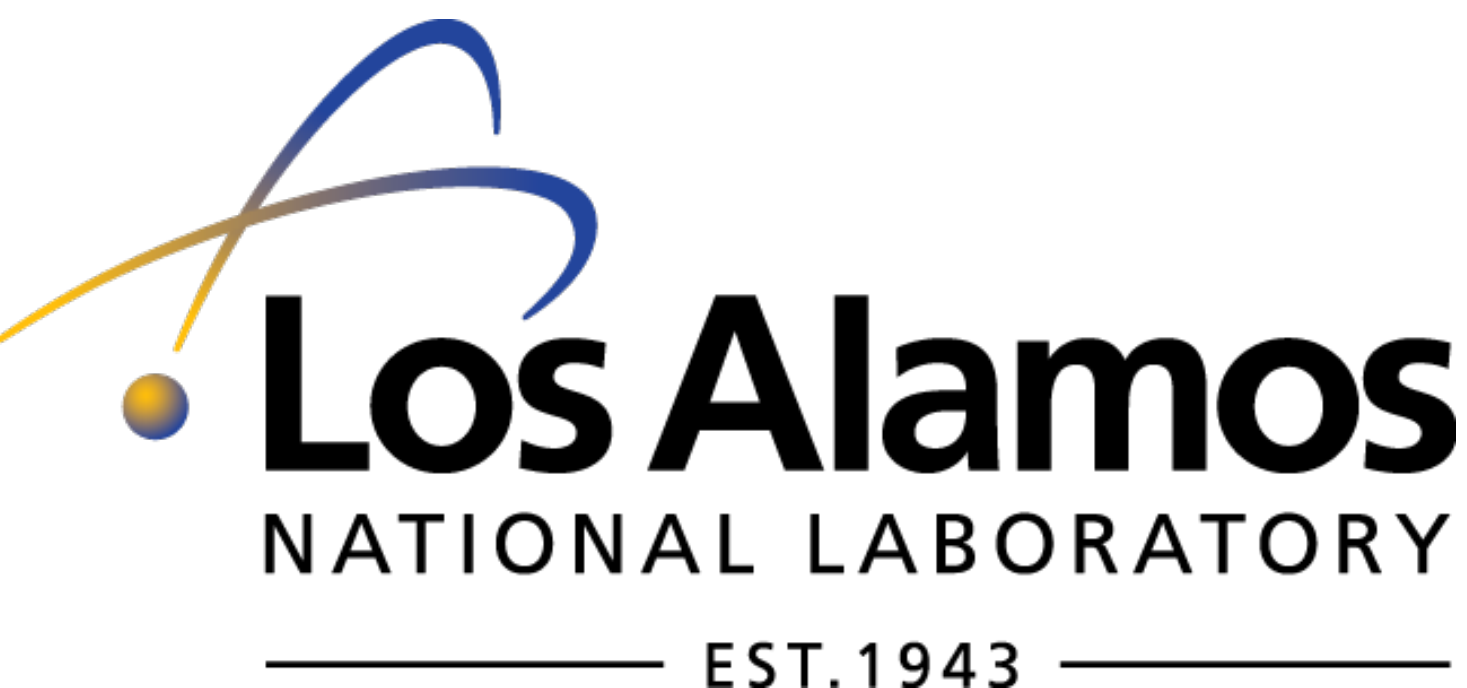


InfraGA/GeoAc - an open source infrasonic ray tracing tool



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Overview (T1.1-P12)

InfraGA/GeoAc is a software tool that models the propagation of infrasonic signals through the atmosphere in the limit of geometric acoustics. It is capable of modeling propagation through an inhomogeneous, moving propagation medium model using Cartesian (2D or 3D) or spherical coordinate propagation schemes for applications at local to global scales. The methods define a set of auxiliary parameters that describe geometric spreading effects along individual ray paths. Eigenray methods leveraging the auxiliary parameters are included and provide a means to efficiently identify propagation paths for specific source-receiver geometry.

