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DIRECTION AND LOCATION OF ARTILLERY ROCKETS BY ACOUSTIC TECHNIQUES

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APRIL 1991

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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13. ABSTRACT (*Maximum 200 words*)

This report discusses possible approaches to the detection and location of artillery rockets by acoustic techniques. The acoustic signal is composed of rocket motor initiation noise, motor burning noise, and ballistic wave noise. An acoustic model is applied to some test results. Distant detection of launched artillery rockets was found to be possible under conditions of low ambient noise. The location accuracy depends on the distance between the source and detector, as well as on the meteorological conditions. In locating the launch point, one must be able to distinguish between the rocket motor initiation noise from the launch point and the ballistic wave noise produced by the rocket in flight. Methods to improve the accuracy of location are suggested.

Projections made for a foreign artillery rocket (140-mm, 3,500-lb thrust motor) show that detection in calm weather is possible to a range of 10 km from the launch point. Beyond 4 km, improved acoustic techniques are needed for locating the launch pont with an error less than 200 m. Seismic and other related signals generated near launch should be investigated for use as a complementary tool to improve location accuracy.

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FOREWORD

Mr. Thompson died suddenly in 1970 with this report nearly completed. Shortly thereafter, SFC Scherer separated from the Army. The manuscript was gradually forgotten until rediscovered in a cleanup in 1988. The subject of acoustic location is of ongoing interest to the Army (see Field Artillery Sound Ranging, FM6-122, December 1983).

Acoustics research at Aberdeen Proving Ground no longer includes location and ranging projects to the editor's knowledge. The topics are vehicle acoustic signatures, muzzle blast, noise relation to troop safety, and especially community (upper Chesapeake Bay) noise exposure. The forward detectors the author speculated on for accurate location of artillery are not in use; but unattended sound level recorders are in routine use by Range Control, Combat Systems Test Activity for noise monitoring.

An acoustic focusing model is run at BRL for predicting noise levels at a location where damage claims were made against the Army.

There is independent reason to suppose that accurate acoustic location of artillery may be possible. Naturalists' studies of nocturnal predators (barn owls) show that the predator depends on listening to locate and strike its prey.

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ACKNOWLEDGMENTS

We would like to thank Mr. John Keefer and Mr. Noel Ethridge of Aberdeen Research Associates, Aberdeen, MD, for reviewing this report.

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1. INTRODUCTION

The Ballistic Research Laboratory (BRL) was requested to investigate the problem of detecting and locating certain foreign tactical artillery rockets by acoustic techniques. The rockets of interest include 107-mm, 122-mm, and 140-mm projectiles. The Soviet 140-mm artillery rocket (Model M-14-OF) is shown in Figure 1a. The 122-mm, single tube, "6-ft" rocket is shown in Figure 1b. The Chinese 107-mm, Type 63 rocket is shown in Figure 1c.

Research at BRL has produced models for predicting the field propagated by a variety of stationary and moving sources of acoustic energy. This report gives the model prediction of noise around the Chesapeake Bay from the largest rocket. This example should provide some indication of from where and how well the launch position of these rockets can be located by acoustic techniques.

2. THEORY

2.1 Prediction Models. Many theoretical and empirical assumptions were required to make a mathematical model which could be solved for particular applications. A part of the BRL model is based on the acoustic wave equation (the ray physics, high frequency approximation in particular). This is complemented by semiempirical relationships in areas where the wave equation or its approximation are difficult to apply. The appropriate equations of ray physics are used for calculating the position, density, and time sequence of acoustic rays in the layered atmosphere, while semiempirical relationships are used for intensity predictions that depend on both the source and atmospheric absorption characteristics. In general, we employ more than one method for intensity spectrum predictions to allow comparison between results obtained using different assumptions. A brief description of semiempirical relationships used with the acoustic ray physics approximation is given in the Appendix. Further details on the theory and application can be found in Thompson (1968); Lassiter and Heitkotter (1954); Mayes, Lanford, and Hubbard (1959); and Humphrey (1957).

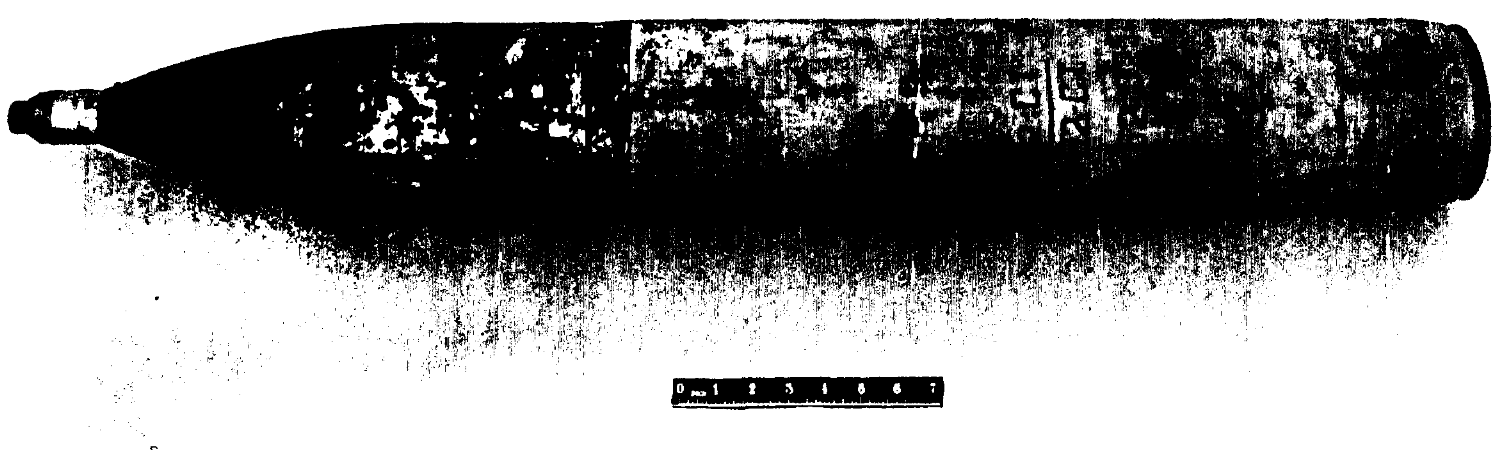

Figure 1a. 140-mm Artillery Projectile.

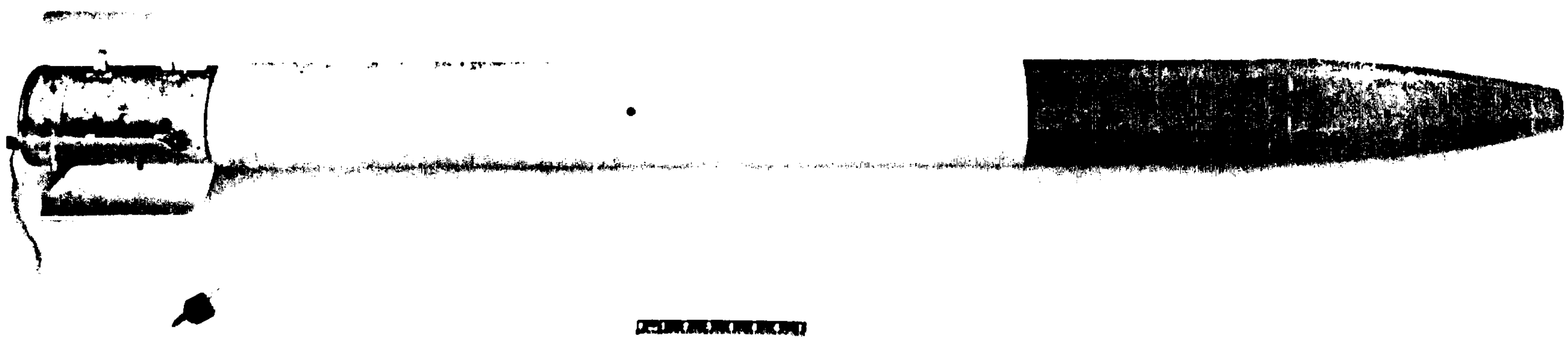

Figure 1b. 122-mm Artillery Projectile.

