculations have been validated with a series of HE experiments. Predictions were very good with the exception of some discrepancies at the shallowest gauges. In terms of refraction, the code is in good agreement with data from underwater nuclear explosion tests (Wigwam, Wahoo, Umbrella, and Swordfish), as well as from HE experimental series performed on a laboratory scale, in flooded quarries, and in the ocean (e.g., Britt e al., 1991; Brockhurst et al., 1961).

We used this code to calculate peak pressures and pressure-time histories. The term "pressure" in this context refers to overpressure (pressure above hydrostatic) as compared to the hydrostatic pressure at the points of observation (gauge, or sensor, locations). More details of the modeling are discussed by Eneva et al. (1999).

100-kg TNT Explosions in Shallow Water

Figure 2 shows the observed pressure-time histories from the explosions of fully immersed charges together with the predicted signals using the REFMS modeling. The modeling was done assuming a constant sound velocity in water of 1500 m/s (i.e., no velocity profile). All other parameters in the modeling matched exactly the configuration of the explosions (depth 1 m, water level 3 m) and the sensors (depth 0.25 m to 2.75 m, horizontal distance from explosion 7.5 m to 30 m), with one exception. Because of limitations of the used version of the code, the bottom layer of 1-m thickness could not be modeled with the original very low sound velocity (270 m/s). This low velocity was likely used so as to not destroy the reservoir in these experiments, and its effect on the measurements was comparable to that of the air above the water surface. The minimum allowed velocity in the modeling (1220 m/s), is higher than the original one, but it matches qualitatively the real low-velocity bottom (i.e., sound velocity in the bottom is lower than the sound velocity in the water). This is the likely cause of the discrepancies between predicted and observed signals at larger sensor depths in Figure 2 (e.g., see the pressure-time histories for sensor depths 2.5 m and 2.75 m at distances 15 m and 22.5 m, and sensor depth 2 m at distance 7.5 m). As to the discrepancies seen at smaller sensor depths (0.25 m and 0.5 m) at larger distances (22.5 m and 30 m), they may be due to an "overinterpretation" of the nonregular surface reflection, with the observations not supporting the predicted spatial extent of such a region in this case. With the above exceptions, the predicted signals in Figure 2 match the observed ones very well, even in what can be considered as essentially the source region of the explosions (at small distances of 7.5 m and sensor depths smaller than 2 m). Predictions are also very good for larger distances at intermediate sensor depths.

Half-immersed explosions are much more difficult to model and larger discrepancies are to be expected. Model parameters in this case followed the test configuration in the same manner as for the fully immersed explosions above, with one additional exception. Charge depth could not be put at 0 m, but a depth of 3 cm was used instead, as the minimum allowed by this version of the code. It is assumed that no significant problems are caused by this discrepancy. Given the difficulty of modeling surface explosions, good agreement between observed and predicted pressure-time histories was obtained in this case as well (see Eneva et al., 1999), although inferior to the modeling of pressure-time histories from the fully-immersed charges. Figure 3 depicts the observed and the predicted relationship between peak pressures and sensor depth for the surface explosion. For sensor depths close to the surface, the modeling probably exaggerates the effect of nonregular reflection and the predicted peak pressures underestimate the observations. The mismatch between the real and model sound velocities in the bottom apparently cause discrepancy at larger sensor depths closer to the source (15 m), but not further (30 m). Model predictions, however, are satisfactory around intermediate sensor depths for both distances. Of the peak pressure measurements available from the 100-kg TNT explosion tests, we further show observed and predicted values for the 11 explosions conducted in the reservoir with water level of 3 m. The effect of explosion depth is depicted in Figure 4 for a fixed sensor depth of 1.5 m. Agreement is very good except for two measurements of explosions on the reservoir bottom.