Usage and Inputs

The *InfraGA/GeoAc* methods are written in C++ and usage is command line based. The syntax to run the code can be generalized to:

```
infraga-[method] [-option] profile.met [params]
```

Methods

The method flag determines which version of the ray tracing algorithm will be used. This includes specifying the coordinate system, if the medium is range dependent, and if accelerated methods are to be used.

Options

The option specifies the task that the software will perform. Options that are currently available or being implemented and evaluated are summarized below.

Option	Task
-prop	Propagate a set of ray paths between min/max inclination and azimuth values out to a set number of bounces
-interactive	Plot individual paths by specifying inclination, azimuth, and bounces
-eig_search	Search for all eigenrays connecting a source-receiver pair between min/max inclination values.
-eig_direct	Identify the nearest eigenray for a source-receiver pair from an estimated inclination, azimuth, and bounce count.
-wnl_wvfrm	Compute the weakly non-linear waveform along a specified ray path.

Parameters

The parameter list defines the specific details of the run including:

- ▶ minimum and maximum launch angles
- ▶ maximum ground reflection count
- ▶ source and receiver locations
- ▶ damping and tolerance for eigenrays
- ▶ frequency (for absorption)
- ▶ ground elevation

Atmosphere Specification

The `profile.met` file is expected to contain columns describing the atmospheric state for use in the simulation in the format,

$$z \text{ [km]} : T(z) \text{ [K]} : u(z) \left[\frac{\text{m}}{\text{s}} \right] : v(z) \left[\frac{\text{m}}{\text{s}} \right] : \rho_0(z) \left[\frac{\text{g}}{\text{cm}^3} \right] : p_0(z) \text{ [mbar]}$$

- ▶ The atmospheric description is interpolated to define continuous functions $c(z)$, $u(z)$, $v(z)$, and $\rho_0(z)$ where the sound speed is defined by $c(z) = \sqrt{\gamma \frac{p_0(z)}{\rho_0(z)}}$.
- ▶ Any perturbations to the atmosphere need to be performed outside of running the code (there are no built in tomography or gravity wave methods)
- ▶ A parameter is available that specifies columns in a different order but only one alternate format is currently available (zuwTdp)

Methods

Cartesian (2D)

- ▶ Propagation paths can be computed using the effective sound speed approximation assuming paths are contained within planes of constant azimuth.
- ▶ Auxiliary parameters are used to compute the Jacobian determinant components describing geometric spreading and caustic locations (Fig. 1) as in Blom & Waxler (2012).

