TACTICAL INFRASOUND

Study Leader:
Christopher Stubbs

Contributors:
Michael Brenner
Lars Bildsten
Paul Dimotakis
Stanley Flatté
Jeremy Goodman
Brian Hearing (IDA staff)
Claire Max
Roy Schwitters
John Tonry

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JASON
The MITRE Corporation
7515 Colshire Drive
McLean, Virginia 22102-0515
(703) 983-6997

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JASON was asked to assist the U.S. Army's National Ground Intelligence (NGIC) in finding ways to enhance the effectiveness of infrasound monitoring. In addition, we were also tasked with determining whether infrasound monitoring was likely to provide information of value in other intelligence venues.

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Contents

1 EXECUTIVE SUMMARY

JASON was asked to assist the U.S. Army's National Ground Intelligence Center (NGIC) in finding ways to enhance the effectiveness of infrasound monitoring. In addition, we were also tasked with determining whether infrasound monitoring was likely to provide information of value in other intelligence venues.

Findings

The tactical application of sound monitoring over ranges of 0-100 km is a qualitatively different problem from either the use of infrasound for nuclear weapons treaty monitoring purposes, or the tactical monitoring of acoustical energy at frequencies above 100 Hz. For treaty monitoring, which exploits sound propagation over thousands of kilometers, the sound is predominantly transmitted by refractive ducting from the upper layers (z$\sim$100 km elevation) in the atmosphere. The strong frequency-dependence of acoustic attenuation in this regime has appropriately led the treaty monitoring community to consider frequencies above a few Hz as uninteresting. On the other hand, the current generation of battlefield acoustical sensors concentrate on frequencies above 100 Hz.

Tactical infrasound sensor arrays trace their heritage to the instruments used for nuclear weapons treaty monitoring. Their sensitivity rolls off at frequencies above about 20 Hz. Local pressure noise is suppressed by the use of spatial filters over scales d$\sim$10 m.

In the tactical case however, for ranges of order 100 km or less, there are a number of factors that favor consideration of frequencies as high as 100 Hz, which has traditionally been considered the regime of acoustics. These factors include:

1. The acoustic power spectrum emitted by many of the sources of interest is a rapidly increasing function of frequency, with considerable energy emitted at frequencies of tens of Hz to a few hundred Hz,

2. Atmospheric propagation over ranges of up to 100 km often transmits energy at frequencies well above the classical infrasound frequency band,

3. The pressure noise against which the detection system is fighting falls rapidly with frequency.

This report encourages closing the gap between "infrasound" sensors, which lose sensitivity above 20 Hz, and the "battlefield acoustical" sensors, which emphasize frequencies above 100 Hz. Acoustic propagation over scales of 100 km is a complex phenomenon, and it depends sensitively on the detailed temperature and wind profiles of the atmosphere. In particular, since wind speeds can often be an appreciable fraction of the sound speed in air, a strong wind can give rise to anisotropic ducting mechanisms from fairly low in the atmosphere ($z <\sim 50$ km). As shown below, this "low-duct" mechanism allows for propagation of sound at frequencies as high as 100 Hz.

The sensitive dependence of acoustic energy propagation on time-variable atmospheric conditions presents a challenge. Since the detected signals (their power spectrum and angle of arrival) depend on both the source power spectrum and the details of atmospheric propagation, the interpretation of the signals would be much easier if the propagation were well characterized.

As stressed in the body of the report, a comprehensive understanding of the source power spectrum, of the anisotropic ducting and attenuation due to the atmosphere, and of the different noise sources, all as a function of frequency, should guide the optimization of tactical sound monitoring systems. As detailed in the recommendations, full exploitation of the deployed apparatus would benefit from a program to map out these parameters. JASON considers the application of sonic monitoring to intelligence problems to have considerable potential, and we advocate an investment in a deployed system as an opportunity to develop and refine this technique, in a real-world setting.

Recommendations

Recommendation #1. Some Near-Term Ideas for Enhancing Monitoring Systems that also include Tactical Infrasound.

We have some specific suggestions that might enhance the effectiveness of these systems:

- Increase the upper limit in frequency coverage by re-arranging the existing filter hoses and increasing the sampling rate.
- Use emplaced sound sources to dynamically calibrate and characterize atmospheric propagation.
- Use infrasound data from the International Monitoring System (IMS), and seismic data from the various sensors near a tactical system to "veto" against sound sources that are not within the region of tactical interest.
- Break the sound barrier: Fuse and correlate infrasound data with acoustic data.

Recommendation #2: Support A Vigorous Program of Source and Noise Characterization

We advocate a program to obtain and archive calibrated sound signatures, from infrasound to acoustic frequencies, from both targets of military interest (trucks, tanks, etc.) as well as potential sources of "clutter" (tractors, commercial aircraft...). In addition we consider it imperative that the sources of noise be fully characterized as a function of frequency, particularly the spatio-temporal coherence of the pressure field fluctuations. A major motivation here is to determine the optimum area over which to average in order to best suppress pressure fluctuation noise, while retaining sensitivity to high frequency sound. This should be part of an ongoing effort to maintain and strengthen the linkages between the program's scientific leadership and those charged with the oversight of the operational arrays. To the extent that source signature archives already exist, access to these should be broadened.

Recommendation #3: Characterize the Propagation Path.

The variability of the near-zone propagation mechanisms is a major impediment to fully understanding and exploiting the measured signals. This motivates a program to measure the atmosphere's transmission properties at a deployed site, on an ongoing basis. This can be done either directly, by emitting a known sound from a known location, or indirectly, by measuring meteorological parameters that can be used in conjunction with models to predict sound propagation. Take proactive steps to engage the scientific community in better understanding the propagation and detection of sound over distances of order 100 km.

Recommendation #4: Investigate Alternative Sensors.

A diversity of sensors can be used to monitor sound in the frequency range of interest. Given the likely importance of energy at frequencies above the classical infrasound regime, we consider it important to carry out a survey of sensor technology, both mature transducers and ones under development, paying particular attention to their noise properties. This information will be important in assessing the price/performance tradeoffs in acoustic arrays, which we describe next.

Recommendation #5: Take a Fresh Look at Array Design, Deployment and Systems Optimization.

The tension between maintaining good sensitivity to high frequencies and averaging over large areas to suppress pressure noise motivates the consideration of arrays of relatively inexpensive sensors. We advocate establishing a sound array test bed, co-located with a "classical" infrasound array, to facilitate the evaluation of different technologies and layouts. This evolution can exploit recent DoD and commercial advances in wireless, distributed sensor networks, and these networks could be rapidly deployed to provide useful information in tactical situations. Such field measurements will be essential to understanding systems trades in future operational sonic arrays.

Recommendation #6: Broaden the infrasound/battlefield-acoustics communities.

In our view these two scientific communities are currently too small (within the US) to produce a healthy and vibrant flow of new ideas, new implementations, and new people. The DoD would derive tangible benefits from fostering more academic participation in this field, and maintaining close links to those efforts.

2 INTRODUCTION

Using sound as a source of intelligence in a tactical setting has a long military tradition. Our study was undertaken to assess how this technique might be exploited in contemporary settings, in particular at at tactical infrasound arrays.

Infrasound is defined to be below audible frequencies, less than about 20 Hz. The only characteristic frequency in this range is the local buoyant Brunt-Vaisala frequency of a stably stratified atmosphere, $\omega_{BV}^2 \approx g/h$, where h is the atmospheric scale height (7-8 km), and g is the local gravity. This gives a frequency $\nu_N \approx 6\,\text{mHz}$, far below the range we will be studying here.

The unit for measuring sound amplitudes is the dB_{SPL}, or sound pressure level in decibels, which is defined as

$$\text{dB}_{\text{SPL}} = 20\log_{10}(P_{\text{rms}}/P_{\text{ref}}) \tag{1}$$

where $P_{\text{ref}} = 20\ \mu\text{Pa}$ (different than what is used in the ocean case). One atmosphere (one bar) is 10^5 Pa, so atmospheric pressure at sea level is 194 dB. A few other numbers for reference: a rock concert is 120 dB, 3 m from a jet engine is 140 dB and a vacuum cleaner is 100 dB (threshold of hearing at 1 kHz is 0 dB). The energy flux in sound is $\approx P_{\text{rms}}^2/\rho c$, so that for spherical spreading $P_{\text{rms}} \propto 1/d$, so a factor of ten in distance leads to a 20 dB loss. (Henceforth all dB values should be interpreted as dB_{SPL}.) In practice the dimensionality of the system of interest is somewhat less than 3, and so the geometrical loss is less than that expected for 3-d spreading. Pressure levels of interest for infrasound monitoring are typically at the level of a microbar, or about 75 dB.[1]– [6]

In the sections that follow we consider the sound spectra emitted by sources of interest, the propagation of the sound through the atmosphere, the various sources of noise against which the signal detection competes, the signal to noise considerations that influence an optimized design, and the problems of source discrimination and characterization. We close the report with a list of recommendations.

We were fortunate to receive briefings from a number of leading scientists in the infrasound community, listed in Table 1. We are most grateful for their willingness to contribute to this study, and to answer our follow-up questions.

Table 1: Study Briefers

Speaker	**Affiliation**
Robert Grachus	NGIC, Army Intelligence Charlottesville VA
Anthony Galaitsis	BBN, Inc Lexington MA
Rod Whitaker	Los Alamos National Laboratory Los Alamos NM
Michael Hedlin	Scripps and IGPP University of California, San Diego
Mark Zumberge	Scripps and IGPP University of California, San Diego

The basic notion that sonic information has tactical value is demonstrated by the availability of a commercial tactical helicopter detection system, made by an Israeli firm.[7] The 'Rafael Helispot' system (web site is www.rafael.co.il/web/rafnew/products/air-helispot.htm) is an array of microphones, and claims the ability to detect and discriminate helicopters at ranges of tens of kilometers. This mobile system is shown in Figure 1, and its claimed success certainly motivates a careful and thorough exploration of the use of sonic information.

Figure 1: The Rafael Helispot system is an example of modern tactical use of sonic information. The microphone array has demonstrated the ability to detect and classify helicopters at ranges of a few Km, at acoustic frequencies.

3 SOURCES OF INTEREST AND THEIR SONIC SIGNATURES

3.1 Introduction

In order to understand what kinds of acoustic information may be most useful for tactical applications, it is essential to know the characteristics of the potential sources of interest. In particular, to optimize the usefulness of existing detection systems and to successfully engineer future systems, it is vital to know the spectral energy distributions of acoustic and infrasound energy emitted from each type of source. In this section we show examples of acoustic energy spectra from specific battlefield-related sources; we discuss the general characteristics of these spectra together with their implications for detection systems; and we conclude with recommendations concerning the compilation and analysis of sonic signatures in the future.

3.2 Typical infrasound and acoustic spectra

The infrasound community has been gathering signatures data on sources such as large explosions, bolides, and space shuttle launches for quite a few years. Infrasound from sources such as these can be detected at large distances (e.g. thousands of km), and can be geolocated using data from multiple IMS sites. An effort is now beginning to create an unclassified Global INfrasound Archive, or GINA ([2] and [8]) to raise the profile of this field and encourage wider participation from the research community. As of March 2003 this archive was in prototype form, with participation from the Geological Society of Canada and the Royal Netherlands Meteorology Institute. We view this development very favorably.

However for the tactical application considered in this study, we are interested in detecting, locating, and identifying acoustic sources at much closer range: from a few km to a few hundred km distance. We are also interested in a different suite of sources: trucks, tanks, and armored vehicles, helicopters and UAVs, artillery and short-range rocket launches, cruise missiles, and similar tactical threats.

Traditionally, information on such tactical sources is obtained and archived by groups interested in battlefield acoustics. We understand from papers in conference proceedings [9] that the Army Research Laboratory's Acoustic Automatic Target Recognition Laboratory maintains an acoustic and seismic signature database. However based on our experience during the Summer Study and on conversations with academic experts in atmospheric acoustics, we have the impression that access to this database is not readily available to scientists outside ARL. Thus we have not been able to ascertain whether this database includes signatures with frequency coverage down through the infrasound range, nor have we been able to access actual digital signatures from this database. We did, however, obtain graphical representations of such spectra in analogue form from Dr. S. Tenney, ARL, [10] and from a variety of conference proceedings which we accessed via the world wide web. We base our discussion of signatures and spectra on the analogue graphical data we have been able to obtain from these sources.

3.2.1 Vehicles

On physical grounds one would expect the acoustic radiated power from a vehicle to fall off at low frequencies, i.e. for acoustic wavelengths that are much larger than the vehicle size. For example if a vehicle of interest is 10 meters long, the acoustic power should fall off at the rate of 6 dB/octave for frequencies $f \ll (330 \text{ m/sec}) / (10 \text{ m}) = 33$ Hz. Indeed land and air vehicles such as trucks, tanks, helicopters, and UAVs typically have a continuous acoustic power spectrum that extends from a few hundred Hz down to a few tens of Hz. Many such vehicles also show distinct narrow-band acoustic signatures, e.g. at harmonics of a gasoline engine's RPM, at tire-slap intervals, or at tread-slap intervals.

We were not able to obtain quantitative estimates of the residual acoustic power at frequencies below 20 Hz, the traditional infrasound region. However we note that the newer generation of microphones used in both the infrasound community and the battlefield acoustics community do have sensitivity down to a Hz or below, and so the low-frequency power spectrum for sources of interest could be measured at the same time as signals in the traditional "acoustic" range, $f > 20$ Hz.

Trucks: Figure 2 shows the acoustic signature of a large truck. Once sees

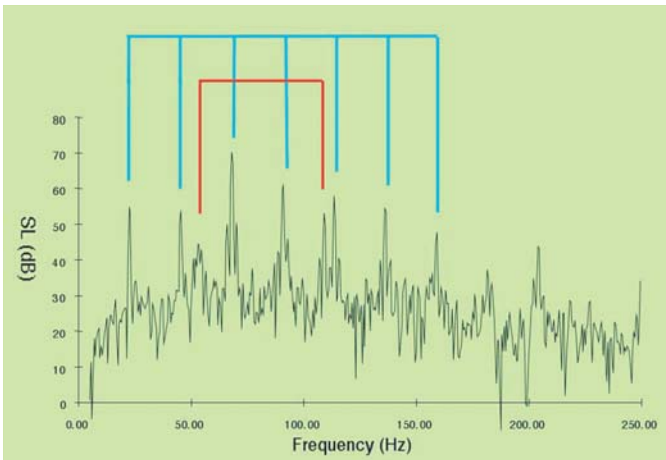

Figure 2: Acoustic power spectrum of a truck, from S. Tenney, ARL. The red lines represent narrowband signals from tire noise. The turquoise lines represent harmonics generated by the firing of the engine's cylinders.

significant power in the continuum from above 250 Hz down to about 25 Hz. In addition there are distinct narrowband features at frequencies representing the rotary motion of the engine's cylinders and the periodic slap of slightly asymmetric tires as they role along the ground. Narrowband features such as these can be used in signal-processing algorithms to enhance detectability and to allow vehicle categorization (e.g. [11]).