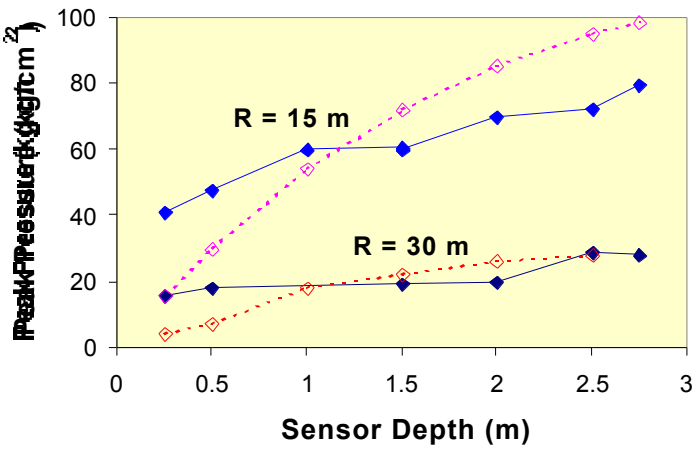


Figure 3. Observed and modeled peak pressures for a half-immersed charge (explosion depth = 0 m), water level 3 m. Measured – solid lines and filled symbols, modeled – dashed lines and empty symbols. Horizontal distance to sensor, as indicated (15 and 30 m).

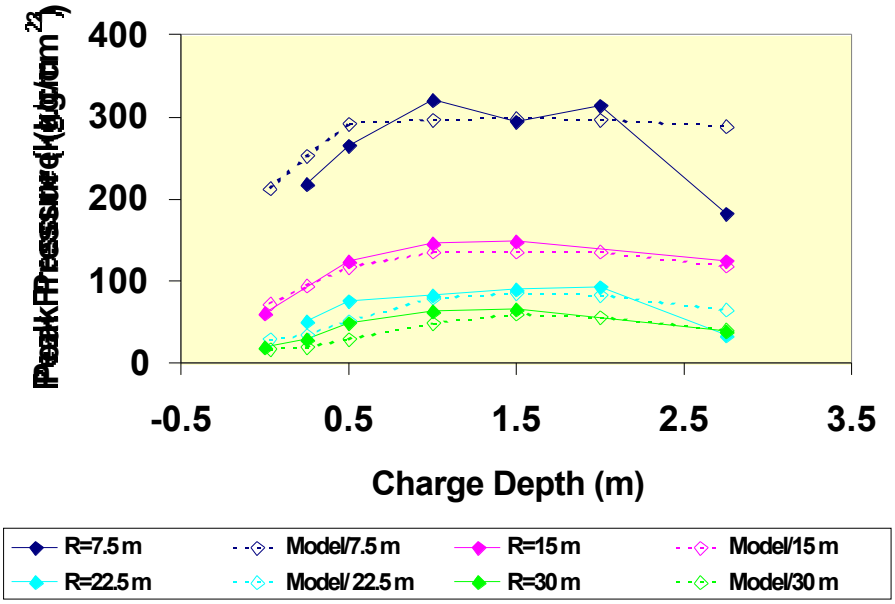


Figure 4. Example of effect of charge depth on peak pressure measured at sensor depth 1.5 m. Observed peak pressures − bold lines and filled symbols; modeled peak pressures − dashed lines and empty symbols. From top to bottom – horizontal ranges 7.5 m, 15 m, 22.5 m, and 30 m, as indicated in legend.

Underwater Nuclear Explosion in the Bay of Chernaya

REFMS was used to model the seven peak-pressure measurements at 235 m from the 1957 underwater nuclear explosion in Novaya Zemlya. The test was conducted in shallow water, with the bottom not deeper than 60 m. No other bottom specifications or sound velocity profile in the water are available at this time. Thus, a constant sound velocity in water (1500 m/s) was used in the modeling, while various reasonable bottom velocities and densities, different yields and variable explosion depths were tried. This limited modeling revealed that the yield of the explosion was probably not much larger than 5 KT and its depth was around 30 m to 40 m. This yield estimate is smaller than the reported yield of 10 KT (*USSR Nuclear Weapons Tests and Peaceful Nuclear Explosions 1949 through 1990*, 1996).

