INFRAMAP ENHANCEMENTS: ENVIRONMENTAL/PROPAGATION VARIABILITY AND LOCALIZATION ACCURACY OF INFRASONIC NETWORKS

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ABSTRACT

Enhancements to the propagation modeling capabilities of the InfraMAP analysis tool kit are reported in three 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 Defense Threat Reduction Agency's (DTRA's) research and development test bed and is currently being utilized by nuclear-explosion-monitoring researchers and analysts.

First, improvements have been made to the environmental variability analysis capabilities. Wind and temperature variability covers a wide spectrum, in both space and time. The dominant source of variability affecting infrasonic propagation is believed to result from gravity waves. A gravity wave spectral model based upon scale-independent diffusive filtering theory has been integrated into InfraMAP. The model is used to predict the horizontal wind perturbations as a function of height. As height increases, the spectral model amplitude increases, and there is an overall shift in energy towards lower wave numbers. Fourier inversion using random phase is applied to generate realizations of wind perturbation profiles. A dominant horizontal length scale and Gaussian weighting functions are used to generate range-dependent perturbation fields.

Second, the enhanced environmental modeling capabilities are used to evaluate the resulting variability in propagation. Multiple wind perturbation realizations are generated, and a Monte Carlo simulation is executed where multiple rays are traced through the sum of mean and perturbed environmental fields. Two ray parameters (travel time, azimuthal deviation) are calculated for each perturbation. The sensitivity of ray tracing calculations to variability in wind profiles is then quantified by computing the mean and variance of the predicted distributions.

Finally, prediction of propagation variability induced by the environment is used to evaluate the performance of infrasonic networks. Source localization is first computed from the measured station data. Then, modeled variance in travel time and azimuthal deviation, along with the uncertainty introduced by measurement error, are used to calculate the confidence bounds of the localization. These bounds are expressed as an area of uncertainty (AOU) for which there is a 90% probability that the actual source location is contained. For locations based upon travel time and azimuth, the AOU takes the shape of an ellipse. Network performance modeling is applied to data from the April 2001 Pacific bolide and compared to the satellite source localization.

OBJECTIVE

InfraMAP is a software tool kit designed for researchers and analysts who are interested in modeling infrasound in the atmosphere. Model output includes ray tracing, wind (HWM) and temperature (MSIS-E) mean atmospheric profiles, and wind perturbation profiles based upon power-law spectra. InfraMAP has been delivered to DTRA's research and development test bed, and enhancements that improve the model characterizations are under development. The ultimate goal is to accurately predict the achievable performance of infrasonic networks under various scenarios and environmental conditions.

Model enhancements and studies are reported in three areas. A gravity-wave spectral model has been integrated into the wind perturbation module; a propagation variability study has been completed using range-independent wind perturbation profiles; and, a network performance analysis of the April 23, 2001, bolide has been completed using both station measurements and propagation modeling.

RESEARCH ACCOMPLISHED

Environmental variability model

The baseline environmental variability model in InfraMAP is based on a power-law wind perturbation spectrum, and it provides realizations of wind perturbation profiles. This spectrum is applicable for small-scale turbulence, even though atmospheric turbulence covers a wide spectrum of spatial scales (Figure 1). The dominant source of variability affecting infrasonic propagation is believed to result from gravity waves. Gravity waves result from oscillations of air parcels displaced by buoyancy and restored by gravity. The oscillations have time scales ranging from minutes to tens of hours. Vertical length scales of gravity waves are in the range of 0.1 to 10 km, and horizontal scales can span from 100 to 10,000 km.

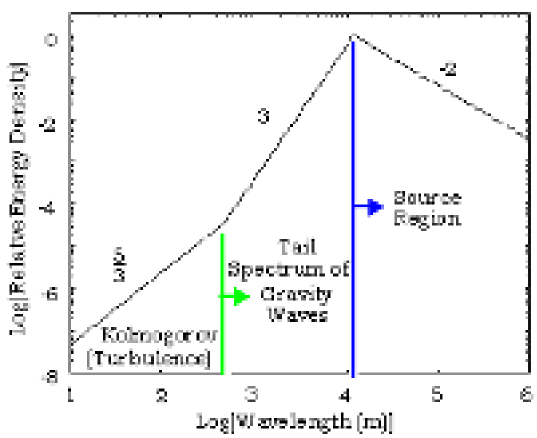

Figure 1. General form of horizontal wind spectrum versus vertical wavelength (from R. J. Sica, University of Western Ontario).