Tanks: Figure 3 shows the acoustic power spectral density generated by an M60 tank under way. As in the case of the truck, this tank has significant acoustic energy in the continuum from 200 Hz down to 20–25 Hz, as well as engine harmonics and track-slap signals at 150 Hz and below.

In the case of moving vehicles with narrowband spectral features, one can use the Doppler shift of one or more of these features to obtain a radial velocity measurement. With multiple sonic detectors at different locations

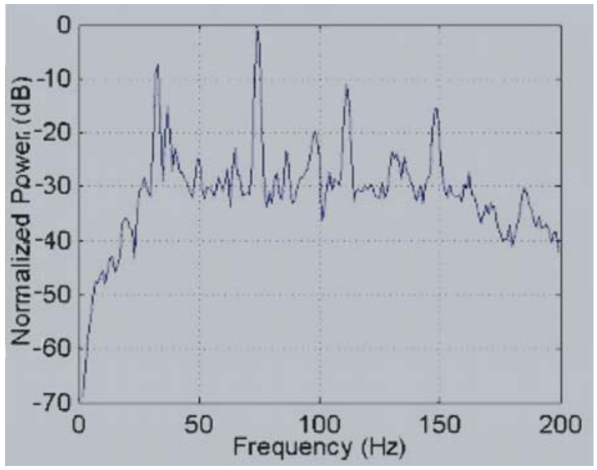

Figure 3: Acoustic power spectrum of an M60 tank, normalized to its maximum signal. From S. Tenney, ARL.

one can estimate the vehicle's direction of travel and range. These techniques are in use and are being refined in the discipline of "battlefield acoustics," that is with emphasis on frequencies larger than 10–20 Hz. However many of these methods would be useful on the battlefield for signals in the whole range between a fraction of a Hz and a few hundred Hz.

Helicopters: Figure 4 shows the sonic power versus time and frequency

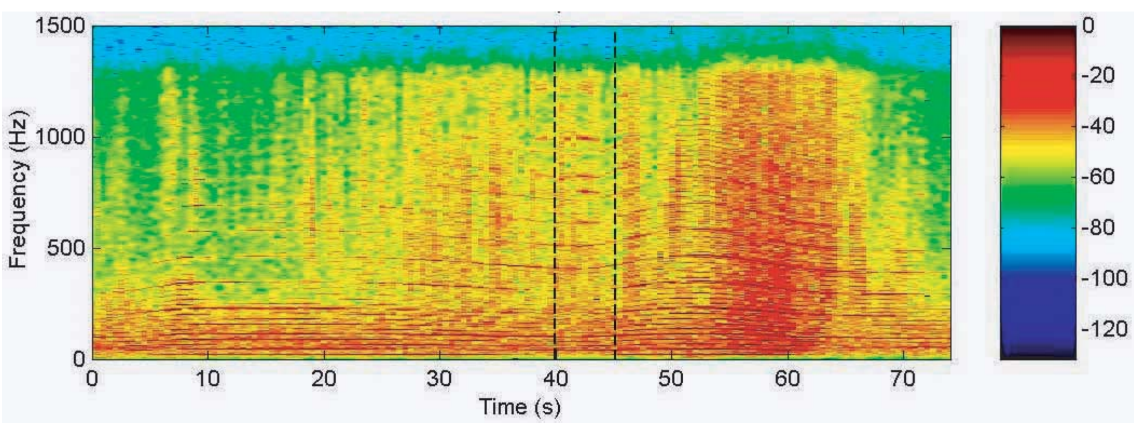

Figure 4: Sound intensity as a function of frequency and time, for a UH-1 helicopter flying past the acoustic detector. From S. Tenney, ARL.

emitted by a UH-1 helicopter. The narrow orange lines show the Doppler-shifted harmonics from the engine and/or the rotors. Harmonics are present up to frequencies of a kHz, and down to 25 Hz or less. These orange harmonic lines are not straight, due to the motion of the helicopter towards and away from the acoustic detector. The shift of a harmonic's frequency with time gives the line-of-sight velocity (radial velocity) via the well-known expression $\Delta f/f = v_r/c$ where f is the frequency, v_r the line-of-sight velocity, and c the speed of sound.

The Israelis have developed two acoustic systems that detect helicopters and have capacity to discriminate between specific helicopter models based upon their tail-to-main-rotor frequency ratio and other distinctive harmonic patterns. One of these systems, HELISPOT, is a mobile land-based microphone array; the other, HELSEA, is a sea-based buoy carrying a microphone open to the air (see http://www.rafael.co.il/web/rafnew/products/nav-helsea.htm). The detection range of HELISPOT is specified to be 4 – 6 km, but in recent tests detections have been made up to 15-20 km away ([7]).

Unmanned Air Vehicles (UAVs) also have characteristic sonic signatures. Gasoline-powered UAVs show continuum emission up to about 400 Hz, and narrowband emission at even higher frequencies, as shown in Figure 5. They can be detected up to ranges of 4 km or more. Electrically

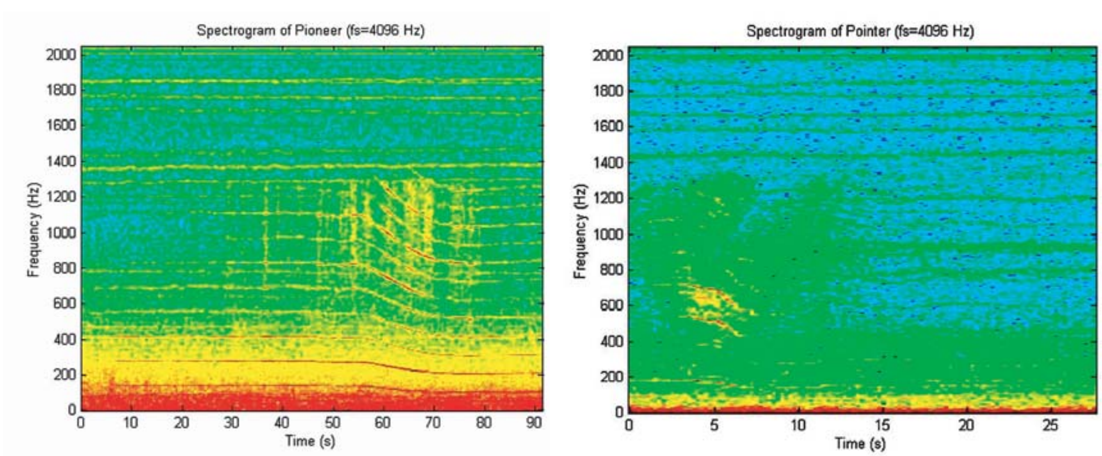

Figure 5: Left panel: acoustic power spectrum as function of time, for gasoline-powered UAV. Right panel: same, for electric-powered UAV. Source: Dr. S. Tenney, ARL.

powered UAVs are much quieter, as might be expected, with typical detection ranges of less than 1 km. But even electrically powered UAVs still show distinctive narrowband harmonics of the blade rate.[10]

3.2.2 Impulsive sources

Impulsive acoustic sources such as rocket launches, explosions, and artillery have broad-band spectral energy distributions, extending to lower frequencies than are produced by vehicles. Because of their low-frequency spectral content, their signals are able to propagate over longer ranges without absorption and are promising targets for detection by tactical acoustic/infrasound sensors at larger stand-off distances.

Artillery and tactical missile launches: Figure 6 shows the acoustic frequency content as a function of time for artillery (left panel) and for a Multiple Launch Rocket System missile (right panel). Both show a broadband acoustic signature for frequencies of 10–20 Hz and below, with strong signals below 5–10 Hz, well into the traditional infrasound range. According to Dr. S. Tenney of ARL, these spectra were measured at a range of about 9 km. Because of the strong spectral content at low frequencies there is good reason

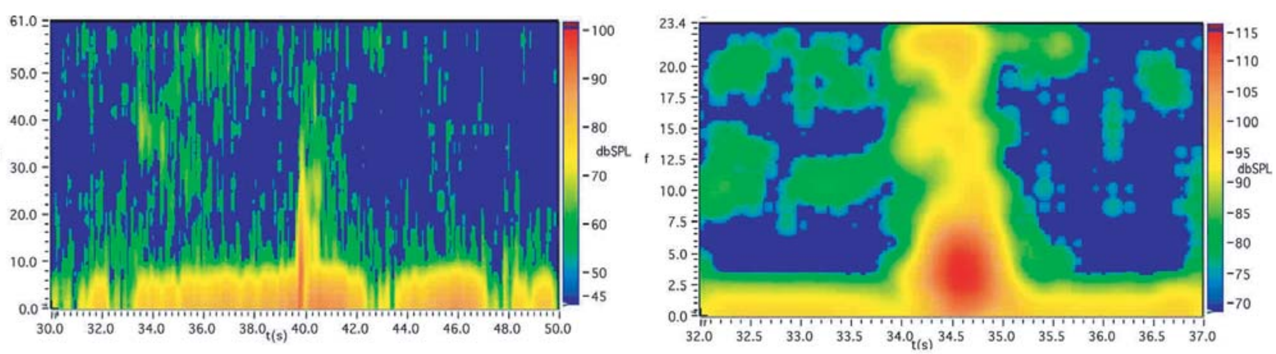

Figure 6: Left panel: Acoustic spectrum as a function of time (in seconds) of an artillery launch seen from 8.6 km. The launch took place at a time of about 40 sec on this plot. Right panel: Acoustic spectrum of an MLRS missile launch seen from 9 km. This launch (or launches; the documentation was unclear on this) took place at about 34.6 sec. Source: S. Tenney, ARL.

to believe that the sonic signals would be detectable at considerably longer ranges than this, at least under some atmospheric conditions.

Scud launches: The launches of longer-range missiles such as Scuds are even more promising for acoustic/infrasound detection at tens of kilometer stand-off distances. Figure 7 shows the acoustic frequency content as a func-

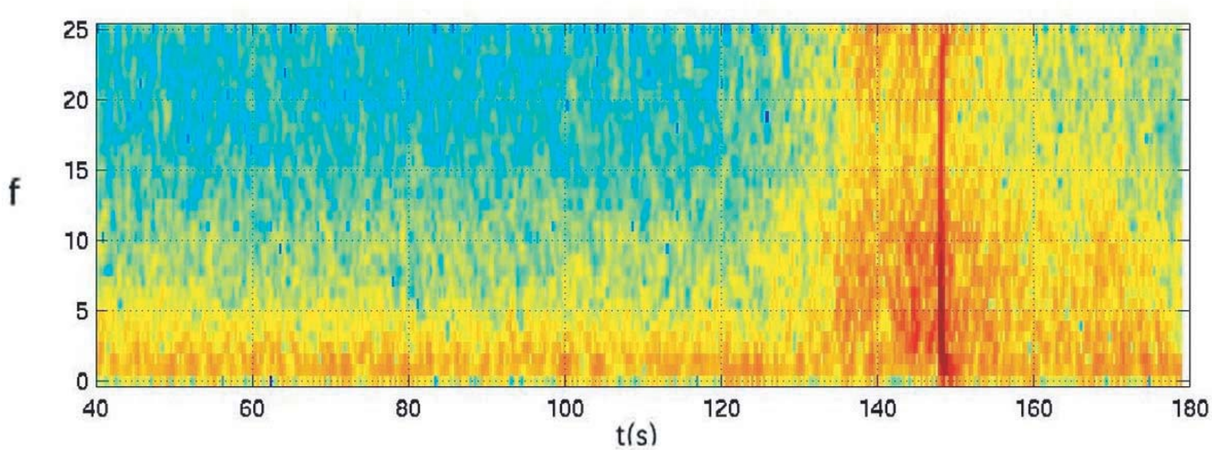

Figure 7: Acoustic spectrum of a Scud missile launch, measured at a range of 27 km. The launch took place at a time a bit less than 150 sec on this plot. Source: S. Tenney, ARL.

tion of time for a Scud launch, measured at a range of 27 km. The actual launch in this case took place at a time a bit less than 150 seconds, where a broadband acoustic signal extends from 1–2 Hz up to 25 Hz (and possibly beyond).

3.2.3 Steady sources: bridges and structures

It has been known for more than 25 years that bridges can emit strong infrasonic signals. In 1974, Donn et al. showed that the strong 8.5 Hz signal that frequently appeared on their infrasound detector at the Lamont-Doherty observatory on the palisades above the Hudson River was generated by the Tappan Zee bridge more than 8 km to the north.[12] Since that time there have been occasional journal articles on infrasound from other bridges and highway structures (e.g. [13]). The consensus seems to be that the vibrations generating the infrasound are driven by traffic on the bridge, but wind remains a possible exciter as well. By analogy, other large structures may also be either persistent or occasional emitters of infrasound.

A characteristic infrasound signal from a fixed location such as a bridge may well be useful to a tactical sonic detection system. The changing apparent direction and location of a sonic signal from a known bridge (which will vary due to atmospheric propagation variations) can aid in deriving the location of transient moving sonic sources by determining their relative position with respect to the known bridge or other structure. With modern sonic detection systems it should be possible to pick up signals from large structures at distances considerably greater than the 8 km reported in [12]. Improvements such as this are discussed further in Section 9.

3.3 Implications for the design of sonic detection systems

The frequency spectra from the various sources discussed in this section have signals that span the range from ~ 1 Hz all the way up to a few hundred Hz. While a single sonic source is not likely to have strong spectral content over this whole frequency range, the ensemble of sources of tactical interest calls for detectors both in the traditional infrasound range (< 20 Hz) and the traditional acoustics range (~ 50 Hz to hundreds of Hz). Moreover, as we shall discuss in a later section of this report, the frequency dependence of propagation in the atmosphere strongly selects for lower frequencies when the propagation path is long.