The lower yield estimate above is further confirmed by the similarity between the peak-pressure measurements at 235 m from the 1957 nuclear explosion and the 100-kg TNT at a distance of 7.5 m (Figure 2), which are between 300 and 350 bars in both cases, regardless of sensor depth. Thus a scaling factor of about 235/7.5=31.33 may be applicable, which leads to 100 kg X 31.33^3=3.08 KT TNT-equivalent when the cube-root scaling rule is applied. Taking into account the difference between HE and nuclear sources, the yield estimate becomes 3.08/0.667= 4.62 KT.

Simulated 10-KT Underwater Nuclear Explosion

We would like to use the data and the available modeling capabilities to predict the variations in the hydroacoustic signals that would be observed at the IMS stations. These might differ from peak-pressure measurements in the strong-shock regime in the near field. In the absence of any more detailed observations from real underwater nuclear explosions, modeling results were obtained for the realistic case of a 10-KT yield detonated in an ocean with a velocity profile modeled with 29 different layers, as shown in Figure 5. This profile (Stevens et al, 1999) features a minimum velocity at a depth of 700 m, consistent with the SOFAR channel in the ocean. An additional layer was used to model the bottom, starting at 3350-m depth, with sound velocity 6100 m/s, density 2750 kg/m^3, and thickness 10,000 m. Pressure-time histories were calculated at a hypothetical depth of 700 m (i.e., in the SOFAR channel) and a 10 km distance from the explosion. This distance is outside the nonlinear region and expected to be a reasonable approximation to the signal that would propagate further with low at-

tenuation to the IMS stations. Figure 5 shows examples of the modeled pressure-time histories for two different explosion depths.

More examples of modeled peak-pressure histories are shown by Eneva et al. (1999). The results from this modeling showed that peak pressures increase up to ten-fold between explosion depths 3 m and 800 m, after which they slowly decrease. Thus the predicted features are consistent with channeling expected in the SOFAR channel (the largest peak-pressures are calculated for explosion depths of 700-800 m). In addition, it was demonstrated (Eneva et al., 1999) that in the presence of realistic sound-velocity profiles, changes in peak pressures with explosion depth may be quite complex (see Figure 6 below).

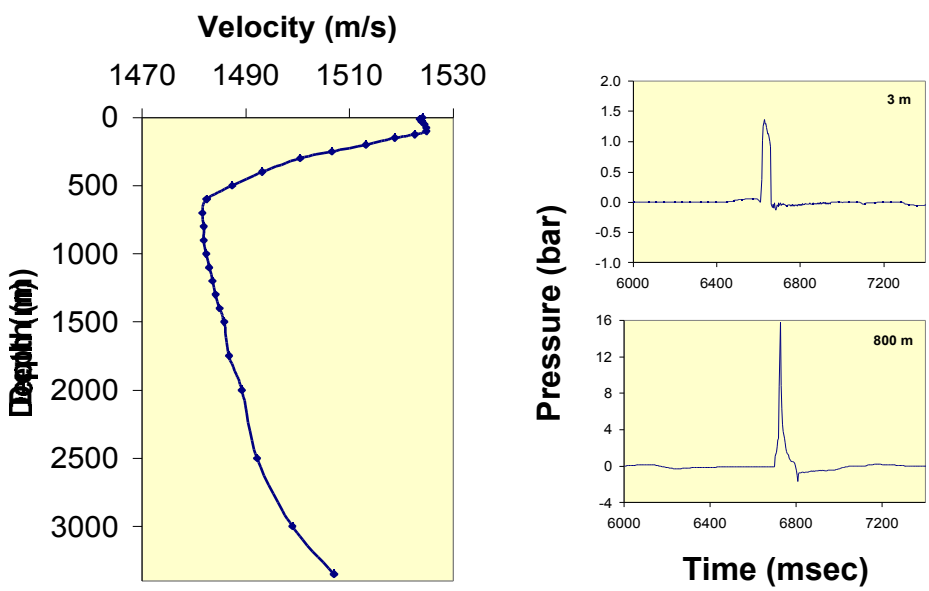


Figure 5. REFMS simulation of a 10-KT nuclear explosion. Left – sound velocity profile used in the simulations. Right – examples of pressure-time histories for two different explosion depths (3 m and 800 m).

