THE INFRASOUND ANALYSIS TOOL KIT *INFRAMAP*: CAPABILITIES, ENHANCEMENTS AND APPLICATIONS

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ABSTRACT

The analysis tool kit *InfraMAP* (*Infra*sonic *M*odeling of *A*tmospheric *P*ropagation) consists of three infrasound propagation models (3-D ray trace, normal mode, and parabolic equation), two atmospheric characterizations (HWM and MSIS), a global topography database, and user interfaces for model execution and data visualization. Software features have been implemented that allow improvements in both fidelity and functionality over previously available infrasound modeling capabilities. The ability to predict propagation characteristics that affect localization is therefore enhanced. *InfraMAP* has been delivered to DTRA and is currently being utilized by CTBT researchers and analysts.

Understanding variability in propagation paths is a necessary step in the development of an infrasound network performance model. *InfraMAP* includes a Propagation Variability module that uses a stochastic approach to assess variability in travel time and arrival azimuth. Environmental perturbation fields are defined using a 1-D vertical wave number spectrum of the horizontal wind. A Monte Carlo simulation is executed where rays are traced through multiple environmental realizations, consisting of the sum of mean and perturbed profiles. Ray parameters are calculated for each realization, and the sensitivity of ray tracing calculations to variability in wind profiles can be stochastically quantified. The modeled distributions of propagation variables can be used in assessing areas of uncertainty in source location. *InfraMAP* provides the infrastructure for incorporation of a localization capability as well as the existing propagation and variability modeling capabilities.

Systematic sensitivity analyses have been conducted to understand the effect of temporal, spatial and environmental parameters on accurate modeling of long-range infrasound propagation. These sensitivity investigations, along with comparisons of model predictions with measured data, serve to identify specific areas where additional infrasound research and further development of modeling techniques are needed.

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. Monitoring 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 dynamic nature of the atmosphere, the uncertainties involved in characterizing high-altitude temperatures and winds, and the long ranges over which infrasound signals propagate combine to make accurate predictions of infrasound propagation difficult. Reliable models are needed in order to predict infrasound propagation paths from potential event locations worldwide. Existing model implementations can be difficult to use and often neglect dynamic atmospheric forcing.

The purpose of this effort was to develop a tool that allows infrasound analysts and researchers to easily model propagation through realistic characterizations of the atmosphere. The tool should provide environmental integration and execution capabilities for a baseline set of acoustic propagation models. Development of such an integrated set of models should allow for high fidelity propagation modeling by offering features such as range-dependent temperature and winds. The ability to predict the critical infrasound propagation characteristics (travel time, azimuth, amplitude) that affect localization and network performance would therefore be enhanced.

The functionality of the software tool developed during this effort addresses these needs and the problems of interest in CTBT monitoring. The tool allows the research community to model or evaluate the performance of infrasound localization and detection algorithms. Use of the software is anticipated to lead to increased efficiency and effectiveness of CTBT operational and research components.

Using the modeling tool, systematic sensitivity analyses and validation studies can be carried out to understand the effect of environmental and model parameters on accurate modeling of long range propagation. These investigations serve to identify specific areas where additional infrasound research and further development of modeling capabilities are needed. They will also help to define requirements for an infrasound knowledge database. The CTBT research community will benefit from improved understanding of modeling issues, e.g., confidence bounds on predictions, the relative importance of temporal and spatial variability in the environment, and the need for *in situ* atmospheric data or synoptic models.

RESEARCH ACCOMPLISHED

InfraMAP Software Delivery

An integrated software package for infrasound modeling was developed and delivered during this effort. 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 *Infra*sonic *M*odeling of *A*tmospheric *P*ropagation, is a systems analysis tool that enables the user to perform propagation studies over global scales and at infrasonic frequencies. It can be applied to predict travel times, bearings, and amplitudes from potential event locations worldwide.