A significant body of research has been carried out to define the spectral character of gravity waves. The spectral model of Gardner (Gardner 1995, 1993) has been selected for integration into the environmental variability module. This model is based on scale-independent diffusive filtering theory. A source spectrum is defined near the ground. As the spectrum is propagated up in height, attenuation is modeled by introduction of diffusive damping. The key spectral properties are:

- an increase in energy with height
- a shift towards larger length scales with height
- an attenuation of smaller length scales with height

The Gardner Spectral model is evaluated at five discrete heights, as shown in Figure 2. These heights capture the dominant gravity wave variability from the troposphere up to the lower thermosphere. Below the troposphere, gravity waves are not fully developed. In the thermosphere, diffusion increases dramatically and gravity waves are damped out.

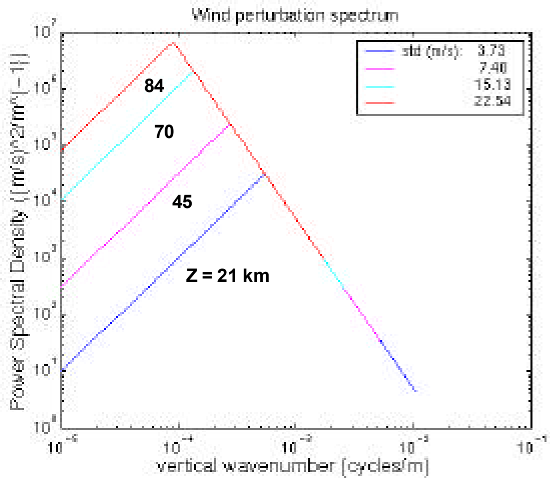

Figure 2. Gardner wind spectral model evaluated at five discrete heights.

Fourier inversion using random phase is applied to the spectra to generate realizations of wind perturbation profiles. A wind perturbation profile is generated for each of the five spectra. A composite profile is then computed by shading each profile spatially with a Gaussian filter and then summing them together, where Gaussian filter half-power points are set to the midpoint between each of the spectral heights. To model range-dependent variability, a dominant horizontal length scale is defined, and Gaussian weighting functions are used to combine the wind perturbation profiles. Figure 3 gives an example realization of a wind perturbation field generated from the gravity wave spectral model.

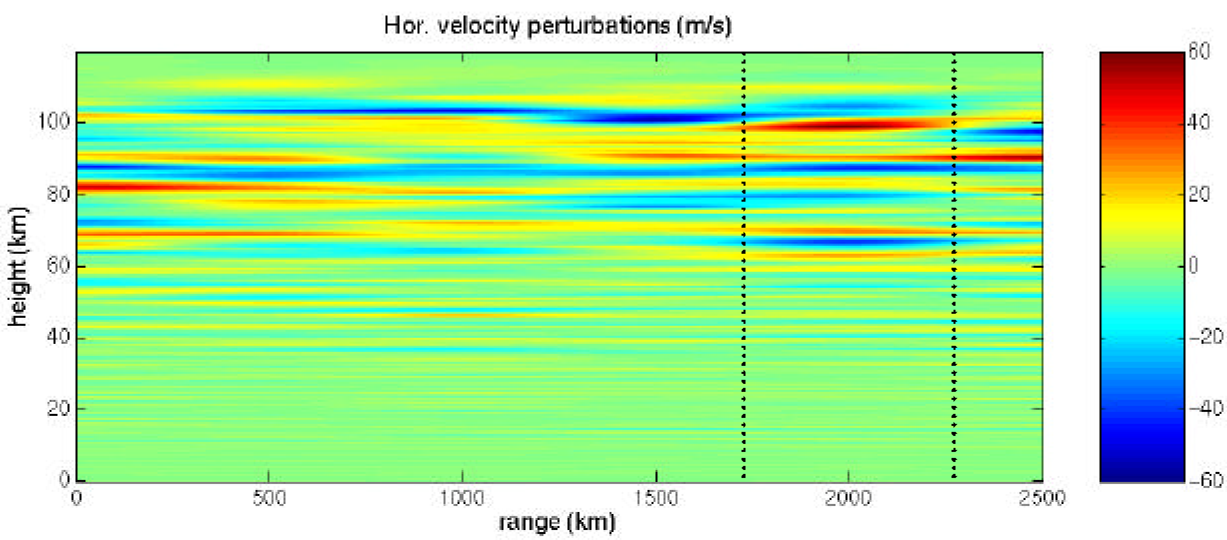

Figure 3. Range-dependent wind perturbations using horizontal correlation length of 500 km.

Propagation variability study

The goal of the propagation variability study is to quantify the bounds in travel time and azimuthal variability that can be expected. Different scenarios are evaluated over different diurnal and seasonal periods. The effects on both stratospheric and thermospheric rays are analyzed.

