DEVELOPMENT AND APPLICATION OF AN INTEGRATED INFRASOUND PROPAGATION MODELING TOOL KIT

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ABSTRACT

Infrasound propagation models and upper-atmospheric characterizations have been integrated into a single software tool kit that allows for user-friendly model execution and data visualization. The tool kit, called InfraMAP, for Infrasonic Modeling of Atmospheric Propagation, can be applied to predict travel times, bearings, and amplitudes from potential event locations worldwide. Temporal and spatial variability of the atmosphere is addressed by allowing range-dependent sound speed and winds to be incorporated with the propagation models. The ability to predict propagation characteristics necessary for localization is therefore enhanced. The integrated software has been used to conduct sensitivity analyses and to model infrasound propagation corresponding to historical events of interest. Results from these analyses and comparisons of predictions with measurements are discussed.

InfraMAP integrates three types of research-grade propagation models with two empirically based atmospheric models. The baseline set of acoustic propagation models consists of a three-dimensional ray theory model (HARPA), a WKB version of Pierce's normal mode model, and a continuous-wave, two-dimensional parabolic equation model. The baseline empirical atmospheric models are the Horizontal Wind Model (HWM) and the Extended Mass Spectrometer - Incoherent Scatter Radar (MSIS or MSISE) temperature model. Wind, temperature, and densities are modeled from the surface into the thermosphere and include spatial, diurnal, and seasonal effects. The InfraMAP tool kit provides a common user interface that allows researchers to use these models efficiently for investigating issues of interest for CTBT monitoring.

Key Words: infrasound, long-range propagation, database, atmosphere

OBJECTIVE

Verification of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) will require the ability to detect, localize, and discriminate nuclear events on a global scale. Verification systems such as the International Monitoring System (IMS) rely on several sensor technologies to perform these functions. The current IMS infrasound system design includes a network of low-frequency atmospheric acoustic sensor arrays, which contribute primarily to the detection and localization of atmospheric nuclear events.

The technical challenges involved in monitoring the CTBT using infrasound include the proper consideration of the effects of upper atmospheric dynamics on propagation. Because of the temporal and spatial variability of the atmosphere, there are no stable, reliable, simply predictable propagation paths that can be used in standard back-azimuth and time-of-arrival localization approaches. Uncertainties inherent in propagation modeling techniques and in characterizations of temperature and wind can result in location errors. The approximations currently in use operationally are expected to result in localization performance significantly worse than the monitoring network design goal of 1000 sq. km [Clauter and Blandford, 1996].

It is anticipated that the ability to identify infrasound phases, and to include the appropriate travel-time and bearing refraction corrections for each arrival into localization procedures, would dramatically improve localization performance. Reducing uncertainties in location estimates from the infrasound network will also improve the ability to associate detected events with hydroacoustic and seismic signals. In addition, improved predictions of infrasound waveform amplitude will aid in the determination of detection thresholds and observability of individual phases; these predictions can be used in source discrimination, in particular for yield estimates.

Infrasound analysts and researchers require tools that will allow them easily to model propagation through realistic characterizations of the atmosphere. Furthermore, operational processing and interpretation of infrasonic data will require computation of a knowledge database that contains accurate atmospheric characteristics, travel times, bearings, path amplitudes and ultimately spectral characteristics of received waveforms. The primary objective of this effort is to develop modeling software that can be used to support these requirements and to improve source localization. The specific goals for this effort are:

1) Develop an integrated software system capable of: (a) defining the state of the atmosphere, such as temperature and wind speed profiles, as required for infrasound propagation modeling; (b) predicting the phases, velocities, travel times, azimuths and amplitudes of atmospheric explosions measured by infrasound sensors; (c) supporting prediction of localization area of uncertainty and detection performance, by quantifying environmental variability and propagation sensitivity.

2) Conduct sensitivity studies to determine the effects of environmental variables on infrasound propagation, and validate that the modeling software techniques are consistent with measured data.

3) Prepare a users' manual and documentation describing the models.

Progress toward these goals is discussed in the following section.

