

**DEVELOPMENT OF ADVANCED PROPAGATION MODELS AND APPLICATION TO THE STUDY OF
IMPULSIVE INFRASONIC EVENTS**

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ABSTRACT

State-of-the-art advances have been made in the areas of advanced model development, GT event studies, and model validation. Through these efforts, some of the driving mechanisms affecting the measured waveforms have been identified, and the prediction performance of the new models quantified. These advances ultimately increase event localization capabilities. More robust prediction of infrasonic arrivals, such as those that reach the ground through diffraction, more accurate travel-time predictions, and more robust amplitude predictions all improve localization. In addition, these advances support discrimination between various infrasonic impulsive events.

A baseline ground truth (GT) event list has been created, which can be used for testing infrasound propagation models, the effect of meteorological conditions on recorded signals, and localization algorithms. This list builds on some of the prior analysis that we have done and incorporates some of the recent information that has been compiled from LANL and other sources in the infrasound community, e.g., International Data Center (IDC), Research and Development Support Services (RDSS), Defense Threat Reduction Agency (DTRA), Koninklijk Nederlands Meteorologisch Instituut (KNMI), Commissariat à l'Énergie Atomique—Département Anahise, Surveillances Environnement (CEA/DASE), Geoscience Australia, Southern Methodist Univ., Univ. of Mississippi, Univ. of Alaska, Univ. of Hawaii and Univ. of Western Ontario.

New propagation modeling capabilities include a ray model that incorporates the effects of diffraction, PE/TDPE models that account for non-zero density gradients, and PE/TDPE models that incorporate small-scale atmospheric variability. Examples applications of these new models applied to specific GT events are presented in detail.

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 GT data sets 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 to 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.

Table 1. Events parameters of near surface nuclear explosions with available waveforms.

Event	Date	Time	Location	Latitude (°N)	Longitude (°E)	Height (km)	Size (kT)
<i>Yankee</i>	5/4/1954	18:10:00	Bikini	11.6655	165.3869	N/A	13500
<i>Wasp</i>	2/18/1955	19:59:59	NTS	37.0867	-116.0219	0.2	1
<i>Turk</i>	3/7/1955	13:20:00	NTS	37.1383	-116.1175	0.2	43
<i>Hornet</i>	3/12/1955	13:20:00	NTS	37.0403	116.0253	0.1	4
<i>Bee</i>	3/22/1955	13:05:00	NTS	37.0947	-116.0239	0.2	4
<i>Ess</i>	3/23/1955	20:30:00	NTS	37.1683	-116.0439	0	1
<i>Wasp Prime</i>	3/29/1955	17:59:55	NTS	37.0867	-116.0578	0.2	3
<i>HA</i>	4/6/1955	18:00:04	NTS	37.0286	-116.0578	11.2	3

Ground Truth Data Sets

A repository of GT data sets will be created and maintained, consisting of both nuclear and nonnuclear 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 GT data sets 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.

RESEARCH ACCOMPLISHED

Ambient Density Gradient Effects and Reference Sound Speed Sensitivity

Derivations of linear continuous wave Parabolic Equation (PE) models start with the Helmholtz equation. Implicit in this formula is the assumption that the ambient density gradient is either zero or negligible. For variable ambient density, ρ , the Helmholtz equation takes the form

$$\rho \nabla \cdot \left(\frac{1}{\rho} \nabla p \right) + \kappa^2 p = 0$$

With a substitution of variables, this equation can be reformulated into the standard Helmholtz equation but with an “effective” index of refraction. Variable density models in ocean acoustics have been carried out to improve propagation predictions in regions such as littoral zones (Collins, 1988). This transformation allows us to estimate the effect of variable density on atmospheric propagation.

The ambient density for a standard atmosphere falls off exponentially with height and it can be equated to a change in the index of refraction. This change can potentially alter predictions of travel times, shadow zone regions, and ground bounce locations. In this task, we have developed PE and TDPE models based on the more rigorous Helmholtz equation that captures the nonlinear physical effect of variable density.

Model-to-model comparisons over infrasound frequencies in the range of 0.01 to 5 Hz have been completed. They suggest that variable density has no discernable effect on travel times, amplitude, or ground-bounce locations. This insensitivity is likely due to the nature of the density profile. Although density changes by several orders of magnitude over the range from the ground to the thermosphere, the density gradient at any given height is relatively small. Thus, the resulting effect on the propagation is minimal.

PE model formulations include the specification of a reference sound speed. It is typically constant and set to a value at the ground. PE predictions have been shown to be sensitive to reference sound speed. A sound-speed insensitive version of the PE has been developed which minimizes this dependence (Tappert et al., 1995).

Model-to-model comparisons have been made to quantify the improvement.