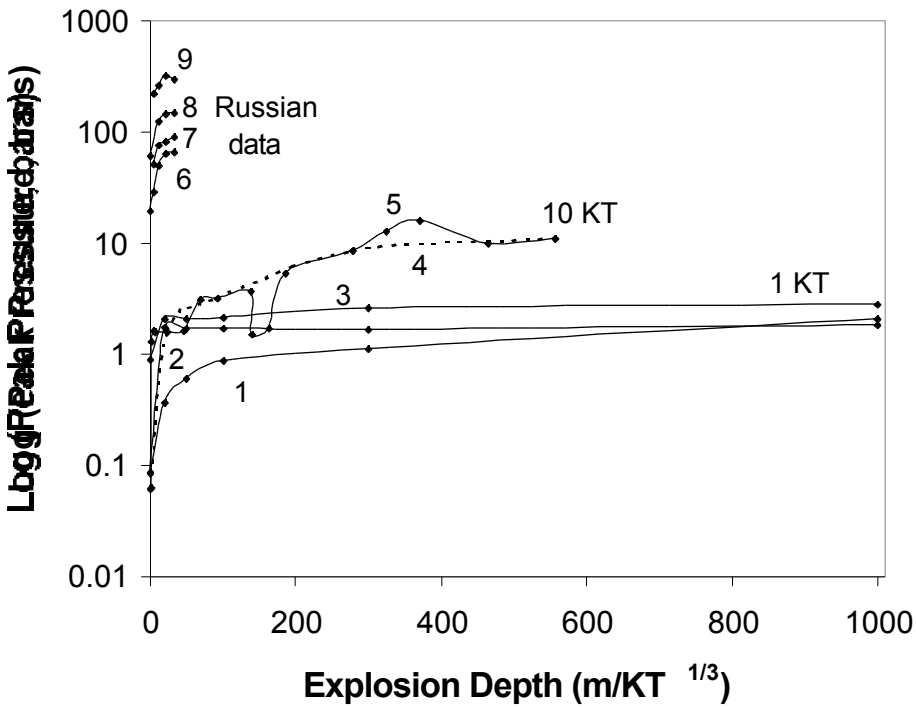
Discussion

The relevance of the Russian small-scale experiments to larger explosions can be determined on the basis of commonly used scaling relationships, relating distances and times with the cube root of the yield (Cole, 1948). That is, the peak-pressure measurements at a distance of 30 m from a 100-kg TNT charge detonated at 1 m depth in a 3 m deep reservoir should be comparable, for example, with measurements (1) at a distance of 646 m from a 1-KT TNT explosion at 22 m depth above a 65 m deep bottom, (2) at a distance of 1400 m from a 10-KT TNT explosion at 46 m depth above a 140 m deep bottom, or (3) at a distance of 30 km from a 100-KT TNT explosion at 1000 m depth above a 3000 m deep bottom. Factors of 21.5 = $(1\ KT/100\ kg)^{1/3}$, 46.4 = $(10\ KT/100\ kg)^{1/3}$, and 1000 = $(100\ KT/100\ kg)^{1/3}$ respectively, are used in this comparison. The scaling in (3) above is the only one somewhat approximating the ocean environment; however, the sound velocity in water was constant in the reservoir, unlike the real sound-velocity profiles in the ocean.