RESEARCH ACCOMPLISHED

Approach

An integrated software package for infrasound modeling has been developed by BBN. The software contains tools for modeling infrasound propagation through a dynamic atmosphere and for visualizing modeled propagation results and atmospheric characteristics. The atmospheric models, acoustic propagation codes, and display functions are integrated in a common software environment that allows for user-friendly data access and model execution. The tool kit, called InfraMAP, for Infrasonic Modeling of Atmospheric Propagation, can be applied to predict travel times, bearings, and amplitudes from potential event locations worldwide.

The development of the infrasound software tool kit followed an approach analogous to that used for the Hydroacoustic Coverage Assessment Model (HydroCAM) [Farrell and LePage, 1996], which was developed under the Department of Energy's CTBT R&D program. The HydroCAM software contains the best available seasonal databases of the ocean environment from the US Navy, the National Oceanic and Atmospheric Administration (NOAA) and other institutional sources, and is used to predict hydroacoustic travel time, amplitudes, travel time variances and network performance throughout the world's oceans.

InfraMAP was rapidly prototyped to develop a baseline functional capability. Following testing and evaluation of each baseline capability, additional functions were then added. The software design philosophy was to use existing models, databases and access software whenever possible. Models and databases were identified and prioritized for integration by using a benefit/cost tradeoff. The benefits included the ability to meet operational requirements and acceptance by the infrasound research community. The cost included the estimated integration effort and computational requirements. As integration of the modeling components progressed, enhancements were added to the software to simplify and speed execution. The graphical user interface (GUI), including forms and data display formats, was designed and implemented using MATLAB®. In addition to the forms contained in the GUI, models can also be exercised at the command line in script mode.

Figure 1 shows the default topographic display and the user interface for selecting the principal menus. Menus are organized by task for the most common operations, and are divided into the categories of "Environment" and "Propagation." Additional functions such as printing, zooming, adding overlays, and defining networks of sensors for analysis are available on separate menu bars (not shown). An overlay of the IMS infrasound network is shown.

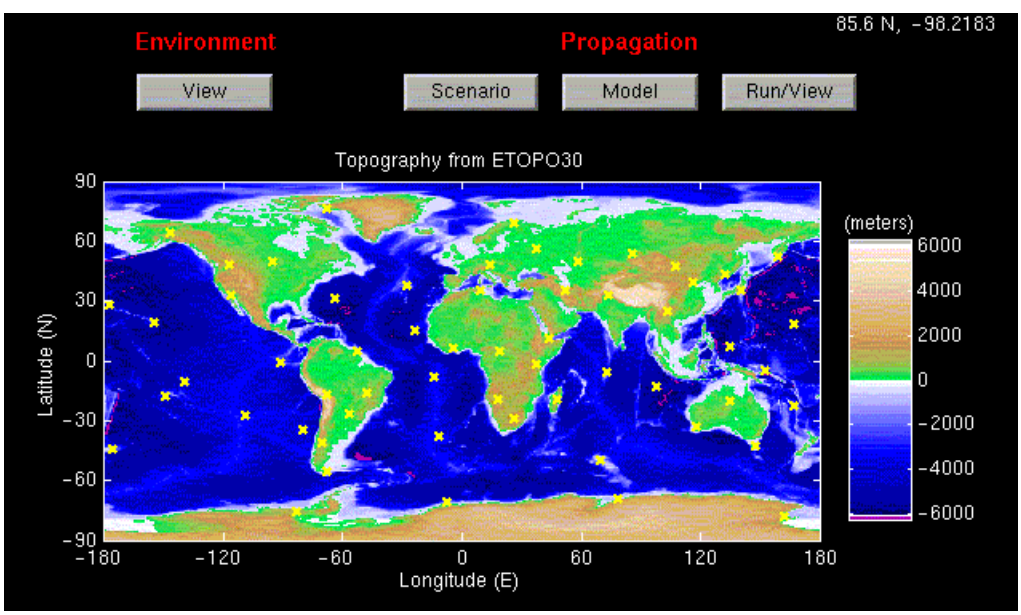


Figure 1: InfraMAP Main Menu and User Interface

Selection of the View Environment menu allows the user to visualize the atmospheric characterizations. From the View menu, the user then makes a number of choices: the environmental database or model, the variable of interest, temporal and spatial parameters, resolution, and the type of data plot desired. Atmospheric characteristics, such as temperature or wind speed, can be presented in a variety of views, e.g., as a function of a spatial or temporal variable or as a function of an environmental model parameter.

