INFRAMAP PROPAGATION MODELING ENHANCEMENTS AND THE STUDY OF RECENT BOLIDE EVENTS

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ABSTRACT

Enhancements to the propagation modeling capabilities of the InfraMAP analysis tool kit are being developed in several areas. InfraMAP (Infrasound Modeling of Atmospheric Propagation) consists of three infrasound propagation models (3-D ray trace, normal mode, and parabolic equation), two atmospheric characterizations (HWM and MSISE), a global topography database, and user interfaces for model execution and data visualization. InfraMAP has been delivered to the research and development test bed and is currently being utilized by Comprehensive Nuclear-Test-Ban Treaty researchers and analysts.

Three specific types of InfraMAP enhancements are addressed here. First, a low-frequency absorption model has been integrated for use by both ray- and parabolic-equation (PE) propagation analyses. The absorption model predicts both classical (translation, diffusion) and relaxation (rotation, vibration) losses. Absorption is calculated from temperature, pressure, and atmospheric gas densities, which are determined using the environmental model MSISE. Second, a waveform synthesis capability has been integrated into the ray model. Eigenray solutions for a specific source-receiver scenario are used to synthesize a time-based waveform. A user-defined source waveform is convolved with weighted impulse functions at the eigenray arrival times. The impulse weighting is based upon a calculated absorption loss along each ray path. Finally, improved environmental variability modeling capabilities are being pursued to model the propagation variability induced by the environment. A sample from the Naval Research Laboratory atmospheric statistics database has been investigated for use in improving predictions of propagation variability.

Propagation modeling studies have been performed for several recent bolide events, including the 1997 El Paso, Texas, bolide, the 2000 Acapulco bolide, the 2000 Yukon bolide and the 2001 Pacific bolide. Predicted absorption curves are compared to the spectra of observed waveforms. Nominal source localizations are computed from measured station azimuths. Enhanced localizations that correct for predicted azimuth deviation are also calculated for comparison. The dependence of eigenray arrival times on source height is shown to be a viable discriminator for source height estimation.

KEY WORDS: infrasound, long-range propagation, modeling, bolides, atmosphere

OBJECTIVE

The objective of this effort is to improve the utility of the InfraMAP software. InfraMAP is an integrated software tool kit designed to support nuclear explosion monitoring research and analysis. It is composed of geospatial, environmental, and propagation models integrated with a menu-driven interface. Figure 1 is a graphical representation of the main InfraMAP menus.

Enhancements to InfraMAP are being developed to increase the modeling capabilities of the tool, which, in turn, will lead to improved prediction accuracy for scenarios of interest to the nuclear explosion monitoring community. New functionality is being added to both the propagation and environmental models. In this paper, several InfraMAP enhancements are described and applied to the study of bolide events. Bolides provide an excellent source of infrasound, and comparisons between predictions and observations are used to help quantify the modeling performance.

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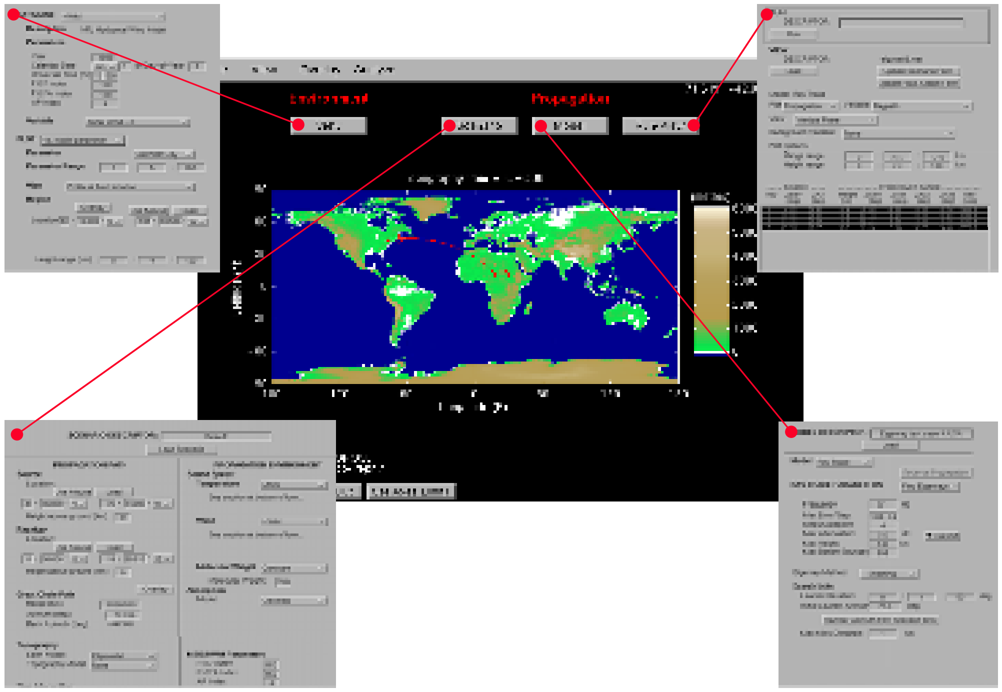

