An Overview of Stochastic Propagation Methods for Infrasound Studies

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Overview
Propagation of infrasonic energy through the atmosphere is complicated by the dynamic and poorly resolved nature of the propagation medium. Temporal variability combined with the limited resolution of measurements for atmospheric parameters result in a dynamic, poorly constrained propagation medium for infrasound energy. A variety of methods have been studied to account for the resulting uncertainty including atmospheric perturbation methods and stochastic propagation models. The details of the latter are presented here and demonstrated using infrasonic signals generated by chemical explosions in the western United States.

Propagati**on Uncertainties**
- Infrasonic energy propagating through the atmosphere is influenced by variations in the temperature, winds, and humidity.
- Due to the dynamic nature of the atmosphere, specific propagation effects are non-repeating and, therefore, typically investigated on a case-by-case basis.
- Speculations of the upper atmosphere are constructed from sparse measurements which produces uncertainties in the propagation medium and results in analysis with uncertainties in the propagation effects for infrasound propagation through the upper atmosphere.
- Two approaches have been applied in the infrasound community to account for this uncertainty: perturbation methods, which update the atmospheric specifications, and stochastic propagation methods, which aim to construct statistical models for observables.

Perturbation Methods
- Given a set of infrasonic observations and an estimate of the atmosphere specifications, perturbation methods can be employed to identify modifications to the specifications which improve agreement between predictions and observations.
- Typically, empirical orthogonal functions (EOFs) are calculated from a large suite of atmospheric specifications to construct a set of relevant “basis functions” describing the atmospheric winds.
- Using the dominant few EOFs, corrections can be computed by performing a parameter search over coefficient values to minimize the difference between the observed characteristics and those predicted using the perturbed atmospheric specifications.

Stochastic Methods
- For a given region of the globe, annual and diurnal variations in the atmosphere produce repeating cycles of atmospheric features which have predictable influences on propagation.
- From a historical archive of atmosphere states, distributions can be constructed which describe likely propagation results given a region of the globe, time of day, and time of year (season, month, week, etc.).
- Empirical infrasonic observations can be used to verify and correct the distributions, improving their accuracy.
- Signal analysis methods can be informed by propagation modeling priors to improve association results and both the precision and accuracy of source localization estimates.

Stochastic Celerity Models
- Celerity, \( v \), is the ratio of the propagation range to the propagation time along a given propagation path and can be estimated using a range and time.
- Using a suite of atmospheres, a distribution, \( \rho_v(r,v) \), can be constructed by fitting the arrival characteristics scatter with Gaussian mixture models as in Fig. 1.

Stochastic Azimuth Deviation Models
- Azimuth deviations are produced by cross-winds and horizontal variations in the atmosphere.
- Such deviations cause discrepancies between the apparent and true source azimuth.
- A moving window and 1D interpolation can be used to compute the bias, \( \delta \phi(r) \), and variance, \( \sigma_{\delta \phi}^2(r) \), as in Fig. 2 following the method in Fig. 1.

UTTR Rocket Motor Detonations
- The DTRA Verification Database contains an archive of ground truth infrasonic events.
- Included in the database are 94 rocket motor detonations from the Utah Test and Training Range (UTTR).
- The infrasonic signals generated by these explosions were detected on several nearby arrays including 675US and 658US, NVMR in Nevada, PDXAR in Wyoming, and DLAJ at Los Alamos National Laboratory. The source and array locations are summarized in Fig. 3.
- Propagation-based priors have been generated for the Western US, Fig. 4, and are in general agreement with the empirical models obtained by Nippress et al. [1].

Figure 1: Computation of celerity-range propagation statistics. (a) Arrival locations computed using ray tracing methods. (b) the scatter of arrival range and celerity for a specific azimuth, and (c) the scatter of characteristics fit using a Gaussian mixture model.

Figure 2: Propagation statistics for azimuth deviation are computed using a similar method to the celerity-range distribution.

Conclusions & Implementation
- The dynamic and poorly sampled nature of the upper atmosphere introduces large uncertainties in the propagation of infrasound.
- A stochastic approach provides an efficient means to estimate propagation characteristics from constructed distributions for various observables.
- Application of the stochastic propagation methods shows significant improvement in localization estimates for large explosions in the Western US when detected at ranges within 1,000 kilometers.
- The methods presented here have been implemented to interface with the InfraPy infrasonic data analysis pipeline being developed at Los Alamos National Laboratory.
- The stochastic propagation models are constructed using propagation modeling methods and will be verified and augmented with empirical data.
- The models are currently used to inform the location methods and inclusion in the association algorithm are planned in the future.

Using Stochastic Propagation Models - Localization
- The source localization has been estimated for one of the UTTR rocket motor detonations using the Bayesian Infrasound Source Localization (BISL) framework [2,3].
- The analysis has been performed with and without the stochastic, propagation-based models and the results are shown in Fig. 5.

Figure 5: Localization results for a UTTR rocket motor detonation in June, 2004. Shown are the ground truth (red), maximum a posteriori (magenta), and 95% and 99% confidence regions (green). Dashed lines in the source time panel indicate the 95% confidence bounds.

References & Related Work

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