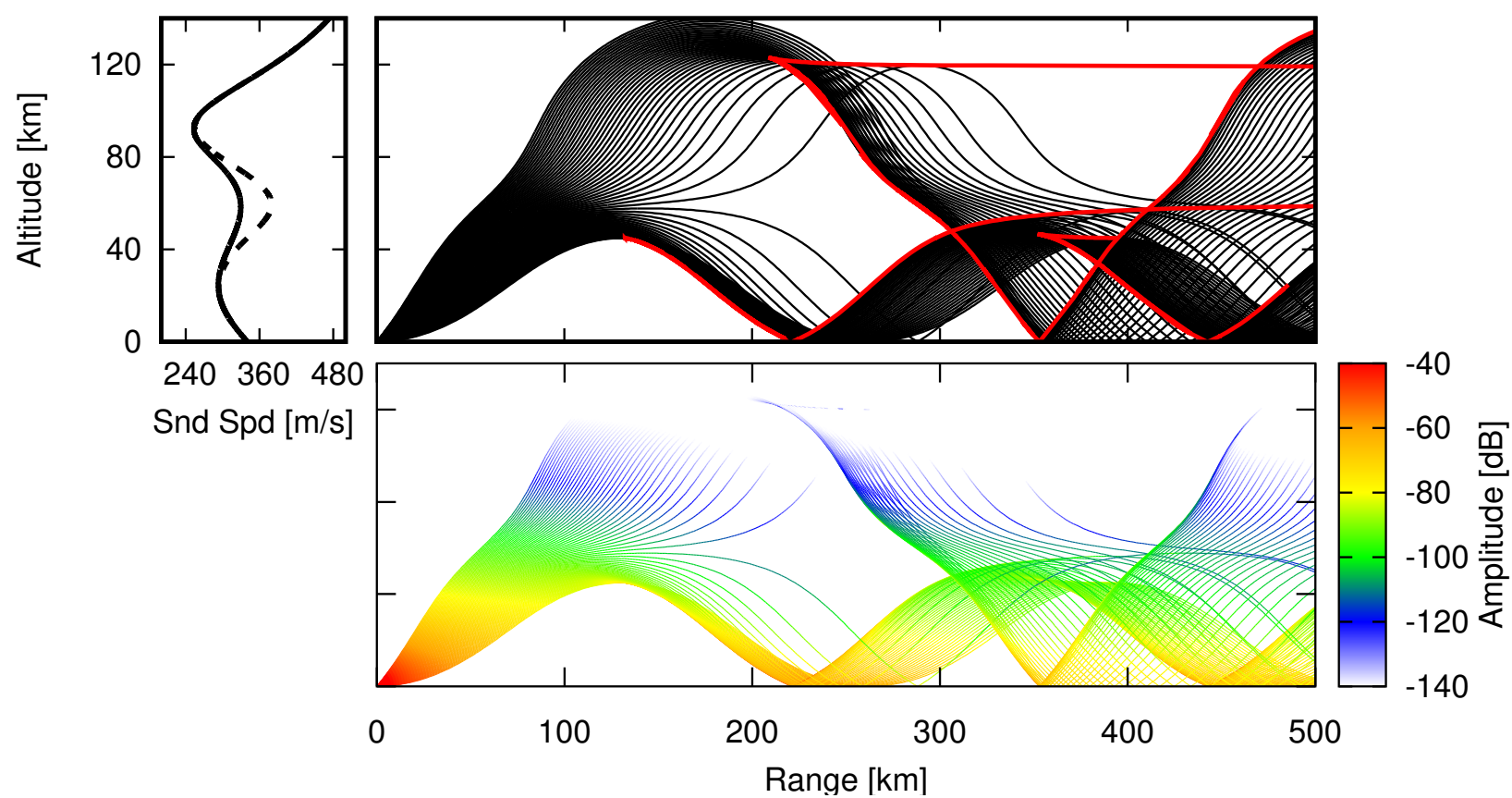


Figure 1 : Propagation paths with caustics (top) and transport coefficient predictions for amplitude (bottom) using a simplistic "toy" atmosphere model (top left).

Cartesian (3D)

- ▶ Propagation paths in an inhomogeneous, moving medium can be computed to identify arrival characteristics as in Fig. 2,
- ▶ Amplitude variations due to geometric spreading and absorption effects can be computed.
- ▶ Direction of arrival (back azimuth) deviations due to cross winds or horizontal gradients can be identified to improve source localization.
- ▶ Celerity and turning height can be used to identify waveguides (tropospheric vs. stratospheric vs. thermospheric).

