TIME-DOMAIN MODELING TECHNIQUES AND THE STUDY OF INFRASONIC PROPAGATION

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ABSTRACT

Numerous propagation models, including ray tracing, normal mode, and Parabolic Equation (PE), are available for the study of infrasound. This paper will focus on time-domain (TD) modeling techniques. PE and nonlinear implementations are reviewed, and comparisons are made between Fourier synthesis TD PE predictions and infrasonic measurements. The atmosphere is defined using climatologic wind (HWM-93) and temperature (MSIS-90) models that capture the dominant seasonal and diurnal features. Normal mode predictions are also included in the comparisons.

OBJECTIVE

Over the last several years, modeling capabilities in the study of infrasound propagation have improved significantly. Atmospheric characterizations have moved beyond climatological models and can now leverage synoptic nowcasts that capture fine-scale features in the wind and temperature fields (Gibson and Norris, 2002). Propagation modeling has mainly focused on application of ray trace, normal mode, and PE formulations, with the latter limited to continuous-wave propagation. Studies comparing modeling predictions and measurements have shown limited agreement in some cases (e.g., Norris and Gibson, 2001).

Despite these successes, state-of-the-art propagation models have failed to consistently predict many of the features of measured infrasonic waveforms, including

- Spectral content
- Arrival times and amplitudes
- Waveform shape and associated parametric descriptors.

Modeling waveform features is critical to advancing our infrasonic capabilities. With improved models, waveform synthetics can be generated and used to evaluate and improve infrasound station detection algorithms. Predictions of received waveforms for different source mechanisms can be used to develop association and classification algorithms. In addition, improved amplitude and travel-time predictions over multiple phase arrivals will reduce event localization uncertainty and provide more robust network performance models.

As a result of these issues, time-domain propagation modeling techniques have experienced renewed interest within the infrasound research and analyst community. Previous time-domain models have been limited to normal mode formulations (Dighe et al., 1998; Pierce and Kinney, 1976). These models can only be used with a range-independent realization of the atmosphere. In addition, they cannot account for atmospheric absorption or complex boundaries. Newer approaches are based upon the PE model. PE-based models have the advantage of being able to accommodate complex boundaries, absorption, and a range-dependent atmosphere.

In this study, a summary is given of the time-domain Parabolic Equation (TDPE) approach. Example predictions are shown from a TDPE model developed for infrasound (Norris and Gibson, 2003a). Finally, comparisons between the TDPE predictions and measurements from the 1996 El Paso bolide are presented.

REASEARCH ACCOMPLISHED

TDPE Model

The Parabolic Equation approach is based upon solving the wave equation in spherical coordinates. Azimuth symmetry is assumed, and the problem is reduced to solving an equation in range vs. height coordinates. In the continuous-wave PE, a single frequency is assumed, and the wave equation is transformed into the Helmholtz equation.

Time-domain PE implementations fall in one of two categories: Fourier synthesis and finite difference. Fourier synthesis involves running a continuous wave model at each frequency bin that defines the source waveform. An inverse Fourier transform of the synthesized spectrum is then computed to derive the received waveform (Tappert et al., 1995). The main advantage of Fourier synthesis is that all capabilities of the continuous-wave model are maintained. The main disadvantage is the high computational loading, especially for large frequency bandwidths and for acoustic arrivals that are widely dispersed in time.

The second approach uses finite-difference methods to solve the propagation equations directly in the time domain (Collins, 1988). The main advantage is a (potentially) significant reduction in computational loading. Additional properties such as nonconstant density gradients and nonlinear effects can also be more easily incorporated into the characterizations. The main disadvantage is that the formulation must be carefully examined for numerical stability. Boundary condition specification can also be more complicated.

A large variety of PE numerical solutions exist for both the Fourier synthesis and finite-difference approaches. As a baseline model, we have implemented a Fourier synthesis approach (Nghiem-Phu and Tappert, 1985) based on the continuous-wave, split-step algorithm (Jensen et al., 1994). This implementation provides predictions of propagation waveforms in a Lagrangian, or wave-following, reference frame that moves with the propagating waveform at a reference sound speed, usually taken to be 0.34 m/s. Figure 1 is an example of a TDPE waveform prediction. A consequence of this "wave-following" reference frame is that the predictions are given in reduced time, which starts at the beginning of the Lagrangian time window. To compute absolute travel time, the reduced time must be added to the reference time (range divided by the reference sound speed). This computed travel time is only an estimate since it depends on choice of reference sound speed. Versions of the TDPE that are not based on a reference sound speed are currently being evaluated for application to infrasound.