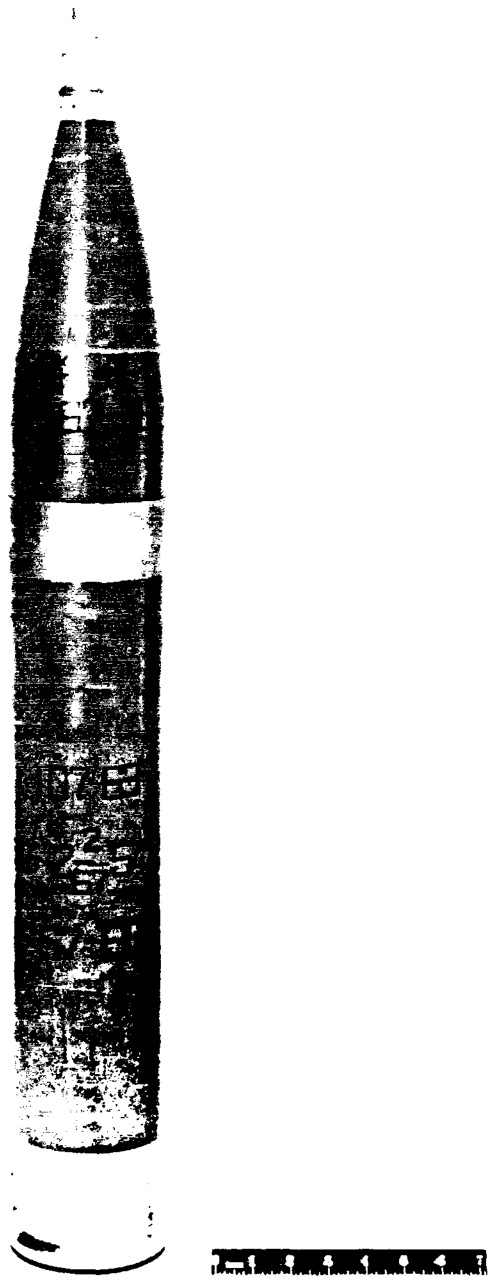

Figure 1c. 107-mm Artillery Projectile.

2.2 Detectability of Rockets. Since the rocket motor noise and possibly the motor initiation or cutoff sounds are the most consistently available signals for launch point location within a range of 10 km, these signals are predicted down to a magnitude of 50 dB. Below this level, ambient noise makes detection difficult.

The rocket motor initiation signal, which contains frequencies below 50 Hz, should be more detectable at the greater distances than the rocket motor noise. In addition to experiencing less attenuation, these lower frequencies are not as readily refracted away from the ground by a negative sonic gradient.

The ballistic wave signal, caused by the shock in front of a supersonic missile, is detectable the farthest, depending on circumstances of missile trajectory and meteorological conditions.

These three rocket signal categories (initiation, motor, and ballistic) can be identified through the use of a spectrogram showing the amplitude spectrum vs. time.

2.3 Location Techniques. In order to locate the launch position of artillery rockets, we can use one or both of the following techniques:

(1) Measure the arrival time of the same part of the signal at three or more positions. With this information, techniques (Dobrin 1976 and Small 1953) are available which can be used for locating the origin of the signals.

(2) Determine two or more azimuths along which the signal is propagating. With this information, the origin can be located.

For applying the first technique, a fast initial rise time of the acoustic signal is desirable to facilitate measurement of the same part of the signal at all stations. A detectable rocket motor initiation signal would permit use of the arrival time technique, provided that it could be distinguished from the (sometimes present) ballistic wave signal.

The second technique is described in sound ranging literature (Fox 1967a; Fox 1967b; Bellucci 1966; Barichivich 1966; and Nordquist 1967). For applying the second technique, each detection station must have a small array of sensors arranged so that their outputs can be correlated to determine the direction of propagation of a signal across the array.

Ballistic wave signals could be detected by certain station arrays, and continuous rocket motor noise (or motor initiation signals) could be detected by other arrays. A small sensor array has been suggested to determine azimuths of acoustic propagation, since it has been proven successful. Other methods of determining azimuth should also be considered, such as the use of vector particle velocities and pressures measured together. Vector particle velocity measurements have recently become more feasible.

From the above discussion, we can see that a practical technique for location depends on the nature and detectability of the signal. Whether either technique can be employed must be determined from feasibility tests designed from prediction models such as those of Thompson (1968).

The accuracy of launch point location for the first (arrival time) technique would depend on (a) the precision of the arrival time of the phase-correlated signal measured at the stations, (b) how well the sonic velocities between the source and the different stations are known (this factor becomes significant at detector distances greater than 2 km), and (c) the distances between the stations and the source. The accuracy obtained using the second (azimuth) technique would depend mostly on the precision of the measured angles and the source-detector distances.

3. PROCEDURE

Predictions in this report are presented for a solid fuel rocket similar to the foreign 140-mm artillery rocket mortar (Model M-14-OF; Figure 1a). Both spectral and peak intensities were estimated at distances considered reasonable for field location of the launch point.

A static test was assumed in a homogeneous atmosphere for the initial predictions. The results obtained under this assumption provided some basic understanding of the propagation of rocket motor initiation signal and the rocket motor noise without the complications of weather and flight path. Since some acoustic measurements were taken by the Air Force (Wathen-Dunn, unpublished) at about 100 m from this foreign rocket fired near Edgewood Arsenal, MD, this measured spectrum was projected to greater distances using the BRL model, then compared with the predictions for the U.S. solid fuel rocket having similar characteristics.

For dynamic test predictions, a set of meteorological parameters (with temperature inversion) is specified, since winds and temperature should be considered in an accurate source-locating technique. For discussion purposes, the meteorological condition existing on 26 October 1964 at Aberdeen Proving Ground, MD, was selected. This condition corresponds to that existing for Case 2 in BRL-MR-1930.

Predictions for dynamic tests are given as maximum surface intensity levels for both the rocket motor noise and ballistic energy signals. Although the directional ballistic energy signal can be detected at greater distances along the surface under selected conditions, the rocket motor initiation and rocket motor burning signals can be detected under most prevailing conditions and in most directions.

With the above prediction estimates under the specified conditions, some results and conclusions are given about detection and location of this type of rocket. In discussing the results, both the arrival time and azimuth techniques for launch point location are considered.

4. RESULTS

Figure 2 shows intensity spectra (decibels of sound vs. frequency) predicted at three distances on the surface in a homogeneous atmosphere from a statically fired U.S. solid fuel rocket similar in size and thrust to the foreign 140-mm rocket.

Figure 3 shows the predicted peak intensity vs. distance curve (solid line) for the U.S. rocket. Also shown in Figure 3 (dashed line) is the intensity vs. distance curve produced by spherical divergence of the wave front alone, i.e., no atmosphere frequency absorption.