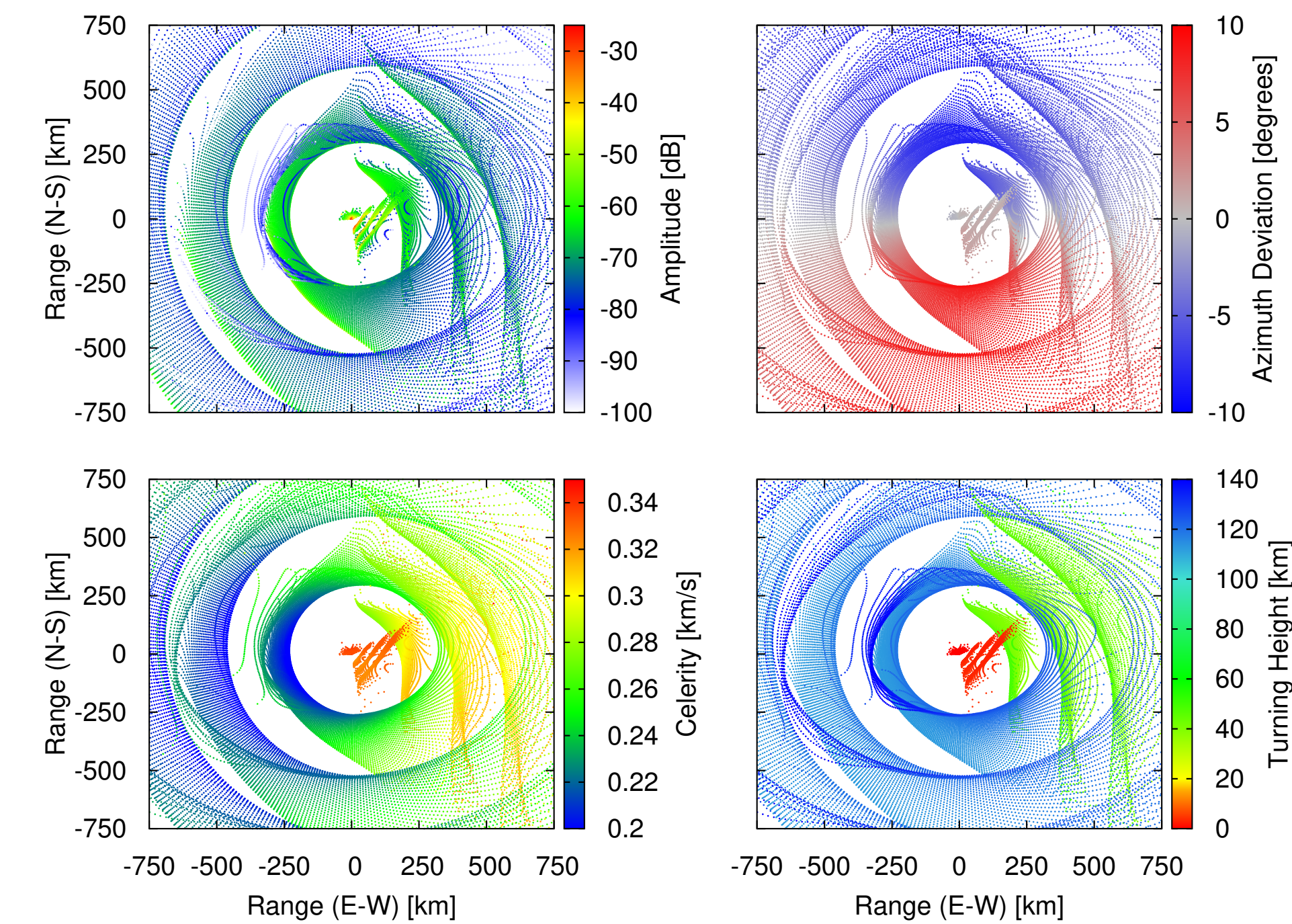


Figure 2 : Predictions for arrival characteristics using an atmosphere specification from the Ground-to-Space archive for the western US on January 1, 2010.

Spherical (Global)

- ▶ A spherical coordinate transformation can be performed to model propagation in an atmosphere layer surrounding a globe.
- ▶ Comparison between the spherical (red) and planar (blue) predictions for propagation paths and arrival characteristics shows significant differences as shown in Fig. 3.
- ▶ In the case of ground curvature, one expects arrivals to shift to larger ranges; however, the coordinate transform causes the atmosphere to curve following the ground surface producing significantly more complicated effects as shown in Fig. 4.

