DEVELOPMENT OF ADVANCED PROPAGATION MODELS AND APPLICATION TO THE STUDY OF IMPULSIVE INFRASONIC EVENTS AT VARIOUS RANGES

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Sponsored by Army Space and Missile Defense Command

Contract No. W9113M-05-C-0135[1]

ABSTRACT

Advanced propagation modeling of infrasound includes the application of Parabolic Equation (PE) and Nonlinear Progressive wave Equation (NPE) models. In this study, the effects of several PE approximations are evaluated in the context of long-range infrasonic propagation. Specifically, the focus is on quantifying the following: phase errors resulting from different split-step Fourier (SSF) implementations, solution stability with respect to step size, and prediction sensitivity to the choice of reference sound speed. The tradeoff between improved performance gain and increased computational loading will be considered. In addition, the expected improvements of applying the NPE will also be addressed.

The study will include comparison of PE waveform predictions with measurements from infrasonic events. These comparisons are of interest in assessing the PE modeling performance, applicability, and limitations. Waveform predictions are made by integrating the continuous-wave PE model into a Fourier-synthesis Time-domain PE (TDPE).

OBJECTIVES

The objective of this research is to improve our ability to understand and characterize infrasonic propagation. This objective will be accomplished by developing advanced propagation models and applying them in comparison studies with ground truth datasets of various infrasonic events.

Through these efforts, the driving mechanisms affecting the measured waveforms will be identified, and the prediction performance of the new models will be quantified. These advances will ultimately improve event localization capabilities. More robust prediction of infrasonic arrivals, for example, those that reach the ground through diffraction, more accurate travel-time predictions, and more robust amplitude predictions will improve localization. Variability bounds placed on travel time and amplitude predictions will provide physics-based predictions that will greatly improve the accuracy of confidence bounds placed around event localizations. In addition, these advances will support discrimination between various infrasonic impulsive events. Waveform synthetics will be generated and compared with measurements, and the physical processes relevant to different sources studied.

Modeling

Advanced propagation models are proposed in areas that will support an improved understanding of the propagation and an improved ability to predict travel times, amplitudes, other waveform metrics, and associated uncertainty bounds.The specific modeling advances are listed in the left column of Table 1.They will focus on diffraction, variability, terrain, and nonlinear effects. Specifically,

- Ray tracing capabilities will be advanced by integrating a diffraction model for shadow zone regions;
- Variable terrain will be integrated into PE and TDPE models;
- Atmospheric density gradients and their effect on refraction will be modeled and evaluated;
- Small-scale atmospheric variability characterizations will be integrated into the PE and TDPE models;
- A version of the Nonlinear Progressive Equation (NPE) model will be developed that addresses the nonlinearities associated with a weak shock front.

Ground Truth Datasets

A repository of ground-truth datasets will be created and maintained, consisting of both nuclear and non-nuclear events. Additional data will be compiled from archived Nevada Test Site (NTS) records that are becoming available, and new events of opportunity will also be used. The ground truth datasets will be used to compare arrival times, amplitudes, and other waveform metrics with model predictions. The comparison studies will leverage state of the art environmental characterizations that are now available, including near real-time formulations.

Model Validation

As the propagation modeling advances are developed they will be applied to study Ground Truth events. The main goals of these model validation studies are to:

- Quantify the accuracy and applicability of the model predictions
- Estimate of the uncertainty associated with the modeling predictions, including contributions from both the modeling assumptions and unresolved atmospheric structure.
- Identify the relevant physical mechanism affecting the propagation for specific ranges and source types

These test goals will be met by laying out the framework for the validation, developing an event list from which the tests will be performed, and listing the hypotheses to be tested. In Table 1, the validation framework and expected benefit is summarized for each propagation modeling advance.

Table 1. Framework for evaluation of modeling advances.

Modeling Advancement	Relevant physical mechanism	Validation Criteria	Benefit
Extended ray predictions	Diffraction in elevated duct	Signal detection; Travel time estimation; Azimuthal deviation	Improved detection, association and localization
TDPE Variable terrain	Terrain shadowing/focusing	Signal amplitude; Travel time estimation;	Improved detection and localization
Propagation variability	Scattering/Diffraction from atmospheric inhomogeneities	Signal amplitude and its variance; signal duration; Travel time variance; azimuthal variation	Improved synthetics for discrimination; improved confidence bounds on localizations
Ambient density gradient	Density-driven refraction	Travel time	Improved detection and localization
Non-linear effects	Weak-shock effects on refraction, diffraction, dissipation, and ground interaction	Signal amplitude; Signal duration; Travel time estimation; Azimuthal deviation	Improved synthetics for discrimination; Improved localization and detection