Figure 4 shows a comparison of the 10-km spectrum in Figure 2 with a 10-km spectrum deduced from Air Force measurements made 100 m from the foreign artillery rocket when it was launched at Edgewood Arsenal (Wathen-Dunn, unpublished).

Figure 5 shows the weather conditions chosen for the dynamic noise predictions.

Figure 6 shows the maximum surface signal intensity contours predicted for the foreign solid fuel rocket motor if it were launched easterly over the Chesapeake Bay under the weather conditions shown in Figure 5.

Figure 7 shows the maximum ballistic wave signal intensities that occasionally can reach the surface if the 140-mm rocket is fired at an azimuth of 89°, at a low angle (3°) under the weather conditions in Figure 5. It should be emphasized that Figure 7 shows only ballistic wave signals coming from the rocket. All the other figures show only the rocket motor initiation and burning signals.

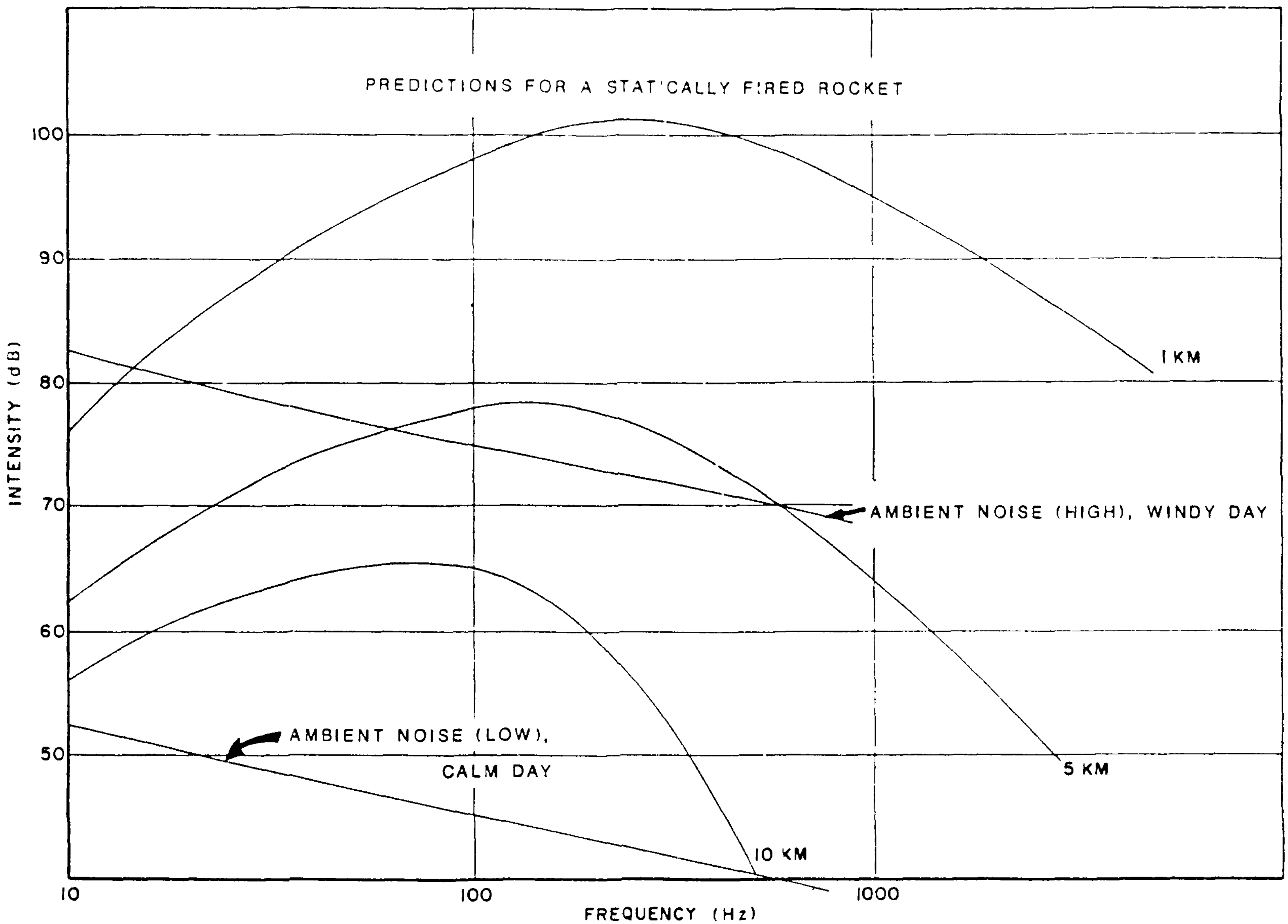

Figure 2. Amplitude Spectra From Solid Fuel Rocket (3,500-lb Thrust).

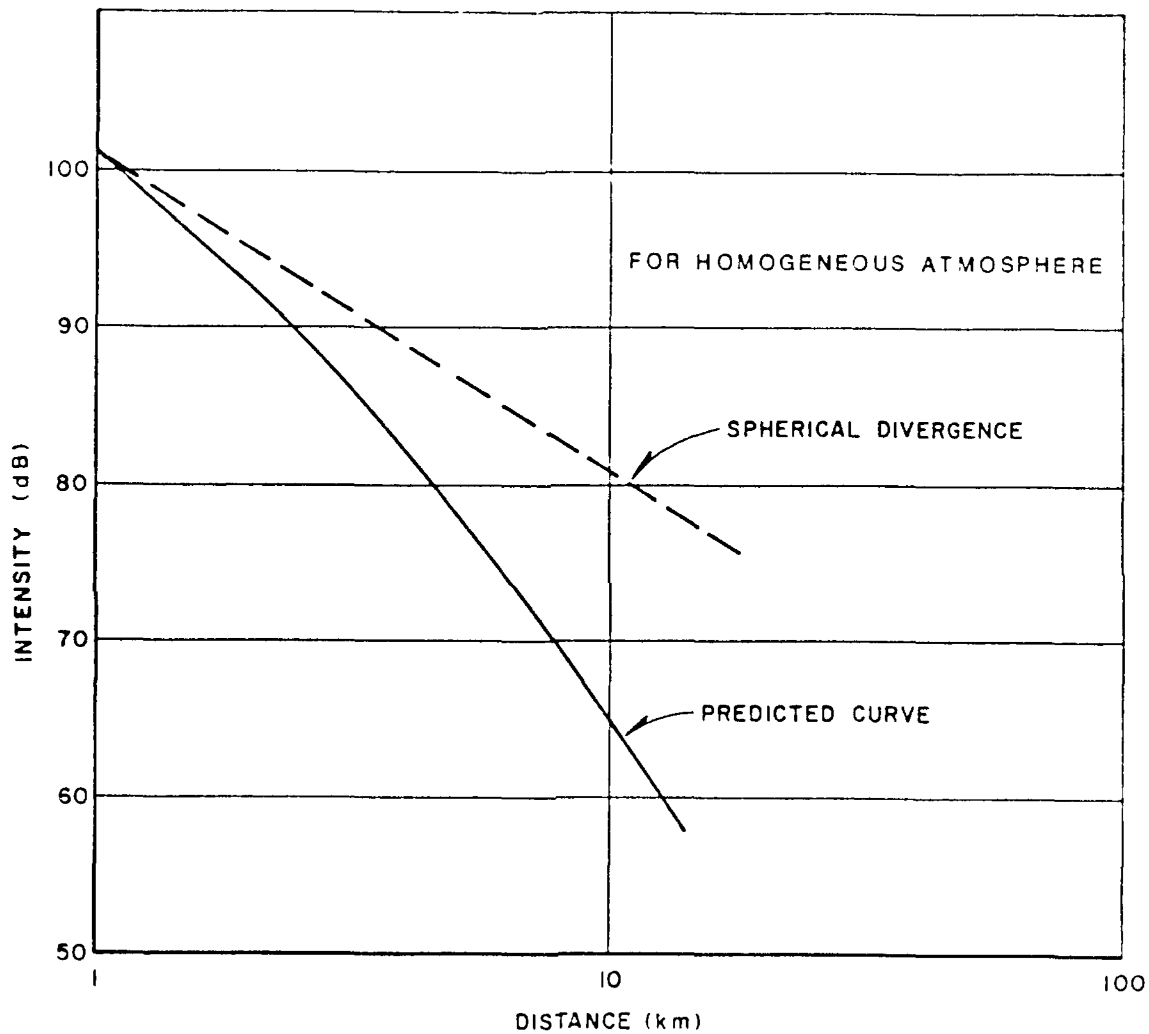

Figure 3. Intensity vs. Distance Curve for Solid Fuel Rocket (3,500-lb Thrust).