The baseline set of acoustic propagation models contained in *InfraMAP* consists of:

- *Ray Tracing:* a three-dimensional ray theory model [Jones *et al.*, 1986],
- *Normal Modes:* 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
- *PE:* a continuous-wave, two-dimensional parabolic equation (PE) model [Jensen *et al.*, 1994; West *et al.*, 1992].

InfraMAP provides integration of these three models with the following baseline environmental characterizations:

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

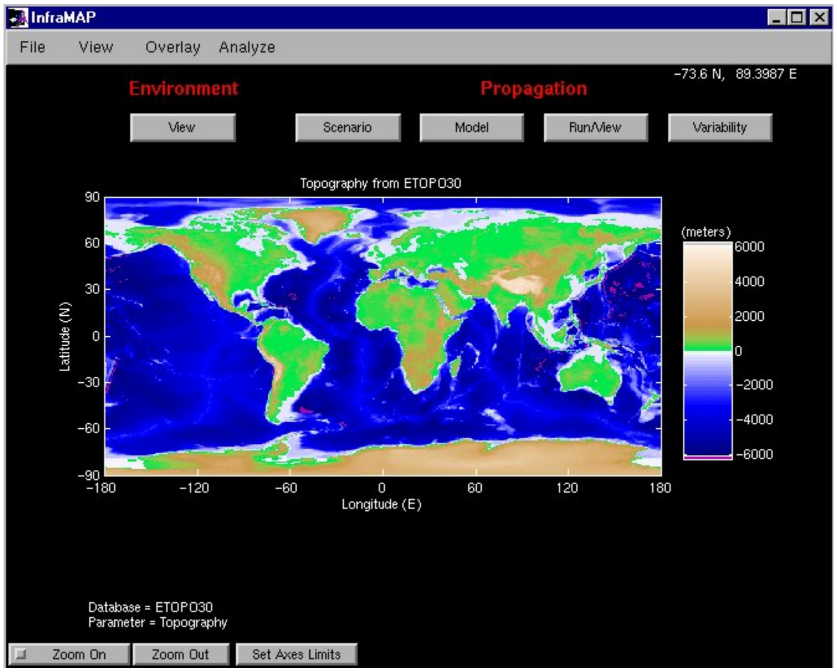
HWM provides zonal and meridional wind components, and MSISE provides temperature, density and atmospheric composition.

Topographic and bathymetric databases in *InfraMAP* are based on standard products from NOAA. The primary database is known as ETOPO (Earth TOPOgraphy) and is available at two resolutions (30 minute and 5 minute).

A software users' manual [Norris *et al.,* 1999] was also developed and delivered during this effort. The user interface runs as a MATLAB application on UNIX-based workstations. Figure 1 shows the main window of the *InfraMAP* user interface.

Enhanced Capabilities

During the development of *InfraMAP*, a number of enhancements were made to the baseline functionality of the propagation models. Several of these capabilities are described in this section.



Database = ETOPO30
Parameter = Topography

Figure 1: Main *InfraMAP* Window

Various options are available for tracing rays. A single ray or a "fan" of rays can be launched from any given point. The ray tracing technique is capable of stepping either forward from a source or backward from a receiver. An option for "Reversing Propagation from a Receiver" is included in *InfraMAP*; when this option is selected, rays are "launched" from the receiver through an inverted propagation environment. During this effort, an algorithm for finding eigenrays, rays that connect a source and a receiver to within a specified tolerance, was developed and implemented. In the eigenray mode, an iterative algorithm is employed to search for rays that connect a source and receiver location to within a tolerance of a user-defined distance. The algorithm utilizes a shooting method to launch rays at various elevations and azimuths until eigenrays are identified. An example of a set of eigenrays identified for a 1000 km path is shown in Figure 2. Both stratospheric and thermospheric rays are shown.