All of this implies that an optimal sonic detection system should include sensors and arrays for both low-frequency (infrasound) and higher-frequency (acoustic) signals, preferably collocated. We note that microphones are available today that span the entire desired range, but systems considerations may point towards using two types of sensors under some circumstances.

Further, signal analysis software and hardware should be aimed at fusing together data from the infrasound and acoustics frequency bands, so that common algorithms for geolocation, direction-finding, and moving target characterization can be utilized.

3.4 Compilation and analysis of sonic signatures

We strongly encourage the compilation of one or more publicly accessible archives containing well-documented sonic signatures of both man-made and natural sonic sources, with spectra spanning the infrasound and acoustic spectral ranges (i.e. from sub-Hz to hundreds of Hz). The infrasound and acoustics communities will benefit from encouraging an infusion of new young investigators who can base their research on digital data from such an archive.

We learned of two databases/archives that are under way. The first, Global Infrasound Archive, or GINA [2, 8] has recently gotten under way, with sponsorship from the Geological Society of Canada and the Royal Netherlands Meteorology Institute. The second, with emphasis on battlefield acoustics, is maintained by the Army Research Laboratory's Acoustic Automatic Target Recognition Laboratory ([9]) and is intended for both acoustic and seismic signature data.

We applaud these efforts. However several issues will need to be vigorously addressed:

1) In order to advance the field vigorously, the databases/archives must be publicly accessible. This will mean that classified signatures will have to be stored elsewhere.

2) There will need to be calibration data (microphone response functions, target distance, meteorological conditions if available) stored along with each source signature.

3) There will need to be a common data format for acoustic signature exchange. We understand that NATO Task Group 25 on Acoustic and Seismic Technology has begun to develop a standard for acoustic signature exchange. This effort (or similar ones if the NATO work has not progressed since its inception in 2001) should be supported by US expertise and, if necessary, funding.

We note that there are several successful examples of public data archives today: the Hubble Space Telescope Multi-Mission Archive, or MAST (http://archive.stsci.edu/hst/index.html), NASA's Earth Science Data and Information System (http://spsosun.gsfc.nasa.gov/eosinfo/Welcome/index.html), or NASA's HEASARC archive (http://heasarc.gsfc.nasa.gov/docs/corp/data.html). Millions of dollars have been spent by these groups (and others) developing software tools and user interfaces. Most function very well. We think that the acoustics community should benefit from this extensive experience base, rather than spending substantial resources on developing these kind of capability anew.

4 A SOUND PROPAGATION PRIMER

The goal of this section is to summarize the properties of propagation of infrasound through *short distances* for tactical applications. Since infrasound has traditionally been used for large distance signals (CTBT), the discussion will differ in several important respects from the traditional one. In general, the properties of sound propagation in the atmosphere depend most sensitively on two atmospheric properties: (a) the temperature profile of the atmosphere, which sets the variation of the sound velocity with height; and (b) dissipative processes, which determine which acoustic frequencies can propagate. In what follows we will discuss each of these properties in turn, and then discuss the consequences for short-distance sound propagation.

4.1 Ducting due to Sound-Speed Variations

4.1.1 Windless atmosphere

In the absence of winds, the way in which outward going sound is returned to the Earth's surface is through variations in the sound speed with altitude. In the WKB limit, the dispersion relation for the sound wave is $\omega = ck$. Evolving at fixed frequency through a medium of changing sound speed constrains the dispersion relation, $\omega = c(k_z^2 + k_\perp^2)^{1/2}$, so that k_z^2 is the changing quantity as the sound moves to higher altitudes. If a region of higher sound speed is encountered, then, at fixed ω, the radial wavenumber will decrease. A turning point can occur when $k_z^2 = 0$. Following the normal convention from the literature, we designate θ as the angle of propagation relative to the vertical, so that $k_z = k\cos\theta$ and $k_\perp = k\sin\theta$.

Now consider propagation through a medium of changing c. Since $k_\perp$ is conserved, we get $k_1 \sin\theta_1 = k_2 \sin\theta_2$, and the fixed frequency constraint, $k_2 c_2 = k_1 c_1$, yields Snell's law

$$\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_2}{c_2}, \tag{2}$$

which is then used to trace the ray through the medium of changing c. Imagine sending a wave up into a medium of increasing sound speed, so that $\sin\theta_2 = c_2 \sin\theta_1 / c_1$ increases with altitude. This refraction of the ray towards the horizontal can turn the ray around at the location where $c_2 > c_1 / \sin\theta_1$.

The sound speed decreases with height in the troposphere, up to the tropopause (at an altitude of 10-14 km for mid-latitudes), after which the sound speed increases again. For sound sources in the tropopause, there is a natural duct for sound, but this duct will usually not trap sound that originates at the surface. Above the tropopause, the temperature increases through the stratosphere, reaching a local maximum at about 50 km, but still about 20 m s^{-1} less than that on the ground (this is true at the equator and mid-latitudes; it nearly matches the ground speed at the pole [34]). It is not until an altitude of $\approx$ 110 km that the sound speed exceeds that at the ground. At this location (the thermosphere) the sound speed is nearly linear with altitude, so we write a simple relation locally valid near the first location where a return can occur, h_o, as

$$c(z) = c_o + (h - h_o) dc/dz \tag{3}$$

where $c_o \approx 340$ m s^{-1} is the sound speed at the ground. The measured value of the derivative (dc/dz) is about 7.5 m/sec over one km ([1]). This linear increase in c does not continue forever, as the temperature at high altitudes eventually becomes constant (with altitude), though with large day/night excursions due to changing solar irradiance. For an average temperature of about 1000 K above 250 km altitude, the maximum contrast with the ground sound speed is $\approx$ 1.8, requiring an initial launch angle $\theta_1 > 33$ degrees for a return to the Earth's surface. Figure 8 illustrates the annual mean sound speed as a function of altitude, in the troposhere, stratosphere, and thermosphere.

The thermospheric bounce is always present. Using equation (3), we can find the minimum downrange distance, which is $\approx$ 200 km. That ray reached an altitude of nearly 150 km, and so likely would be strongly attenuated at high frequencies. We will consider these effects quantitatively below. If the losses were simply transmission and the sound were spherically spreading out

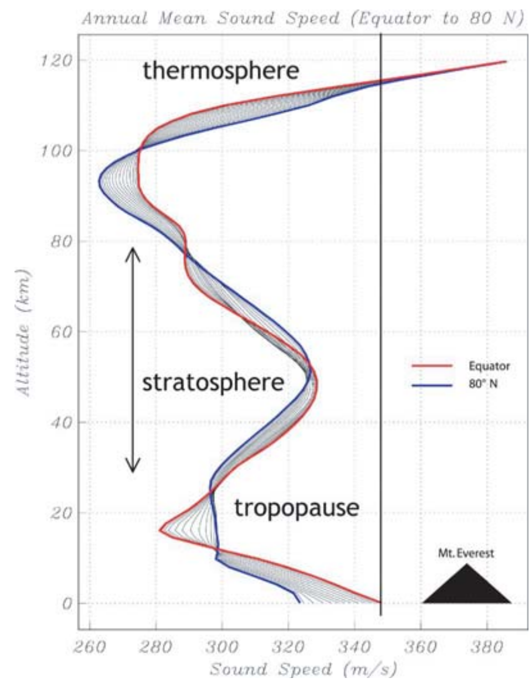

Figure 8: Typical sound speed vs. elevation, from Hedlin [34]

.

to this distance from a source dimension of 1 meter, the transmission loss would be 106 dB.

A well documented example is a blast at an explosives factory in France, at Billy-Berclau on March 27, 2003. The DBN array "heard" the infrasound from the explosion at an amplitude of $\approx$ 0.1 Pa (74 dB) from a distance of $\approx$ 400 km. The sound was also detected at arrays in France and Germany. Presuming spherical spreading (1 bar = 194 dB) from 100 m to 400 km. Intensity on a 100-m sphere surrounding the source was 146 dB.

4.1.2 Ducting due to Wind Shear

Under the ray tracing approximation and in the absence of scattering, the only way to receive a strong signal at a downrange distance of less than 200 km is to have favorable winds duct the sound. To understand how this can help, we first note the dispersion relation of sound in a wind of transverse velocity $\vec{v} = v_o\hat{x}$, where $\hat{x}$ lies in the horizontal plane. Call k_x the component of k in $\hat{x}$ direction, then we get $(\omega - k_x v_o)^2 = c^2 k^2$. For the case of $v_o \ll c$, we expand this, assuming, $\omega \approx kc$, to reach a new relation $\omega \approx ck + k_x v_o = c_{\text{eff}} k$, where

$$c_{\text{eff}} = c + v_o \frac{k_x}{k} = c + \vec{v} \cdot \hat{n}, \tag{4}$$

is the familiar relation for an effective sound speed c_{eff}.

This relation makes clear that the wind speed acts to effectively increase the sound speed when the wind blows in the direction of source to listener. Hence, ducting can occur once there is an altitude where c_{eff} exceeds that on the ground. The most likely altitude for this to occur is around 50 km, where there is a peak in the thermal sound speed that allows a favorably aligned 20-40 m/sec (depending on season) wind to create a duct. See Figure 9, which shows (via red lines) the effective sound speeds C_{eff} for two directions of propagation. The vertical black line shows that the effective sound speed

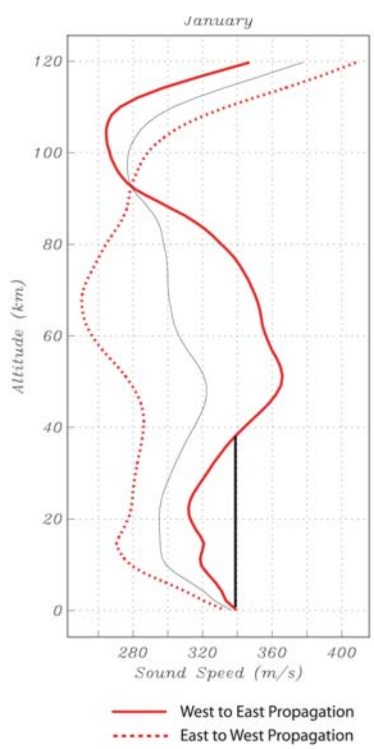

Figure 9: Sound speed vs. elevation in windy conditions. From ([34]

at ~ 38 km equals that at 0 km. The advantages to this duct are numerous: primarily, the ducted sound will return to the ground at much shorter distances, hence less transmission loss will occur. Hence, not only are the sites audible, they are also louder.

4.1.3 Ray Trajectories

The ray trajectories in the ducted atmosphere follow from supposing that the sound field is represented by the velocity potential $\Phi = e^{i\psi(\mathbf{x})}$. Then the normal to the wavefront points in the direction $\hat{n} = d\mathbf{x}/ds = \nabla\psi/|\nabla\psi|$. Straightforward algebra then implies that the normal vector obeys the equation

$$\frac{d}{ds}\left(\frac{\mathbf{x_s}}{c_{\rm eff}}\right) = -\frac{\nabla c_{\rm eff}}{c_{\rm eff}}. \tag{5}$$

If we assume that $c_{\rm eff}$ depends only on z, then this equation reduces to the following equation for the trajectory $z(x)$ of the ray:

$$\frac{d^2 z}{dx^2} = -\frac{c_{\rm eff}(0)^2}{\sin^2\phi}\frac{dc_{\rm eff}/dz}{c_{\rm eff}^3}, \tag{6}$$

where $c_{\rm eff}(0)$ is the sound velocity at ground level, and ϕ is the initial angle the ray is launched (relative to the vertical).

The equation for $z(x)$ is identical to Newton's laws for the position z of a particle of unit mass moving in an effective potential $U_{\rm eff} = -(2/\sin^2\phi)(c_{\rm eff}(0)/c_{\rm eff})^2$. By equating the total energy $z_x^2/2 + U_{eff}$ at the top and bottom of the trajectory we recover the turning condition $c_{\rm eff} = c_{\rm eff}(0)/\sin(\phi)$ derived above.

If the peak in $c_{\rm eff}$ near z=50 km has $c_{\rm eff} = c(0) + \Delta$, then the rays bend back to earth in the range $\pi/2 - \Delta/c_{\rm eff}(0)$ □ ϕ □ $\pi/2$. The range is given by

$$x = 2\int_0^{z_{max}} \frac{dz\,\sin(\phi)}{c_{\rm eff}(0)^2/c_{\rm eff}(z)^2 - \sin^2(\phi)}. \tag{7}$$

Figure 10 shows a calculation of ray trajectories for infrasound in the N-S and E-W planes, for a representative profile of temperature and sound speed. Ducting at $\sim$ 100 km, $\sim$ 35 km, and in the troposphere can be seen.

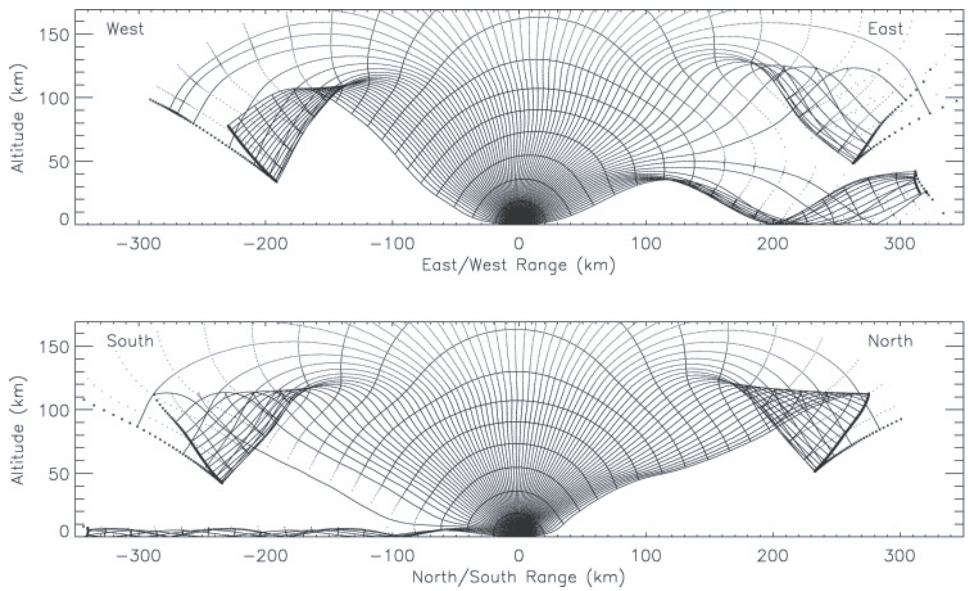

Figure 10: Model calculation of sonic propagation. Note the low-elevation duct in the lower panel, due to ambient wind. From [1]

4.2 Attenuation

A burst of sound on the ground will send out rays in all directions. The loudest sounds that are received depend on attenuation. We have already mentioned the fact that there is attenuation due to spherical spreading, which causes the sound intensity to decrease by 20 dB when the distance from the source increases by an order of magnitude, independent of the frequency. However the dominant loss mechanism is through dissipative processes, which cause the energy in a sound wave to decrease exponentially with distance. The characteristic length scale over which this energy loss occurs is given by

$$L^{-1} = \frac{\omega^2}{\rho c^3}\Big(\frac{4}{3}\eta + \zeta\Big), \tag{8}$$

where ρ is the density of air, c the sound velocity, and η, ζ the shear and bulk viscosities. This formula exposes the prime advantage for low frequency acoustic propagation: the attenuation length increases dramatically with decreasing frequency.

