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BBN Technical Memorandum W1291

Infrared Model Feasibility Study

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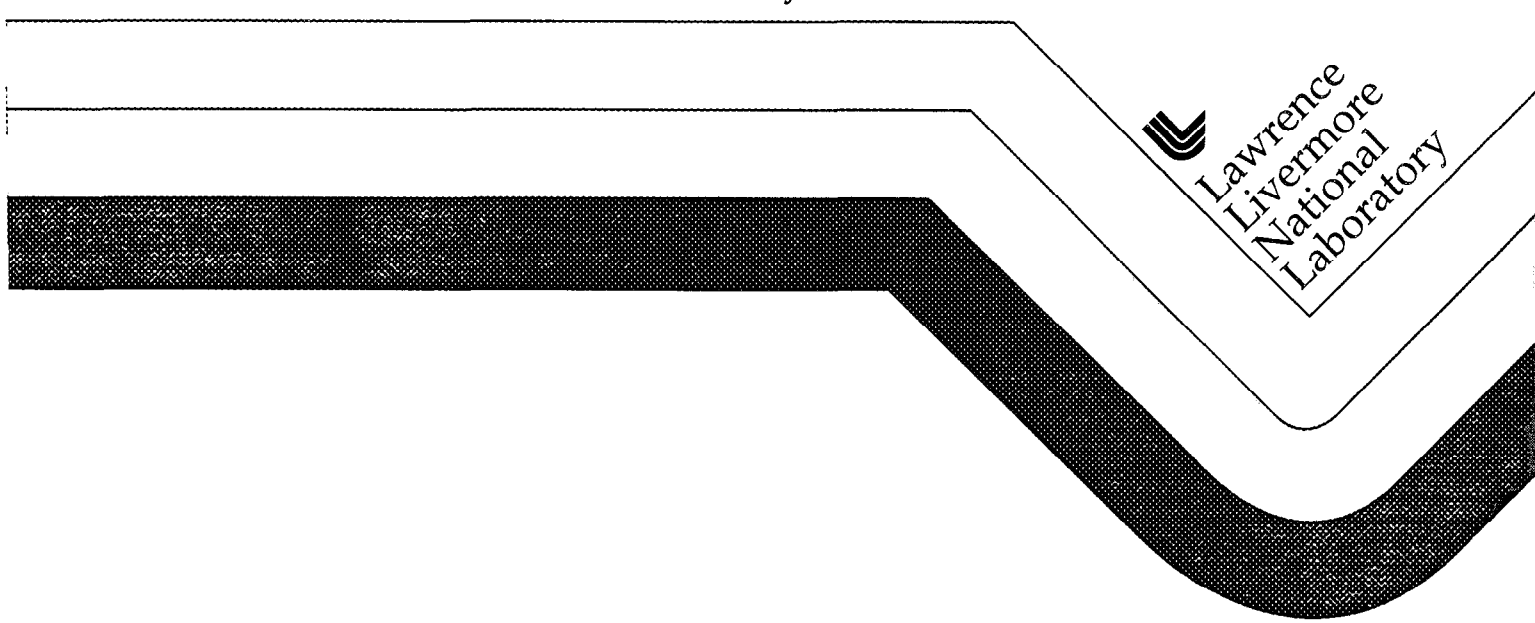
May 1998



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1.0 Introduction

The purpose of this study is to determine the need and level of effort required to add existing atmospheric databases and infrasound propagation models to the DOE's Hydroacoustic Coverage Assessment Model (HydroCAM) [1,2]. The rationale for the study is that the performance of the infrasound monitoring network will be an important factor for both the International Monitoring System (IMS) and US national monitoring capability. Many of the technical issues affecting the design and performance of the infrasound network are directly related to the variability of the atmosphere and the corresponding uncertainties in infrasound propagation. It is clear that the study of these issues will be enhanced by the availability of software tools for easy manipulation and interfacing of various atmospheric databases and infrasound propagation models. In addition, since there are many similarities between propagation in the oceans and in the atmosphere, it is anticipated that much of the software infrastructure developed for hydroacoustic database manipulation and propagation modeling in HydroCAM will be directly extendible to an infrasound capability.

The study approach was to talk to the acknowledged domain experts in the infrasound monitoring area to determine:

1. The major technical issues affecting infrasound monitoring network performance.
2. The need for an atmospheric database/infrasound propagation modeling capability similar to HydroCAM.
3. The state of existing infrasound propagation codes and atmospheric databases.
4. A recommended approach for developing the required capabilities.

A list of the people who contributed information to this study is provided in Table 1. We also relied on our knowledge of oceanographic and meteorological data sources to determine the availability of atmospheric databases and the feasibility of incorporating this information into the existing HydroCAM geographic database software.