A set of propagation menus allows the user to define and execute InfraMAP's integrated modeling capabilities. First, via a Scenario menu, source and receiver locations, event date and time, and environmental parameters are chosen. Second, a Model menu is used to select the propagation model and its required input parameters. Default values of model parameters are provided automatically but may be modified by the user. Third, a Run/View menu is used to commence model execution and to display results upon completion of the run. Model results are automatically stored and can be recalled later for analysis or display. A range of display options is available. In addition to propagation model results, the atmospheric characteristics used in the run can also be viewed.

The software design enables a user to run propagation models quickly and efficiently via the pre-defined menus, and simultaneously provides flexibility both in the choice of model parameters and by allowing user-defined manipulation of data via the command line input. The remainder of the section describes the models in more detail and presents examples of the tool kit's capabilities.

Environmental Characterization

The existence of multiple atmospheric layers and large spatial and temporal variability of the atmospheric temperature and wind speed produces a very complicated infrasound propagation environment in which sound speed varies with time, location and altitude. Lower, middle and upper atmospheric temperature and wind data, required for predicting infrasound propagation paths, are currently available in a variety of formats at varying temporal and spatial resolutions, but no one data source contains all of the required environmental parameters at all locations and altitudes. Multiple atmospheric databases and models have been evaluated for use in InfraMAP, with consideration given to spatial and temporal resolution, coverage, and ease of implementation.

Two empirical atmospheric models, developed at NASA and currently maintained by the Naval Research Laboratory, have been integrated with the propagation models in InfraMAP. They are:

1. the Horizontal Wind Model (HWM) [Hedin *et al.*, 1996] and
2. the Extended Mass Spectrometer - Incoherent Scatter Radar (MSIS or MSISE) temperature and density model [Picone *et al.*, 1997].

HWM provides zonal and meridional wind components, and MSISE provides temperature, density and atmospheric composition. These environmental models, which extend from the ground into the thermosphere, were constructed using observed data from a variety of sensors (e.g., satellite, rocket, ground-based radar) as constraints on a set of low-order spherical harmonics. The models produce the mean estimate of the atmospheric parameters at a particular time and location, and they incorporate spatial, diurnal and seasonal effects. Other databases are being used to estimate variances in atmospheric data for incorporation in studies of propagation variability and localization.

Examples of output from the environmental models are presented in Figures 2 and 3. Figure 2 shows a global image of wind magnitude at a fixed altitude of 120 km, with wind vectors superimposed. Figure 3 displays temperature profiles at 500 km increments along a great circle path from the equator to the north pole.

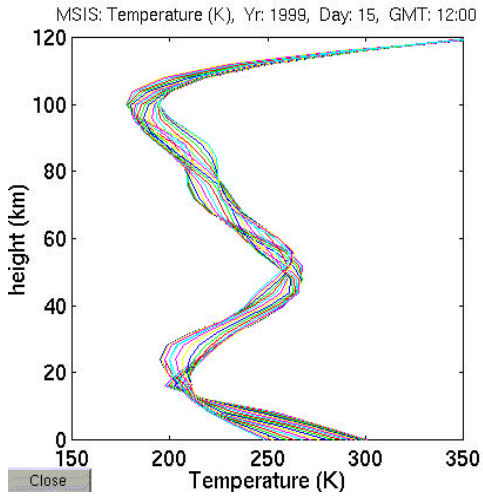
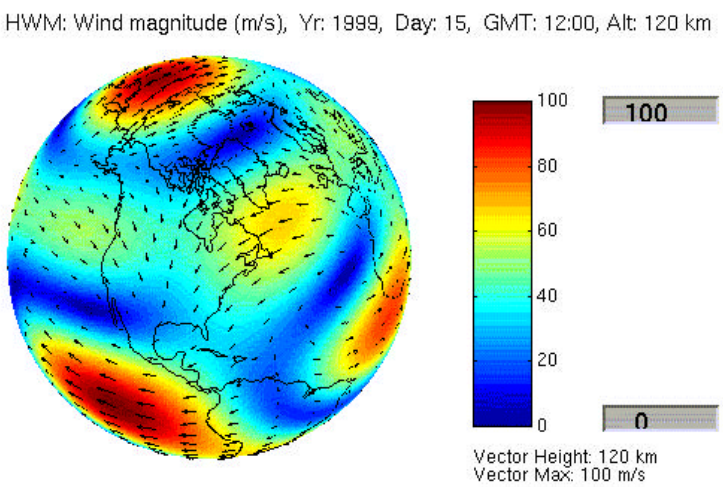