Figure 1. Screen graphic of main InfraMAP menus.

RESEARCH ACCOMPLISHED

Modeling improvements have been integrated into the InfraMAP software toolkit in several distinct areas. Here, the areas of propagation loss, synthetic waveforms, and environmental variability are addressed.

Propagation Loss

Predicting the loss of an infrasonic signal as it propagates from source to receiver is important in the study of network performance. It helps determine the receiver station coverage and detection threshold for a given event scenario. It also aids in determining the observability of acoustic paths that sample the thermosphere, a region of high acoustic absorption. Thermospheric paths are of particular interest because, when analyzed along with lower atmospheric paths, they can be used to estimate source position.

The two main sources of acoustic attenuation are spreading loss and environmental absorption. Spreading loss in acoustic pressure is inversely proportional to range for spherically expanding waves and the square root of range for cylindrically expanding waves. The PE propagation model is solved in cylindrical coordinates and includes the cylindrical spreading loss in its amplitude predictions. In the ray-tracing model, amplitudes associated with individual rays include losses from spherical spreading.

An acoustic absorption model has been integrated for use with the PE and ray codes to improve the accuracy of the amplitude predictions. The absorption model chosen was developed specifically for use with low frequencies and altitudes up to 160 km (Sutherland and Bass, 1996). It includes the contributions from both classical (translation and diffusion) and relaxation (rotation and vibration) losses. The model computes absorption from vertical profiles of temperature, pressure, and the concentration of gases that make up the air. All of these input variables are obtained from the MSISE model (Picone et al., 1997).

Figure 2 gives example profiles of predicted absorption coefficients at 0.2 and 0.5 Hz. Translation and diffusion losses are plotted together as classical loss, of which the diffusion loss makes up less than 1% of the sum. Below 60 km, vibrational loss dominates, but the total absorption is still relatively small. Propagation of a 0.5-Hz signal over a 500-km path would only experience about 0.5 dB of attenuation in this region (neglecting spreading loss). The effects are much different within the thermosphere. At 120 km, the absorption coefficient increases dramatically with frequency; at 0.2 Hz, it is 0.1 dB/km, and at 0.5 Hz, it increases to 1 dB/km. Even acoustic signals that sample these regions for a small percentage of their propagation path can experience significant attenuation. As an example, a 0.5-Hz signal that spends 10% of its 500-km path at 120 km or above would have an absorption loss of at least 50 dB.

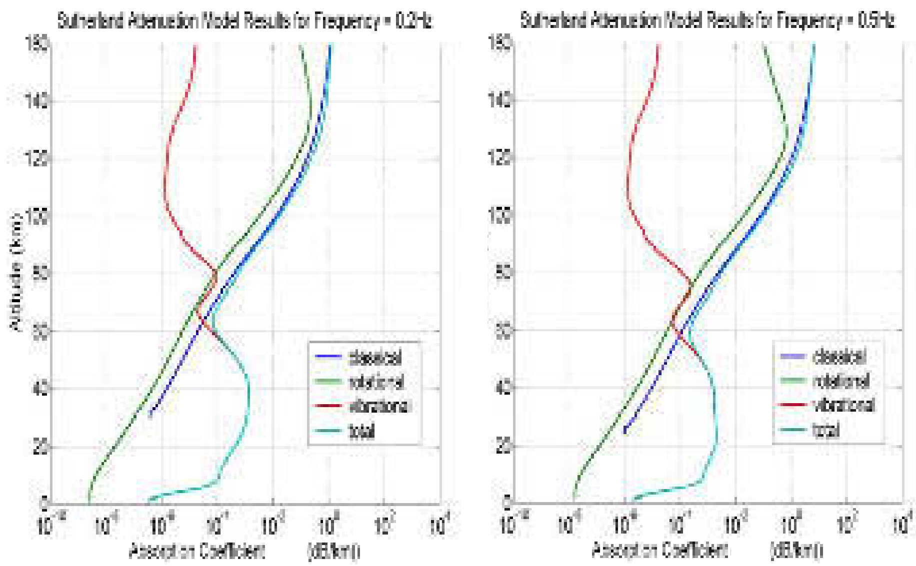

Figure 2. Absorption coefficients computed from a low-frequency, high-altitude model (Sutherland and Bass, 1996) at 0.2 and 0.5 Hz.