Table 1: Infrasound Study Resources*

Name	Affiliation
Dr. Dean Clauter	Air Force Technical Applications Center (AFTAC)
Dr. Steven Warshaw	Lawrence Livermore National Laboratory (LLNL)
Dr. Bob Blandford	AFTAC
Prof. Allan Pierce	Boston University
Dr. Rod Whitaker	Los Alamos National Laboratory (LANL)
Dr. Marcus Bunting	Sandia National Laboratory (SNL)

* The people included in this table acted as sources of information only. The conclusions reported herein were developed by BBN and are not claimed to be subscribed to by all interviewees.

This report presents a summary of the need for an integrated infrasound modeling capability in Section 2.0. Section 3.0 provides a recommended approach for developing this capability in two stages; a basic capability and an extended capability. This section includes a discussion of the available static and dynamic databases, and the various modeling tools which are available or could be developed under such a task. The conclusions and recommendations of the study are provided in Section 4.0.

2.0 Need for modeling capability

It is well-known in the test-ban verification community that the location performance of an infrasound monitoring network is poor relative to the performance of the seismic and hydroacoustic monitoring networks. The primary reason is the existence of multiple atmospheric layers and large spatial and temporal variability of the temperature and wind speed, which produces a very complicated infrasound propagation environment. (See Figure 1). It has been suggested that the uncertainties in upper-atmospheric wind patterns can produce bearing errors as high as 27 degrees at long ranges [3]. In addition, azimuth biases of 5-6 degrees due to horizontal winds are not uncommon [4,5]. These atmospheric uncertainties also result in difficulty identifying the detected phases and uncertainty in determining the actual propagation velocities for the phases. Historically, this has precluded the operational use of travel time and phase (multipath) information, which could improve the infrasound source location estimates. At a recent R&D Symposium, Dr. David Russell from AFTAC indicated that the highest priority research issues in infrasound monitoring include path identification, path velocity estimation and the corresponding impact on localization performance [6]. Methods for associating infrasound events with seismic and hydroacoustic data are also a high priority [6]. When an atmospheric explosion is initially detected and localized using the infrasound network, any associated hydroacoustic and seismic travel times could be used to improve the infrasound localization. Clearly the development of these "data fusion" methods requires an understanding of the environmental factors affecting both infrasound and hydroacoustic localization.

A recent infrasound network performance study [3] indicated that an order of magnitude reduction in the "uncertainty radius" is possible if both bearing and accurate travel time are used in the location procedure. This report concluded that in order to realize these performance gains:

> (1) *Research is needed to determine the best procedure to identify phases from unknown source locations and origin times.*

and

> (2) *Research is needed to develop methods for applying velocity and azimuth corrections to acoustic propagation paths from satellite wind data.*

An additional operational requirement was mentioned in an International Data Center (IDC) Progress Report [7]:

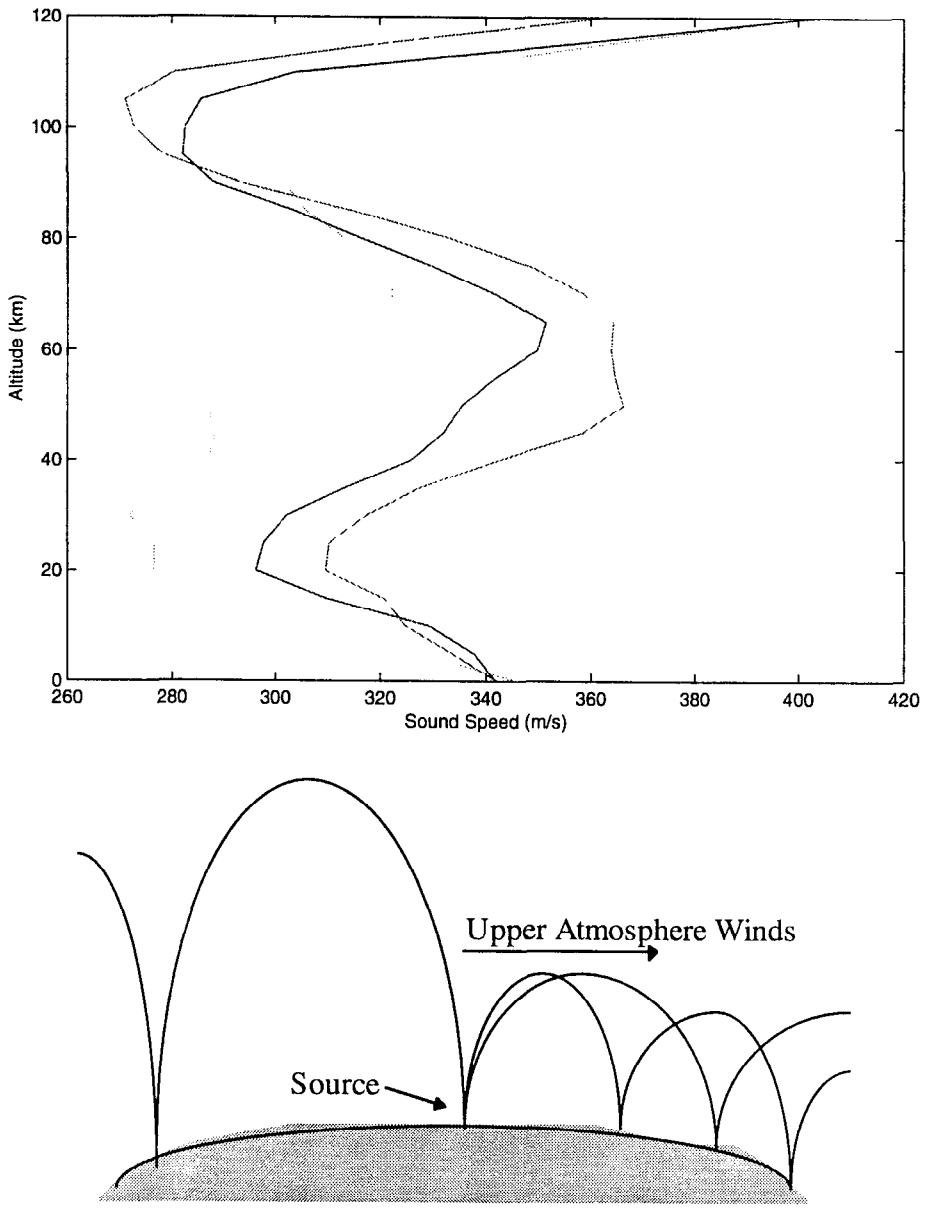

Figure 1: (upper) Typical atmospheric sound speed profiles showing two ducts and (lower) typical East-West raypaths. Wind is moving from the West to the East.

> *"Atmospheric events generate multiple phases traveling through different atmospheric layers, resulting in multiple phases detected at an infrasound array for a given event. The speed of the infrasound signals can be influenced by high-altitude wind patterns. Databases for these wind patterns will have to be included in the prototype IDC".*[7]

It appears that all of these related research areas could be significantly enhanced by a common, easy to use software package for (a) access to complex atmospheric data (from both historical databases and new research satellites), (b) for using this data in high-fidelity propagation models, and (c) for visualizing the results. This capability is needed to study infrasound bearing bias, phase identification and travel time prediction issues critical to infrasound localization performance. Example research issues that could be addressed using this software package include:

1. Evaluate bias issues associated with simplified forward models, such as bearing estimate bias due to horizontal winds and biases due to diurnal and seasonal atmospheric fluctuations.
2. Evaluate the impact of environmental fluctuations on time of arrival (TOA) and bearing estimates.
3. Evaluate improvements in infrasound network performance by incorporating detailed propagation information (such as reduced bearing bias and reduced AOU) through mode identification and use of TOA estimates with bearing.
4. Evaluate the performance of joint hydroacoustic/infrasound association and localization algorithms.
5. Determine the requirements for atmospheric database/propagation model fidelity, the required frequency of atmospheric updates, and the feasibility of using interpolation methods to upgrade the performance of an operational infrasound localization processing system.

The following section describes why a combined infrasonic database, propagation and localization tool analogous to HydroCAM is feasible to develop quickly, and outlines the recommended development approach.

3.0 Development Approach

There are many physical and data structure similarities that exist between the infrasound and hydroacoustic data management, propagation modeling and localization performance estimation problems. As an example, both the atmosphere and the ocean are usually measured via profiles (e.g. rocketsondes or expendable bathytermographs) or satellite images (e.g. wind speed from the Geostationary Operational Environmental Satellite and sea surface temperature from the Defense Meteorological Satellite Program). Because of this similarity, the existing HydroCAM software infrastructure will allow infrasound databases and propagation models to be integrated in an efficient manner. In addition, many new sets of atmospheric data are now being distributed electronically over the internet. The availability of this data, which includes historical data, atmospheric model data, and data from upper-atmosphere research satellites, will allow more sophisticated modeling applications to be developed. Due to the object oriented data access structures and modular software design features of HydroCAM, an efficient evaluation of the utility of this atmospheric data for infrasound applications is feasible. The recommended approach is to develop the capability in stages:

1. Develop a basic capability that incorporates existing empirical infrasound detection and bearing error models into the network location software in HydroCAM.