For infrasound propagation, it is important to examine the altitude dependence of this propagation length. This can be obtained by noting that the shear viscosity is given by $\eta/\rho \sim \ell c$, where ℓ is the mean free path between the air molecules, whereas the bulk viscosity $\zeta/\rho \sim \tau c^2$, where τ is the relevant relaxation timescale (typically these depend on vibrational relaxation of molecules N_2, O_2, etc.) We have discussed above the fact that the sound velocity changes by about ten percent with altitude. Therefore, we expect that the change in the bulk viscosity ζ will be roughly at the twenty percent level (the molecular vibration timescale is not altitude dependent). On the other hand the shear viscosity will increase strongly with altitude, because the mean free path increases with decreasing density (as ρ^{-1}). Force balance in the atmosphere implies that the gas density decreases exponentially with height $\rho = \rho_0 e^{-z/L_a}$. Thus we expect the shear viscosity to increase as $\nu(z) = \eta/\rho(z) = \nu_0 e^{z/(L_a)}$, where ν_0 is the viscosity at ground level. Data (CRC) demonstrate that the viscosity increases by seven orders of magnitude from ground to 100 km. Between the ground and 20 km, ℓ increases from 10^{-5}cm to 10^{-4} cm with a corresponding η/ρ change from 0.1 cm^2/sec to 1 cm^2/sec. At 100 km, $\ell \approx 10^2$ cm, and the viscosity is 10^6cm^2/sec! A fit to the data yields $L_a \approx 6$ km. This is in reasonable agreement with the isothermal atmospheric scale height $c^2/g = 11$ km.

4.2.1 The dominant rays

We are now in the position to calculate the attenuation of a sound ray. Let us suppose that the ray travels along the path $z(x)$ through the atmosphere. The viscous attenuation of this ray is by the factor

$$\exp(-\Gamma) = \exp\left(-\int_{path} ds\ \frac{\omega^2}{c^3}\left(\frac{4}{3}\nu(z) + \zeta\right)\right) \tag{9}$$

The attenuation factor Γ is clearly dominated by the high altitude part of the path, owing to the exponential increase in $\nu(z)$. If we expand $z(s) = z_{max} - s^2/R$ around the top of the ray path, we find that

$$\Gamma \approx \frac{4}{3}\frac{\omega^2}{c^3}\nu_{max}\int ds \exp(-s^2/R\ell) \approx \frac{4\sqrt{\pi}}{3}\frac{\omega^2}{c^3}\nu_{max}\sqrt{\ell R}. \tag{10}$$

Now, from the previous section, we know that the radius of curvature of the path $R^{-1} = |z_{xx}| = c'_{\rm eff}/c^3_{\rm eff}c_{\rm eff}(0)^2/\sin(\phi)$, so that the attenuation factor is

$$\Gamma = \frac{4\sqrt{\pi}}{3}\frac{\omega^2}{c^3}\nu_{max}\sin(\phi)\sqrt{\ell\frac{c^3_{\rm eff}}{c'_{\rm eff}c_{\rm eff}(0)^2}}. \tag{11}$$

We are interested in the ray of minimum attenuation. On the surface equation (8) implies that this occurs for the ray with minimum deflection angle $\phi = \pi - \Delta/c(0)$. However, at the minimum deflection ray, formula (8) breaks down, because at this point R^{-1} vanishes since $c'_{\rm eff} = 0$. The problem can be corrected by noting that for the minimum deflection ray, $z(s) = z_{max} - Cs^4$, where $C = c'''_{\rm eff}c_{\rm eff}(0)^2/c^3_{\rm eff}/sin^2(\phi)$. If we write $c'''_{\rm eff} = (c(0)+\Delta)/\ell_a^3$, then we find (in the limit of small Δ)

$$\Gamma_{min} = \frac{4\sqrt{\pi}}{3}\frac{\omega^2}{c^3_{\rm eff}}\nu_{max}\sin(\phi_{min})\left(\ell\ell_a^3\right)^{1/4}. \tag{12}$$

Interestingly, the attenuation properties of the atmosphere imply that attenuation of the ray is essentially independent of the range (other than the dependence of viscosity on altitude $\nu(z)$)! The atmosphere is a low pass filter. (This fact must be known from CTBT, as the same argument applies to the 120 km reflection point).

We now are in the position to determine the useful frequency range for both the 50 and 100-km ducts. Figure 11 plots the attenuation as a function of frequency for both of these ducts. For the 100-km duct, the transmission drops by an order of magnitude at about 2 Hz, whereas for the 50-km duct, the transmission drops by an order of magnitude at about 100 Hz.

4.2.2 Turbulent Eddy Viscosity and Acoustic Attenuation

Turbulence is present at a variety of altitudes and can contribute to the attenuation of sound if the effective eddy viscosity, $\nu_{\rm eddy}$, exceeds the molecular viscosity. In the absence of detailed measurements, we will estimate $\nu_{\rm eddy}$ by presuming isotropic turbulence with Kolmogorov scalings (see [14]). In this view of turbulence, the prime driver is a large-scale shear that leads to a local energy dissipation rate (due to molecular viscosity at the smallest

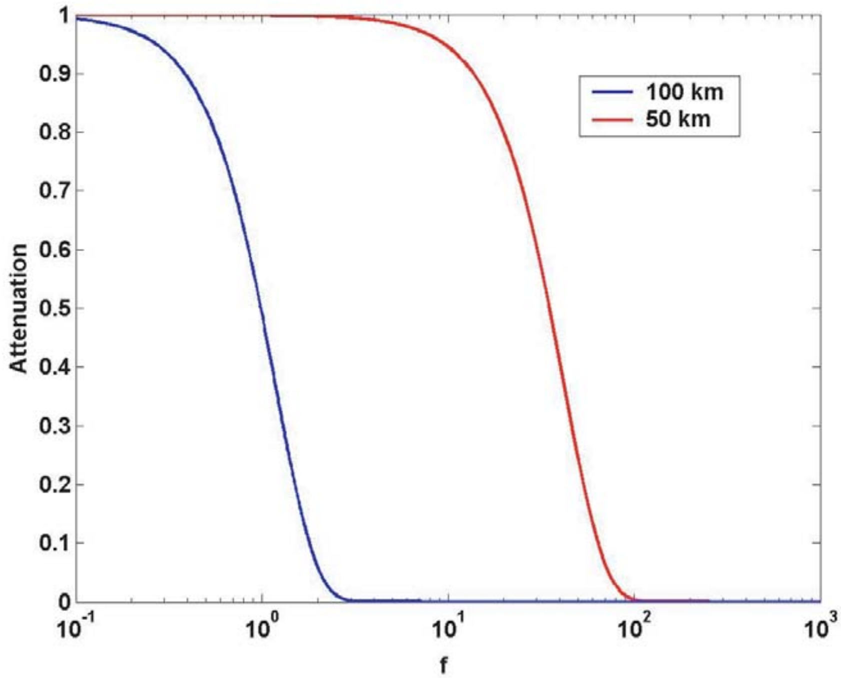

Figure 11: Attenuation as a function of frequency (in Hz) for scattering into the 50- and 100-km ducts.

eddy size)

$$\epsilon = \frac{\Delta v^3}{l}, \tag{13}$$

where Δv is the characteristic shear velocity (roughly equivalent to the largest eddy speed) at the largest length scale, l (or largest eddy size). These quantities will vary with altitude in the atmosphere. The velocity of a turbulent eddy of size λ is $v_\lambda \approx (\epsilon\lambda)^{1/3}$, giving

$$\nu_{\rm eddy} \approx \lambda v_\lambda \propto \lambda^{4/3}, \tag{14}$$

which clearly increases with the length scale of turbulent eddies that are allowed to contribute, and if allowed to go to the outer scale would yield $\nu_{\rm eddy} \approx \Delta v l$. Something like this viscosity is shown in Figure 40-3 of [15] and was a cause of concern, as this number is quite large, possibly $\nu_{\rm eddy} \sim 1 - 100\ {\rm m^2 s^{-1}}$ at an altitude of 50 km, leading to an attenuation of the sound that would be more dramatic than that from molecular viscosity.

However, we feel that the turbulent viscosity relevant to acoustic attenuation should only include those eddies which turn over on a timescale, $t_{\rm eddy} \sim \lambda/v_\lambda \propto \lambda^{2/3}$, shorter than the wave period. This then defines a maximum λ,

$$\lambda_{cut}^{2/3} \approx \frac{2\pi\epsilon^{1/3}}{\omega}, \tag{15}$$

which then yields a frequency dependent eddy viscosity for acoustic attenuation

$$\nu_{eddy} \approx \epsilon \left(\frac{2\pi}{\omega}\right)^2, \tag{16}$$

and a cancellation of the frequency dependence in the attenuation formula,

$$L \sim \frac{c^3}{\nu\omega^2} \sim \frac{l}{4\pi^2}\left(\frac{c}{\Delta v}\right)^3. \tag{17}$$

Now, what does this give us? It seems that at most, the turbulent velocity amplitude is $0.1c \approx 30$ m s^{-1}, and that the length scale is of order 1 km. For those scalings, we get $L \sim 25$ km for the scalings, including the 2π etc. This estimate of the eddy viscosity is still likely a high guess and would not be present over the whole region.

An alternative scaling (though we don't feel is likely appropriate) is to use all eddies of wavelengths smaller than the acoustic wavelength, λ_s (remember, these eddies will not overturn during the wave passage). In that limit, the scaling for the attenuation length becomes $L \sim (c/\Delta v)(\lambda_s^2 l)^{1/3}$, which for a 1 Hz wave and $l = 1$ km gives a 5 km range or so. It might well be possible to eliminate such a viscosity scaling with direct measurements.

4.3 Detections in the Shadow Zone

There are documented instances (particularly in the Netherlands; see the excellent website of Evers [16]) where infrasound detections have been made in the "shadow" zones, where ray-tracing predicts that there is no propagation path to this location. These have been at frequencies near 1 Hz and at separations ranging from 3 km (Utrecht explosion in an office building) to 70 km (Fireworks factory explosion in Holland). In these publications, passing mention is made of turbulence in the Earth's atmosphere as the cause of “spurious” reflections, but we have found few quantitative theoretical calculations of this effect.

It is generally acknowledged that there are two basic mechanisms that contribute to acoustic scattering in the shadow zone: diffraction, and the turbulent scattering of sound.[17] Here, diffraction refers to corrections to the geometric optics approximation. In general we expect that diffraction will be most important at low frequencies (since the size of diffractive effects will be of order the ratio of the wavelength of sound to the scale over which the sound velocity is varying).

The frequency range where turbulent scattering can dominate depends on the characteristics of the turbulence; it is generally acknowledged that scattering of sound from turbulence involves fundamentally scattering off of the vortices in the flow (see, e.g. [18]). If the wavelength of sound is much smaller than the size of the vortex, then a "geometrical optics" approach can be formulated; the wavefront is bent by the interaction with the vortex (see, e.g. the appendix of Colonius et. al.[18]). If the sound wavelength is much larger than the size of the vortex, the scattering is essentially isotropic and the Born approximation is appropriate.

It is unclear which of these two contributions dominates the turbulent scattering into the shadow zone: on one hand, the Born scattering is isotropic, so the amplitude is diminished relative to the scattered signal of shorter wavelength sound, where geometrical optics applies. On the other hand, the magnitude of the scattering is enhanced by larger vortices. As described above, most of the energy in a turbulent flow is in the larger scales. There is clearly a balance between these two effects where the dominant scattering will take place, though the optimal condition is not known.

We believe that there could be a significant opportunity for further research here, as developing an understanding of what dominates scattering into the shadow zone could well provide the needed insight for starting to use shadow-zone detections to identify sources. The opportunity is significant, because by definition, acoustic waves in the shadow zone have shorter path lengths, and reach lower altitudes, than their counterparts in the high altitude ducts. The resulting lower attenuation should therefore allow even higher frequencies to become accessible.

5 CHARACTERIZING THE PROPAGATION PATH

The propagation of sound energy over the distances of interest, from a few km to perhaps a hundred km, is highly variable as it depends on the wind and temperature profiles of the atmosphere along the path from the emitter to the detector. In order to properly understand the nature of a detected source of sound, or (of equal importance!) to properly interpret the absence of detections, it is vital to understand the propagation properties of the atmosphere.

Infrasound's traditional use has been for monitoring of atmospheric explosions over large distances across the Earth's surface and it is under active development and use for CTBT monitoring at the present time. On these 1000-5000 km length scales, the dominant propagation effects are from the changing temperature profile in the atmosphere, and global winds. As such, it is usually treated as a global problem, although local topography/meteorology does play a large role. There are abundant examples of the successful application of global (seasonally adjusted) atmospheric models to the problem of locating sources of infrasound.

The frequencies that are typically of interest are in the range of 0.1 to 100 Hz (wavelengths of 3 km to 3 meters), and the propagation calculations are nearly always carried out by ray-tracing. Hence, the changes in all atmospheric quantities are assumed to occur over length scales much longer than a wavelength. Alternative approaches are presently under development.

The pressure signal detected by the sensor system contains the combination of the source's sonic power spectrum and the distortions (in both spectrum and wavefront direction) introduced by the atmosphere. In order to extract the source characteristics from the data, and to properly translate angle of arrival information into a location, the atmospheric contribution must be understood.