To perform the study, multiple wind perturbation realizations are generated, and a Monte Carlo simulation is executed where multiple rays are traced through the sum of mean and perturbed environmental fields. Two ray parameters (travel time, azimuthal deviation) are calculated for each perturbation. The sensitivity of ray tracing calculations to variability in wind profiles is then quantified by computing the mean and variance of the predicted distributions. Figure 4 gives an example of the predicted distribution of azimuth deviation of a thermospheric ray over a 500-km path. In this case, the deviation was under 0.2 degree.

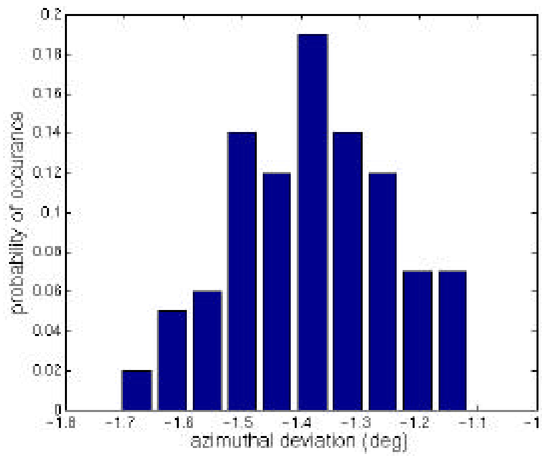

Figure 4. Example probability distribution of azimuthal deviation from Monte Carlo analysis of thermospheric ray along 500-km path.

Network performance study

A network performance model is integrated into InfraMAP that includes the effects of environmentally driven propagation variability. For a selected network of sensors, source localization is computed from measured travel times and azimuths. Predicted uncertainty in ray azimuthal deviation and travel time is added to user-defined station measurement error, and confidence bounds for the localization are computed. These bounds are expressed as an area of uncertainty (AOU) for which there is a 90% probability that the actual source location is contained. For locations based upon travel time and azimuth, the AOU takes the shape of an ellipse. Network performance modeling is applied to data from the April 2001 Pacific bolide and compared to the satellite source localization. Figure 5 illustrates a sample localization and associated AOU ellipse.

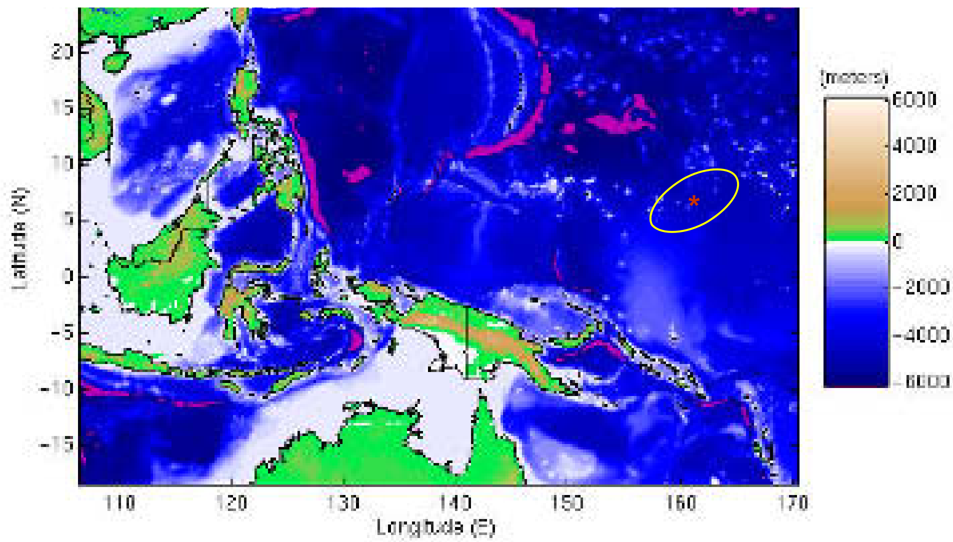

Figure 5. Sample network localization and AOU ellipse.

CONCLUSIONS AND RECOMMENDATIONS

Gravity waves are believed to be the dominant source of environmental variability that affects infrasonic propagation. A gravity wave spectral model has been integrated into InfraMAP based upon scale-independent diffusive filtering arguments. From the model, realizations of wind perturbation profiles are generated. The profiles are based upon five separate spectra in the vertical direction and one dominant Gaussian length scale in the horizontal direction.

Propagation variability is studied by propagating rays through the perturbed profiles, and Monte Carlo statistics are found for travel time and azimuthal deviation. These characterizations are applied to network performance, and AOU confidence bounds are calculated for source localizations.

Network performance studies need to be done over a variety of scenarios and environmental conditions. In areas of high station density, the localization AOU will be small, while in areas of sparse coverage they can become quite large. Defining these regions of best and worst localization accuracy is critical to evaluating the overall performance of an infrasound network.

REFERENCES

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