We would further like to compare the Russian observations, REFMS modeling results obtained here, and LLNL modeling results reported by Clarke et al. (1995). Direct comparison is not possible, because the Russian measurements were taken at much smaller scaled distances (160 $m/KT^{1/3}$ to 646 $m/KT^{1/3}$) than the distance in the LLNL modeling (10,000 $m/KT^{1/3}$). This was dictated by the limited dimensions of the reservoir. The difference between homogeneous and refractive water is another complication. However, some general conclusions can be still drawn. In their modeling of a 5000-m deep ocean with a mid-latitude sound velocity profile, without incorporating bottom interactions, Clarke et al. (1995) combined two numerical codes. The first code, CALE, is a LLNL hydrodynamic code used for the strong-shock calculations. The second code, NPE, is a Naval Research

Laboratory (NRL) code used to model weak-shock propagation. The coupling factor was estimated by calculating the energy of the shock waves at a 10-km range from a 1-KT nuclear source for a variety of explosion depths below the ocean surface (0 m to 1000 m) and heights above it. In particular, the total acoustic energy at 10 km range from a fully-coupled reference explosion with depth 1000 m was calculated to be 31.3 T, while for explosions at depths 20 m and 0 m (on the surface), this energy is 2.1 T and 174 kg, respectively. We can then deduce that the energy coupling ratios in the LLNL simulations are about 1:14 for a 20-m explosion depth and 1:180 for a surface explosion and thus the total wave energy from the 1-KT shallow bursts at these depths should be equivalent to that of about 71.4 T and 5.6 T TNT, respectively, detonated at 1000 m depth. In view of this, since even kilogram-size HE explosions can be detected under the right conditions, the LLNL modeling shows that the IMS hydroacoustic network should not miss 1-KT explosions detonated at any depth in the ocean, including on the surface.

Figure 6. Summary of observed and simulated peak pressures. 1 - LLNL simulation of a 1-KT nuclear source, scaled distance 10,000 m/KT$^{1/3}$, mid-latitude sound-velocity profile. 2 and 3 - REFMS simulations, scaled distance 10,000 m/ KT$^{1/3}$, sound velocity profile shown in Figure 5: 2 – 1-KT nuclear source; 3 – 1-KT TNT source. 4 and 5 – 10-KT nuclear source, scaled distance 4,640 m/KT$^{1/3}$, sound velocity profile shown in Figure 7: 4 – smooth (dashed line); 5 – detailed (solid line). 6 to 9 – largest observed peak pressures (at sensor depth of 1.5 m) from the Russian experiments, explosion depths $\leq$ 32 m/KT$^{1/3}$ (1.5 m), at the following scaled distances:



6 – 646m/ KT$^{1/3}$ (30 m); 7 – 485 m/KT$^{1/3}$ (22.5 m); 8 – 323 m/KT$^{1/3}$ (15 m); 9 – 162 m/KT$^{1/3}$ (7.5 m).

To compare with Clarke et al.'s simulations, we performed REFMS modeling of a 1-KT explosion using the sound-velocity profile shown earlier in Figure 5. To address the possible difference in the way coupling of energy to water changes with depth for HE and nuclear explosions, 1-KT nuclear and 1-KT TNT sources were modeled. The REFMS predictions in both cases (HE and nuclear) were calculated for explosions with varying charge depth, at 10 km distance and 700 m depth. The explosion depths in these REFMS simulations matched those used by Clarke et al. (1995). Figure 6 shows the peak-pressure predictions from the LLNL (Clarke et al., 1995) and REFMS modeling of 1-KT explosions, together with the previously performed modeling of 10 KT and the most representative Russian observations in this context.