Comparisons were made of PE amplitudes with and without the atmospheric absorption effects. Results are shown in Figure 3 for a source at the ground. The amplitude predictions are made for upwind conditions, so a stratospheric return, with an upper turning height of 40-60 km, is not present. In the cases where absorption is not included, significant thermospheric energy reaches a receiver on the ground at 500-km range. With absorption included, a received signal at 500-km range would still contain a thermospheric return at 0.2 Hz, although the amplitude is reduced. However, at 0.5 Hz, the signal experiences strong absorption at altitudes between 110 and 120 km, and any thermospheric energy arriving at the receiver will be heavily attenuated.

Synthetic Waveforms

The integrated ray model within InfraMAP is useful for predictions of travel times and azimuth deviations. However, its output cannot be directly compared with time-series waveforms, either from normal mode predictions or direct measurements. A synthetic waveform capability has been integrated into the ray model to enable these types of comparisons.

The source waveform must first be selected. It can be defined as blast wave, Gaussian waveform, or user-defined waveform. The blast wave is computed from the formulation used in InfraMAP's normal mode code (Pierce and Posey, 1970). Figure 4 shows a blast wave for a 1-kT source on the ground. The synthetic waveform is computed by convolving the source waveform with weighted impulse functions at the arrival times of the selected rays. The impulse functions are weighted by the attenuation loss calculated over each ray. An application of the synthetic waveform functionality is presented in the Tagish Lake bolide study below.

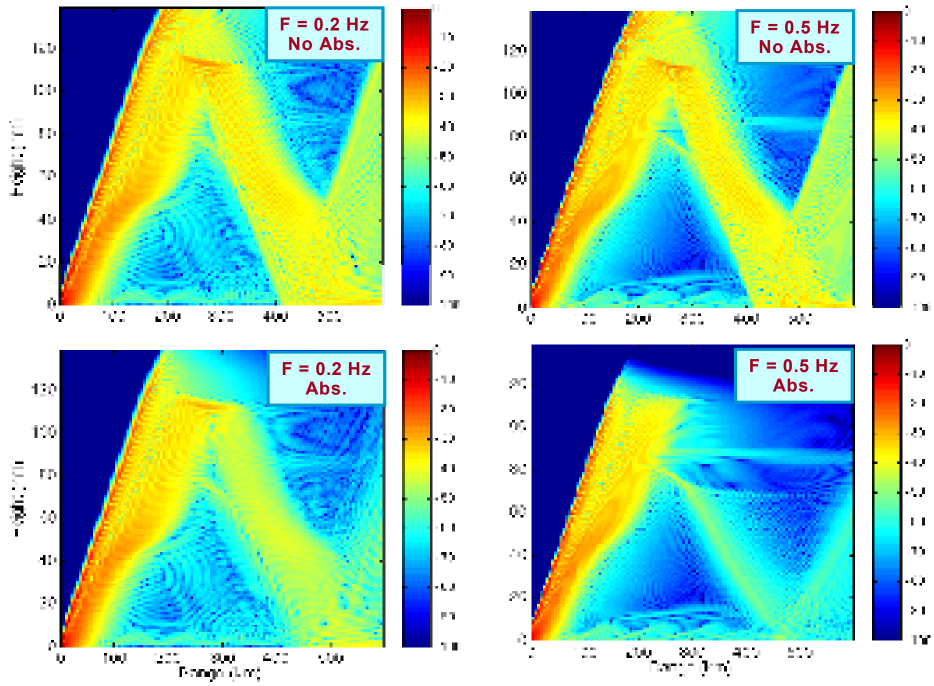

Figure 3. Comparison of PE amplitude predictions with and without absorption. Absorption effects at 0.5 Hz are apparent in the thermosphere, where energy propagating above 115 km is heavily attenuated.