Figure 2: Global Display of Wind Magnitude at Fixed Altitude (from HWM)



Propagation Models

A range of modeling capabilities is required in order to meet the CTBT monitoring objectives of predicting travel time, azimuth, amplitude, and ultimately waveform or spectral characteristics. No one model is sufficient for predicting all essential features. The baseline set of acoustic propagation models contained in InfraMAP consists of:

1. a three-dimensional ray theory model [Jones *et al.*, 1986],
2. a WKB version [Dighe *et al*., 1998; Hunter and Whitaker, 1997] of the normal mode model [Pierce and Kinney, 1976; Pierce *et al.*, 1973; Pierce and Posey, 1970], and
3. a continuous-wave, two-dimensional parabolic equation (PE) model [Jensen *et al.*, 1994; West *et al.*, 1992].

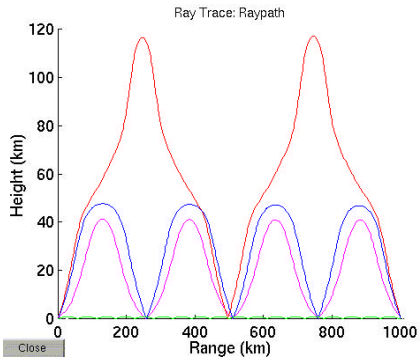


Figure 4: Vertical Projection of Ray Paths (Eigenrays)

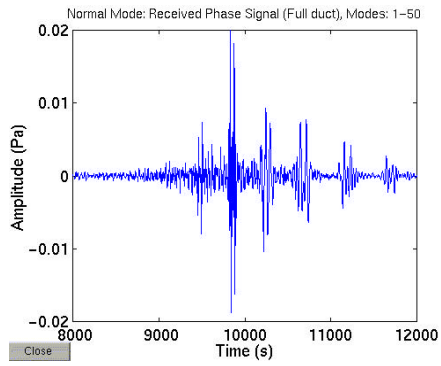


Figure 5: Waveform Predicted Using Normal Modes

A sample of output from each of the three models is shown in Figures 4 through 6.

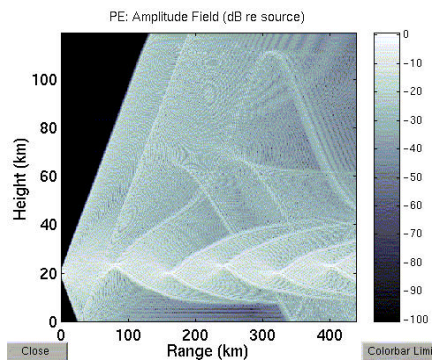


Figure 6: Amplitude Field From Parabolic Equation Model

The 3-D ray tracing code, developed at NOAA, is capable of incorporating a range-dependent atmosphere in propagation calculations. In addition to vertical and horizontal refraction, the model accounts for horizontal translation of the ray path due to the moving medium. It is well established that horizontal refraction and translation can cause significant azimuth biases in the propagation path [Georges and Beasley, 1977]. Azimuth and elevation angles, travel time, and absorption can be readily calculated at each point along a ray path. The ray tracing technique is capable of stepping either forward from a source or backward from a receiver. In InfraMAP, an algorithm has been implemented for finding eigenrays, rays that connect a source and a receiver to within a tolerance of a user-defined distance.

A version of Pierce's normal mode code, modified to determine propagation of higher frequency modes, was provided to BBN by Los Alamos National Laboratory and has been integrated into InfraMAP. The model uses the Wentzel-Kramer-Brillouin (WKB) method to calculate a dispersion curve, which in turn is used to predict received waveforms at a given range and azimuth. Only range-independent environments are supported. The environmental profiles can be retrieved from the source location, receiver location, or from averaged values along the entire path. InfraMAP automates the selection of the waveform time window, based upon the signal velocity and range. In addition, the special case of dual-duct propagation is identified and automatically processed; in which case the full waveform solution is a linear sum of those for the upper and lower ducts.