The Russian data appear in a separate cluster in Figure 6 as they represent measurements much closer to the source, for much shallower explosion depths. The REFMS predictions for a 1-KT nuclear source match the LLNL modeling for surface (0 m) and deep explosions (1000 m) quite well; about 95% decrease with depth is

found in both cases. However, the REFMS change is much steeper for subsurface explosion depths. That is, in the REFMS modeling of the nuclear source, full coupling is approached much faster than in the LLNL modeling. Otherwise, the 1-KT TNT REFMS predictions remain above the predictions for the nuclear source by a factor of 0.667, as expected (Cole, 1948). The REFMS predicted change in peak pressure is much smaller for the HE source (67.5%) than for the nuclear source (95%), when explosion depths of 0 m and 1000 m are compared. In addition, the change in the HE case is more gradual. In fact, the rate of change in coupling for shallow explosion depths suggested by the LLNL modeling is closer to the REFMS curve for the 1-KT TNT than to the REFMS curve for the nuclear source. Although our sound-velocity profile may be somewhat different from the profile used by Clarke et al. (1995), the discrepancies are more likely due to differences in the modeling than to differences in the water profiles.

The 10-KT predicted values in Figure 6 are shown in two versions – a smooth curve using only calculations for explosion depths similar to the ones used by Clarke et al. (1995) and higher-resolution predictions including calculations at more explosion depths (Eneva et al., 1999). It is obvious that changes in coupling as explosions approach the ocean surface may be much more complicated than a smooth decrease.

Figure 7 illustrates the shallow depths, showing together the 1-KT predictions, the observations in the shallow reservoir at a sensor depth of 1.5 m, and averaged data from the 1957 underwater nuclear explosion.

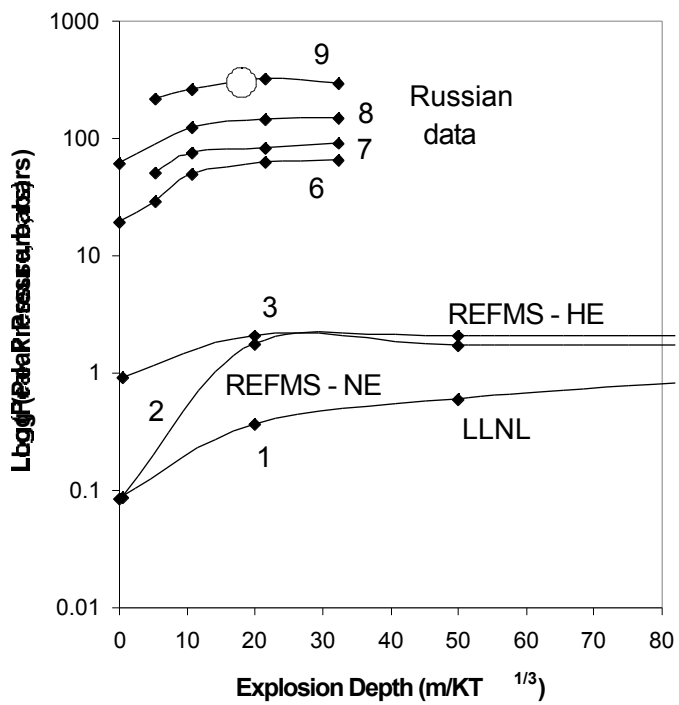


Figure 7. Russian observations and 1-KT simulations from Figure 6, with focus on small explosion depths. Circle shows the peak pressure averaged over various sensor depths (300 bars) measured at 235-m distance from the 1957 underwater nuclear explosion. A yield in the range 3 KT to 6 KT translates into a scaled distance of 160 m/KT$^{1/3}$ to 130 m/KT$^{1/3}$ (see text for details). This fits well the scaled range of 162 m/KT$^{1/3}$ (real distance 7.5 m) for curve 9 of the small-scale observations, on which the circle falls.