2. Extend the basic infrasound capability by:

    a) Adding existing historical atmospheric databases
    b) Adding "static" access to dynamic sources of atmospheric data (such as the output of atmospheric models and/or raw satellite measurements).
    c) Adding existing high-fidelity infrasound propagation models, and
    d) Extending the current HydroCAM hydroacoustic modeling approach to include infrasound propagation

3. Improve the capability as indicated by the results of research performed using the tools developed in 1-2.

The following sections describe the technical issues and recommended approach for developing the basic and extended infrasound assessment capability.

3.1 Basic Infrasound Assessment Capability

We are aware of two existing infrasound network performance models; IVSEM [8] and a infrasound extended version of NETSIM [3]. These two models essentially use the same type of empirically derived equations for detection performance (relating observed pressure to yield, range and wind-speed), and an empirically derived model for travel time and bearing errors. There are three reasons for integrating these basic infrasound models into HydroCAM. The first is that these empirically derived models can serve as a baseline against which the extended capability models described later can be compared. The second reason is to allow estimation of the performance of a joint hydroacoustic/infrasound network using the higher-fidelity hydroacoustic propagation models contained in HydroCAM, but not available in IVSEM or NETSIM. The third reason is to enable bias studies comparing the impact of using these empirical bearing and/or travel times estimates to more data oriented predictions that include information about the horizontal wind structure and higher-order atmospheric effects. Integrating this basic infrasound assessment capability into HydroCAM is anticipated to require minimal effort. The required tasks would include:

1. *Incorporate empirical ambient noise database/receiver models.* The HydroCAM receiver model includes the ability to use measured ambient noise (as a function of frequency and azimuth) or to use the standard Wenz ocean ambient noise model. Current infrasound models usually estimate the ambient noise from the local wind speed based on empirical relations [3,8]. Historical wind speed data and/or measured ambient noise relationships for receiver locations will be used when available. For receivers on islands in open-ocean areas, an option to use the Navy standard historical wind speed database currently in HydroCAM (HWS, version 3.0) will be provided. However, since this database covers ocean areas only, an additional terrestrial surface wind-speed database (such as those available from the National Climactic Data Center, NCDC) will need to be integrated to estimate local wind speed at new infrasound stations in mainland areas.

2. *Incorporate empirical infrasound detection models.* These models will be as documented in [3,8] or as supplied/specified by AFTAC, LANL or SNL. In general, these models specify the received pressure as a function of the source-receiver range, source yield, and high altitude (50 km) wind speed based on measured data from explosive sources scaled to 1 kT yield. There appears to be some disagreement in the community as to the impact of high-level winds on the received amplitude. Some models account for these winds at all ranges, while other models account for the wind effects only in the shorter-range "shadow zone" region. This task will add the high-level wind speed models/databases used by IVSEM (such as the Global Upper Air Climactic Atlas available from NCDC)

into HydroCAM. The availability of these databases will also allow direct comparisons with other wind speed databases as they become available.

3. *Incorporate empirical bearing error models.* The bearing error models available in [3,8] are piecewise linear functions of the source-receiver range. These models could be easily incorporated into the HydroCAM network performance evaluation module. We also recommend incorporating an alternative model which has proved useful in underwater acoustics, radar and other fields. Under this model, the bearing error σ is an explicit function of the signal-to-noise ratio (SNR)

$$\sigma = \frac{k}{\sqrt{SNR}},$$

where k is a constant that depends on the array geometry and the bearing estimation algorithm used. This model will be useful for performing array geometry tradeoffs and for incorporating hydroacoustic bearing measurements.

4. *Incorporate bearing measurements* into the network localization performance module. This task involves adding a Fisher information matrix that contains the bearing and travel time errors into the AOU calculation, and adding a flag to the receiver description files indicating whether a station should produce bearing measurements, arrival time measurements or both. This improved network performance module would also be capable of determining the impact of *hydroacoustic* bearing estimates on localization performance.

5. *Update the HydroCAM Users Manual* to include the definition of infrasound receiver stations, instructions on running the infrasound models and a description of how to access the atmospheric databases.

3.2 Integration of Atmospheric Data Sources

Significant effort was spent in the 50's, 60's and 70's on both the theoretical and operational aspects of infrasound monitoring. Much of the work stopped in the 70's due to the availability of satellite monitoring technology. Since then, many new sources of information about the atmosphere have become available, including historical atmospheric databases on CD-ROM, atmospheric measurements via internet, and data from new high-altitude research satellites. In addition, there have been significant advances in computer processing speed and software technology. It now appears feasible to put together a modeling capability that can investigate corrections for upper-atmosphere wind speed based on measured data. The relevant atmospheric data falls into two general categories; historical data and dynamic data. This section describes the approach for integrating both types of atmospheric data into HydroCAM.