We therefore consider a program of path characterization as an essential ingredient in successfully exploiting tactical sonic signatures, over the ranges of interest. There are two possible approaches to this problem: 1) direct acoustic measurement of the atmosphere's propagation characteristics, and 2) indirect techniques that blend meteorological measurements with atmospheric modeling. The two are not mutually exclusive, and it makes sense to us to pursue them both.

5.1 Direct Path Characterization: Acoustic Tomography

By installing sources with known sonic spectra at known locations, the propagation character of the atmosphere can be measured directly. We have in mind a set of emitters that produce sonic waves, probably in the 1-10 Hz band, which are in continuous operation, perhaps with complementary time-domain sharing duty cycles. One could imagine installing sources at the tactical array sites, or at other advantageous locations. Ships at sea may well provide very valuable platforms from which to test atmospheric propagation properties. It may also turn out that monitoring the atmospheric propagation in accessible regions surrounding an array may produce valuable information about the propagation properties in inaccessible regions surrounding an array.

Constructing a source of pressure waves that efficiently couples energy into the atmosphere is by no means trivial, but we stress that knowing the source characteristics (location and frequency) should ease detection. We recommend that some experiments be done to determine the viability of real-time acoustic tomography.

5.2 Indirect Path Characterization: Meteorology and Models

Given sufficient knowledge of the wind and temperature structure of the atmosphere, its acoustic propagation properties could be calculated. If terrain effects are also taken into account, a complete real-time model for propagation, including attenuation, could be developed. This model could then be used to compensate for variations in path propagation properties. Unfortunately the relevant section of the atmosphere extends up to 100 km above the surface, and includes regions of the atmosphere that are not typically measured by radiosonde sensors, since they don't have much effect on weather at the Earth's surface.

The G2S (ground to space) project at the Naval Research Laboratory (NRL) is an ambitious effort [1] to integrate low level real-time meteorological data with empirical models of the upper atmosphere. This project, or perhaps a suitable modification with appropriate grid sizes, could prove very useful in calculating near-zone sonic propagation through the atmosphere. Incorporating this sort of model into the ray tracing infrasound source location software presently being used is a sensible goal. Figure 12 shows how the G2S model splices lower level data onto validated models of the upper atmosphere.

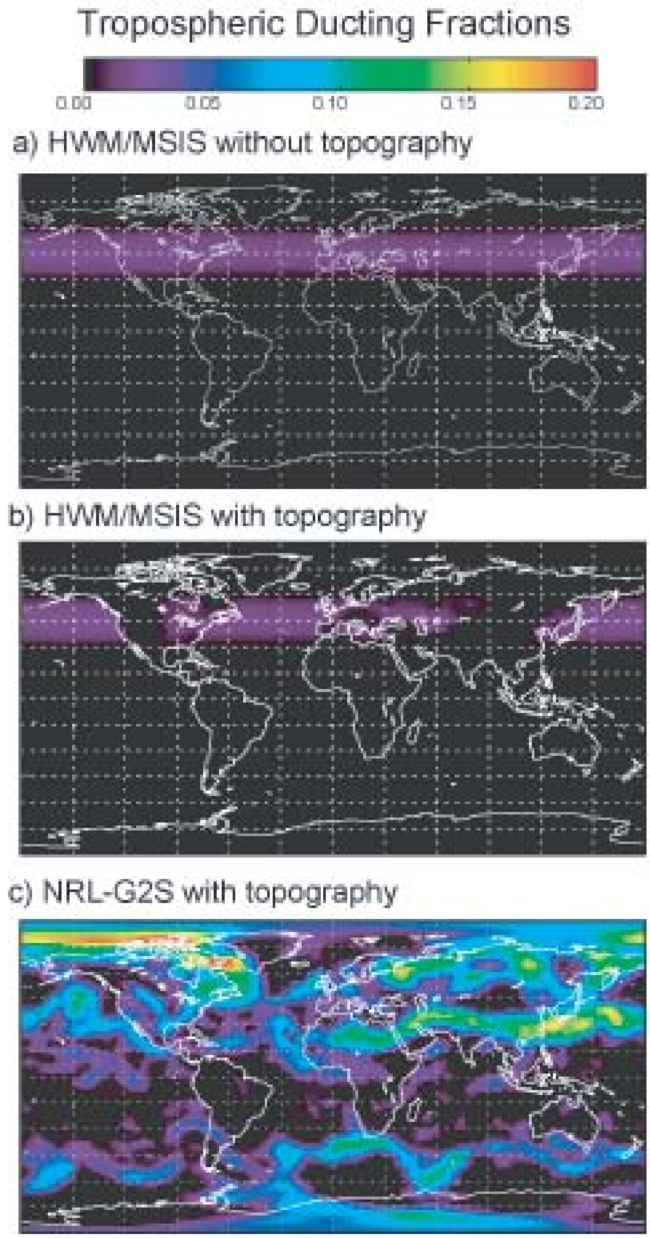

Figure 12: Combining low elevation meteorology with upper atmosphere models. This figure is taken from reference [1], and shows (in the lower panel) the substantial effect of topography and meterological data.

6 SIGNAL TO NOISE CONSIDERATIONS, AND OPTIMAL FREQUENCIES

The optimum frequency range over which to listen for sound from sources of interest is determined by 1) the sound spectrum emitted by the source, 2) the frequency-dependent attenuation along the propagation path, and 3) the noise spectrum seen at the sensor. As shown in Section 3 above, most of the sources of interest have emission spectra that rise steeply with increasing frequency. On the other hand, atmospheric transmission imposes an effective cutoff frequency that depends on the maximum elevation reached by the ray bundle.

The noise at the sensor includes contributions from

- Intrinsic thermal noise in the sensor,

- Non-sound fluctuations in the ambient pressure field, including sensor-induced turbulence,

- Detector artifacts, such as thermal and seismic feedthrough,

- Sound noise, including wind-generated sound from terrain and structures, and sounds emitted by uninteresting sources of both natural and man-made origin.

Each of these noise terms has a particular frequency dependence. Furthermore, the different noise mechanisms exhibit different dependence on wind speed and direction. We will defer the consideration of the nuisance acoustic sources, perhaps more properly termed 'clutter', until the section on source discrimination and characterization.

6.1 Sensor Noise

Thermodynamics imposes a limit on the performance of any sensor system, at both the transducer and (in a well designed system) at the preamplifier. For any capacitive sensor, as long as there is not an electrical resonance within the passband of interest, the RMS voltage fluctuations will obey $V_{RMS} = \sqrt{kT/C}$, where T is the temperature of the transducer, C is its capacitance, and k is Boltzmann's constant. This can be converted into an equivalent RMS pressure noise by dividing this quantity by the transducer's sensitivity S, in Volts/Pa. These fluctuations have a flat spectrum in equivalent acoustical energy per unit bandwidth (up to a cutoff frequency f_{cutoff}) at a level given by $P^2(f) = \frac{kT}{2\pi RC^2S^2}$ where R is the parallel resistance seen by the sensor, and the other variables are as defined above. Other sensor types will have some other, but similar, fundamental limit to their performance.

The noise characteristics of the preamplifier, typically parameterized in terms of input voltage noise and current noise, in conjunction with the source impedance of the transducer, also must be taken into account. As shown below, at frequencies up to a few Hz, the sensor properties seldom limit system performance. At higher frequencies, however, in quiet conditions a noisy sensor can limit detection thresholds.

We note that there is a wide range in the thermal noise properties quoted for various sensors, differing by orders of magnitude. This observation, coupled with the realization that frequencies above the traditional infrasound regime are likely of great interest, motivates our recommendation that the DoD maintain an ongoing assessment of pressure transducer technology, bearing in mind the cost-performance tradeoff.

6.2 Pressure Noise, and Spatial Filtering

We define pressure noise as those fluctuations in the pressure field at the sensor which do not obey the wave equation. These fluctuations arise from turbulence and other complex effects, usually with a strong dependence on wind speed. Figure 13 shows typical noise power spectra measured with an IMS sensor, parameterized by wind speed.[19]

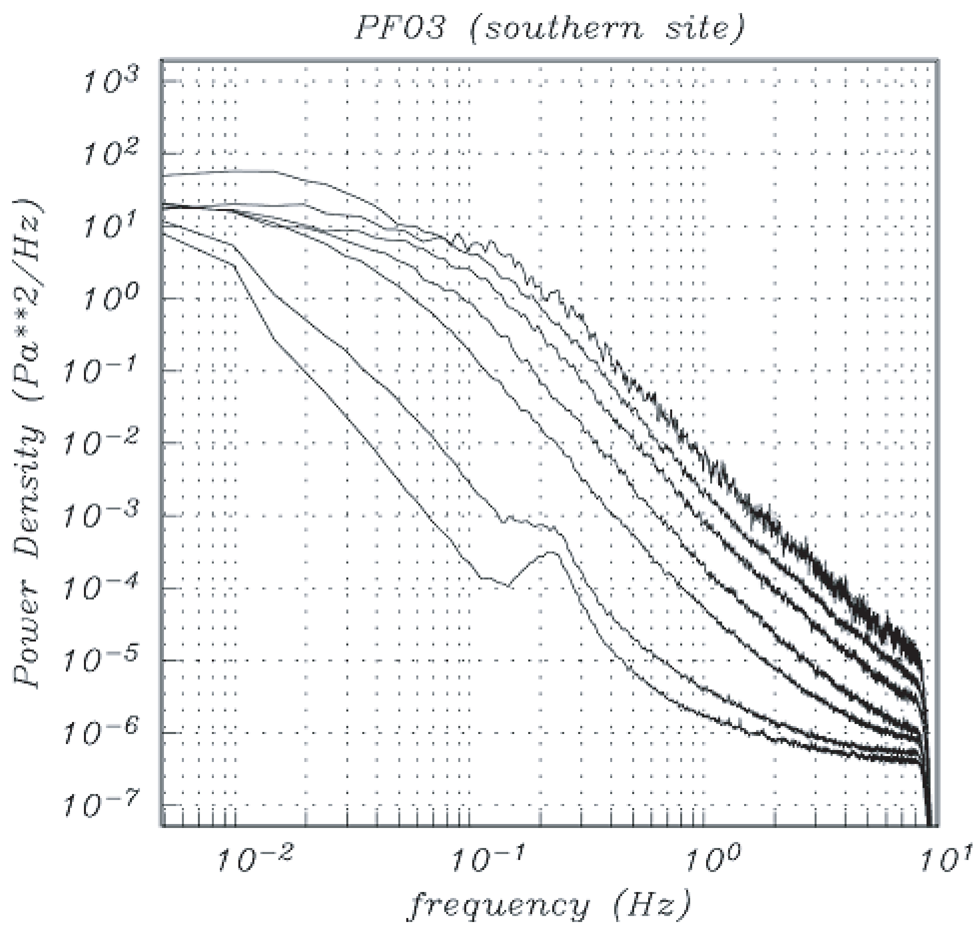

Figure 13: This figure shows the acoustical energy per unit bandwidth, in Pa^2/Hz, parameterized by wind speed. For appreciable wind speeds the energy per unit bandwidth falls at $1/f^3$. At low wind speeds the 'microbarom" of geophysical origin is clearly visible. Note also the sensor noise floor at 3×10^{-7}. From [34].

We can provide a rationalization for the frequency dependence of the pressure fluctuations in the context of turbulence. Fully developed Kolmogorov turbulence has a characteristic scaling relation such that the typical rms velocity on a scale λ (over a logarithmic scale range) goes as

$$v \sim \lambda^{1/3}$$

We can use this to estimate the fluctuations this causes in a pressure sensor. The turnover frequency time for an eddy ω at this scale size is related to the scale and velocity as

$$\lambda \sim v/\omega$$

which leads to

$$v \sim \omega^{-1/2}$$

The pressure fluctuation associated with characteristic rms velocity v goes as v^2 from the momentum and rate of delivery of momentum, so

$$P \sim v^2 \sim \omega^{-1}$$

The acoustic power spectrum then is

$$\frac{dP^2}{d\ln\omega} \sim \omega^{-2}$$

or

$$\frac{dP^2}{d\omega} \sim \omega^{-3}$$

The acoustic power density characteristically rises as f^{-3} at low frequencies. Note also that we would expect the amplitude of the power density to increase with increasing wind velocity at least as v^4, and probably somewhat faster than this because higher wind speeds will increase the scale of the shear above the ground, which can couple energy into the Kolmogorov turbulence from larger length scales. This picture is in agreement with the features seen in Figure 13.

The combination of increased source strength and decreasing pressure noise at higher frequencies provides a compelling motivation to listen for sources at frequencies right up to the atmospheric cutoff. Under atmospheric conditions where the sound is returned from elevations $z < 50$ km, this cutoff frequency can extend up to 100 Hz. We think there is considerable merit in extending the frequency coverage of the DMZ systems into this frequency regime.

6.2.1 Spatial Filtering, and Coherence Functions

Sensor arrays that average over a scale $D_{\text{node}} \approx 40$ ft have a reduced sensitivity to horizontal audio waves at frequencies above 25 Hz [3]. One would expect the variance in observed pressure, when averaged over an area A, to scale as

$$\sigma^2 = \sigma_0^2/(1 + A/A_0),$$

where σ_0^2 is the variance in pressure seen without spatial averaging, and A_0 is a typical area over which the pressure noise is coherent. We will return to the pressure coherence length, which determines A_0, below.

Acoustic sensors are more concerned with higher frequencies, where instrument-generated noises dominate, and have traditionally used foam or other materials to move the turbulent boundary layer away from the sensing element. This is an effective way to reduce the wind-driven noise that plagues microphones at audible frequencies.

There is clearly an upper limit to the area over which pressure measurements should be averaged. As soon as the averaging scale D_{node} approaches the acoustical wavelength of interest, λ, the system begins to average over a wavelength and sensitivity is suppressed. For example, a circular averaging area of diameter D_{node} has a null in sensitivity for horizontally propagating sound at frequencies with $\lambda = 0.82 \times D_{node}$.

The sensor arrays in place at the DMZ presently average over a scale $D_{node} \approx 40$ ft and therefore have reduced sensitivity to horizontal audio waves at frequencies above 25 Hz. Note that the propagation considerations outlined earlier in this report indicate that the sounds of interest will be arriving at fairly low angles from the horizon, and that we strongly suspect that there is interesting information at frequencies above 25 Hz. Our recommendations therefore propose re-arranging the hoses to enhance the existing system's sensitivity at higher frequencies. A bow-tie configuration would retain directional sensitivity to sounds, and would enhance signal strengths at higher frequencies.