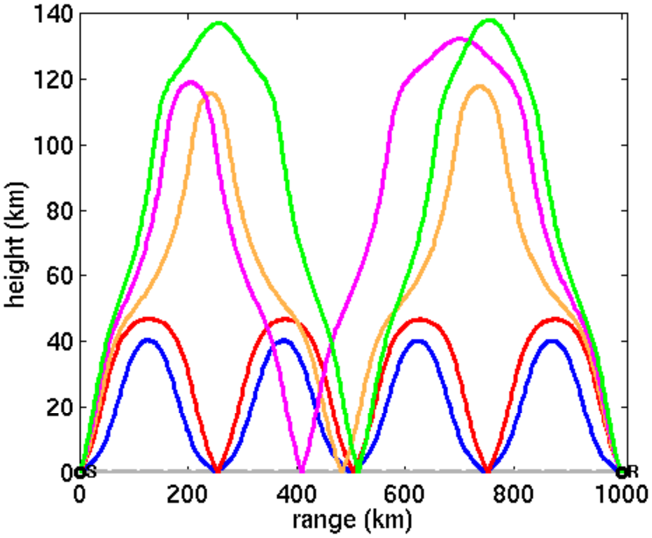


Figure 2: Eigenrays over a 1000 km path

Both range dependence and time dependence of the atmosphere are automated during ray tracing. At each step along a ray path, the local sound speed and wind components are determined from the environmental characterizations evaluated at the corresponding location and time. Time stamps can be displayed at user-selected intervals along ray paths. A plotting option was also developed for the display of ray paths on an azimuthally equidistant projection of the earth's topography.

For normal modes, *InfraMAP* automates the selection of the waveform time window, based on 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 the sum of the upper and lower duct solutions.

Propagation Variability

InfraMAP incorporates propagation variability tools that support the assessment of localization performance of an infrasound network. Understanding variability in propagation paths is a necessary step in the development of a complete infrasound network model. The uncertainty bounds in a propagation model prediction depend to a large degree on uncertainties in the environmental characteristics.

A Monte Carlo approach to assessing the variability of both bearing and travel time was developed for infrasound propagation paths, based on application of ray tracing through a perturbed set of atmospheric profiles. This stochastic approach has the advantage of allowing flexibility in the choice of wind perturbation spectra, so the sensitivity of localization parameters to realistic characterizations of environmental variability can be assessed. The technique has been implemented so that it can be applied to any infrasound station in a user-defined network or at another location of interest.

InfraMAP's Propagation Variability menu provides the capability of performing a Monte Carlo perturbation analysis about a reference eigenray. There is a choice of analysis variables: either azimuth deviation or travel time. This analysis approach allows assessment of (a) the sensitivity of ray tracing calculations to variability in wind profiles, and (b) the resulting effect on the key parameters that affect source localization. The resulting distributions of propagation variables can be used in assessing areas of uncertainty in source location.

In the Propagation Variability analysis, the environmental perturbation fields are defined using a 1-D vertical wave number spectrum of the horizontal wind, and individual realizations of spatial fields are generated through a random-phase technique [Peitgen and Saupe, 1998]. Wind profiles are perturbed over multiple realizations. A Monte Carlo simulation is executed where rays are traced through each realization, consisting of the sum of a mean and a perturbed profile. Ray parameters are then calculated for each realization, and a statistical analysis is done over the entire set of realizations.

- If azimuth deviation is chosen, then the wind component normal to the great circle path (crosswind) is perturbed.
- If travel time is chosen, then the wind component along the great circle path (headwind or tailwind) is perturbed.

The wind perturbation is based on a power spectral density (PSD). Default values of the power law exponent, the perturbation wavelength range (in km), and the PSD magnitude are provided. The user must specify the number of realizations in the Monte Carlo simulation.