3.2.1 Historical data

Relevant historical data consists of global databases of atmospheric temperature and wind speed which are available from the National Climactic Data Center (NCDC), the US Navy Oceanographic Office, the Air Force Global Weather Center (AFGWC), and other sources. (See Table 2) Most of these databases are provided in gridded or profile formats similar to the format of the sound speed profile databases already included in HydroCAM. However, there are two limitations to this historical data. First, most of the data pertains to altitudes less than 30 km, whereas infrasound propagation requires information well into the thermosphere (approx. 120 km). Secondly, atmospheric fluctuations occur on relatively short time scales, implying that the historical data will primarily be of use for (a) determining statistics of the current propagation situation (such as the variance of the travel time or probability that a propagation path should be available) and (b) for filling in gaps in dynamic sources of information.

Table 2: Representative Historical Environmental Databases

Database Name	Organization	Contents	Coverage	Altitudes
Historical Wind Speed (HWS) *	Navy	Wind speed and direction	Global at 0.5° resolution	Ocean surface
Radiosonde Data of North America 1946-1994	NOAA	temperature, dew point, wind speed and direction,	North America	Surface to 100 mb (~ 16 km)
Upper Atmosphere Gridded Climatology (UAGC)	Navy/NOAA	Mean and std deviation of pressure, wind speed, air temperature, dewpoint, and density	Global at 2.5° resolution	Surface to 10 mb (~ 30 km)
COSPAR International Reference Atmosphere (CIRA)	NASA/GSFC	Zonal average wind speed and temperature profiles	80S to 80N	0 to 120 km
Horizontal Wind Model (HWM)	NASA/GSFC	Wind speed and direction	Global	0 to 300 km
Earth Topography 5 Minute (ETOPO5) *	NOAA	Topography	Global	N/A
DATSAV2 Surface	AFGWC	Wind speed and direction	13,000 stations world-wide	surface only
Range Reference Atmosphere (RRA)	AFCCC	Mean, std deviation and correlation of wind speed	Limited areas	0-30 km and 0-70 km

* databases already integrated into HydroCAM

3.2.2 Dynamic data

A number of dynamic data sources are also available. These include both *assimilated-data* sources such as the output of atmospheric models and *raw-data* sources such as meteorological satellites. (See Table 3). As with the historical data sets, most of these datasets are in gridded or profile formats which can be readily inserted into HydroCAM.

Assimilated data sources provide data on a standard grid (e.g. lat/lon). In many cases, assimilated data sources are constructed using data from a variety of sensors as constraints on a complicated atmospheric/weather model, which produces the best estimate of the meteorological parameters on a grid. As an example, the Navy Oceanographic Data Distribution System (NODDS) provides gridded wind speed at several altitudes every 12 hours. This data is the output of the NOGAPS (Naval Operational Global Atmospheric Prediction System), which uses an extensive data set of

ship-based, land-based and satellite measurements. BBN is a registered NODDS user, and has used the oceanographic data products from this system for a variety of efforts since 1994. Assimilated data sources will normally be favored over raw data sources, since the data quality control, interpretation and extrapolation of the measurements have been performed by the generating organization.

Table 3: Representative Dynamic Sources of Atmospheric Environment Data

Name	Organi-zation	Type	Contents	Coverage	Altitude (km or mb)	Update Rate
Naval Oceanographic Data Distribution System (NODDS)	Navy	Assimilated	Wind speed, directions, shear, temperature, etc.	Global	0 to 100 mb	12 Hours
4-D Assimilated Data Set	NASA/GSFC	Assimilated	Wind speed, wind direction. temperature, humidity	Global on 2.5 degree grid	0 to 25 km	6 hours
Upper Atmospheric Research Satellite (UARS) (WINDII, HRDI)	NASA	Raw	Wind speed	-80 to 80	10 to 40 and 50 to 115 km	36 Days
NASA Scatterometer (NSCAT)	NASA	Raw	Wind velocity	90 % of Ocean	Ocean Surface	2 Days
Geostationary Operational Environmental Satellite (GOES)	NOAA	Raw	Wind velocity temperature and moisture profiles	Northern Hemisphere Centered on US	100, 250 , 400 and 700 mb, 1000 to 0.1 mb for profiles	6 hours
Defence Meteorological Satellite Program (DMSP)	Air Force	Raw	Wind speed, sea ice	Global	Ocean Surface	Variable
DATSAV2	AFGWC	Raw	Wind speed, wind direction, temperature, pressure, density	Global	0-90 km	
OL-A High Resolution Analysis	AFGWC	Assimilated	Wind speed and direction, temperature	2.5 degree grid	Surface to 10 mb	6 hours
Weather Anchor Desk	DARPA	Assimilated				
CATS	DSWA	Assimilated				