An implementation of the wide-angle finite-difference PE model was developed internally at BBN for use in InfraMAP. The PE technique steps forward from a source, which is characterized by a starter field, and calculates an attenuation field useful for predicting amplitudes along a vertical slice of the atmosphere. The 2-D model can accommodate a range-dependent atmosphere, but does not account for horizontal refraction and therefore cannot provide predictions of azimuth deviation.

Validation Studies

Data describing a number of historical infrasound events have been reviewed and compared with modeled results using InfraMAP. One important aspect of these investigations is assessment of the utility of three-dimensional ray tracing for predicting infrasonic travel time and azimuth resulting from impulsive events in the atmosphere. Comparisons between observations and predictions are presented here for one event: the meteor-fireball, or super-bolide, of 9 October 1997 above Horizon City, Texas, near El Paso, as observed at TXAR.

Infrasound from the bolide was observed at the two arrays at Los Alamos, NM and at the TXAR array in West Texas [ReVelle *et al*., 1998; Armstrong, 1998; Herrin *et al*., 1998]. The atmospheric explosion was determined to have occurred at 18:47:15 UTC at the location 31.8° N, 106.1° W, and an altitude of 28-30 km, based on visual observations, satellite data and seismic signals [ReVelle *et al*., 1998]. Four separate arrivals were associated with this event at both Los Alamos [Armstrong, 1998] and TXAR [Herrin *et al*., 1998]. Ray tracing comparisons with the Los Alamos observations (at a range of 453 km and a back azimuth of 177°, corresponding to near-northward propagation) have been published previously [Gibson *et al*., 1998].

InfraMAP was used to identify eigenrays from the source location, at a height of 29 km, to the TXAR array location on the ground (at a range of 359 km and a back azimuth of approximately 320°). A tolerance, or miss-distance, of 5 km was allowed for each ray at the receiver. The HWM and MSISE models were used to characterize the environment. Vertical projections of five ray paths resulting from range-dependent propagation modeling through the empirically modeled atmosphere are shown in Figure 7. Two stratospheric rays (channeled below approximately 50 km) and three thermospheric rays (passing above approximately 90 km), two of which include a ground reflection, were identified. The rays represent distinct infrasonic "phases," or separate bundles of energy that could constitute separate observed arrivals.

Table 1 presents the modeled travel time and modeled deviation from the geodesic azimuth for each ray and also presents corresponding data for the observed arrivals [Herrin *et al*., 1998]. The main arrival at 1239 seconds is well modeled as a stratospheric path. The arrival at approximately 1465 seconds is also well modeled as a thermospheric path with a ground bounce. The weak first phase was observed to arrive approximately 6% earlier than predicted. The predicted thermospheric phase at 1365 seconds was not reported as observed. The modeled azimuth deviations are within 1 degree of the observed deviations.

Travel Time (seconds)		Azimuth Deviation (degrees)	
Observed	**Modeled**	**Observed**	**Modeled**
1139		+1.8	
	1211		+1.7
1239	1233	+1.2	+1.1
	1365		+3.4
1464 1466	1475 1476	+4.0 +4.0	+3.2 +3.2

Table 1: Comparison of Observed and Modeled Arrivals at TXAR Array

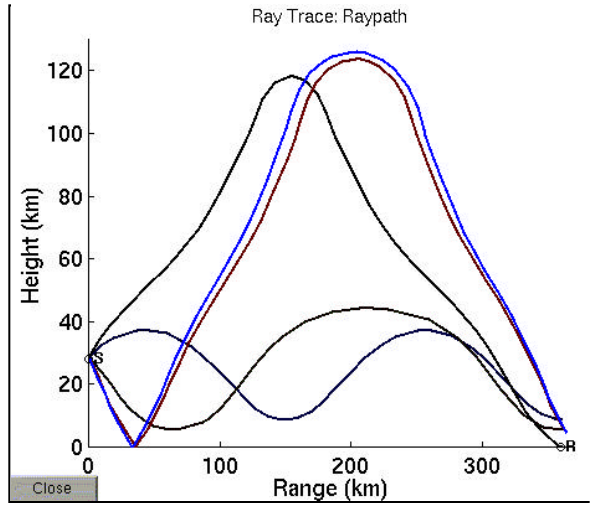


Figure 7: Modeled Eigenrays from El Paso Bolide to TXAR Array

Sensitivity Analyses

The InfraMAP tool kit allows sensitivity analyses to be conducted readily. Model parameters can be varied systematically in order to compare results from a range of propagation scenarios. Such studies are useful for assessing the accuracy, flexibility, and robustness of different modeling approaches and for defining spatial and temporal resolutions required for accurate predictions of infrasound travel times, bearings, and amplitudes. They can also be used to identify systematic biases in travel time and azimuth that it may be possible to eliminate in a localization technique.