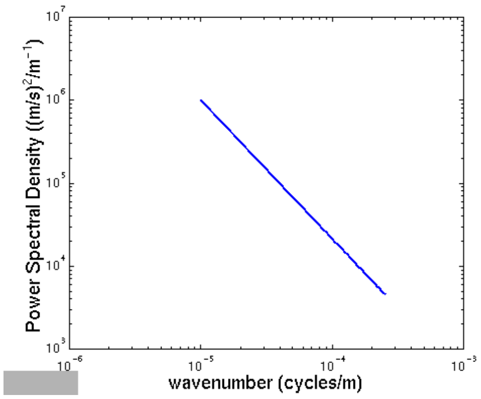


Figure 3: Wind perturbation spectrum

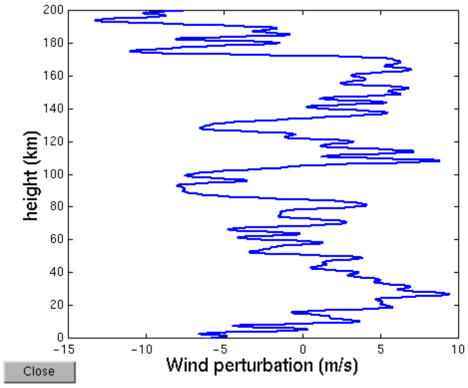


Figure 4: Wind perturbation profile

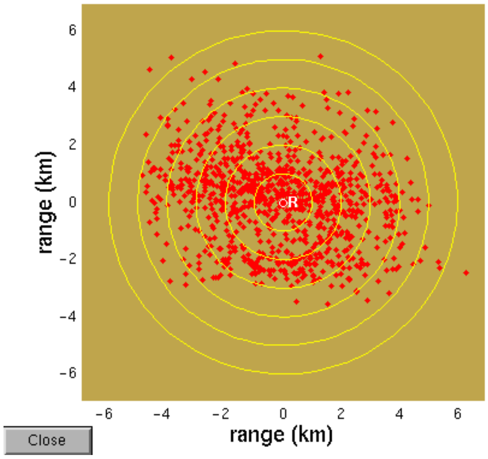


Figure 5: Ground hit points of multiple rays

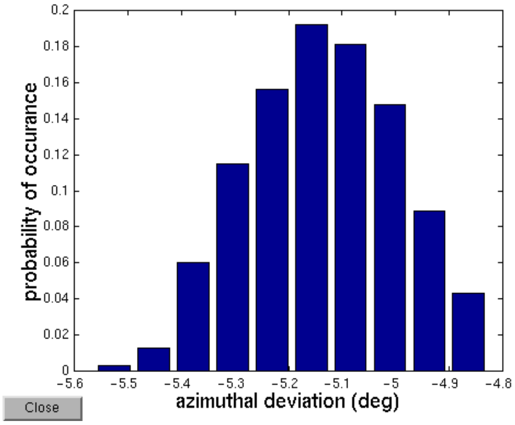


Figure 6: Probability density estimate

Three output displays of analysis results are presented:

- Probability density function estimate,
- Density of calculated ray ground hit points as a function of range, and
- Locations of ray ground hit points (overlaid on an azimuthally equidistant projection of topography). Perturbed ray endpoints are shown compared to the ground hit point of the unperturbed reference ray.

Examples are shown in Figures 3 through 6. Figure 3 depicts a wind perturbation spectrum, and Figure 4 shows a realization of a perturbation profile calculated using this spectrum. Figure 5 is a plot of ray ground hit points resulting from a Monte Carlo simulation, and Figure 6 is the corresponding probability density function estimate.

The software provides the infrastructure to add additional capabilities to support network performance evaluation, for example, station detection characteristics, estimates of noise levels, area of uncertainty estimates, etc.

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. Analyses have been presented that address temporal sensitivity of propagation [Gibson *et al.*, 1999; Norris and Gibson, 1999]. Other studies have been conducted to address spatial or environmental sensitivity; one such study is summarized here.

InfraMAP was used to evaluate the effect of variability in solar magnetic activity on ray paths. Geomagnetic disturbances from solar activity influence atmospheric temperature and winds at high altitudes. The planetary equivalent daily disturbance amplitude, A_P, is used as an input parameter in the wind and temperature models and it affects the modeled environment at altitudes above 100 km.

Archived values of A_P over a six-year period were reviewed to determine a realistic parameter range for the study.

- Values of A_P ranged from approximately 1 to 100.
- Approximately 97% of the days had A_P values of less than 50.

- 10% of the days had A_P equal to 4.