For our purposes, raw data sources are defined as those sources that provide measurements without interpolation onto a standard grid. The primary sources of raw data are individual satellites, which in some cases are research sensors (as opposed to sensors used by official operational weather forecasting systems). An example raw data source is the High Resolution Doppler Imager (HRDI), which is one of the instruments on board the Upper Atmospheric Research Satellite (UARS). This satellite was launched in 1991 as a part of NASA's effort to study the earth's atmosphere. HRDI measures the emission and absorption lines of molecular oxygen in small volumes of the atmosphere. From the Doppler shift of these lines, the horizontal winds can be estimated, while the shapes and strengths of the lines provide information about the atmospheric composition and temperature. A related instrument on UARS is the Wind Imaging Interferometer (WINDII). The WINDII measures wind, temperature, and emission rate over the altitude range from 80 to 300 km by using the Doppler interferometry on the airglow emission. Another wind measurement sensor, the NASA Scatterometer (NSCAT), was launched in August 1996. This sensor is a microwave radar, which measures near-surface wind velocity (both speed and direction) over the 90% of the oceans every 2 days. The data from this sensor is planned to be incorporated into official meteorological forecasts.

3.2.3 Atmospheric data integration approach and issues

For predictions of infrasound propagation, complex databases of temperature and windspeed profiles will need to be filtered for data quality, merged and interpolated onto a uniform grid, which will be supplied as input to the propagation models. Much of the HydroCAM infrastructure is designed for exactly this purpose; i.e. to create gridded sound speed fields for use as inputs to ray, normal-mode and parabolic equation underwater propagation models. Currently available methods range from standard techniques such as bilinear and spline interpolation, to the use of empirical orthogonal functions (EOFs). In addition, HydroCAM uses C++ object classes to represent and manipulate geographic data at multiple resolutions. This allows calculations such as raytracing to naturally progress from geographic regions with low resolution data into regions with high-resolution data.

An examination of Tables 2 and 3 shows that multiple sources of data will be needed since no one data source contains all of the required environmental parameters at all locations and altitudes. Thus, the primary technical issues pertaining to the atmospheric data will be (1) the selection of the appropriate set of data sources, and (2) the merging of data sources which cover different altitude regions, especially when the component databases have different resolutions, coverage and even different data of the same type (such as zonal averaged temperature versus temperature at a geographic cell). The tasks required for integration and use of the atmospheric data are as follows:

1. *Integrate the historical atmospheric databases into HydroCAM:* This task will require a selection of the appropriate databases, integration, and distribution to HydroCAM users. The databases should be selected after consultation with NOAA, NAVOCEANO, AFGWC, AFTAC and scientists at LANL. For research purposes, we recommend that most of the historical databases outlined in Table 2 be integrated.

2. *Integrate appropriate dynamic sources of information:* Again, this task requires selection of the appropriate sources of information and consultation with the experts. Although the databases are dynamic, we recommend that the initial access be set up statically, i.e. data can be accessed from a number of locally saved versions of the data. A mechanism should also be provided to download new datasets as they are required.

3. *Develop methods for preparing propagation model input data:* This task will require the implementation and testing of several methods for merging and interpolating the atmospheric data to provide appropriate gridded fields to the infrasound propagation models.

When completed, the software should be capable of providing the complete set of temperature and wind speed profile information needed for infrasound modeling. When used in combination with the models discussed in the next section, the specific advantages and disadvantages of each identified data source can be determined. Some of the issues that will need to be addressed include:

- Which sources of information have the most complete coverage (geographic, altitude and local time)?
- Are these data at a resolution sufficient for accurate infrasound modeling?
- Are these data updated at a rate that is sufficient?
- How should different data sources at different atmospheric layers be joined together?
- How sensitive are the model predictions to the methods for joining data and interpolation (both spatial and/or temporal)?

In addition, several of the research data sources may not provide global coverage, a sufficient update rate, or may not be operational 24 hours a day. These sources could be investigated by performing a sensitivity analysis to show the effect of the data on the

travel times and available paths predicted by the models. The final product may require a different set of data sources for different geographic locations and different local times.

3.3 Extend infrasound prediction capabilities with existing models

With the availability of additional environmental information, the use of more sophisticated propagation algorithms may be contemplated. The purpose of using these models would be to try to reproduce observed arrival characteristics such as arrival bearing and arrival time as a function of the arrival mode. Several existing models are available which can provide this increased fidelity.