Results from one sensitivity study are presented here. InfraMAP was used to evaluate the effect of diurnal variability of atmospheric winds and temperature on ray paths. The environmental models HWM (for wind) and MSISE (for temperature) were used to model the diurnal changes. The effect on eigenrays calculated for several representative scenarios was studied. Specific attention was given to azimuthal deviation and travel time, as these ray parameters impact localization algorithms.

Example results from the modeling are shown, as a function of event time, in Figures 8 and 9. For this event scenario, the source was located in Central Asia (50.5 N, 78.0 E), and the receiver was due West at a range of 2500 km. The time of year was mid-September. Five eigenrays were identified and all had turning points within the thermosphere at altitudes in the range 110-130 km. Over the 24-hour period of the sensitivity study, the travel time variability was up to 2.3% and the change in azimuthal deviation was up to 4.3 degrees. The diurnal variability in temperature was small and found to have a negligible impact on the eigenrays. However, changes in the zonal and meridional winds were significant; winds at the source location are shown in Figures 10 and 11. The greatest variability occurs above 100 km, where the effects of the semi-diurnal solar tide are apparent.

The travel along a ray path is directly influenced by the projected wind along the path; the wind subtracts or adds to the effective sound speed depending on wind direction. This property is observed in the high correlation between the zonal wind and travel time. For example, the ray travel times reach a maximum for events at 10-11 UT. This correlates with the minimum extreme in the eastward zonal wind above 100 km. Westward ray paths at this time of day encounter a headwind with a maximum speed of 60 m/s at their turning points. Similar observations can be made regarding the azimuthal deviations. The crosswind along a ray path acts to translate and/or refract the path, resulting in a change in the observed azimuthal deviation at the receiver. Maximum azimuthal deviation in the negative direction occurs for events at 6 UT. This correlates with the maximum in the meridional winds above 100 km. Ray paths at this time of day encounter a maximum crosswind of 60 m/s at their turning points.

In summary, it is concluded from the diurnal sensitivity study that modeled diurnal changes in the winds can generate observable changes in travel time and azimuthal deviations for ray path solutions over fixed source-receiver geometries. These changes correlate strongly with the wind at the ray turning points. Only thermospheric rays are discussed here. Similar, although weaker, diurnal effects were also found to hold for stratospheric rays [Norris and Gibson, 1998].