A determination of the optimal spatial averaging scale requires knowledge of the coherence properties of the pressure field. We were somewhat surprised to learn that this is not an area of current activity within the sound monitoring community, and strongly encourage more basic work on this topic. We did find one nice example of the sort of work we have in mind, which is shown in Figure 14.[20]

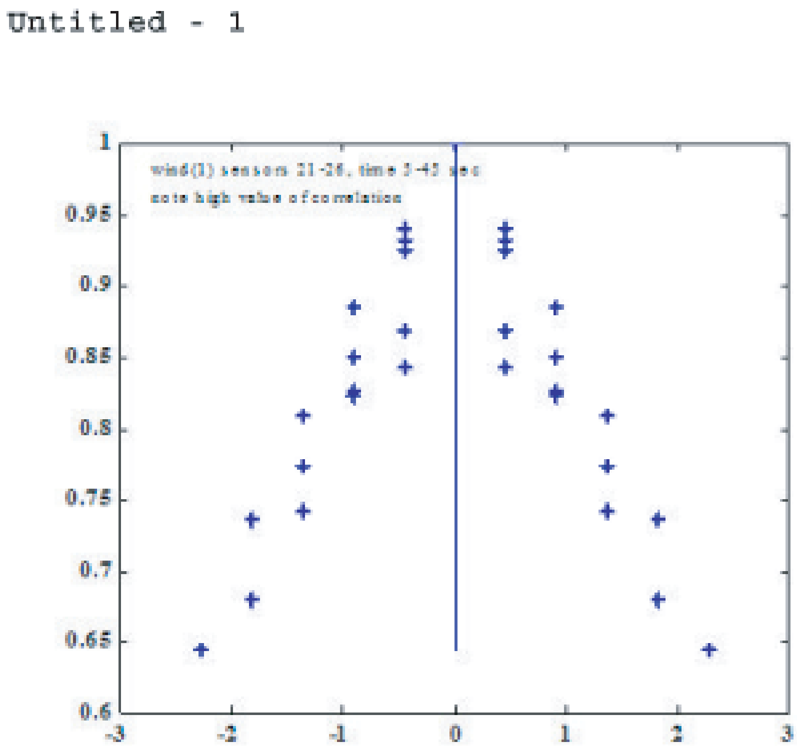

Figure 14: Pressure Field Correlation Measurements. This figure, from [20] shows how the pressure field correlation depends upon the separation (in meters) between two sensors. In order for spatial averaging to be effective under these conditions, the system must average over length scales of many meters.

Both field experience and the noise power curves shown earlier suggest that at frequencies above 20 Hz the dominant source of pressure noise is microphone-generated turbulence. In fact, in order to retain sensitivity to sounds at frequencies of 5 KHz, an audio microphone's averaging length must conform to $D_{node} < \lambda/2 < c/2f < 35$ mm. This accounts for the small characteristic length scale of typical microphones. The acoustic baffling used around microphones is effective because it moves the turbulent boundary layer away from the sensing element. The dominant noise at these frequencies, namely the microphone-induced (non-sound) pressure fluctuations, fall off exponentially in distance away from the boundary layer, and their effect at the sensing element is correspondingly suppressed.

Since the power spectrum of the pressure noise, and its spatial and temporal coherence, is a major factor in designing an optimized system, we strongly endorse the idea of mounting a vigorous program of both theory and measurement to better understand the pressure noise against which the detection of tactical sources of interest must compete. Specifically, we suggest a program to measure the pressure field's power spectrum, and its spatial and temporal correlation properties, at tactical infrasound array sites, over frequencies from 0.01 to 100 Hz, under a variety of wind conditions.

6.3 Overcoming Detector Artifacts

The pressure signals of interest are very subtle, and the instruments used to detect them are very sensitive devices. At some level the pressure sensors act as thermometers and seismographs, for example. We learned that the data stream from the existing systems suffers on occasion from artifacts due to thermal effects, seismic sensitivity, and the like. We suggest that a sensible approach to overcome these gremlins is to use an identical transducer that has no sensitivity to pressure, but that retains its instrumental sensitivity to the other confounding factors. For a differential pressure transducer this can be accomplished by pneumatically 'shorting' the two inputs together, for example. An absolute pressure sensor could be fitted with a series of cascaded pneumatic low pass filters with very long time constants, say $\tau >$ 5000 sec, which would greatly suppress its sensitivity to pressure fluctuations in the passband of interest. By measuring one such 'dummy' transducer's output as an integral part of the data set from each array site, these detector artifacts can be identified and largely eliminated.

7 DETECTION SYSTEM OPTIONS

7.1 Introduction

The charge for the 2003 JASON Summer Study on Tactical Infrasonics included determining whether infrasonic monitoring was likely to provide broader intelligence value. As part of this task, a survey and comparison of existing infrasonic sensor systems and conventional acoustic systems was conducted to identify the state of the art in sensor system technologies. Results of the surveys were then used to explore options for future infrasonic sensor system designs. This section first describes conventional infrasonic sensor systems; then, tactical acoustic sensor systems are reviewed and compared to the infrasonic systems. Finally, a preliminary design approach for a new tactical infrasonic sensor system is described.

7.2 Conventional Infrasonic Sensor Systems

During the 2003 Study, JASON received briefings on a variety of infrasonic sensor systems. Materials were also received from the 2001 and 2002 Infrasonic Technology Workshops and results of an internet and literature search. From this information, three distinct groups of activities related to infrasonic monitoring were found: international monitoring stations, Army's monitoring program, and a group of experimental systems. This section will briefly describe each activity.

7.2.1 Comprehensive Test Ban Treaty/International Monitoring Stations

In 1996 the Comprehensive Test Ban Treaty (CTBT) was endorsed at the United Nations banning all explosive tests that lead to a nuclear chain reaction [21]. In order to verify compliance with the treaty, the International Monitoring System (IMS) consisting of seismological, hydroacoustic, radionucleide, and infrasound monitoring stations was established. The infrasound network consists of sixty stations equipped with microbarographs distributed all over the world (Figure 15). These sensors use infrasonics to detect nuclear–weapon scale detonations thousands of kilometers away. The mission is at the strategic level and the sensor clusters are spaced on the order of thousands of kilometers apart. IMS cluster installation costs are on the order of $470,000 and consists of a microbarometer and digitizer monitoring frequencies of 0.01-10Hz (Figure 16) [22]. Elements within each cluster are spaced at one to three kilometers and the power and communications infrastructure are fixed. The IMS stations are intended to be permanent, long-term facilities with extended mission lifetimes.

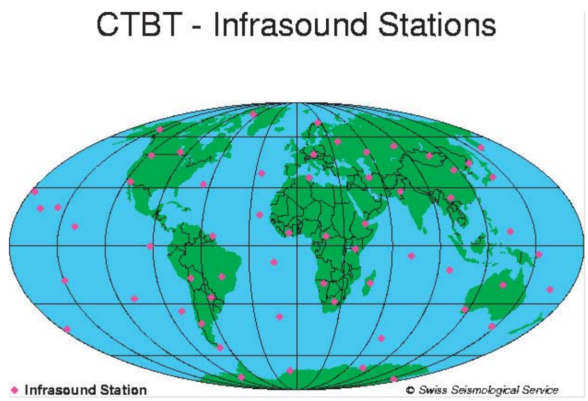

Figure 15: Infrasonic monitoring stations, from `www.seismo.ethz.ch/bsz`. (Note the IMS stations near the Korean peninsula.)

7.2.2 The Army's Infrasonic Collection Program

The Army maintains several infrasonic monitoring stations [23]. Sensors use infrasonics to detect threat activities; the mission is at the tactical/operational level and the targets are transient explosions, missile launches, underground facilities, and possible vehicles. The range is intended to be less than 100 km and the sensors monitor frequencies less than 20 Hz. Elements are spaced at about seven meters (20 ft) and the clusters are approximately 30 km apart. Power and communication subsystems appear to be fixed. The

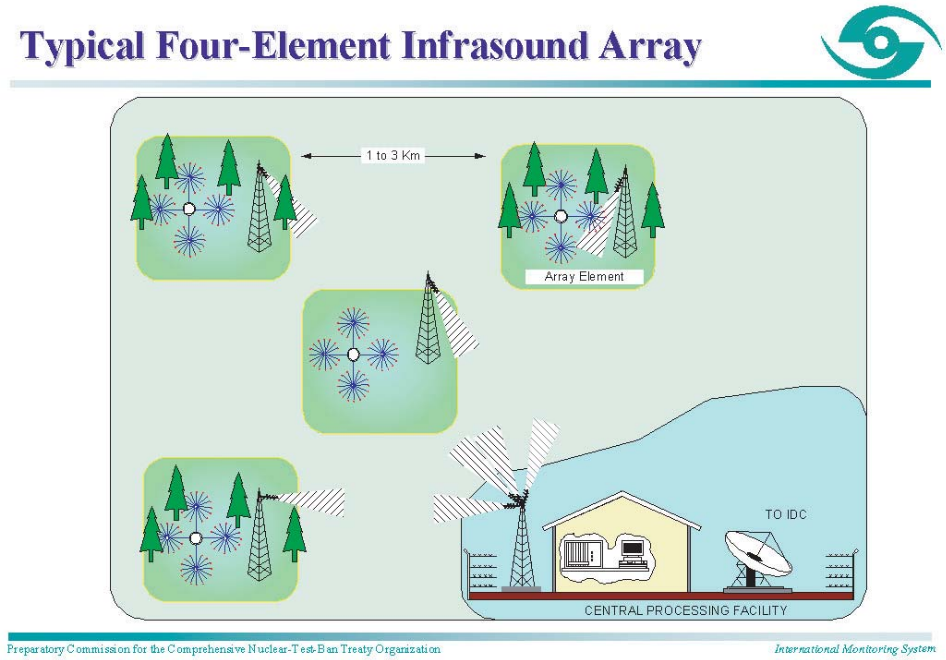

Figure 16: Infrasonic monitoring station layout, from [22]

stations appear to be relatively long–term with an extended mission lifetime.

7.2.3 Emerging Infrasonic Systems

A variety of research laboratories (Army Research Laboratory, Los Alamos National Laboratory, etc.) are developing a new generation of experimental infrasonic sensor systems, as illustrated in Figure 17. This generation of systems appears to be designed to detect transient events (such as explosions and missile launches) with ranges of 250 to 1,000 kilometers [24]. One system has clusters of sensors spaced on the order of hundreds of kilometers at the national laboratories. Within each cluster the elements are spaced approximately 20 meters apart and monitor frequencies below 50 Hertz. The current systems appear to be large and may require long–term, fixed facilities to operate.

Figure 17: A prototype infrasound array, from [24]

7.2.4 Conclusions

The survey of infrasonic sensors revealed a variety of systems that can be grouped into three categories of International Monitoring Stations, the Army's program, and a new generation of developmental infrasonic systems. Most systems were found to be developed to detect long–range transient events such as explosions and missile launches. It was found that the majority of these systems have strategic missions and require long–term, fixed facilities and are not considered tactically deployable

7.3 Tactical Acoustic Sensor Systems

JASON also collected information on tactical acoustic systems. Our objectives were to determine the state of the art in tactical acoustic sensor systems and to provide a benchmark for comparison to infrasonic systems. The survey was conducted through briefings, discussions, and literature searches. The scope was limited to three groups of acoustic sensor systems: Conventional remote sensor systems, emerging distributed ground sensor systems, and future ubiquitous sensor systems.

7.3.1 Conventional Remote Sensor Systems

Acoustic sensing in unattended ground sensors has a long history beginning back with naval sonobouys in the 1950's and the 'McNamara Line' of ground based sensors in the 1970's. Today, currently fielded systems such as the Remote Battlefield Sensor System (REMBASS) and the Tactical Remote Sensor System (TRSS) are hand emplaced and provide early warning of enemy vehicular activity [25]. These sensor packages detect, classify, and report direction of travel of vehicles up to a range of 350 meters. They employ acoustic, seismic, magnetic, and infrared sensors and have a mission lifetime of 30 days.

Helicopter detection systems using acoustics to detect and locate helicopters are also currently available, as illustrated earlier. Targets are rotary wing aircraft and ranges are advertised up to 20 km. The sensor system is co–located with the monitoring station and requires two people to set up. Sensor elements are spaced up to 12 meters apart and monitor frequencies from 30 to 375 Hz. While currently available systems are not autonomous the next generation system is advertised to be autonomously deployable with ranges up to six kilometers.

7.3.2 Emerging Distributed Ground Sensor Systems

Emerging systems such as the Future Combat System's Unattended Ground Sensors (FCS UGS) and the Defense Advanced Research Projects Agency's Micro–Internetted Unattended Ground Sensor (DARPA MIUGS) system are air-deployable, autonomous, and capable of providing targeting information for the networked battlefield, as illustrated in Figure 18 [27]. These tactical systems use self–organizing radio frequency (RF) networks to detect, identify, and track targets out to three kilometers. The sensors monitor the acoustic spectrum at frequencies above 100 Hertz. Sensor elements are spaced less than one meter apart and the nodes are spaced about 0.5km apart. These systems are short–lifetime tactical sensors designed for the fast–moving battlefield.