Figure 1 shows a comparison of predictions at 5.0 Hz for the sound-speed insensitive and reference PE models. There are significant differences between the two predictions. Within the thermosphere, the baseline predictions have an upper turning height in the range of 120 km, while the sound-speed insensitive predictions have energy penetrating well above 150 km. These differences can effect both absorption calculations and ground bounce ranges.

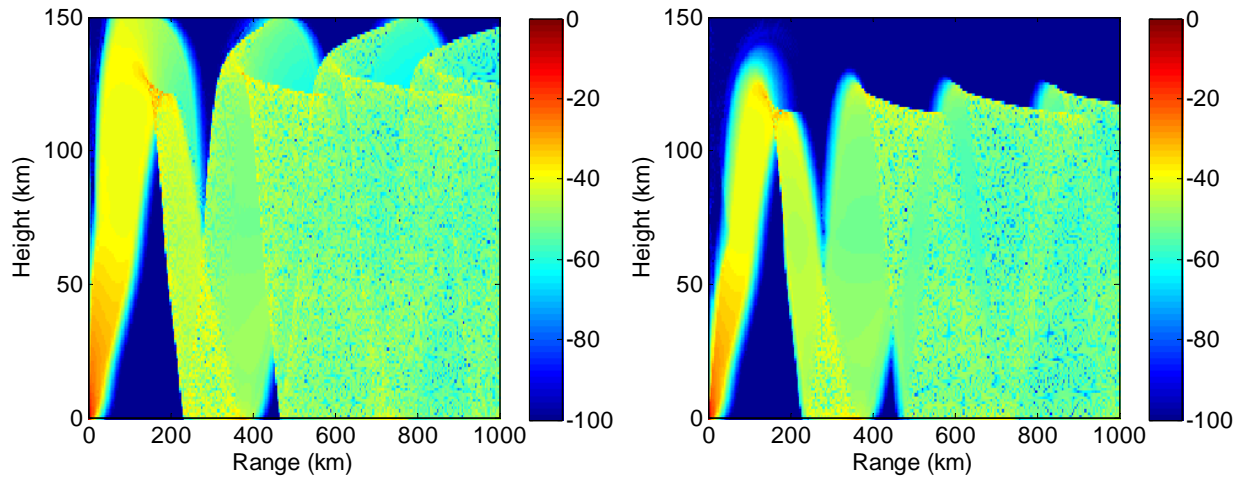


Figure 1. PE amplitude field predictions at 5.0 Hz for baseline formulation (left) and that including variable density term (right).

To quantify the effect of the reference sound speed over a band of frequencies, TDPE waveform predictions were computed. Significant differences in amplitude, waveform shape, and arrival time are observed. Stratospheric energy for the sound-speed insensitive PE arrives approximately 3 percent later, while the thermospheric arrival difference is approximately 2 percent. Differences in amplitude and waveform shape are also observed. They need to be quantified further in relation to each other and with respect to observations.

Propagation Variability

In this task, we have extended propagation modeling capabilities by integrating atmospheric variability models into the PE and TDPE models. The model predictions can be made through atmospheric snapshots of the inhomogeneities. These predictions capture the effects of the atmospheric variability on the waveform metrics such as amplitude, travel time, duration, and spectral content.

Small-scale atmospheric structure not characterized by near-real-time atmospheric models, such as NRL-G2S, has been identified as a likely source of diffraction and scattering effects that may play a significant role in accurate propagation predictions. In particular, gravity waves are of interest because their spatial scales are of the same order as infrasonic wavelengths. They have been modeled spectrally (Norris and Gibson, 2002), based on a horizontal wave number model (Gardner, 1993). An example realization of wind fields associated with the Watusi effect, discussed below, is shown in Figure 2. The gravity waves are seen as thin layers of coherent wind anomalies. The total atmospheric wind realization is seen to be the sum of the mean NRL-G2S specification and fine-scale gravity wave structure.