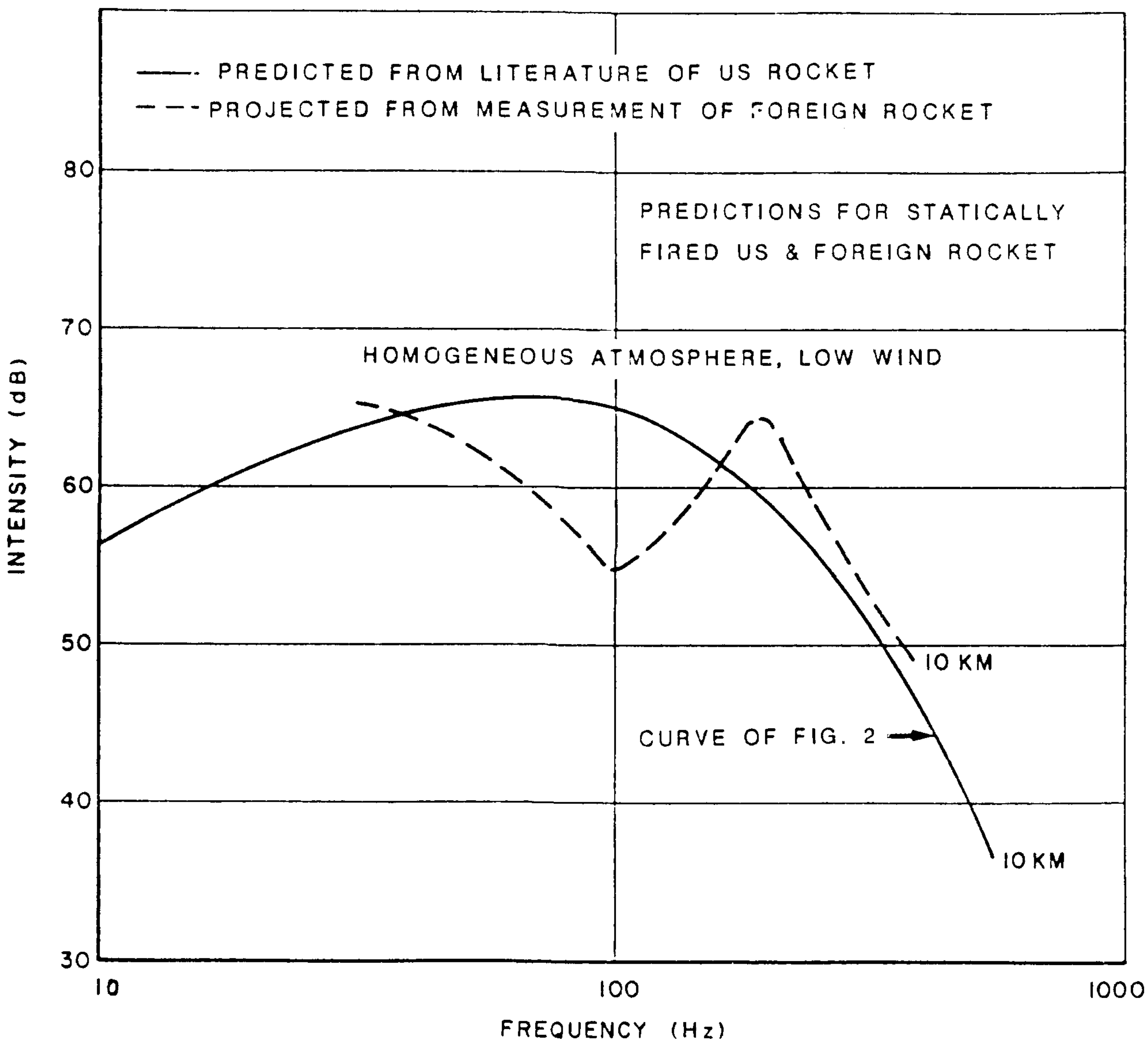

Figure 4. Comparison of 10-km Amplitude Spectrum With Amplitude Spectrum Measured at 100 m and Projected to 10 km.