3.3.1 HARPA

The HARPA [9] model from NOAA is similar to the HARPO model already integrated into HydroCAM, with the distinction that it treats the "inverted hydroacoustic" problem where the ocean surface is replaced with the earth's topography, and the ocean bottom is replaced by the upper halfspace of the upper thermosphere. The advantage of this model is that the ray trace is done in all three coordinates, and therefore includes the effects of laterally varying winds explicitly. The disadvantage is that the ray trace can be quite slow to compute, therefore increasing the time required to compute knowledge grids or to run detection scenarios. Another disadvantage is that the ray trace is a forward model, and the process of finding eigenrays will require significant additional computations.

3.3.2 INFRASONIC WAVEFORMS

The INFRASONIC WAVEFORMS code was developed by Pierce and collaborators for AFCRL (Air Force Cambridge Research Lab) during the period 1968-1975 [10]. This model is currently being maintained at LANL. The model synthesizes waveforms from nuclear blasts received over regional distances. The wavefield is synthesized over discrete sets of modes over a spectrum of infrasonic frequencies. The code was originally developed to model hydrogen bomb tests conducted high in the atmosphere. Therefore, there is an emphasis on frequencies below 0.01 Hz. The environmental model includes the effects of winds as a function of height over the ground, but lateral variation of the wind over trans-global distances cannot be explicitly included. Conversations with Dr. Whitaker at LANL [11] indicate that the code is still being used and enhanced. For instance, LANL has included a WKB type approximation into the code for higher frequency waveform synthesis, as would be appropriate for tests in the kT yield area currently of interest.

It is interesting to note that Pierce's efforts also have resulted in the generation of at least two alternative methods for modeling long range infrasonic propagation. One of these

methods was an edge wave synthesis of the fastest part of the arrival, and the second approach was a ray tracing model. The final report for the contract under which this work was accomplished discussed these two alternative approaches [12]. It is our impression from this report that the extension of the modal synthesis to frequencies below cutoff enabled the INFRASONIC WAVEFORMS code to effectively replicate the edge wave synthetic for the early part of the arrival structure. In this case it seems that the modal synthesis available in the INFRASONIC WAVEFORMS code effectively encompasses all the capabilities of the edge wave code. In a similar manner, the capabilities of the Pierce's ray trace code seem to be replicated by the better supported and maintained HARPA code. Therefore, of the three models developed under Pierce's efforts, we recommend integrating only the INFRASONIC WAVEFORMS code.

3.3.3 NRL Codes

Mike Collins at NRL has recently published work directed towards explaining the atmospheric impact wake of the comet Shoemaker-Levy 9 on Jupiter [13]. This work represents a significantly different approach than INFRASONIC WAVES, since the wind speed is treated as a small perturbation and gravity waves are neglected. However, the lateral variability of the propagation environment is explicitly accounted for in this approach. The outgoing wave equation is solved mode by mode in ellipsoidal coordinates using the local modal indices of refraction. There is assumed to be no coupling between the modes. Using this approach, effects such as horizontal refraction and focusing caused by lateral variations in the wind profile can be explicitly included. Also developed for this study were a set of horizontal ray equations which explicitly included the effects of laterally varying winds. These effects are important because bands of atmospheric winds can focus energy into ducts under certain conditions.

In order for this work to be used for modeling infrasound propagation, the quality of the perturbation approximation would have be evaluated for upper atmospheric winds. There is a concern that a different approximation for the horizontal phase speeds of the individual modes would be required when the wind speed is a significant percentage of the sound speed in the air. This can occur for upper atmospheric winds, where wind speed can approach 100 m/s, compared to the nominal air sound speed of 340 m/s.

Neither of the NRL codes is distributed from the NRL ftp site. Collaborative arrangements would have to be worked out between LLNL and NRL in order to obtain this software. Similar arrangements were made during the initial HydroCAM development efforts

3.4 Extend infrasound prediction capabilities with modifications to existing HydroCAM models

With a moderate amount of effort, the existing propagation models in HydroCAM could be upgraded to give a consistent modeling capability for infrasound. The current approach for hydroacoustic propagation modeling is to compute local modes through sound speed structures obtained from data bases, and then to connect endpoints together with horizontally refracted eigenrays. For infrasound modeling, these codes could be enhanced through the following efforts:

Upgrading WKB to windy wave equation: For infrasound propagation, the altitude separated wave equation contains convective terms related to the horizontal wind stratification. Mode shapes and eigenvalues therefore depend on the direction of the propagation with respect to the wind. It is anticipated that the existing HydroCAM WKB mode program would be enhanced to solve for wavenumbers and mode shapes as a function of the wind profiles and the propagation direction.