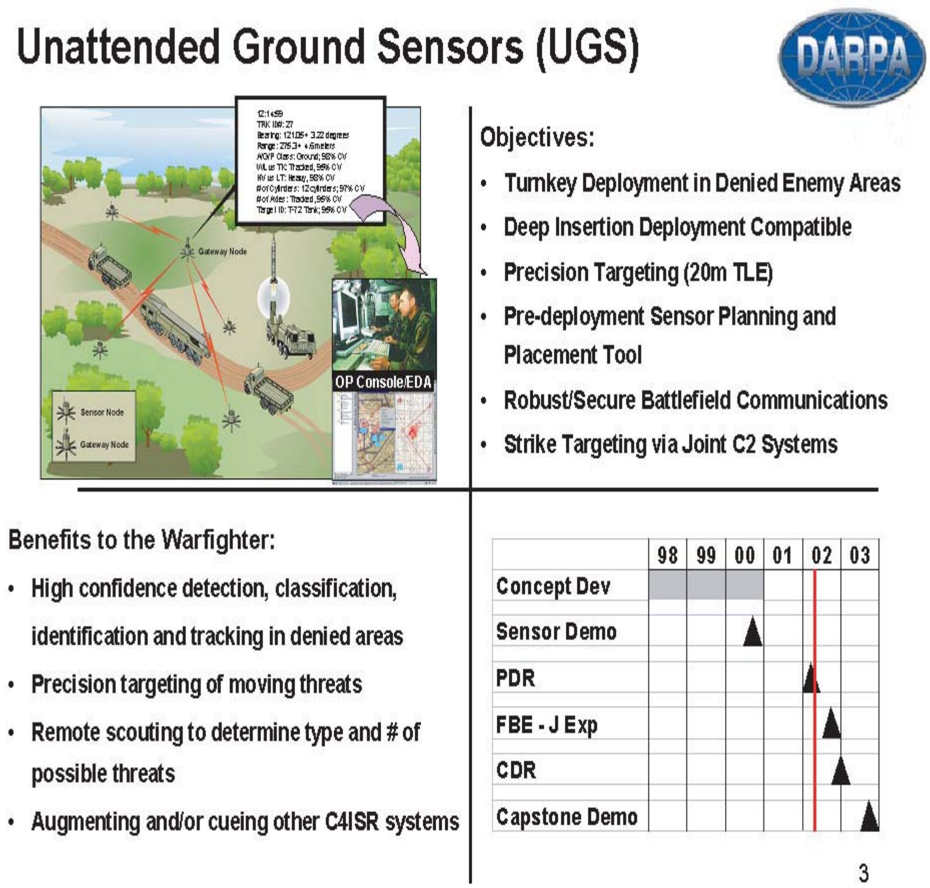

Figure 18: DARPA's MIUGS program, from [27]

The Self Healing Minefield is another DARPA program that aims to develop a networked anti–vehicle minefield that detects when one of the mines detonates, then rearranges itself to close the gap [28]. Densities are on the order of 10 meters and the deployed minefield has a lifetime on the order of one month. Aside from sensing when a target vehicle is near, the minefield does not share sensor information and is in a sense not truly a distributed sensor system. However, it has many characteristics similar to a distributed ground sensor system in that nodes frequently communicate to each other to detect and react to changes in the network.

7.3.3 Future Ubiquitous Sensing Systems

Future sensor systems are often described as ubiquitous because they are inherently coupled to the environment which they are sensing. Future military sensor systems will be coupled to the battlefield by being closely linked to munitions to create effects. Trends in future sensor systems indicate that sensor density will increase as the sensor nodes themselves will shrink. The SensIT program is another DARPA effort that is developing the self–forming and dynamic networking software that is required to operate large fields of wireless sensor nodes [29]. Goals of the program include the development of algorithms and software enabling cheap, smart, micro–sensors for rapid and accurate detection, classification, and tracking.

Smart Dust is a private corporation that originated from a DARPA project and aims to develop extremely small distributed sensor nodes [30]. Commercial off the shelf designs incorporate communications, processing, sensors, and batteries into a package about a cubic inch in size, as shown in Figure 19. Future visions include RF communication nodes that are short range (1-100m), low power (10nJ/bit), and low bit rate ($\sim$ 100 kbps).

7.3.4 Comparison of Infrasonic Systems to Tactical Acoustic Systems

One issue to be considered in the evaluation of a potential tactical infrasonic system is the ability to develop sensors that collect long–range information (such as the IMS system) through a tactically useful form factor (such as the UGS system). To assist in this evaluation, three systems considered in this study are compared in Table 2: the IMS system, the Army's infrasonic system, and a nominal UGS system. As shown, the Army's infrasonic system appears to be appropriately scaled, in terms of cluster and element spacing,

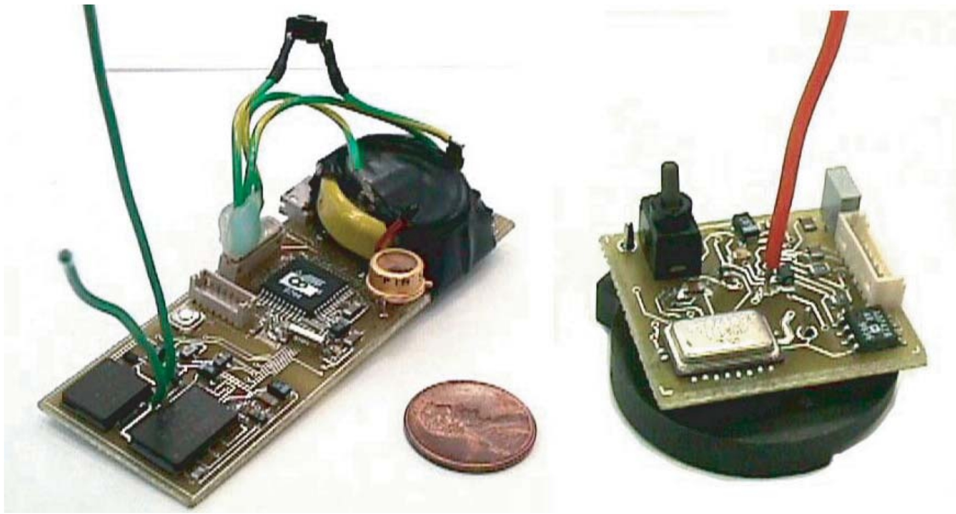

Figure 19: Commercial off the shelf wireless nodes from the Smart Dust group

between the IMS and UGS systems. However, it is also shown that in order for a system to be tactically useful, with rapid deployment, additional work in areas of deployability, autonomous operation, smaller form factor, and tactical communication links is necessary.

7.3.5 Conclusions

The survey to assess the state of the art in acoustic sensors revealed several fieldable systems. Objects that are detected by these systems include ground vehicles, helicopters, and snipers, and ranges are on the order of tens of kilometers. The systems were found to be rapidly deployable, autonomous, and have short lifetimes. A comparison of the Army's infrasonic system shows that the geometry appears appropriate but is not tactically deployable. A logical next step would be to explore whether such a system is technically feasible.

Table 2: Comparison of nominal infrasonic and acoustic sensor system characteristics

Metric	**IMS Infrasound**	**Army's Infrasound**	**UGS Acoustic**
Targets	Nuclear explosions	Transients, vehicles	Vehicles
Detection range	1,000's kms	30 km	3 km
Cluster spacing	1,000's kms	30 km	0.5 km
Element spacing	1,000 m	100 m	1 m
Cost per cluster	$470,000		$10,000
Detection frequency	<10 Hz	<20 Hz	>100 Hz
Deployment mode	Manual	Manual	Autonomous
Lifetime	Permanent	Permanent	14 days
Form factor	Large	Large	120mm dia
Geolocation	Manual	Manual	Automatic
Initialization	Manual	Manual	Automatic
Self–organizing	Manual	Manual	Automatic
Communication range	Fixed	Fixed	5 km

7.4 A Design Approach for a Future Tactical Infrasonic Sensor System

This section describes a procedure used to briefly explore the technical feasibility of a tactical infrasonic sensor system. First, requirements for the system are estimated. Then, a design approach based on a tactical acoustic system is used to identify nominal system requirements. Finally, these requirements are compared to existing and emerging systems to estimate feasibility.

7.4.1 Requirements

Requirements of a sensor system begin with the signature of the target. For this effort, consider an M60 tank which has an acoustic harmonic of approximately 10 dB less than peak at approximately 25 Hz [31]; also, assume the peak sound pressure level of a tank is approximately 100 dB.

The spherical propagation model is given by

$$P_r = \frac{P_t c^2}{4\pi r^2 f^2} \tag{18}$$

where P_r is the signal power received at the sensor, P_t is the source transmitted power, c is the speed of propagation, r is the range, and f is the frequency. From this simple estimate, and assuming a background noise level of 16 dB, the tank acoustic harmonic at 25 Hz and 90 dB would begin to be detectable approximately 35 km away.

For the sensor system to provide useful intelligence information, the location of the target must be estimated. One approach to localization is multiple bearing estimation (triangulation) where the bearing accuracy of a cluster is given by

$$\sigma_\theta = \frac{c}{2\pi f r \rho \sqrt{MN}} \tag{19}$$

where σ_θ is the bearing error, ρ is the signal to noise ratio per element, M and N are the number of elements and number of estimates measured together (assumed to be 4), c is the propagation speed, f is frequency, and r is the array size. The MIUGS system, described above, located targets with an accuracy of 20 m. An infrasonic system operating with two clusters spaced 30 km apart, containing 200 elements within a 50-m cluster diameter would be able to locate the above example target 30 km away with approximately a 46-m accuracy. This is roughly consistent with the ARL system, which uses multiple hose ports to average four microphones over a triangle spaced about 40 m apart.

Another requirement to consider is deployability. The tactical acoustic sensor systems reviewed above were all deployed via air platforms such as the Volcano or Gator deployment systems. Aside from the difficulties in deploying and arranging the conventional hose filtering system, other system requirements can be determined from the launch platform. The Volcano is capable of deploying 800 anti–tank mines and 160 anti–personnel mines, weighing 1.7 kg and 1.44 kg, respectively, bringing the total payload to 1,590 kg. The Gator is a fixed-wing air–deployable mine system that can carry 72 anti–tank and 22 anti–personnel mines for a total payload of 154 kg.

Payload volumes are 650,880 and 63,732 cm^3, respectively. Finally, the last requirement on the system is lifetime, which may be estimated from the acoustic system lifetimes of approximately 30 days.

7.4.2 Design Approach

The goal of this design exercise is to replace a soaker–hose filtering system with a rapidly deployable sensor system. As reviewed in the acoustic sensor system section, wireless sensor networks are becoming widely available. Requirements of the system, as stated above, are to distribute approximately 200 elements in a circle of 50 m radius with the whole system weighing less than 154 kg and containing less volume than 64,000 cm^3. The system is to last 30 days.

One widely available wireless networking system that may be able to meet these requirements is the MICA2 system from Crossbow Technologies, shown in Figure 20 [32]. The system is a third generation module used for enabling low–power, wireless, sensor networks. Various sensor and data acquisition boards can connect to the MICA2 through a 51–pin connector. The communications capabilities enable a 38.4 kb rate over a distance of 167 m (500 ft). Each node requires two AA batteries and weighs 18 grams and 13 cm^3, and the batteries weigh a total of 48 grams. Hundreds of these wireless nodes could fit into the Gator deployment system described above and may be able to meet the platform requirements of a tactical infrasonic system.

7.5 Sensor Options

Although the Army's infrasonic system uses the venerable Chapparal microphone, for the reasons outlined above we consider it prudent to consider other potential sensor options. This section demonstrates that there is considerable merit in pursuing alternative approaches, and gives specific examples that may be worth further evaluation and development.

Figure 20: The Crossbow MICA2 wireless node

7.5.1 Semiconductor Differential Pressure Sensors

Recent developments in semiconductor transducers have produced sensors that may be useful in acoustic monitoring applications. An example is the DUXL10D, marketed by Honeywell [33]. This device can be used in conjunction with a single low power integrated circuit, the INA125 from Burr Brown (now Texas Instruments) to make differential pressure measurements in the frequency range of interest. Figure 23 shows the DUXL10D.

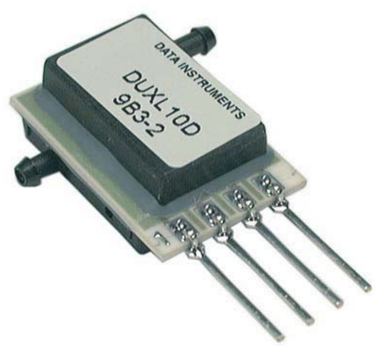

Figure 21: One potential low cost sensor, the Honeywell “Ultra-Low Differential Pressure Sensor” is shown.

Although semiconductor sensors that measure absolute pressure are available, we favor configurations that are sensitive to pressure differences. By connecting one of the two differential ports to an appropriately spatially filtered pressure signal, and the other to a temporal low pass filtered version of the pressure field, the dynamic range of the sensor can be used to full advantage for varying pressure over short ($\tau < 10$ sec) time scales, rather than slow changes in barometric pressure. This can be accomplished using a volume V fed by a pneumatic conductance G such that the characteristic time constant $G/V \approx 100$ sec.

During the course of the JASON study we procured both the Honeywell DUXL10D and the INA125 instrumentation amplifier, and the infrasound group at Scripps/IGPP has begun a program of sensor evaluation and characterization.

7.5.2 Microphones with Low Frequency Response

One way to bridge the infrasound/acoustics gap is to use microphones at frequencies below the traditional acoustic regime. Bruel and Kjaer markets a low-noise microphone, their type 4193, which responds at frequencies as low as 0.05 Hz. This device costs around $2,000, and has impressive noise properties. Used in conjunction with an appropriate spatial filter, with a judicious choice of preamplifier, this sensor could be a cost-effective choice for nodes in an acoustical sensor array.

7.5.3 Optical Fiber Infrasound Sensor

The Scripps team has developed an innovative sensor, the Optical Fiber Infrasound Sensor (OFIS), that measures the average pressure along a linear sensor using differential path length changes along a tube around which is wound an optical interferometer.[34] The OFIS system is straightforward to model, as there is no propagation delay of pressure along the pipe. The detector's directional sensitivity can be tuned by an appropriate choice of geometry.

The developers of the OFIS sensor have claimed a noise performance that is superior to that of the Chaparral sensor (M. Zumberge, JASON briefing).

7.6 Observations Regarding Development Potential for Tactical Sonic Monitoring Systems

In this section the results of surveys of infrasonic and conventional acoustic sensor systems were reviewed. Infrasonic systems were found to be mostly large, strategic monitoring stations requiring fixed facilities, power, and communication subsystems. It was concluded that conventional infrasonic systems are not tactically deployable. Acoustic sensors were found to be mostly tactical systems with rapid deployability and autonomous operation abilities. A comparison of the Army's system to these two benchmarks showed that the geometry appears to be appropriately scaled but additional work would be needed to make the system tactically useful. Finally, a design approach was described that could be used to examine the feasibility of a distributed, networked, and wireless tactical infrasonic system. Recent advances in wireless networks may enable development of a tactically deployable infrasonic sensor system.

There is ongoing development activity within the academic infrasound community, and we consider these development efforts worth fostering, especially in the context of arrays and noise characterization.

8 IMPROVED DISCRIMINATION AND CHARACTERIZATION OF SOURCES

Once a source is detected with high confidence, the challenge of extracting intelligence begins. This requires locating and characterizing the sound source. It is sobering to realize that a large fraction of the infrasound sources detected by IMS stations are of unknown origin. The location and spectral character of the source are both important in understanding its origin and nature. We stress the point that simple angle of arrival information is inadequate in determining unambiguous source location, due to variations in atmospheric propagation.