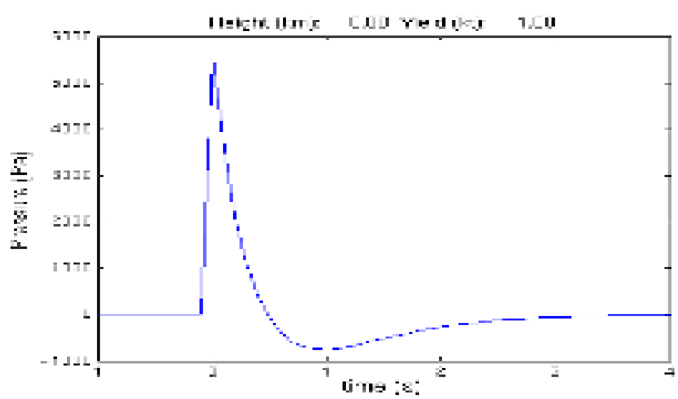

Figure 4. Blast waveform model for a 1-kT source on the ground (Pierce and Posey, 1970).

Environmental Variability

The main environmental models integrated in InfraMAP are HWM-93 for winds (Hedin, 1996) and MSISE-90 for temperature and gas densities (Picone et al., 1997). These are empirical models based on climatological data. They provide mean predictions from the ground up to several hundred kilometers and resolve both diurnal and seasonal trends in the variables.

In predicting infrasound propagation for a given scenario, it is important to predict not only the mean parameters, but also the uncertainty about the mean. The propagation uncertainties are needed to quantify the area of uncertainty in the source localization predictions. In the baseline version of InfraMAP, a variance model was integrated to compute this uncertainty. It was based upon a Monte Carlo analysis of ray propagation through multiple environmental perturbation realizations. These realizations were based upon a user-selected power-law spectrum that defines the relevant length scales.

Recently, a new variability dataset has been generated at the Naval Research Laboratory (NRL) (Drob and Picone, 2000). It quantifies the variance of the mean HWM and MSISE predictions over a global grid. Below 50 km, this dataset was derived from daily numerical weather prediction (NWP) analysis fields. Above 50 km, it was derived from UARS-HRDI satellite data.

An example of the variance database is given in Figure 5. The plot image shows the 15-day average standard deviation of the meridional winds at 0 degrees longitude. As identified by Dr. Doug Drob at NRL, the prominent areas of variability are the mid-latitude troposphere jet streams at 5 - 15 km, and the high- to mid-latitude winter stratospheric vortex at 40 - 60 km. We are currently investigating the NRL variance database for use in improving the modeling of the environmental variability. These improvements will then be used in quantifying the propagation variability and localization uncertainty.

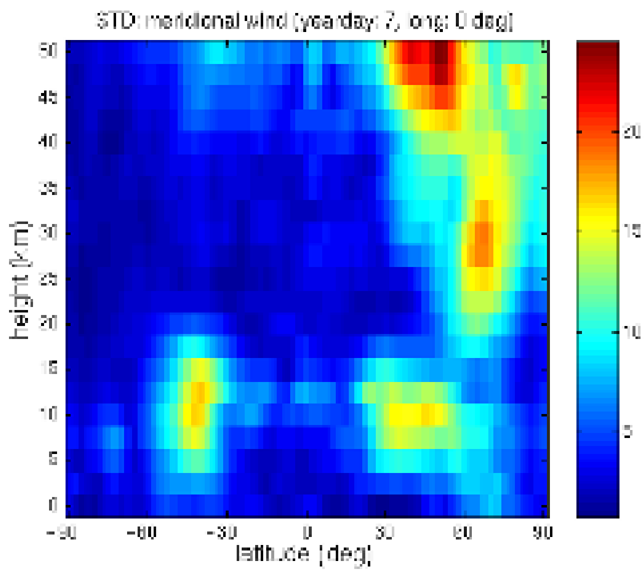

Figure 5. Example of the variance database from the NRL atmospheric statistics database (DOE-AT04-99AL66330). A sample data set was informally provided to BBN by Dr. Doug Drob (NRL-7643) for DTRA/DOE - CTBT R&D scientific investigation and product development.

Comparison Studies

Bolides are excellent impulsive sources of opportunity for acoustic frequencies below a few Hertz. When combined with ground truth data, they can support research and development for nuclear explosion monitoring. Infrasonic modeling of recent bolide events has been used to evaluate the enhanced modeling capabilities of InfraMAP and to quantify their accuracy with respect to observations. In this paper, we present results from three bolide events: the El Paso bolide of 9 Oct 1997, the Tagish Lake bolide of 18 Jan 2000, and the Pacific bolide of 23 Apr 2001. General information concerning these and other bolides can be found at the URL: http://phobos.astro.uwo.ca/~pbrown/usaf.html .