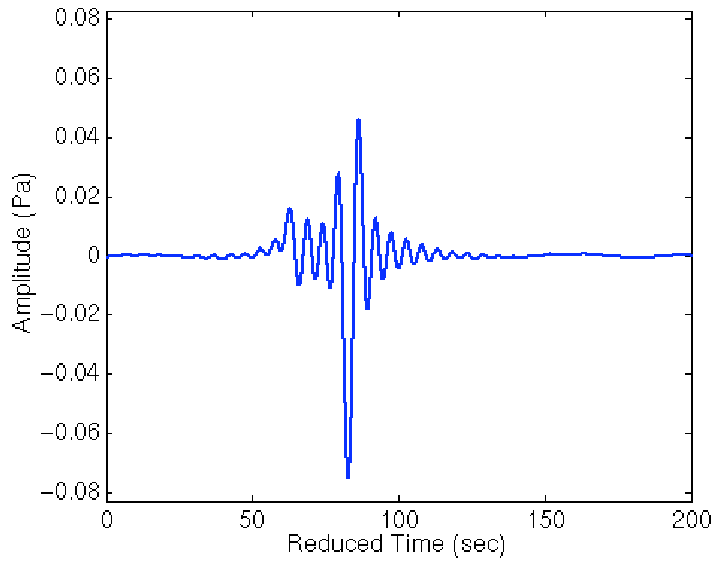

Figure 1. Example of TDPE predictions in wave-following reference frame.

Comparison Studies

Comparison studies with observations are critical to assess the performance of the models. To date, large-scale validation exercises for infrasound have been few (e.g., Whitaker at al., 2003; O'Brien et al., 2003). In this study, we focus on comparing TDPE predictions to a bolide observation that includes ground truth.

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). In a previous study, eigenrays were computed over a range of source heights from 0 to 50 to evaluate the ability to verify or refine the source height estimate (Norris and Gibson, 2003a). 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 2). The eigenrays were compared to the measured waveform (top of Figure 2), and a source height estimate was made by correlating the measured arrival times with the predicted amplitudes. The three measured arrivals matched 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.

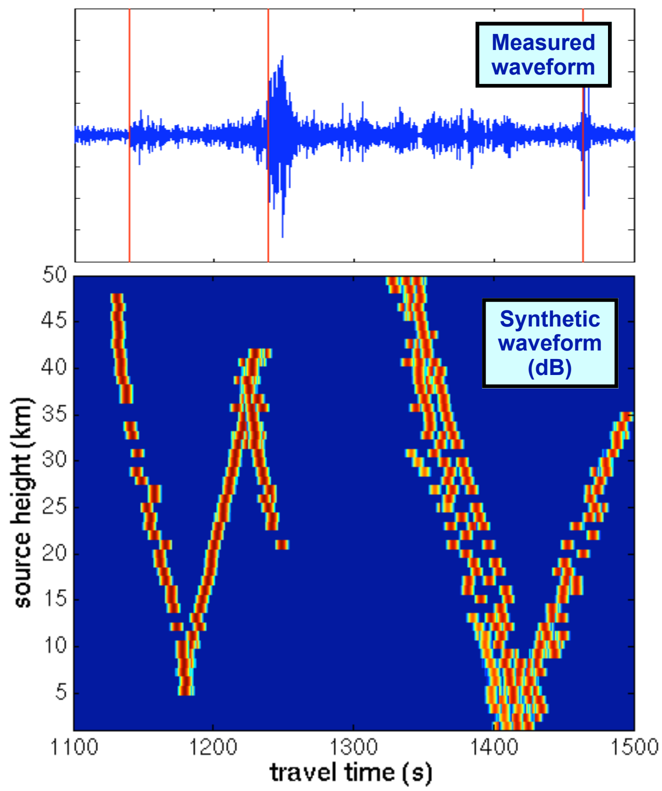

Figure 2. Comparisons between measured waveform and ray synthetic waveforms over a span of source heights.

In this study, initial broadband predictions are made using the Fourier synthesis TDPE. At the writing of this paper, predictions have only been made at the ground truth source height of 29 km, although predictions over the entire height range are in process. Figure 3 shows the waveform structure at the receiver over a range of receiver heights. A waveform time series is generated by taking a slice at a given height. At the ground, stratospheric energy is observed at reduced times of 75 and 150 s. Thermospheric energy is seen arriving at 300 s.