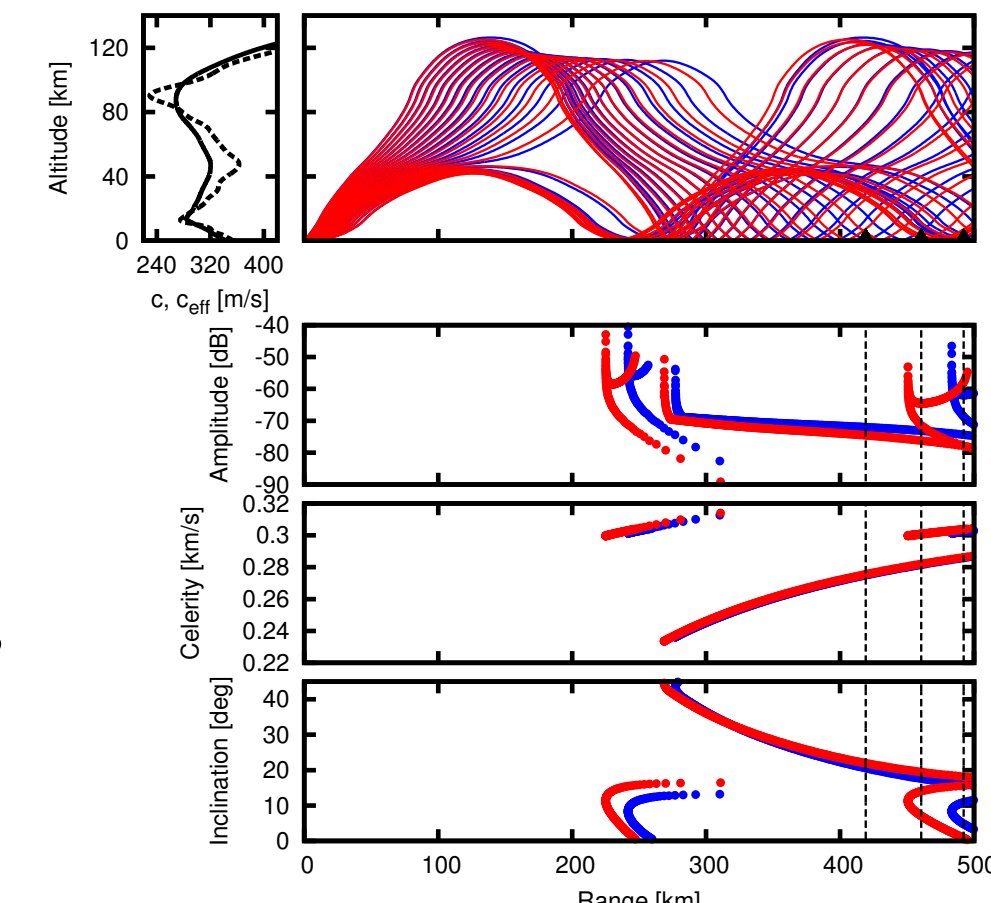


Figure 3 : Predicted differences in propagation paths for an event in the western US using spherical (red) and 3D Cartesian (blue) models.

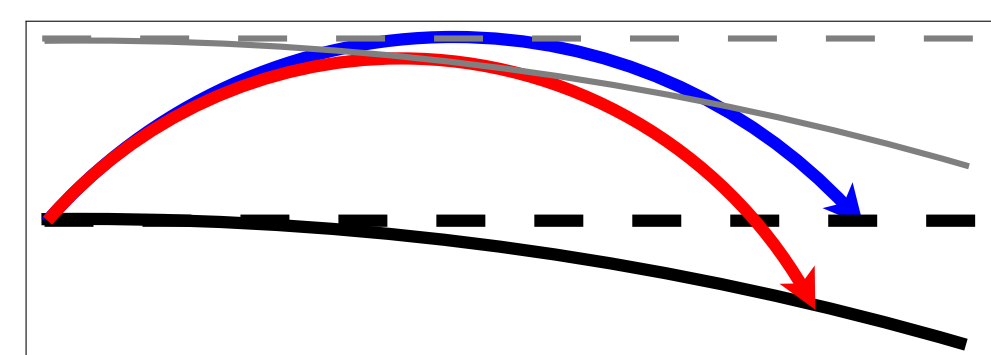


Figure 4 : A simplified explanation for the difference in propagation when considering a spherical coordinate transformation.

Special Features

Eigenrays

- ▶ Predicting signals observed at specific locations requires identifying propagation paths connecting that specific source-receiver geometry (termed eigenrays).
- ▶ The auxiliary parameters introduced to compute the Jacobian components are leveraged for use in an algorithm that efficiently identifies eigenrays as detailed in Blom & Waxler (2017).
- ▶ Eigenray analysis enables one to predict arrivals characteristics at a specific location (Fig. 5) or identify paths to a network of sensors or arrays for tomography applications (Fig. 6).