El Paso Bolide

On 9 Oct 1997, a large bolide traveled above Texas near El Paso. The height of the bolide, as determined from satellite observations, was 29 km. This bolide was detected at both the Los Alamos DLIAR array (range 445 km) and the Southern Methodist University TXIAR array (range 359 km). The received data at TXIAR has been studied to evaluate the ability to verify or refine the source height estimate.

To model the bolide signal, eigenrays were computed over a range of source height from 0 to 50 km. Figure 6 shows the eigenray solutions at 30-km source height. Over the range of heights, there are 1-3 stratospheric eigenrays and 2-3 thermospheric eigenrays.

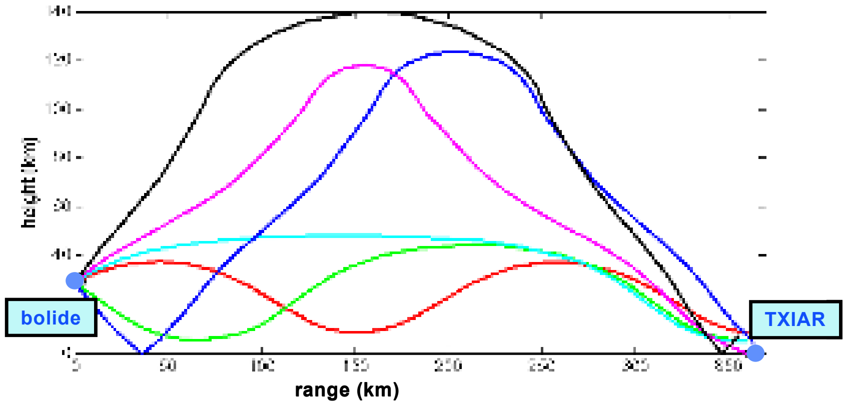

Figure 6. Eigenray solution between El Paso bolide at source height of 30 km and receiver at TXIAR.

Synthetic waveforms were next computed for each source height and mapped into an image as a function of arrival time and source height (bottom of Figure 7). A Gaussian waveform of standard deviation 10 sec was used as the source function. For sources near the ground, single eigenrays can be observed, which then split into multiple eigenrays as the height increases. The split rays for a given v-shaped branch correspond to two similar paths, one propagating up at the source, the other propagating down, reflecting off the ground, and then propagating up. The eigenray image can be compared to the measured waveform (top of Figure 7), and a source height estimate can be made by correlating the measured arrival times with the predicted amplitudes. The three measured arrivals match the predictions at source heights of 33, 26, and 23 km, respectively. Although there is a spread in these heights, they are in general agreement with the satellite-determined source height of 29 km.

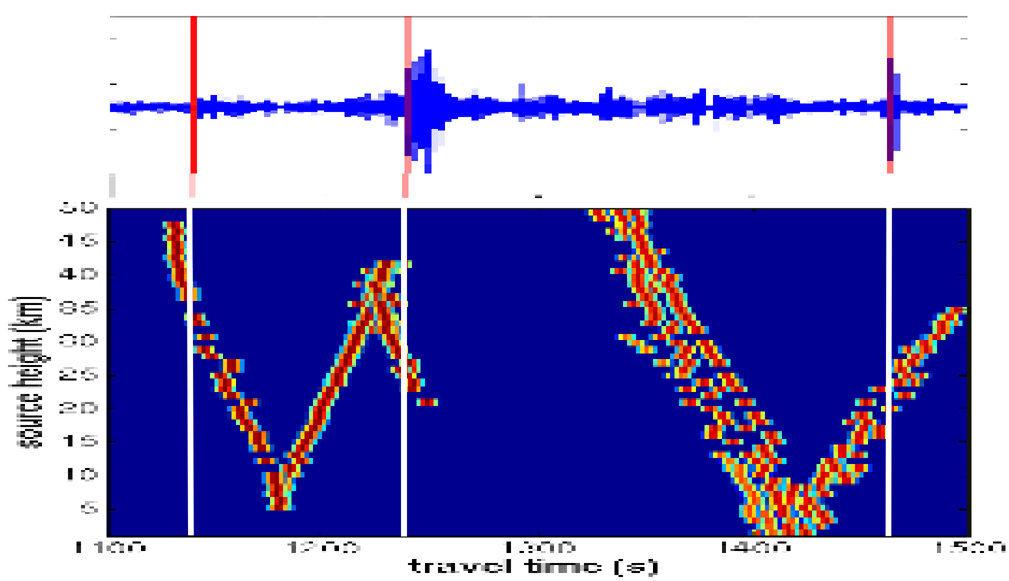

Figure 7. Comparison of measured arrival times (above) with synthetic waveform prediction from eigenrays solved over 0 to 50 km (below).