RESEARCH ACCOMPLISHED

Propagation Modeling and Comparisons

As part of the task to advance the PE and TDPE propagation models, including the integration on ambient density gradient effects, work has begun on quantifying the effect of algorithm approximations on long-range predictions. The baseline PE model uses the split-step Fourier (SSF) algorithm (Jensen et al., 1994). Figures 1 and 2 illustrate the difference between the wide-angle and narrow-angle implementations for thermospheric propagation predictions at 2 Hz. A significant difference can be seen in the first bounce range. It is 320 km for the standard-angle approximation and 230 km for the wide-angle version. The closer arrival of energy in the latter case can be attributed to the ability to model the high angle propagation that reaches 115 km and above in the thermosphere.

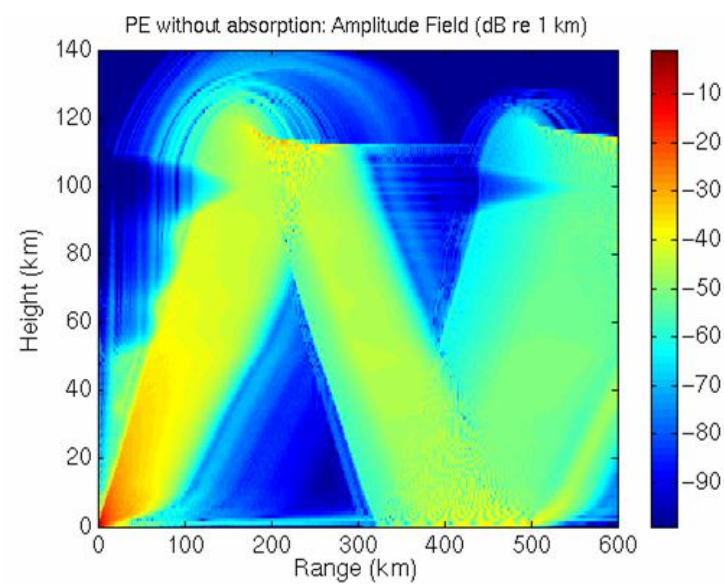

Figure 1. PE model prediction at 2 Hz using the narrow-angle approximation.

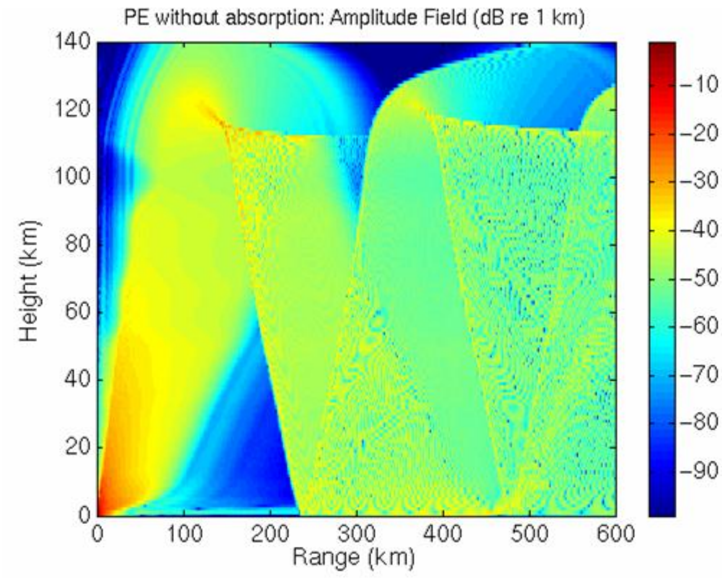

Figure 2. PE model prediction at 2 Hz using the wide-angle approximation.

Waveform predictions can be made from Fourier synthesis implementations of the wide-angle PE model [Nghiem-Phu and Tappert, 1985].The train car explosion in Neyshabur, Iran on 18-Feb-2004 is a ground-truth event that provides a good opportunity for model to data comparisons. This event was observed at the International Monitoring System (IMS) array Kazakhstan (I31KZ).The range was 1579 km and the observation had a 10-minute and 35-second duration. Figure 3 shows the observed waveform and TDPE prediction through a NRL-G2S characterization of the atmosphere. There is general agreement in arrival time and shape, although the predicted waveform arrives approximately 100 seconds before the observation.