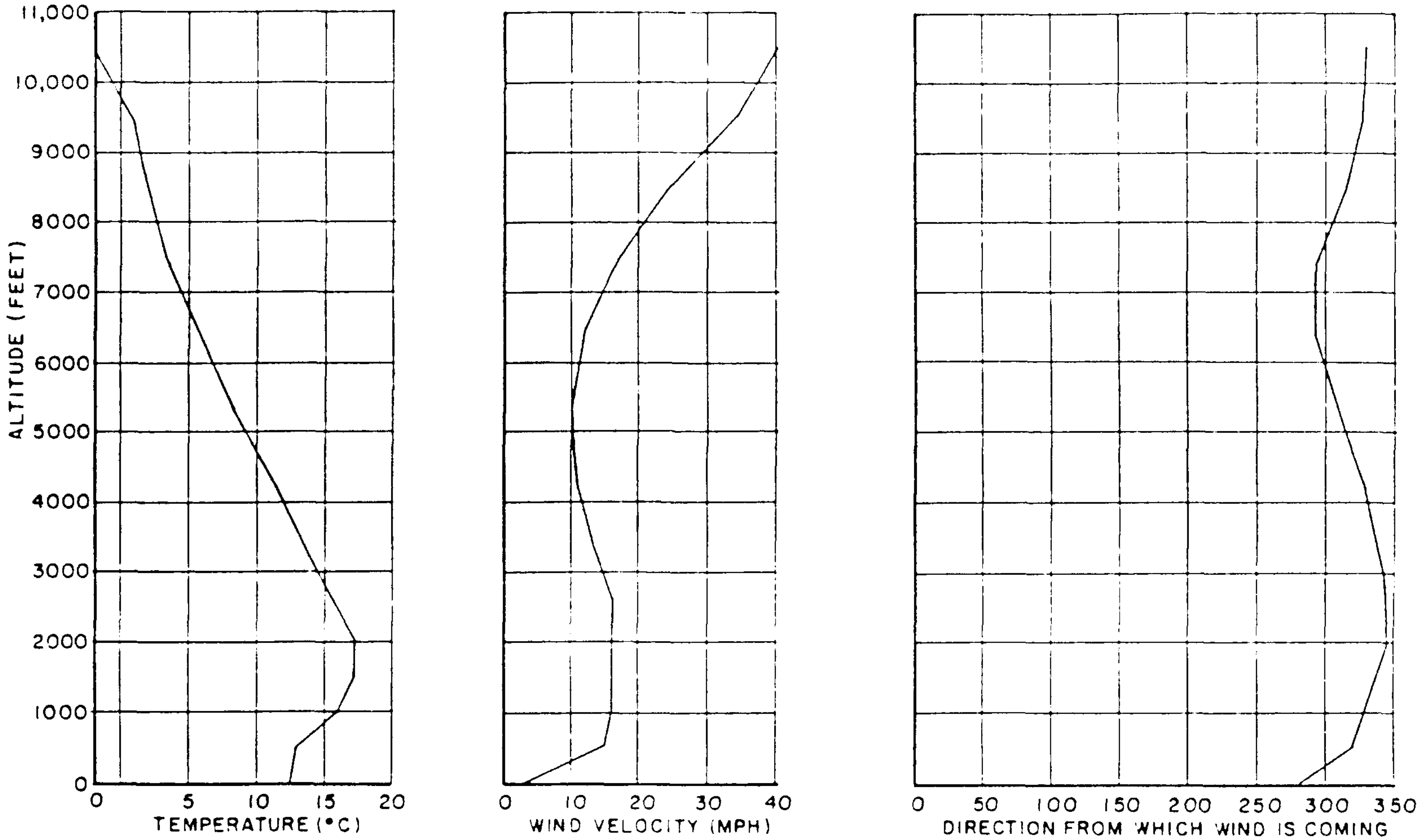

Figure 5. Temperature and Wind vs. Height Selected for Predictions in Figures 6 and 7.

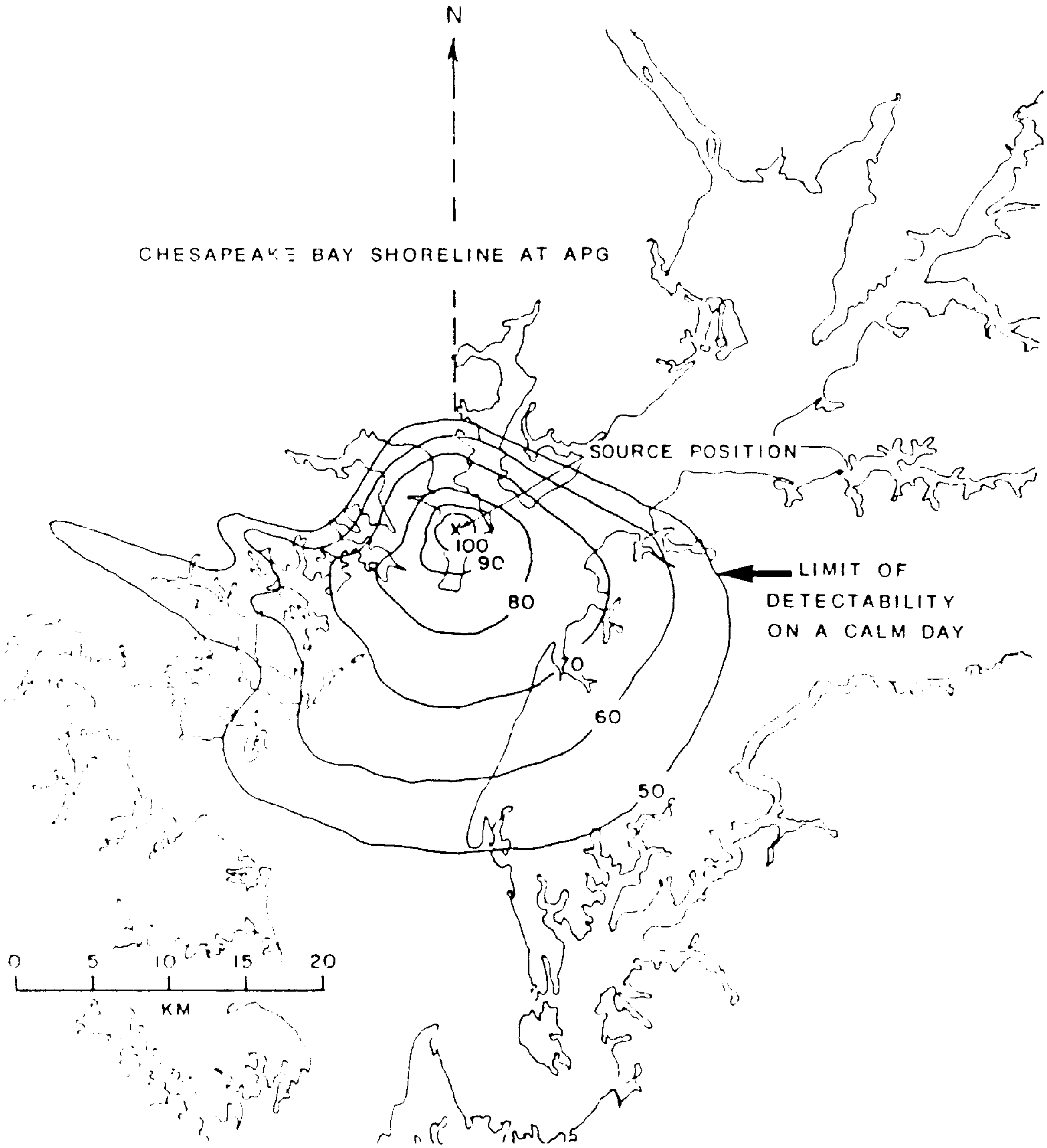

Figure 6. Predicted Surface dB Contours for the 140-mm Artillery Rocket Fired During a Selected Weather Condition.