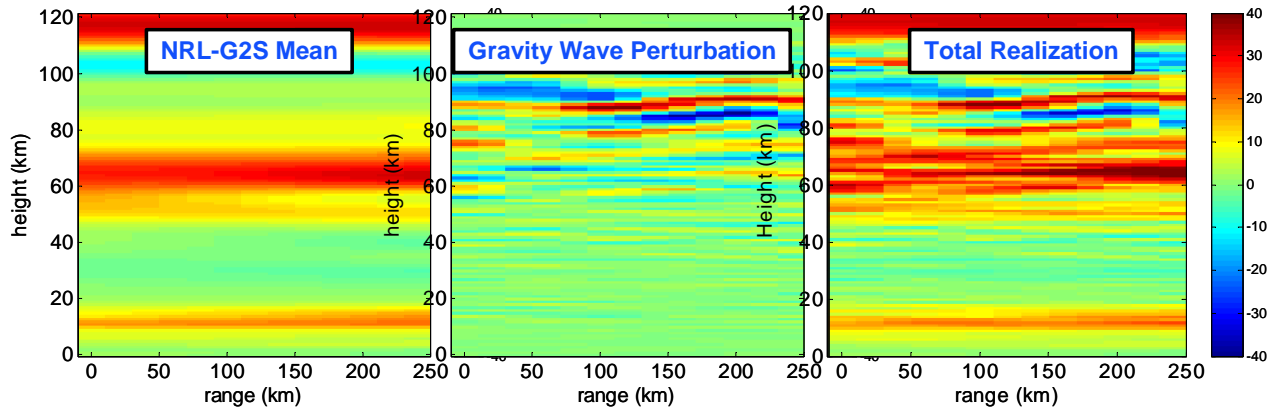


Figure 2. Atmospheric specification for Watusi study showing the NRL-G2S mean wind fields (left panel), wind perturbations from gravity waves (middle panel), and resulting total realization (right panel).

As a first step in quantifying the effects of the atmospheric variability, the Watusi event of 2002 is studied. This event was a surface explosion of 38,000 pounds (0.019 kT) of TNT equivalent. It was detonated at 21:25:17 UTC on 28 Sept 2002 and located at Nevada Test Site (NTS) (37.099° N, 116.092° W). Here we consider the 219 km path to the SGAR infrasound station. Figure 3 shows the PE predictions at 0.5 Hz for the cases in which small-scale gravity wave perturbations are excluded and included. Without gravity wave perturbations, no energy penetrates the shadow and reaches the receiver locations. With the gravity wave perturbations, scattered energy is predicted to penetrate the shadow zone and reach the receiver.

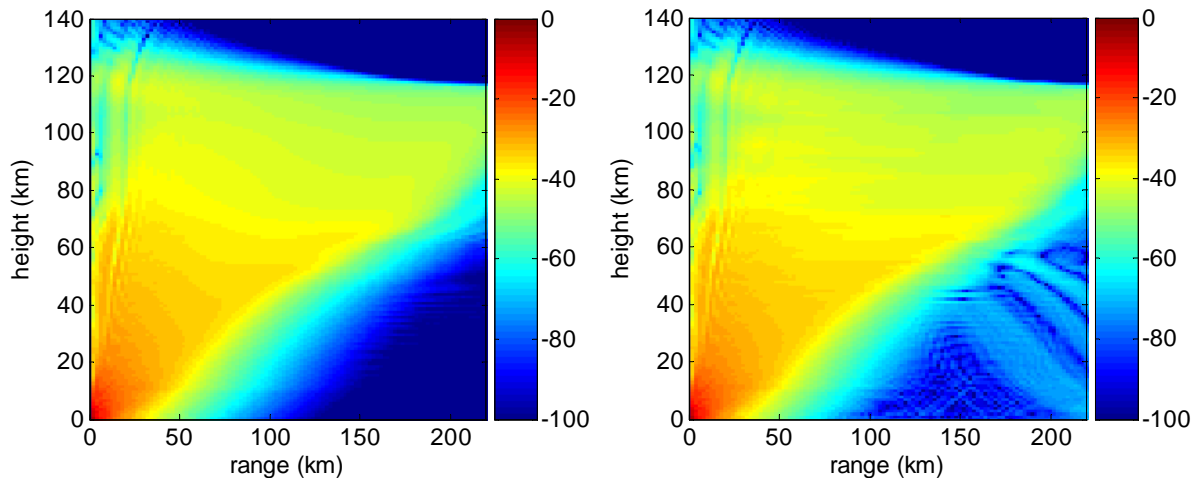


Figure 3. PE predictions at 0.5 Hz without gravity waves (left panel) and with gravity waves (right panel).

Substantial proof in the importance of small-scale variability is indicated by TDPE waveform predictions along the same propagation path. TDPE waveform predictions without gravity wave perturbation predict no received energy. However, with gravity waves, waveform predictions show substantial received energy. The comparison between predicted and observed waveforms is shown in Figure 4. The agreement in arrival time is excellent and that for amplitude differ by approximately 3 dB.