The values of A_P chosen for the study were: 4, 8, 16, 32, 64, and 128.

In the modeled scenarios, the source was located in Central Asia (50.5° N, 78.0° E), and the receivers were due West and due North at a range of 2500 km. The time of year was mid-September and the time of day was 12 UT. Five eigenrays were identified and all had turning points in the thermosphere at altitudes in the range 110-125 km. At these altitudes, modeled temperatures and winds are sensitive to solar effects.

The effects on travel time and azimuth deviation of the eigenrays are shown in Figures 7 and 8, respectively, for the northward path. Over the A_P range of the sensitivity study, the travel time variability was up to 2% for each ray path. This effect due to A_P is small compared to the range of travel times among the five rays. The change in azimuth deviation was up to 2 degrees, which is of the same order as the range among the five rays.

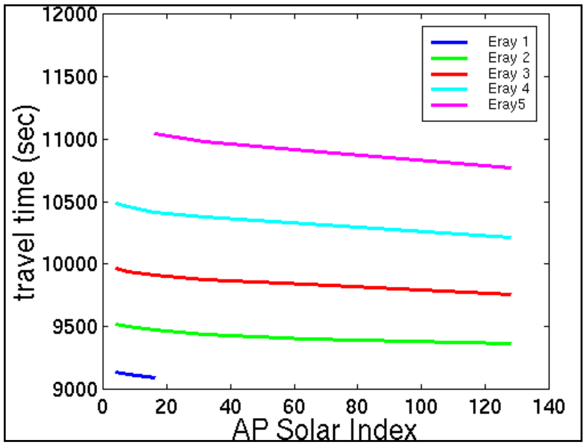


Figure 7: Travel time variability due to solar magnetic disturbance

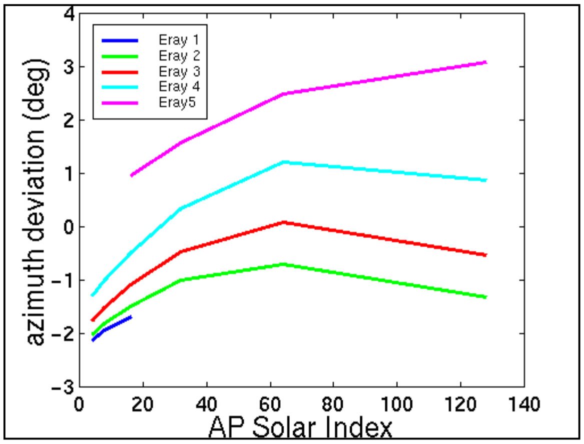


Figure 8: Azimuth deviation variability due to solar magnetic disturbance

For this particular modeled event scenario, it is concluded that solar magnetic disturbance effects may result in observable changes to thermospheric ray paths but are unlikely to represent a large source of variability in propagation. However, the effect of A_P variability may be more prominent in other geographic regions or in other event scenarios.

CONCLUSIONS AND RECOMMENDATIONS

A user-friendly software tool kit has been developed to predict the critical propagation characteristics that affect localization and detection performance of an infrasound monitoring network. The integrated set of models allows for higher fidelity propagation modeling than has previously been available to the infrasound monitoring community. It has been shown via modeling that significant biases in travel time and azimuth over ranges of CTBT interest are anticipated, and that these biases must be corrected for in order to avoid large location errors.

A perturbation approach to model propagation variability has been developed and is included in the software. Further investigations of environmental variability and its effect on propagation should be conducted. Additional development of network performance models incorporating these variability effects should also be performed.

Model-to-model comparisons are planned, during a subsequent effort, in order to validate the modeling techniques and to define confidence levels. Further enhancements to the functionality and efficiency of the baseline models will be incorporated into an updated version of the software. As higher fidelity environmental characterizations become available, they should be integrated into a next-generation version of the software. Efforts should also be made to incorporate near-real-time updates to the propagation environment, based on updated measurements or synoptic models, and to evaluate resulting improvements over the current environmental models.

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

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