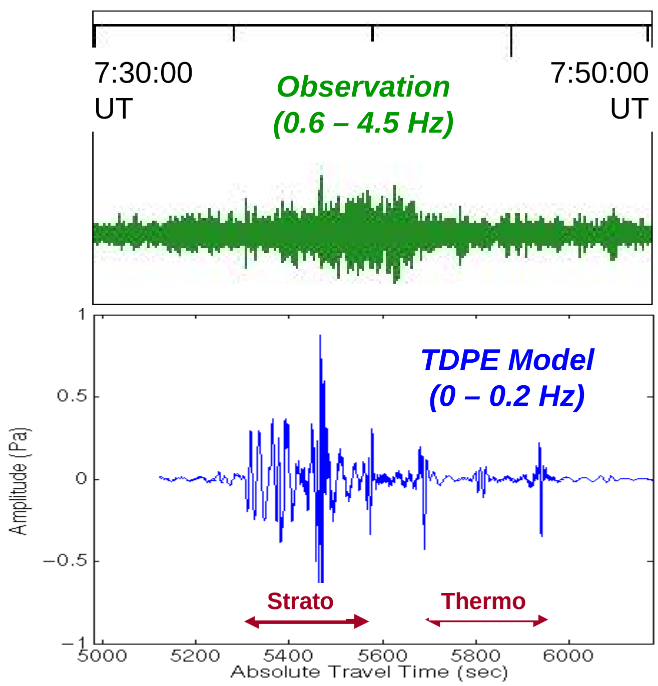

Figure 3. Comparison between TDPE prediction and measured wavefrom recorded at I31KZ from train car explosion in Neyshabur, Iran, 18-Feb-2004, 06:07 UT.

Ground Truth Database Compilation

Over the last several years, the members of the BBN and Los Alamos National Laboratory (LANL) teams have been developing such a dataset that span different propagation ranges and event types. Moreover, we have obtained GT information from our international colleagues for several global events and from published GT studies (Blinkhorn and McCormack 2003; Israelsson et al., 2003; O'Brien et al., 2003; Bass et al., 2003).

Our current GT dataset contains 102 events for which we have source and receiver information and recorded waveforms. These dataset can be broken up into the following source types, with the number of events in the parenthesis: Aircraft (3),Bolide (15), Chemical Explosion (12), Earthquake (2), Gas Pipe Explosion (2), High Altitude Nuclear Explosion (2), Microbarom (3), Mine Explosions (28), Near-Surface Nuclear Explosion (16), Space Shuttle Re-entry (4), Rocket Launch (9), Static Motor Test (1), and Volcano (5).