Tagish Lake Bolide

On 18 January 2000, sensors aboard Department of Defense (DoD) satellites detected the impact of a meteoroid at 16:43:43 UTC near Whitehorse in the Yukon Territory, Canada. The object detonated at an altitude of 25 km at 60.25 degrees North latitude, 134.65 degrees West longitude.

An infrasonic signal was detected at the International Monitoring System (IMS) station in Lac du Bonnet, Canada, a range of 2641 km from the bolide. A received waveform is shown in Figure 8. This waveform is filtered over the frequency band of 1.0 - 1.5 Hz. The main arrival appears at an arrival time of approximately 8200 sec with a possible secondary arrival at 11,300 sec.

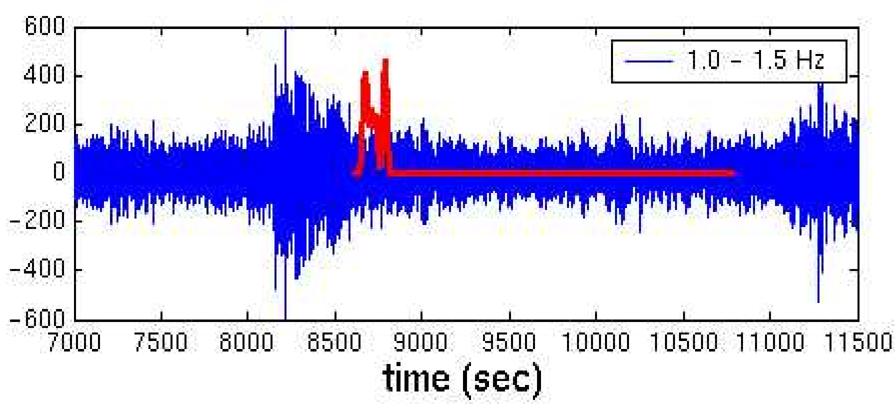

Figure 8. Filtered waveform measured at Lau de Bonnet IMS station (blue), and synthetic waveform generated from eigenrays (red). Amplitude units are arbitrary.

Measurements across the three elements of the array were beamformed using an F-K processing algorithm. The results were inconsistent across the observed waveform, possibly due to low signal-to-noise ratios or loss in coherence of the signals across the array, resulting from turbulence. The strongest coherent cluster in the F-K slowness plane was found using a time window from 8400 - 8500 sec and a frequency band of 0.2 - 1.0 Hz. The back azimuth for this cluster was 306.5 deg.

Eigenrays were computed for this path and are shown in Figure 9. Both stratospheric and thermospheric rays are present. The stratospheric rays have back azimuths at approximately 310 deg, and the thermospheric at approximately 311 deg. These predictions differ by several degrees from the measured value of 306.5 deg.

Synthetic waveforms were generated from the eigenrays for comparison with the measurements. The source function was a Gaussian waveform with a standard deviation of 10 sec. The predictions are overlaid on the waveforms in Figure 8. A bias of approximately 500 sec is apparent in the arrival times. This difference may be due to discrepancy between the predictions of temperature and wind from the HWM and MSISE models and the actual environmental conditions during the propagation. It may also result from inadequate modeling of the source function.