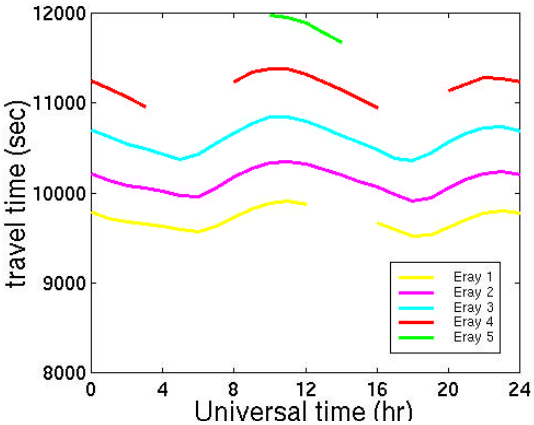


Figure 8: Travel Time Variations over Diurnal Cycle; 2500 km Path

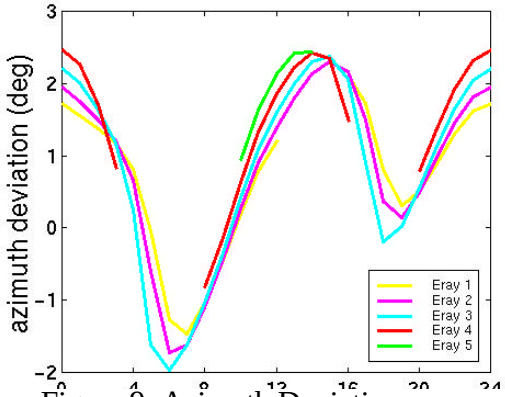


Figure 9: Azimuth Deviations over Diurnal Cycle; 2500 km Path

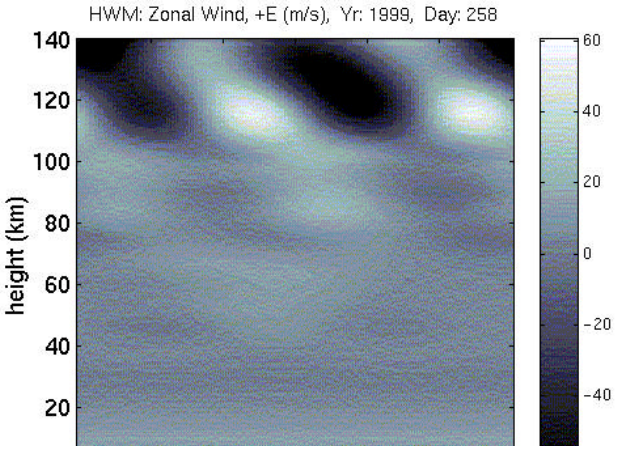


Figure 10: Zonal Wind Variations over Diurnal Cycle; Central Asia (+Eastward)

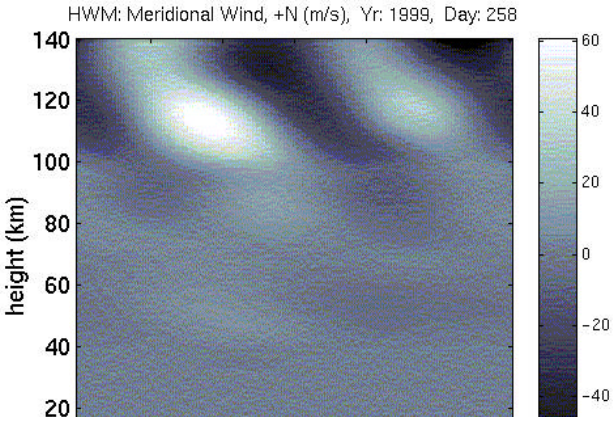


Figure 11: Meridional Wind Variations over Diurnal Cycle; Central Asia (+Northward)

CONCLUSIONS AND RECOMMENDATIONS

Atmospheric characterizations (worldwide temperature and wind profiles) and infrasound propagation models (ray tracing, normal mode and parabolic equation) have been integrated in a single software package. The software incorporates a common user interface for accessing the various models and for viewing output data. Prior to the development of the InfraMAP tool kit, the component models were used primarily in basic research, were individually exercised on a case-by-case basis, and were often restricted by assumptions such as range-independence or a windless, constant sound speed. The integrated set of models allows for higher fidelity propagation modeling by offering features such as the inclusion of range-dependent sound speed and winds and the identification of eigenrays that connect a source and receiver. The ability to predict the critical infrasound propagation characteristics (travel time, azimuth, amplitude) that affect localization and network performance is therefore enhanced.

The functionality of the software is directed toward application to problems of interest in CTBT monitoring. The tools allow the research community to model or evaluate the performance of infrasound localization and detection algorithms. They also allow studies of network performance to be conducted. Use of the InfraMAP tool kit is anticipated to lead to increased efficiency and effectiveness of CTBT operational and research components.

Systematic sensitivity analyses and validation studies are being conducted to understand the effect of environmental and model parameters on accurate modeling of long range infrasonic propagation. These investigations serve to identify specific areas where additional infrasound research and further development of modeling capabilities are needed. The CTBT research community will benefit from improved understanding of modeling issues (e.g., confidence bounds on predictions, need for *in situ* atmospheric data or synoptic models, relative importance of temporal and spatial parameters).

InfraMAP provides the software infrastructure to incorporate improved propagation and localization models, as they are developed, and updated atmospheric characterizations, as available. These upgrades may be needed to improve the estimate of current propagation conditions in order to help the operational monitoring community reduce the area of uncertainty in infrasound source location. Furthermore, the capabilities of the tool kit can be leveraged to generate an accurate infrasound knowledge database for use in CTBT monitoring.

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