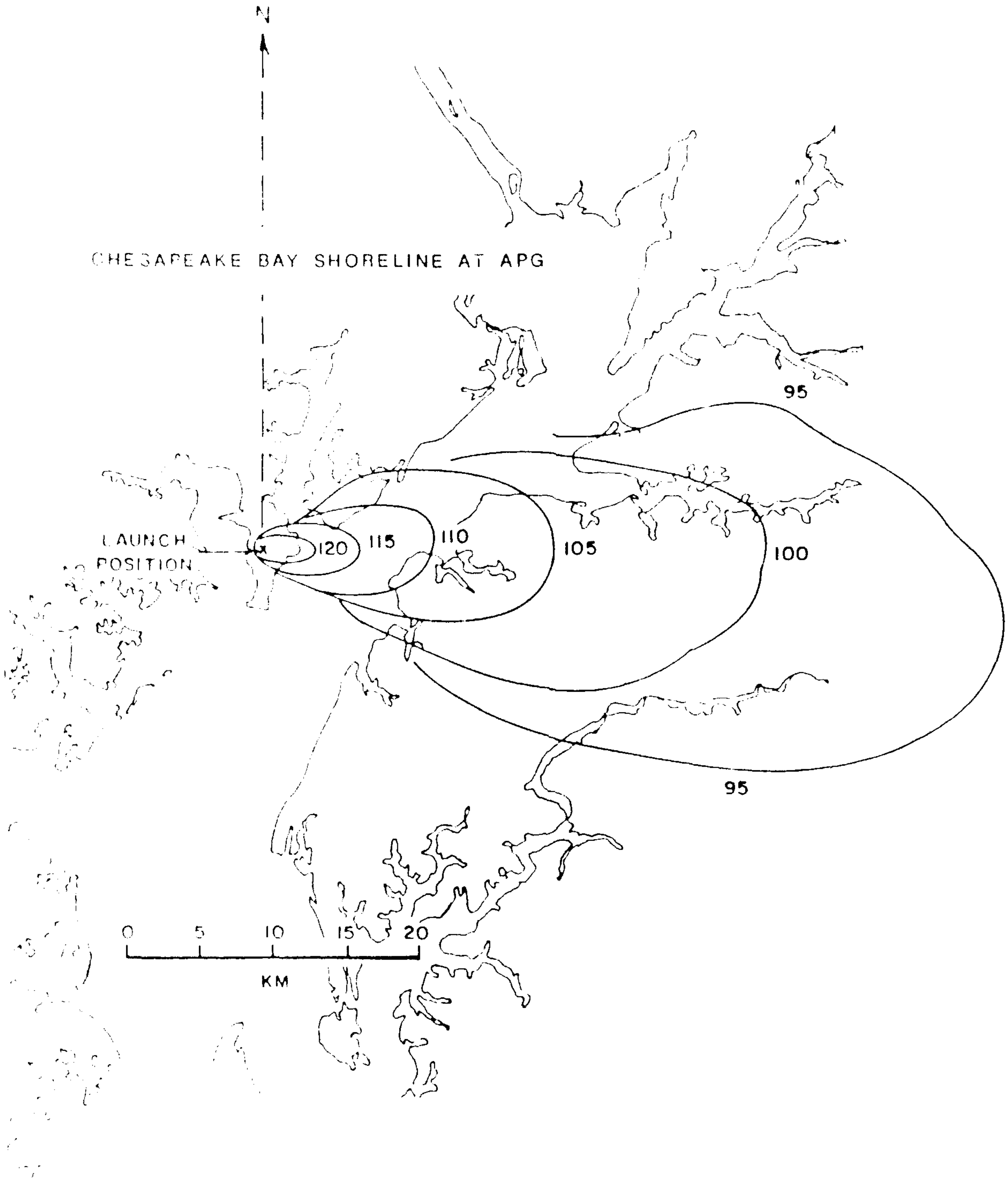

Figure 7. Predicted Surface dB Contours for the Ballistic Wave Energy From the 140-mm Rocket Artillery Fired at a Low Angle During the Selected Weather Conditions.

5. DISCUSSION OF RESULTS

5.1 Detection. From the frequency spectra in Figure 2, we can see that detection of artillery rockets having about 3,500 lb of thrust is possible for distances greater than 10 km under low ambient noise levels. Higher background noise levels from moderate winds would severely reduce this range of detectability, unless wind screens, filters, or other noise reduction techniques were used.

Other factors influencing signal detectability that were not taken into account in Figure 2 include weather conditions, height of rocket motor cutoff, propellant temperature, and acoustic directivity of the source.

In Figure 4, the 10-km spectra of the U.S. and foreign motor look somewhat similar. It is at these greater distances, of course, that identification and location of source are most needed. The foreign spectrum is a distance projection from the BRL model and is based on only one set of measurements made very close (100 m) to the trajectory. The projection uses divergence and absorption laws formulated like Equations A-3, A-4, and A-5 in the Appendix.

Other factors besides divergence and absorption must be considered before we can effectively project these very close-in measurements to the distant environment. Some examples of these factors will now briefly be discussed.

The measurements (Wathen-Dunn, unpublished) that we projected (Figures 6 and 7) were made very close to a moving source that generated Doppler effects which changed with time, direction, and distance. A gage was located where leaking (indirect) ballistic wave signals could be recorded along with rocket motor initiation and rocket motor burning signals. The more directional ballistic wave signal would have considerably more variation with location and trajectory than the less directional rocket motor and staging signals. The response of the measuring sensor dropped off rapidly below 30 Hz, where initiation signals may have substantial energy. In spite of these problems, it is fortunate that the Air Force measurements were made.

The dashed line in Figure 4 shows that the most suitable frequencies for detection at 10 km are 40 and 200 Hz. If the Air Force instruments could register below 40 Hz, it is expected that the 40-Hz peak shown in the dashed line in Figure 4 would be shifted to a higher peak near 20 Hz.

This expected low frequency peak is attributed to the rocket motor initiation pulse, while the 200-Hz peak is attributed to rocket motor noise.

It is suggested that signal recordings to a range of 10 km be obtained for revised predictions. These measurements should have flat frequency response from 10 to 500 Hz.

Spectrograms similar to those presented in the Air Force report (Wathen-Dunn, unpublished), but made from measurements at greater distances (1-10 km) and including a lower frequency range (to 5 Hz), are suggested to explore rocket identification from acoustic signals. Preferably, a spectral contour plotter would be used to present the signals obtained at this 1-km to 10-km range. These contour plotters are commercially available. Once the signature has been measured and its energy spectrum analyzed, a readily available artificial source (Galloway, Watters, and Baruch 1965) could be found to test various location techniques under different environmental conditions.

The peak intensity levels from the burning motor were estimated at intermediate distances with a peak intensity vs. distance curve similar to that shown in Figure 3. The difference between the dashed curve (showing only spherical divergence) and the lower solid curve (showing the predictions) results from acoustic absorption, which increases with frequency. Since theoretical absorption laws do not agree with absorption as measured from rocket motors, semiempirical laws for absorption were selected in preference to the purely theoretical estimates (see Equation A-4 in the Appendix).

In order to obtain realistic estimates of the possible acoustic signals for a dynamic rocket flight under typical weather conditions, we would have to present data for several weather and flight conditions. Since this report is not written for such extensive treatment, one weather condition was selected for maximum intensity predictions resulting from both the rocket motor signals and the ballistic wave signals.

From Figure 6, which shows the distribution of acoustic intensity from the rocket motor, we can see that the 60-dB contour extends more than 10 km in the southerly direction and less than 10 km in the northerly direction. From the weather profile in Figure 5, it can be deduced that this lack of acoustic symmetry in Figure 6 results from a sonic inversion of the south and the absence of such an inversion to the north. Although a 60-dB signal is detectable over the ambient noise level for most light wind conditions, more signal amplitude may be necessary for sufficient phase correlation for use of the arrival time location technique.

Figure 7 shows that ballistic wave signals, much stronger than the motor signals, are generated if the rocket exceeds the speed of sound. However, these signals reach the surface only in the direction of launch (89° in Figure 7), and only for very low firing angles, and only if sonic inversions exist in the launch direction. The possible existence of a ballistic wave signal must be considered since its earlier arrival may give an erroneous location if used in the arrival time technique with the rocket motor initiation signal obtained at another station.

5.2 Location Accuracy. Although accuracy of launch point location was not considered in the results in this report, it must be discussed. It is difficult to estimate the possible accuracy without studying the nature of the acoustic signals measured at distances between 3 and 10 km. Such signals would be used in the initial attempt at rocket launch point location. From such signal measurements, we must determine various parameters such as phase correlatability, frequency content, the motor initiation signals, rise times, and other characteristics. Some of these effects are discussed in the literature on sound ranging from guns. It is not the purpose of this report to discuss published sound ranging techniques that could be partially applied to rocket artillery. The reader is referred to Fox (1967a; 1967b), Bellucci (1966), Barichivich (1966), and Nordquist (1967).

From the azimuth and arrival time errors reasonable for these foreign rockets, it can be estimated that a launch point location error of less than 200 m is not likely for such artillery with measurements made at distances between 4 and 10 km.

A good potential exists for improving the accuracy of acoustic location techniques if applied research efforts are directed to this problem. With a slight improvement in the state-of-the-art of the 1970s, acoustic techniques should be useful for identification and approximate location of launch sites. This identification may allow a more immediate notification of any rocket artillery attack. Such notification could enable more people to take cover and also provide more time for counterattack.