The scaled distance for the nuclear explosion in Figure 7 is between 130 and 160 m/KT$^{1/3}$, if an yield between 3 KT and 6 KT is assumed. The rates of change in the small-scale observations agree very well with the rates in the REFMS predictions of the HE source and some of the estimates in the LLNL modeling. As an example, there is 58.6% (at a distance of 15 m) to 71% (at 30 m) decrease in observed peak pressures when explosions on the surface are compared with explosions at mid-pool depths (e.g., 1.5 m), for which the largest peak pressures were measured in the Russian experiments. This matches very well the 67.5% decrease predicted by REFMS for the 1-KT TNT explosion when an explosion on the surface is compared with an explosion at 1000 m depth,

and is predictably smaller than the 95% decrease for the nuclear sources in both the REFMS and the LLNL modeling.

CONCLUSIONS AND RECOMMENDATIONS

The REFMS modeling performed in this work made it possible to make detailed predictions directly relevant to the experimental setup of the Russian tests. The good agreement between predictions and measurements provides a further validation of the REFMS code, previously performed only with U. S. data. Given the inherent limitations of comparing near-field measurements with far-field simulations, and the additional shortcomings of comparing homogeneous, but severely bounded water, with sound-velocity profiles characteristic for the real ocean, the above results and discussion lead us to conclude that a reasonable agreement exists between the Russian observations and both the REFMS and the LLNL predictions. Thus the reservoir experiments and the REFMS modeling performed here can be considered as an additional confirmation that a 1-KT TNT explosion detonated at any depth in the ocean will be detected by the existing IMS network. Further work is needed to address in more detail the relevance of small-scale HE tests in the study of energy decoupling from underwater nuclear explosions.

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REFERENCES

Britt, J.R., Application of Cagniard theory to reflection and refraction of explosion shock waves in soil and water, in *Proceedings II 9-th Int. Symposium on Military Applications of Blast Simulations, Oxford, England, 23-27 September 1985*, 1985.

Britt, J.R., R.J. Eubanks, and M.G. Lumsden, *Underwater Shock Wave Reflection and Refraction in Deep and Shallow Water. Volume I – A User's Manual for the REFMS Code (Version 4.0)*, SAIC (Science Application International Corporation), DNA-TR-91-15-VI, June 1991 (U).

Brockhurst, R.R., J. Bruce, and A.B. Arons, Refraction of underwater explosion shock waves by a strong velocity gradient, *J. Acoust. Soc. Am.* **33**, 452-456, 1961.

Cagniard, L., E.A. Flinn, and C.H. Dix, *Reflection and Refraction of Progressive Seismic Waves*, McGraw-Hill, New York, 1962.

Clarke, D.B., J.W. White, and D.B. Harris, *Hydroacoustic Coupling Calculations for Underwater and Near-Surface Explosions*, Lawrence Livermore National Laboratory, UCRL-ID-122098, 1995.

Cole, R.H., *Underwater Explosions*, Princeton University Press, Princeton, New Jersey, 1948.

Eneva, M., J.L. Stevens, B.D. Khristoforov, J. Murphy, and V.V. Adushkin, Analysis of Russian hydroacoustic data for CTBT verification, submitted to *Pure Appl. Geophys.*, 1999.

Korobeinikov, V.P. and B.D. Khristoforov, Underwater explosions, *Hydromechanics* **9**, 54-119, 1976 [in Russian].

Kozachenko, L.S. and B.D. Khristoforov, Shock waves in a shallow-water reservoir, *J. Appl. Mech. Tech. Phys.* **4**, 166-171, 1970 [in Russian].

Stephens, T. and C.S. Kelly, DNA updates Computational Aids, *Science & Technology Digest*, September, 29-30, 1995.

Stevens, J.L., G.E. Baker, R.W. Cook, G. D'Spain, L.P. Berger, and S.M. Day, Empirical and numerical modeling of T-phase propagation from ocean to land, submitted to *Pure Appl. Geophys.*, 1999.

USSR Nuclear Weapons Tests and Peaceful Nuclear Explosions 1949 through 1990, Ministry of the Russian Federation for Atomic Energy, ISBN 5-85165-062-1, pp. 63, 1996.