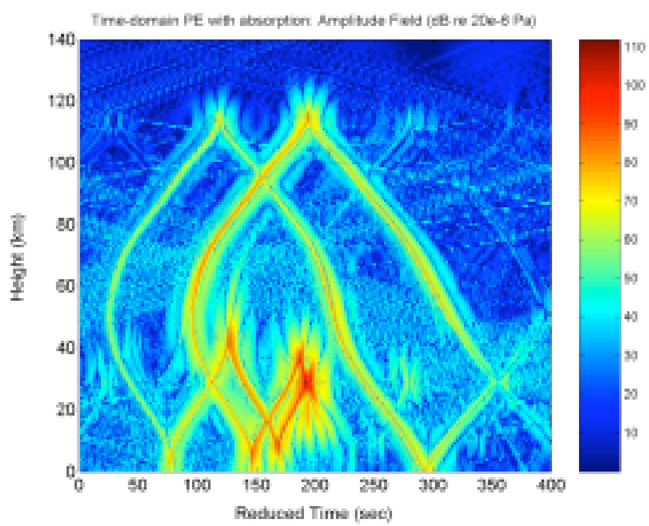

Figure 3. TDPE waveform arrival structure at receiver.

To compare the TDPE predictions with the observations, a reference sound speed of 0.34 km/s is assumed. The results are shown in Figure 4. Three observations are seen both the observations and predictions. The time-of-arrival difference between the first two arrivals is similar, but the third predicted arrival is approximately 70 s earlier than that observed.

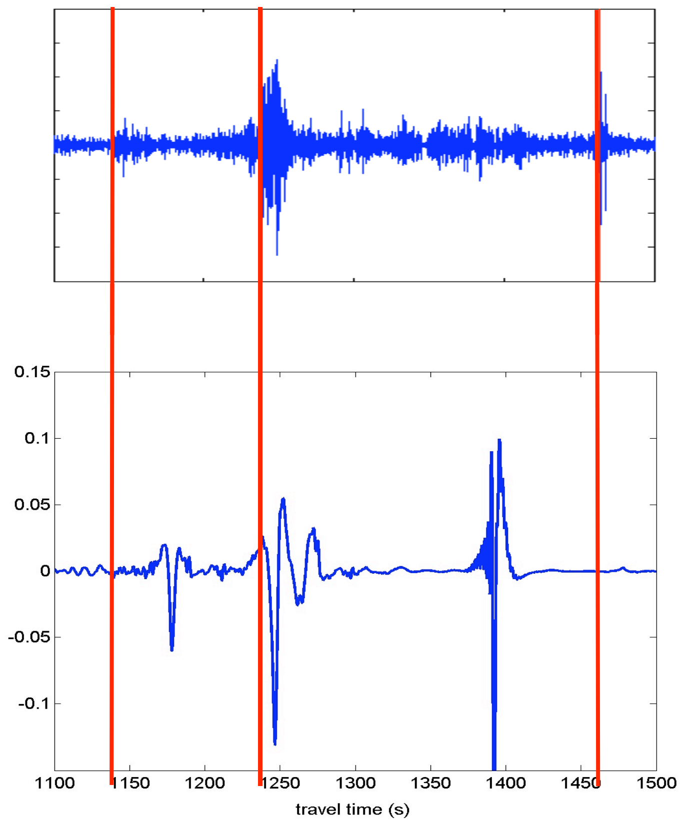

Figure 4. Comparison between measured waveform and TDPE prediction at 30 km source height.

CONCLUSIONS RECOMMENDATIONS

A baseline TDPE model has been implemented using the continuous-wave split step algorithm and Fourier synthesis. Initial comparison studies have yielded some limited agreement with observations, although more comparisons are needed over a variety of infrasonic sources and atmospheric conditions.

One source of the modeling limitations may be the neglect of nonlinear effects. By including nonlinear terms in the model formulations, predictions that account for some of the dominant nonlinear effects can be made. Evaluation of nonlinear models applied to infrasound is currently in progress. It is anticipated that the nonlinear modeling efforts will help identify more of the relevant physics affecting the propagation and thus contribute to better predictions of travel time, amplitude, and other waveform characteristics.

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