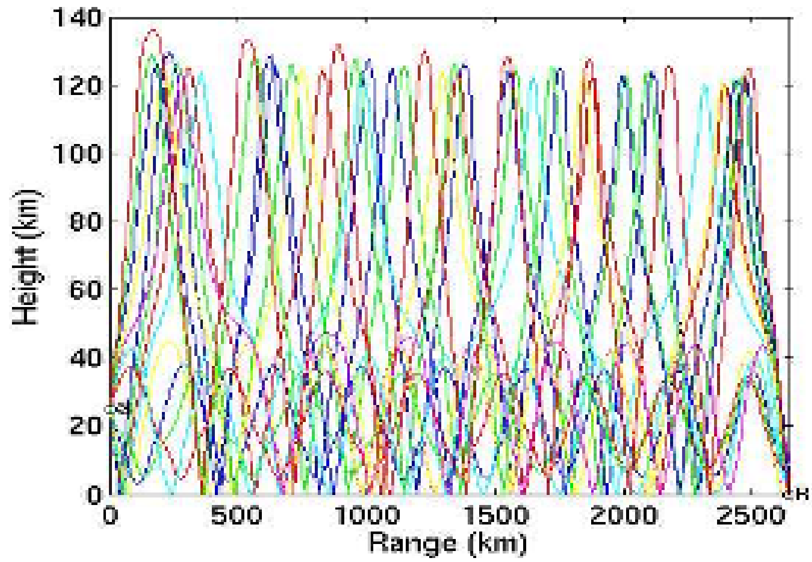

Figure 9. Eigenrays from Tagish Lake bolide to Lac du Bonnet IMS station.

Pacific Bolide

On 23 April 2001, a large bolide was observed over the Pacific Ocean in the area between California and Hawaii. This bolide was observed at several infrasonic stations. We used data from five stations in a study to determine the bolide location (Figure 10). The IMS arrays used were IS59 (Hawaii), IS10 (Lac du Bonnet, Canada), IS57 (Pinon Flats, California). Two additional IMS prototype arrays were also used: SGAR (St. George, Utah) and DLIAR (Los Alamos, New Mexico).

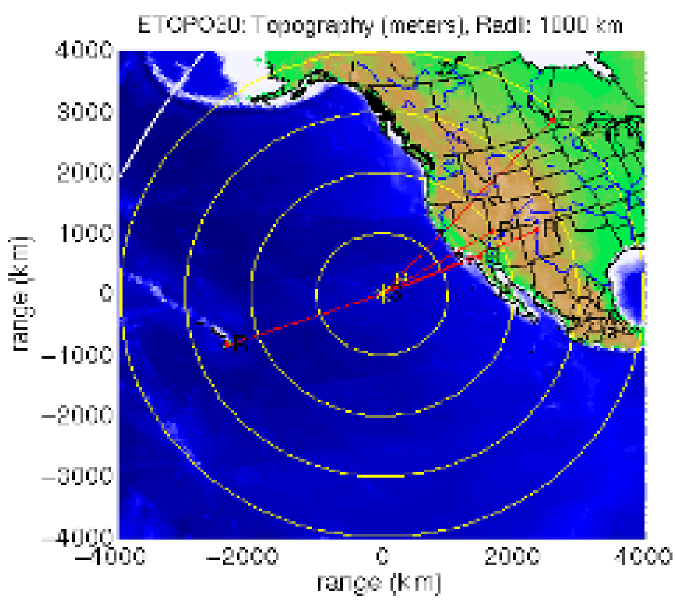

Figure 10. Nominal location of Pacific bolide and great circle paths to infrasonic stations. Yellow circles are contours of constant distance from source with 1000-km interspacing.

An iterative technique was used to estimate source location from azimuths and travel times at the five stations, incorporating environmental effects. Signal onset times, peak of signal correlation, and signal duration were estimated from the measured waveforms. Back azimuths were calculated by beamforming, using an F-K analysis technique. An initial location estimate was determined from the intersections of fans of rays propagated back from the five stations, using the mean observed azimuth at the station to launch each ray. Modeled signal velocities (range/travel time for each ray) were used to estimate the event time, and the initial location was perturbed to improve consistency in the event time estimates. A nominal event height was selected, and eigenrays were then calculated between the estimated location and each station. Consistency in event time was again used to perturb the location estimate, and eigenrays were recalculated.

The estimated location for the Pacific bolide, determined using the iterative ray-tracing technique, is shown in Figure 11. Also shown is the location determined from DoD satellite observations, as reported in a press release from 22 May 2001 (http://phobos.astro.uwo.ca/~pbrown/usaf.html). The colored line segments represent the projections of the initial fan of rays from each of the five stations used in the study.