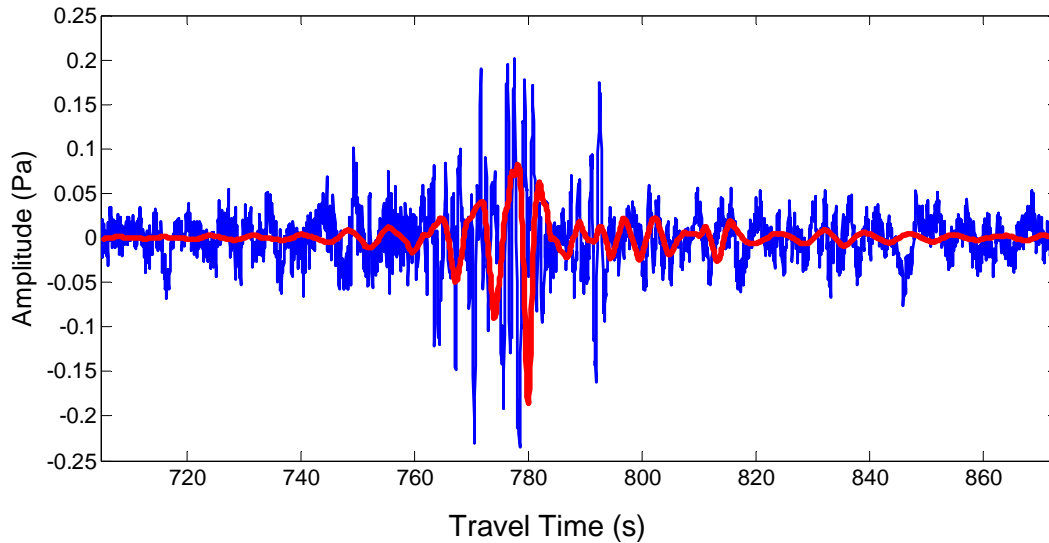


Figure 4: Observations (blue) and TDPE predictions (red) for the Watusi event at SGAR.

Ground Truth Database Compilation

The members of the BBN and LANL teams have been developing a Ground Truth data set repository that spans different propagation ranges and event types. Over the last year, progress has been made by adding the following data sets to the repository.

Underground nuclear explosion

We have obtained digital archives from infrasound arrays operated by Los Alamos National Laboratory in Nevada, New Mexico, and Utah since the early 1980s. These were mostly four-element arrays, with three sensors arranged in a triangle and the fourth at the center. In some cases, seismic data were also recorded at the same sites. Over the years, these arrays have recorded a variety of acoustic events, including underground nuclear tests at NTS and subsequent cavity collapses, and conventional explosions both above and below ground.

Near-surface nuclear explosion

We have obtained digital waveform data for the near surface nuclear explosions from Operation Teapot carried out in the spring of 1955 from Eric Chael of SNL (Chael and Whitaker, 2004). This series included several events with yields from 1 kt to 43 kt, all detonated a few hundred feet aboveground (Table 1). Chael has extracted about 15 traces per test from the available stations, some of which used two sensors separated about 1 mile along the direction from NTS. For the larger events, detected signals are distinct at frequencies between 0.5–3.0 Hz; for the smaller events (<20kT), higher frequencies are observed (Chael and Whitaker, 2004). The smaller yield, higher frequency events are more compatible with current array configurations and monitoring goals, and therefore they will be the primary focus.

CONCLUSIONS AND RECOMMENDATIONS

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 fully leverage these existing atmospheric capabilities in prediction performance.

Variable atmospheric density does not appear to have a discernable effect on infrasound propagation, likely due to the gradual change in density with height. Model-to-model comparisons suggest the sound-speed insensitive PE algorithm provides higher-fidelity predictions of ground bounce range and arrival time. The relative improvements with respect to absorption and waveform characteristics still need to be quantified.

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Integrating small-scale atmospheric structure into PE and TDPE models have been shown to influence the predictions of waveform structure. Additional comparison studies need to be completed to further quantify the influence of this physical phenomenon over various propagation scenarios.

Expanding the Ground Truth database has enabled careful comparison of model predictions with ground-truth data sets, enabling assessment of model performance. The data sets support evaluation of the strengths and weaknesses of the models and recommendations as to an analyst's course of action with respect to which models to apply for specific scenarios and ranges of interest.

REFERENCES

Chael, E. and R. Whitaker (2004). Infrasound Signal Library, in *Proceedings of the 26th Seismic Research Review: Trends in Nuclear Explosion Monitoring*, LA-UR-04-5801, Vol. 2, pp. 618–623/.

Collins, M. (1988). The time-domain solution of the wide-angle parabolic equation including the effects of sediment dispersion, *J. Acoust. Soc. Am.* 84: 2114–2125.

Gardner, C. (1993). Gravity Wave Models for the Horizontal Wave Number Spectra of Atmospheric Velocity and Density Fluctuations, *J. Geophys. Res.* 98: D1, 1035–1049.

Norris, D. and R. Gibson (2002). InfraMAP enhancements: Environmental/propagation variability and localization accuracy of infrasonic networks, in *Proceedings of the 24th Seismic Research Review—Nuclear Explosion Monitoring: Innovation and Integration*, LA-UR-02-5048, Vol. 2, pp. 809–813.

Tappert, Frederick, John L. Spiesberger, and Linda Boden (1995). New full-wave approximation for ocean acoustic travel time predictions, *J. Acoust. Soc. Amer.* 97: (5), part 1, 2771–2782.