In order to more accurately locate rockets that can be used against a community, an appropriate monitoring system must include detectors between the launch point and the community. This system might consist of a pattern of battery-operated telemetering sensors located around the community. These sensors would send back any large (or impulsive) signal to a central receiver in the community. By timing the signal arrivals at several sensors close to the source, the source could be more accurately located. Such a monitoring system is being built for test purposes at Aberdeen Proving

Ground in order to control the problem of community annoyance from explosive sources. This gage package is being designed to telemeter only those signals exceeding a prescribed intensity level. The package will have additional sensors attached to lines (50-ft lengths) that will turn on telemetry of the central sensor in time to respond to a blast wave greater than a selected intensity level.

Another technique which can be used to improve accuracy is to fire a live round back on the estimated target location and compare the explosion signal arrival times (or azimuths) from this round with those produced by the rocket launch. Appropriate adjustments, based on acoustic comparisons, could bring accurate counterfire on the launch position.

Seismic signatures should also be considered for use in locating a rocket launch position. It has been estimated that the seismic air-induced signals could be detected beyond 5 km from the launch point.

If an accurate zero launch time could be determined for use with the acoustic signal, much greater location accuracy would be possible. Although electric or electromagnetic signals generated at motor ignition would provide such a zero time, the evidence supporting the possibility of detecting such signals has not been encouraging.

6. CONCLUSIONS

There is a paucity of measurements of acoustic signals in the 1-km to 10-km range from dynamic firings of solid fuel rocket artillery weapons (Figures 1a, 1b, and 1c). Without such data to test theoretical assumptions, it is difficult to predict the identification potential or the accuracy with which such rocket launches could be located with acoustic detectors. The following preliminary conclusions can be listed for later experimental verification.

(1) It is probable that the rocket motor noise around 300 Hz can be detected out to a range of 10 km under low ambient noise conditions.

(2) Sound spectrograms measured at 1 to 10 km from the launch site should be useful for signal identification.

(3) Proof of the existence of an impulsive motor initiation or cutoff signal with energy between 10 and 40 Hz is needed. Having these signals would improve the accuracy with which the launch could be located from distant detectors. These signals, at the lower frequencies, should have greater amplitudes beyond 1.5 km than the amplitudes of the rocket motor noise.

(4) The ballistic wave signal should occasionally be detectable on the ground at distances greater than 10 km in the launch direction when the artillery rocket is fired supersonically at low angles in a direction where sonic inversions exist to bring this ballistic wave energy to the surface. Under these circumstances, ballistic wave signal azimuths measured at the greater distances may also be used for identification and location purposes. If an arrival time technique is used, location errors will result if the earlier ballistic wave signal arrivals are mistaken for a rocket motor initiation signal. The higher frequency content of the ballistic wave signal could be used to prevent this mistaken identity.

(5) The most logical methods for location should use either correlated phase arrivals or calculated azimuths at two or more stations.

(6) Launch location with an error between 100 and 500 m should be possible using detectors at distances between 4 and 10 km.

(7) For better location accuracy, one should give more attention to battery-operated telemetering detectors that can be placed close to the source.

(8) Arrival times from a launch could be compared with those from the explosion of a live round fired back at the enemy launch position. With this information, counterbattery fire can be adjusted.

(9) Other signals (besides acoustic) propagating from the launch site should be further investigated. If such signals exist, a better locating system using several signal types could be developed.

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APPENDIX:

SEMIEMPIRICAL RELATIONSHIPS
USED WITH THE
RAY PHYSICS APPROXIMATION

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The ray physics approximation to the wave equation can be very useful for predicting acoustic propagation. In a layered atmosphere, if the velocity is a function of only one space coordinate (altitude), the ray physics solution reduces to the familiar form of Snell's law:

$$\frac{\sin\theta}{c} = \frac{\sin\theta_o}{c_o} = p \qquad \text{(A-1)}$$

where θ is the angle that the ray makes with the vertical direction, c_o and θ_o represent a constant reference velocity and ray angle at its source, and p is a constant parameter for each ray. Ray physics is inaccurate for quantitative description in such areas as quiet zones, ducts, and focal points. For the predictions in this report, a smoothing process has been employed that allows energy to leak or diffract from areas (caustics and ducts) of high infrasonic intensity to areas (quiet zones) of low intensity (see alternative expression for refraction anomaly, A in Equation A-3).

An approximation to the propagation velocity, c, in space is obtained from wind and temperature information vs. height. If there is no wind, the sonic velocity at any height can be calculated by

$$c = \sqrt{\gamma k T} = 20.06\sqrt{T} \text{ meters/sec, where:}$$

c = sonic velocity	T = temperature (K)
γ = ratio of specific heats	k = gas constant for dry air.

In the presence of wind,

$$c = 20.06\sqrt{T} + W_c, \qquad \text{(A-2)}$$

where W_c = velocity of wind components in meters/sec in direction of interest. The effects of humidity on sound velocity have been considered negligible compared with other variables and are therefore omitted in this report.

As we can see from Equation A-2, the sonic height profile is obtained from a combination of temperature and wind velocity gradients, and this sonic profile varies with direction. Also, the sonic velocity is anisotropic since the horizontal wind components are not the same as the vertical components.

With a description of how the propagation velocity varies in space, we can develop or select an appropriate ray physics. Although the ray physics used in this report was developed by the first author from Equation A-1 specifically for the BRL studies, many other investigators have developed ray solutions for similar purposes (Officer 1958; Mabry 1962). The ray physics used in this report has been adjusted and combined with semiempirical equations, such as those given in the appendix. For a static (or point) source, ray tracing is initiated at the source for various elevation angles and azimuths, and these rays are extended throughout the layered atmosphere. This procedure is repeated for every source location. For the supersonic source, a directional ray tracing was developed. Since the ray physics is not readily found in the literature for supersonic sources following complicated trajectories, these techniques are briefly described in the following paragraph.

The sound field generated by a source as it moves supersonically along its trajectory can be considered a cone directional source that moves. At any instant, the ray directions near the projectile form a conical shape perpendicular to the shock cone as sketched in Figure A-1, and both the apex angle (a function of Mach No.) and the cone altitude are continuously changing along the trajectory. For this ballistic wave energy, the ray tracing part of the program calculates and plots the position, time, cusps, and intensity anomaly which are due to either refraction throughout the layered atmosphere or to accelerations of the source. Those ray calculations are made only over the appropriate cone; however, this ray tracing process must be repeated all along the trajectory for a number of cones whose shape and attitude depend on the speed and path of the shell. Since the sonic velocities vary with both altitude and direction, a three-dimensional program is required. As with the point source, the layered atmosphere is determined from temperature and wind data as described by Equation A-2. Also, as with the point source, semiempirical formulas must be used along with the ray tracing technique to quantitatively predict the intensity field. (Of course, the appropriate formulas and techniques for the moving source cannot be the same as for the point source.)

Techniques predicting sound intensity spectrums include the effect of absorption for a range of frequencies.

$$I(w) = I_o(w)\, D A_e^{-\alpha\gamma}, \qquad \text{(A-3)}$$

where $I(w)$ = sound intensity spectrum prediction which can be calculated for a number of frequencies. If both amplitude and phase are required for time histories, the complex notation for intensity, $\bar{I}$, must be used (see Equation A-5). The frequency for peak intensity will decrease with increasing distance from the source because of α, the attenuation coefficient which decreases with frequency.