Upgrading GlobeRay to directional wavenumber capability: Once direction dependent wavenumbers and modal slownesses are obtained through an enhanced WKB capability, it is foreseen that horizontally refracted eigenrays could be traced between hypothetical source locations and receivers using horizontal ray tracing equations substantially the same as those used in the current version of HydroCAM. The only modification anticipated would be to trace rays through a horizontal wavenumber field which is an implicit function of the local propagation direction, in addition to the longitude and latitude dependence currently considered by HydroCAM.

The incorporation of these capabilities would form a bridge between the fully 3-D HARPA ray trace code, and the essentially 2-D INFRASONIC WAVEFORMS waveform synthesis code. In addition, improvements to network coverage and AOUs would be possible to quantify by modifying and enhancing HydroCAM's network coverage and performance assessment modules to include the following capabilities:

Include travel time variability model: With the improvements described in the "Basic Capability" section, HydroCAM will be capable of determining localization performance using travel time and bearing measurements. However, the improved atmospheric databases and increased fidelity of the "Extended Capability" model should allow for better predictions of travel time variability, more consistent with those predicted by the hydroacoustic portion of HydroCAM [1]. With the availability of comprehensive atmospheric data and the models which can accept it as input, infrasound network performance improvements could be characterized as

functions not only of the network geometry, but also ambient noise, environmental variability and signal arrival characteristics in time and angle.

Include mode association in infrasound localization algorithm: An infrasound received time series is likely to contain contributions from multiple propagation paths. The multipaths are identified with various routes which infrasonic energy takes as it passes through the atmosphere. The energy propagates along each of these paths with different velocity, and arrives at the receiver at different times. One of the main problems expected in using travel times for infrasound localization is the association of particular arrivals with various paths through the atmosphere. The detection module in HydroCAM should be enhanced to provide the capability to estimate the potential benefits of mode association, and the associated performance degradation caused by miss-identification of modes.

It is worthwhile to compare the infrasound mode identification problem with the mode identification problem in over the horizon (OTH) radar. Traditional OTH techniques are based on forward or predictive modeling of sufficient accuracy that modes can be associated by proximity to modeled travel time. New techniques from the underwater acoustics community highlight the potential benefits of a more stochastic approach, where a-priori probabilities of mode travel time distributions are obtained through simplified forward modeling, and then modes are identified statistically through a hidden Markov modeling (HMM) technique. As mentioned above, HydroCAM already has the capability to predict travel time standard deviations for underwater acoustic normal mode arrivals. It would seem to be a rather straight forward matter to extend this capability to the infrasound mode identification problem to facilitate the HMM approach.

4.0 Conclusions and Recommendations

In summary, there appear to be several high-priority infrasound monitoring research issues that could be addressed by a high-fidelity database/modeling capability. Enough existing atmospheric data and propagation modeling methods are available to begin development of such a capability now. We believe that by building this capability based on the existing DOE HydroCAM infrastructure, much of the initial design and integration costs can be avoided. This approach would have the additional benefit of providing consistent user interfaces and support for researchers in the hydroacoustic, infrasound and data fusion project areas.

The first step would be to integrate the existing empirical infrasound detection and localization models into HydroCAM as a baseline capability. Then, access to historical and dynamic sources of atmospheric data should be developed. An enhanced infrasound modeling capability could then be introduced in order to evaluate the potential performance benefits obtained by using the environmental information to correct infrasonic travel times and arrival angle deviations. The most promising development approach would be to work closely with other DOE laboratories such as SNL and LANL, which have been stewards of the US infrasonic capability, to interface the appropriate existing models into HydroCAM. This is the same approach used for the development of HydroCAM, where we worked closely with the Naval Research Laboratory and others to integrate existing underwater acoustic models. At this point, it appears that the two codes which are most desirable to interface are HARPA and INFRASONIC WAVEFORMS. The underwater acoustic version of HARPA, HARPO, has already been interfaced into HydroCAM. While we have a source listing for the INFRASONIC WAVEFORMS code, the code is old and may not be very well supported so the incorporation of this code will take more effort than the integration of HARPA. However, since these codes offer complimentary capabilities (HARPA global scale travel time and horizontal veering estimation, INFRASONIC WAVEFORMS wave form prediction on continental scales,) both models should be incorporated.

Our evaluation of the computational issues also suggests that the expansion of the BBN/NRL adiabatic mode raytrace modeling capability to the infrasonic problem is a moderate risk, high payoff proposition. In a sense, extension of this capability to the infrasonic problem would be akin to extending the INFRASONIC WAVEFORMS capability to global scales, for it would allow horizontal veering of eigenrays to be evaluated over more complex wind fields, which would not necessarily remain constant over the horizontal ray trajectory. A further advantage of extending the HydroCAM modeling capability would be the computation of the travel time variances associated with the various infrasonic modes. The availability of these types of measures would prove useful for evaluating the potential of source localization algorithms which include mode identification.

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