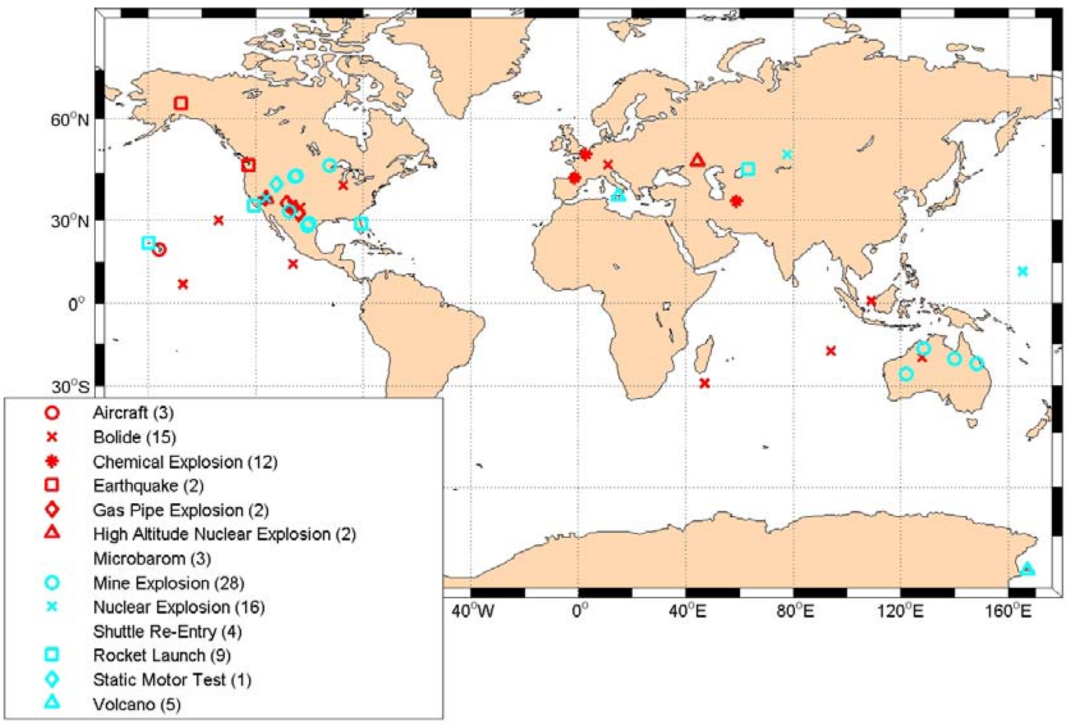

Figure 4. Geographical distribution of ground truth events, with received waveforms, available to us for this project. We list the event types and the number of events in each source category in the attached table. We do not show the locations of similar sources within the same area, e.g., events in the same mining region or test site, and events which have a large source location uncertainty like microbaroms and shuttle re-entry.

The geographical distribution of these events is given in Figure 4.The distance range of the observations range from about 20 km (Mt. Erebus to I55US) to more than 10,000 km (Pacific Bolide to IS26).The richness of spatial sampling and source types is apparent and will allow us to thoroughly evaluate the model predictions over multiple scenarios. We should note that some of the abovementioned sources, e.g., microbaroms and rocket re-entries, are not impulsive events. However, they will be available as secondary events for evaluation, if appropriate.

The ground truth dataset includes data from a Sandia National Laboratory (SNL) and LANL project, which involves digitizing infrasound records from atmospheric explosions carried out in the continental United States in the 1950s (Chael and Whitaker, 2004).Currently, this project has digitized nine events over a range of yields and heights, including underground, near surface, and high-altitude tests and from test sites in Bikini Atoll and NTS. For the larger events, detected signals are distinct at frequencies between 0.5–3.0 Hz; for the smaller events (<20 kT), higher frequencies are observed. The smaller yield, higher frequency events are more compatible with current array configurations and monitoring goals, and therefore they will be the primary focus.

Software Tools

Over the last several years, state of the art atmospheric and propagation modeling capabilities have been integrated into the tool kit Infrasonic Modeling of Atmospheric Propagation (InfraMAP). InfraMAP has been developed by BBN for use by researchers and analysts active in the study of infrasonic propagation and monitoring. The tool kit is composed of propagation models and upper-atmospheric characterizations, integrated to allow for user-friendly model execution and data visualization. It can be applied to predict travel times, bearings, amplitudes, and waveforms for a wide range of man-made and natural infrasonic events. InfraMAP also provides the ability to define a local network of stations and compute event localizations and associated error ellipses from station measurements and propagation predictions.

Currently, InfraMAP is used by approximately 50 researchers within government laboratories, universities, and industry. The most recent version includes near-real-time atmospheric modeling capabilities (Gibson and Norris, 2004).

CONCLUSIONS AND RECOMMENDATIONS

We anticipate that the results of this research effort will improve state of the art capabilities in accurately predicting infrasonic propagation parameters and assessing the influence of fundamental physical processes. Recent improvements in environmental characterization, particularly with near-real-time model, enable the ability to generate high-fidelity, global environmental fields for a specific event time. Advanced model developments described here will fully leverage these existing atmospheric capabilities in prediction performance. Specific areas of improvement are given below.

Increased applicability of ray models. Ray modeling will be extended in the regions beyond an elevated duct through integration of a diffraction model. This advancement will enable ray predictions and localizations in scenarios that currently cannot be addressed.

Determination of terrain effects. New versions of the PE and TDPE models will provide waveform predictions over variable terrain. This capability will improve predictions capabilities by accounting for terrain blockage, travel time, and amplitude effects.

Quantification of small-scale atmospheric effects. Integrating small-scale atmospheric structure into PE and TDPE models will predict the associated impact on waveform structure. Uncertainty bounds of travel time predictions will improve confidence in error bounds placed on localization prediction.

Prediction of nonlinear propagation effects. By developing the NPE model, predictions that include nonlinear effects can be made. Comparing the results of linear and nonlinear models with measurements will identify the significant nonlinear processes. Predictions improvements in travel time, amplitude, and other waveform characteristics will be achieved, depending on the nonlinear mechanisms at work.

Increase in model applicability. Through careful comparison of model predictions with ground-truth datasets, an assessment can be made as to model performance. Strengths and weaknesses of the models can be delineated and recommendations established as to an analyst's course of action with respect to which models to apply for specific scenarios and ranges of interest.

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