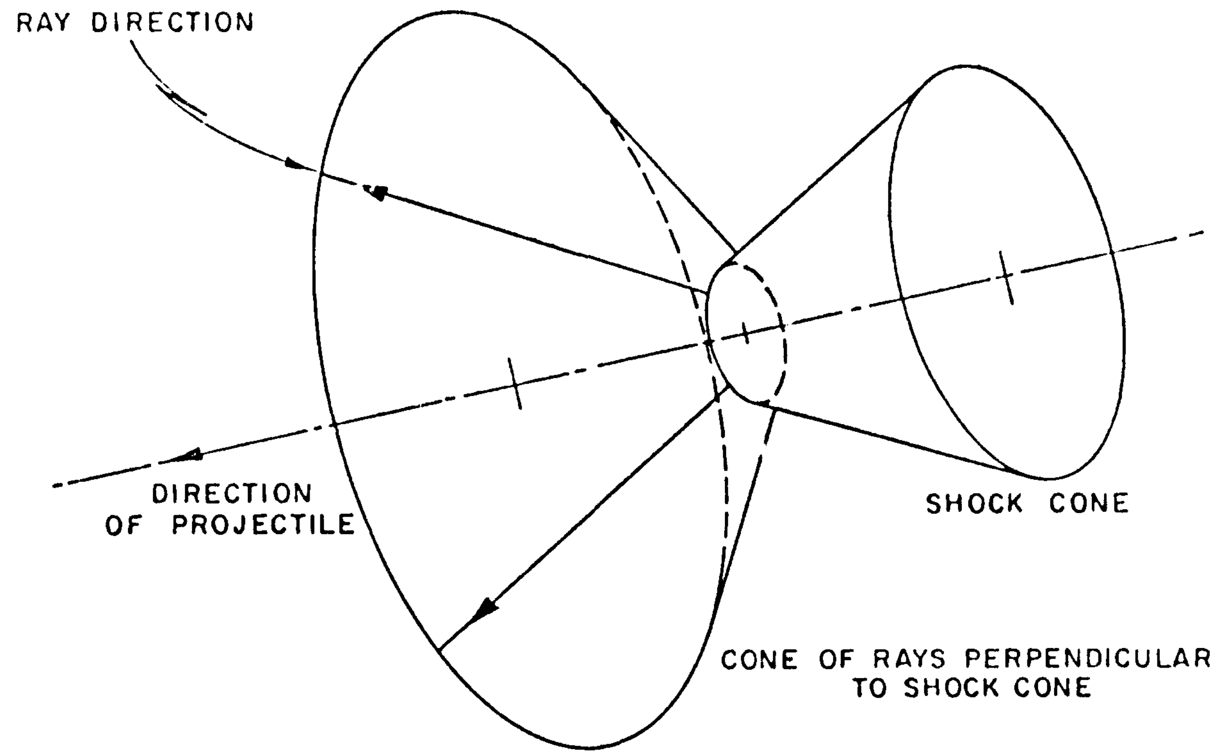

Figure A-1. Diagram of Rays Generated by Projectile at a Point on the Trajectory.

$I_o(w)$ = sound intensity spectrum known at some point. For an explosive source, $I_o(w)$ is calculated by a semiempirical scaling formula at a selected distance.

D = divergence factor from spherical or conical (cylindrical) spreading, depends on the type of source.

A = refraction anomaly calculated from ray density $|r/(dr/d\theta_o)\ tan\theta_o|$ or $r/|\dot{r}^2 + C\dot{r}|^{1/2} tan\theta_o$ for a point source. C is a constant.

r = ... ant distance from source to any position in space.

γ = distance along ray from source to position in space for prec... ion.

θ_o = initial inclination ... sound ray.

α = attenuation coefficient which varies with frequency and altitude, y. Since there is some discrepancy between theory and available empirical results in the determination of α, empirical results from the NASA rocket firing measurements have been used with theory as a guide to develop a reasonable functional relationship.

w = $2\pi F$ where F is frequency in Hz.

It can be seen above that α, the attenuation coefficient, varies with the frequency. For the frequencies in this report, the following empirical relationship was used for dB attenuation per kilometer at the surface:

$$\alpha(dB/km) = 0.015F - 0.00001\ F^2. \qquad \text{(A-4)}$$

The following equation is the complex form of Equation A-3. It is used when time histories, $I(t)$, as well as spectrums, $I(w)$, are required.

$$\bar{I}(w) = \left[\bar{I}_o(w)\right]\left[\bar{F}(w)\right] \qquad \text{(A-5)}$$

$$I(t) \updownarrow \bar{I}(w) \qquad I_o(t) \updownarrow \bar{I}_o(w)$$

where $\tilde{F}(w)$ is the vector functional relationship between $\bar{I}_o(w)$ and $\bar{I}(w)$. $\bar{I}(w)$ is the vector power spectrum at one position (where both amplitude and phase of I can be plotted against frequency). $\bar{I}_o(w)$ is the vector power spectrum at another position.

The upward arrows in the symbolic system used here (↔) stand for the Fourier transforms of the signal intensity-time histories; the downward arrow stands for the inverse Fourier transform of signal. In other words, by these mathematical transforms in Equation A-5, indicated by the arrows, we can go from the signal time domain (as measured) to the signal frequency domain (as used in the model) or vice versa. The type of mathematical transform to be used depends on whether the signal is considered a periodic or transient function. If the signal is assumed periodic (e.g., jet engine), a line spectrum is used since the harmonic order assumes only discrete values. If the signal is a transient function (e.g., explosive, initiation, or ballistic), the Fourier integral is used (the period of the series is allowed to approach infinity) and the Fourier transform in this case is represented by a continuous spectrum where all frequencies are assumed possible instead of only discrete values. We should remember that the two types of Fourier transforms (line and continuous) can only be compared for relative values. In other words, an upward adjustment in amplitude for the continuous spectrum is required if absolute comparisons are to be made between the line and continuous spectrum.

If we refer to Equation A-5, we can see that the vector functional relationship $\tilde{F}(w)$ can be empirically determined from two or more measurements, $I(t)$ and $I_o(t)$, if the form of this relationship is known from theoretical considerations. With a good approximation of $\tilde{F}(w)$, the acoustic environment can be predicted at other locations.

For the supersonic (moving) source, the BRL program uses an extension of theory (Whitham 1950) to predict quantitative intensities along the rays in a layered atmosphere. Two useful results of Whitham's work can be summarized in the following two formulas (Equations A-6 and A-7) that predict the excess pressures p_m and time constant τ for the N wave produced by a body of revolution moving supersonically.

$$p_m = K_1 P_g P_s K_2 dl^{-1/4} (M^2 - 1)^{1/8} h^{-3/4}, \quad \text{(A-6)}$$

$$\tau = C_s^{-1} 1.9\, dl^{1/4} (M^2 - 1)^{2/3} h^{1/4}, \quad \text{(A-7)}$$

where

p_m = excess pressure of N wave,

K_1 = reflection coefficient (usually close to 2),

P_g = pressure at gage,

P_s = pressure at source,

K_2 = aerodynamic shape factor, between 0.54 and 0.81,

d = maximum diameter of body,

l = effective length of body,

M = Mach number,

h = perpendicular distance from gage to line of body's flight path,

τ = time constant or duration of N wave,

C_s = velocity of sound at source.

From calculations of p_m and τ in Equations A-6 and A-7, the time history of the ballistic N wave can be determined. With the use of the continuous Fourier transform described under Equation A-5, the power spectrum can be obtained from the predicted N wave in the vicinity of the source, and this spectrum can be calculated at the greater distances with the use of Equations A-3 and A-5.

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