We expect that in order to fully exploit the intelligence value of sound data, representative source spectra and real-time propagation path properties will both need to be well understood. In the interim, in order to reduce the time spent analyzing uninteresting sources, we propose to take full advantage of the limited geographical region of interest. By definition, the objects of tactical interest are within 100 km of the sensor arrays. Any information that can be used to determine source location is therefore extremely valuable.

8.1 Improved Discrimination Using "Veto" Channels

We propose that the discrimination of sound sources would be much improved by incorporating all available relevant information on detected events, to better identify those of most tactical interest. A joint analysis of the Army's infrasound data with seismic data, infrasound data from the IMS system and other sensors, and acoustic information from microphones will provide significant added value.

Any infrasound event that produces a measurable signal in the IMS sensors is unlikely to be of tactical interest. This information can be used to "veto" events that arrive from sources that are outside the tactical region of interest. Figure 15 shows IMS infrasound and seismic monitoring stations.

This infrasound veto can be supplemented by similar data from seismic and acoustic sensors. Joint analysis of seismic and infrasound data obtained by the academic community demonstrates the value of comparing seismic and sonic arrival time differences in constraining event locations.

By concentrating on those events that produce coincident detections in the Army's infrasound arrays, but which do not have corresponding detections in the "veto" channels, the intelligence analyst efforts can be concentrated on events of tactical interest. This will require some development, in order to provide the analysts with a means to access, visualize and interpret the data from these other sensor systems.

8.2 Differential Source Localization?

One possible way to empirically compensate for variation in apparent angle of arrival due to changes in atmospheric propagation is to take advantage of any fixed locations that reliably produce a detectable signal. The apparent azimuth bearings of these sources can then be used to make real-time corrections to the bearing of sources of intelligence interest. This differential source location technique of course requires some at least intermittent sources of known location. These acoustic sources could include essentially anything at a known position, including perhaps airports, wind-driven excitations of bridges or other structures, wind-driven sound from terrain features, or industrial activity, as examples. This approach essentially amounts to using natural sources to perform a modest amount of acoustic tomography of the atmosphere. We think it may be worthwhile to search the existing data for evidence of sources that may be useful in this fashion.

8.3 Constraining Range by Sonic Spectroscopy?

The spectral content of a detected signal provides an important clue to its distance. In general, the farther away the source is, the stronger the atmospheric attenuation at high frequencies, and the lower the atmospheric cutoff frequency. In order to fully exploit this phenomenology, the spectral energy distribution of the source must be known. Even in the absence of full knowledge of the source's spectral characteristics, however, we suspect this "spectral ranging" approach may be of considerable value. Sources that show little sonic energy content above 1 Hz are likely to have been detected via high-atmospheric returns, and are most probably outside the tactical region of interest. We know of no man-made source that shows a falling spectrum at frequencies of 1-100 Hz.

9 REGARDING THE BROADER UTILITY OF SONIC INFORMATION IN INTELLIGENCE PROBLEMS

Infrasound instrumentation was an active field of research in the early era of nuclear weapons development [35]. More recently, the value of infrasound in monitoring test ban treaties has led to a resurgence of interest. A number of academic groups are pursuing infrasound research as a multidisciplinary tool to investigate phenomenology ranging from avalanches to meteorites. The deployment of tactical monitoring arrays is an innovative step, and we encourage refinement of the deployed system capabilities.

The JASON group thinks there is considerable merit in supporting continued development of sonic monitoring tools and techniques, ranging from sensor development to atmospheric modeling, in anticipation of their application to intelligence problems. An array of low power robust sensors could be used to monitor diverse activities from a distance. Sonic data could provide strategic information to corroborate rocket launches that are detected by other means, including perhaps location information for mobile launch vehicles. Activity levels at military airfields could be monitored from a safe distance. Real time bomb damage assessments could be augmented with sonic data; particularly when attacking targets below the surface, listening for the explosions can help identify instances when the ordinance fails to detonate. These are but a few examples of the potential utility of sonic monitoring in the intelligence arena.

A tactical infrasound system would provide an interesting test-bed for a real-world application of this approach. As described elsewhere in this report, there is considerable opportunity to enhance the performance of a tactical infrasound system by refining both the sensors and the data analysis tools. A community investment in addressing the outstanding issues faced by a tactical infrasound system will pay dividends throughout the intelligence community, as we learn how to better exploit new applications of sonic monitoring.

10 RECOMMENDATIONS

Our recommendations fall into two categories. We have collected the suggestions that might provide a near-term enhancement of the effectiveness of a tactical infrasound system into Recommendation #1. The other suggestions point out research opportunities that should accrue benefits over a longer term.

Recommendation #1. Near-Term Ideas for Enhancing Tactical Infrasound Monitoring Systems

1.1 Increase the upper limit in frequency coverage, by re-arranging the filter hoses and increasing the sampling rate.

Given the likely increase in signal to noise ratio at frequencies up to the (variable) atmospheric cutoff, we suggest that the spatial filter be re-arranged to provide more sensitivity at high frequencies, that any low pass filter on the sensor be modified to pass frequencies up to 100 Hz, and that the sampling rate be increased to 200 Hz. The existing passband can always be reconstructed by performing a low pass operation in software. Although a parallel arrangement of the spatial filter hoses may not provide quite the same suppression of pressure noise as a star configuration, we suspect the higher frequency information will more than compensate. We recognize that this arrangement will introduce directionality in the array's beam pattern, but we consider this to be a good thing!

1.2 Use emplaced sound sources to dynamically calibrate and characterize atmospheric propagation.

An ongoing calibration of the propagation path would provide important input to interpreting tactical infrasound data. We suggest picking perhaps 6 sites where sources could be permanently installed, some even perhaps as far as 100 km apart, and driving the sources at about 10 Hz. This frequency should be largely inaudible to people, and will be heavily attenuated before reaching any IMS stations that surround the tactical array. They don't need to be on continuously, but only need sample the atmosphere periodically. It would also be a good idea to make a mobile source, and to run exercises in locating it from the tactical infrasound data set.

1.3 Use infrasound data from the International Monitoring System (IMS), seismic and other data from the surrounding area to "veto" events that are outside the region of tactical interest.

The limited geographical region of interest can be exploited, by rejecting sonic events that are detected across much wider regions and that have origins outside the zone of interest. There is much to be gained by declaring certain events to be uninteresting because they fall outside the zone of interest. A combined analysis that joins locally sonic data stream with other regional infrasound, seismic and acoustic information should help determine which events reside outside the area of tactical interest, and should be ignored.

We note that by increasing the bandwidth of the sensing system, the spectral character of the signal from a sonic event can provide important information

1.4 Break the sound barrier: Fuse and correlate infrasound data with acoustic data.

Recommendation #2: Support A Vigorous Program of Source and Noise Characterization

We advocate a program to obtain calibrated sound signatures from both targets of military interest (trucks, tanks, etc.) as well as potential sources of "clutter" (tractors, commercial aircraft...). In addition we consider it imperative that the sources of noise be fully characterized as a function of frequency, particularly the spatio-temporal coherence of the pressure field fluctuations. A major motivation here is to determine the optimum area over which to average in order to best suppress pressure fluctuation noise, while retaining sensitivity to high frequency sound.

Recommendation #3: Characterize the Propagation Path

The variability of the near-zone propagation mechanisms is a major impediment to fully understanding and exploiting the measured signals. This motivates a program to measure the atmosphere's transmission properties around the tactical array, on an ongoing basis. This can be done either directly, by emitting a known sound from a known location, or indirectly, by measuring meteorological parameters that can be used in conjunction with models to predict sound propagation. Take proactive steps to engage the scientific community in better understanding the propagation and detection of sound over distances of 100 km.

Recommendation #4: Investigate Alternative Sensors

A diversity of sensors can be used to monitor sound in the frequency range of interest. Given the likely importance of energy at frequencies above the classical infrasound regime, we consider it important to carry out a survey of sensor technology, both mature transducers and ones under development, paying particular attention to their noise properties. This information will be important in assessing the price/performance tradeoffs in acoustic arrays, which we describe next.

Recommendation #5: Take a Fresh Look at Array Design and Deployment

The tension between maintaining good sensitivity to high frequencies and averaging over large areas to suppress pressure noise motivates the consideration of arrays of relatively inexpensive sensors. We advocate establishing a sound array test bed, co-located with a "classical" infrasound array, to facilitate the evaluation of different technologies and layouts. This evolution can take exploit recent DoD and commercial advances in wireless, distributed sensor networks.

Because of the vagaries of atmospheric propagation it will probably be useful to install arrays over a wide geographic band. The pattern of intensity over this band can be such that high intensity may occur further from the source at times.

11 ACKNOWLEDGMENTS

We are indebted to the speakers listed in Table 1 for taking the time to share their expertise with us. We are also grateful to Dr. Steve Tenney of the Army Research Laboratory for responding to our request for information on source characteristics. Finally, we thank Michael Hedlin and Mark Zumberge of Scripps/IGPP for taking up the suggestion of testing an inexpensive alternative sensor scheme.

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Director of Space and SDI Programs
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1000 Navy Pentagon
Washington, DC 20350-1000

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Defense Programs, DP-12
National Nuclear Security Administration
U.S. Department of Energy
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287 Somers Court
Suite 10041
Washington, DC 20393-5446

Headquarters Air Force XON
4A870 1480 Air Force Pentagon
Washington, DC 20330-1480

Defense Threat Reduction Agency [6]
Attn: Dr. Arthur T. Hopkins
8725 John J. Kingman Rd
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Dr. Jane Alexander
Homeland Security: Advanced Research
Projects Agency, Room 4318-23
7th & D Streets, SW
Washington, DC 20407

Dr. William O. Berry
Director, Basic Research ODUSD(ST/BR)
4015 Wilson Blvd
Suite 209
Arlington, VA 22203

Dr. Albert Brandenstein
Chief Scientist
Office of Nat'l Drug Control Policy Executive
Office of the President
Washington, DC 20500

Ambassador Linton F. Brooks
Under Secretary for Nuclear Security/
Administrator for Nuclear Security
1000 Independence Avenue, SW
NA-1, Room 7A-049
Washington, DC 20585

Dr. Darrell W. Collier
Chief Scientist
U. S. Army Space & Missile Defense Command
PO Box 15280
Arlington, VA 22215-0280

Dr. James F. Decker
Principal Deputy Director
Office of the Director, SC-1
Room 7B-084
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dr. Patricia M. Dehmer [5]
Associate Director of Science for Basic Energy Sciences, SC-10/Germantown Building
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585-1290

Ms. Shirley A. Derflinger [15]
Technical Program Specialist
Office of Biological & Environmental Research
SC-70/Germantown Building
U.S. Department of Energy
1000 Independence Ave., SW
Washington, D.C. 20585-1290

Dr. Martin C. Faga
President and Chief Exec Officer
The MITRE Corporation
Mail Stop N640
7515 Colshire Drive
McLean, VA 22102

Mr. Dan Flynn [5]
Program Manager
DI/OTI/SAG
5S49 OHB
Washington, DC 20505

Ms. Nancy Forbes
Senior Analyst
DI/OTI/SAG 5S49 OHB
Washington, DC 20505

Dr. Paris Genalis
Deputy Director
OUSD(A&T)/S&TS/NW
The Pentagon, Room 3D1048
Washington, DC 20301

Mr. Bradley E. Gernand
Institute for Defense Analyses
Technical Information Services, Room 8701
4850 Mark Center Drive
Alexandria, VA 22311-1882

Dr. Lawrence K. Gershwin
NIC/NIO/S&T
2E42, OHB
Washington, DC 20505

Brigadier General Ronald Haeckel
U.S. Dept of Energy
National Nuclear Security Administration
1000 Independence Avenue, SW
NA-10 FORS Bldg
Washington, DC 20585

Dr. Theodore Hardebeck
STRATCOM/J5B
Offutt AFB, NE 68113

Dr. Robert G. Henderson
Director, JASON Program Office
The MITRE Corporation
7515 Colshire Drive
Mail Stop T130
McLean, VA 22102

Dr. Charles J. Holland
Deputy Under Secretary of Defense Science & Technology
3040 Defense Pentagon
Washington, DC 20301-3040

Dr. Bobby R. Junker
Office of Naval Research
Code 31
800 North Quincy Street
Arlington, VA 22217-5660

Dr. Andrew F. Kirby
DO/IOC/FO
6Q32 NHB
Central Intelligence Agency
Washington, DC 20505-0001

Dr. Anne Matsuura
Army Research Office
4015 Wilson Blvd
Tower 3, Suite 216
Arlington, VA 22203-21939

Mr. Gordon Middleton
Deputy Director
National Security Space Architect
PO Box 222310
Chantilly, VA 20153-2310

Dr. Julian C. Nall
Institute for Defense Analyses
4850 Mark Center Drive
Alexandria, VA 22311-1882

Dr. C. Edward Oliver   [5]
Associate Director of Science for Advanced Scientific Computing Research
SC-30/Germantown Building
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-1290

Mr. Raymond L. Orbach
Director, Office of Science
U.S. Department of Energy
1000 Independence Avenue, SW
Route Symbol: SC-1
Washington, DC 20585

Dr. Ari Patrinos   [5]
Associate Director of Science for Biological and Environmental Research
SC-70/Germantown Building
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-1290

Dr. John R. Phillips
Chief Scientist, DST/CS
2P0104 NHB
Central Intelligence Agency
Washington, DC 20505-0001

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Bedford, MA 01730-1420

Dr. John Schuster
Submarine Warfare Division
Submarine, Security & Tech Head (N775)
2000 Navy Pentagon, Room 4D534
Washington, DC 20350-2000

Dr. Ronald M. Sega
DDR&E
3030 Defense Pentagon, Room 3E101
Washington, DC 20301-3030

Dr. Alan R. Shaffer
Office of the Defense Research and Engineering
Director, Plans and Program
3040 Defense Pentagon, Room 3D108
Washington, DC 20301-3040

Dr. Frank Spagnolo
Advanced Systems & Technology
National Reconnaissance Office
14675 Lee Road
Chantilly, Virginia 20151

Mr. Anthony J. Tether
DIRO/DARPA
3701 N. Fairfax Drive
Arlington, VA 22203-1714

Dr. Bruce J. West
FAPS - Senior Research Scientist
Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

Dr. Linda Zall
Central Intelligence Agency
DS&T/OTS
3Q14, NHB
Washington, DC 20505-00