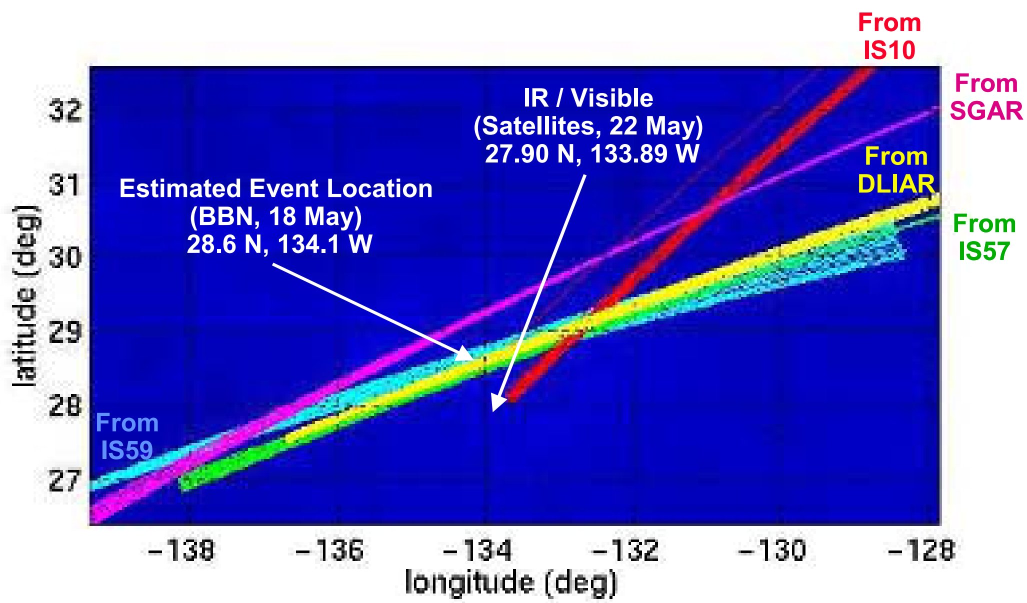

Figure 11. Estimated source location of the Pacific bolide from infrasonic modeling and from satellite observations. The colored line segments represent the projections of the initial fan of rays from each of the five stations used in the localization.

CONCLUSIONS AND RECOMMENDATIONS

Several enhancements have been made to the modeling capabilities of the InfraMAP tool kit. An absorption model developed for low frequencies and high altitudes has been integrated into the package. Absorption is particularly significant within the thermosphere. PE modeling for upwind propagation over a 500-km path indicates that thermospheric energy becomes heavily attenuated at the frequency increases from 0.2 to 0.5 Hz.

A synthetic waveform capability has been added to the ray model. The source waveform can be specified as a blast waveform, Gaussian waveform, or user-defined waveform. The source waveform is convolved with ray arrival times and weighted by ray attenuation factors to synthesize a received waveform.

Environmental variability is necessary to determine variability in the propagation predictions and ultimately the uncertainty of source localizations. The baseline environmental variability model is based on a power-law perturbation spectrum. The task of implementing an improved model has begun with the evaluation of a

HWM/MSISE gridded database of wind and temperature variances. A sample of this database has been provided by Doug Drob of the Naval Research Laboratory.

Large bolides provide a strong source for infrasound and, in conjunction with ground truth data from satellites, were used to evaluate the performance of the models. Source height estimates of the El Paso bolide were made using data at the TXIAR station. The propagation range in this case is under 400 km. Synthetic waveforms were computed from eigenray solutions over a range of hypothesized heights. They were then compared with the detected arrivals in the measured waveform. The predicted heights all fell within 6 km of the ground truth height. This result is significant in that it suggests that information important to source location can be predicted from single-station data.

Arrival times and back azimuths were predicted at the IMS Lac du Bonnet station for the Tagish Lake bolide. This propagation path is over 2500 km. Both stratospheric and thermospheric eigenrays were found along the path. A measured back azimuth was computed from the data using an F-K analysis, but the azimuth was not consistent over the entire signal. The measured azimuth differed from the predictions by several degrees. Comparison of arrival times indicates a 500-sec lag in the predictions. The bias may result from discrepancies in the environmental models or from inadequate modeling of the source.

The Pacific bolide was detected at multiple stations and provided the opportunity to perform multi-station source localization. Using three IMS stations and two prototype stations, a source localization was computed that was in reasonable agreement with the satellite-derived position.

Research topics that would support improved modeling of infrasonic events are listed below.

1. There are two types of infrasound from bolides: a linear blast wave associated with supersonic flight, and an impulsive point source associated with fragmentation. The relative strength of these two sources and modeling them for use in linear infrasound propagation models are areas that need further study.
2. The Tagish Lake bolide predictions suggest the possibility that a bias exists in the environmental models for the day and time of this event. Further improvements to the environmental models in InfraMAP should be investigated. In addition, data assimilation of empirical models with *in situ* measurements should be pursued to increase the accuracy of the propagation predictions.
3. The largest errors contributing to source localization uncertainty are generally in the back azimuth estimates. Improvements in either the array geometries or beam-forming algorithms would be desirable to help reduce this error term.

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