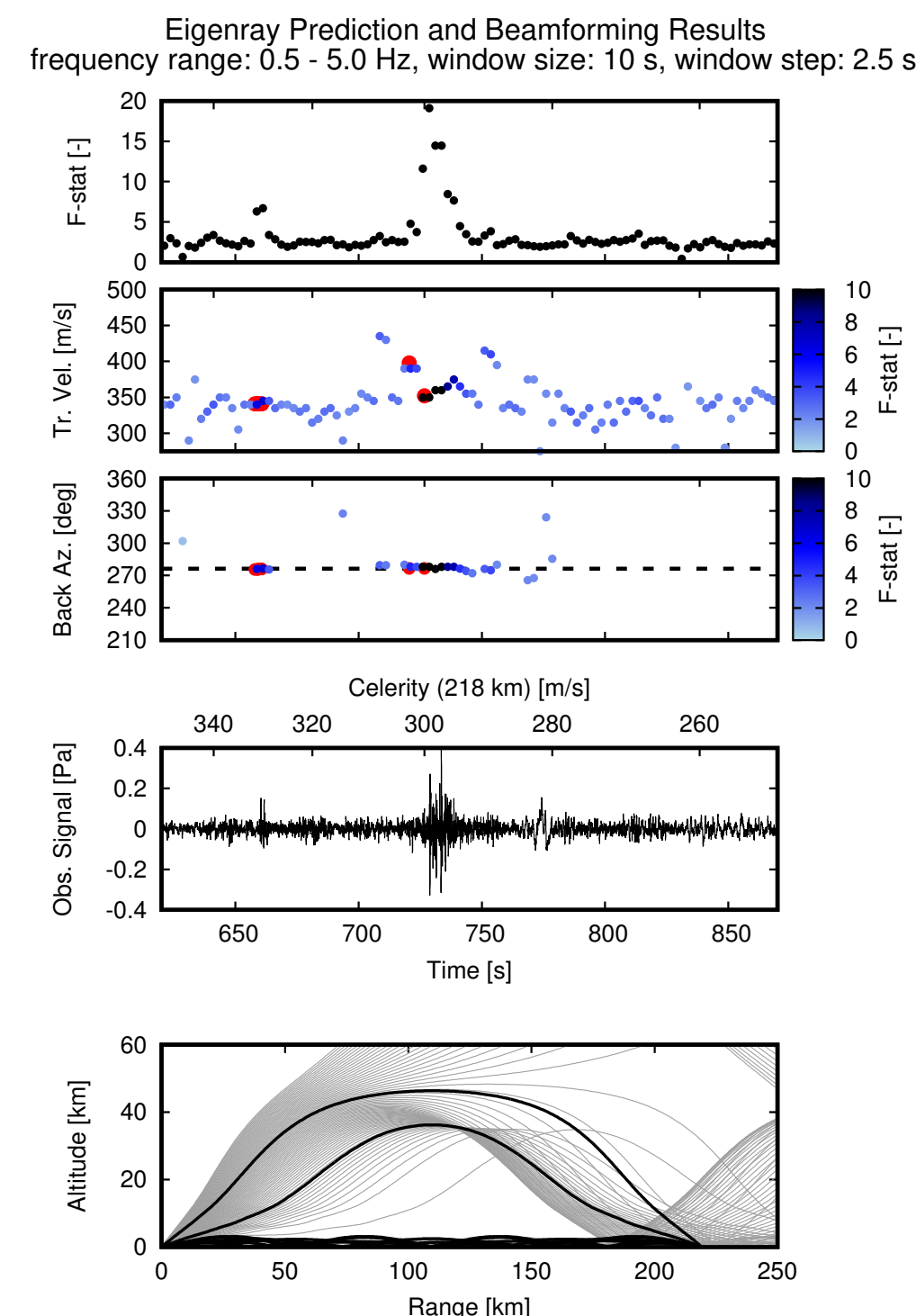


Figure 5 : Predicted eigenrays for an above ground explosion in the western US and comparison with beamforming analysis results.

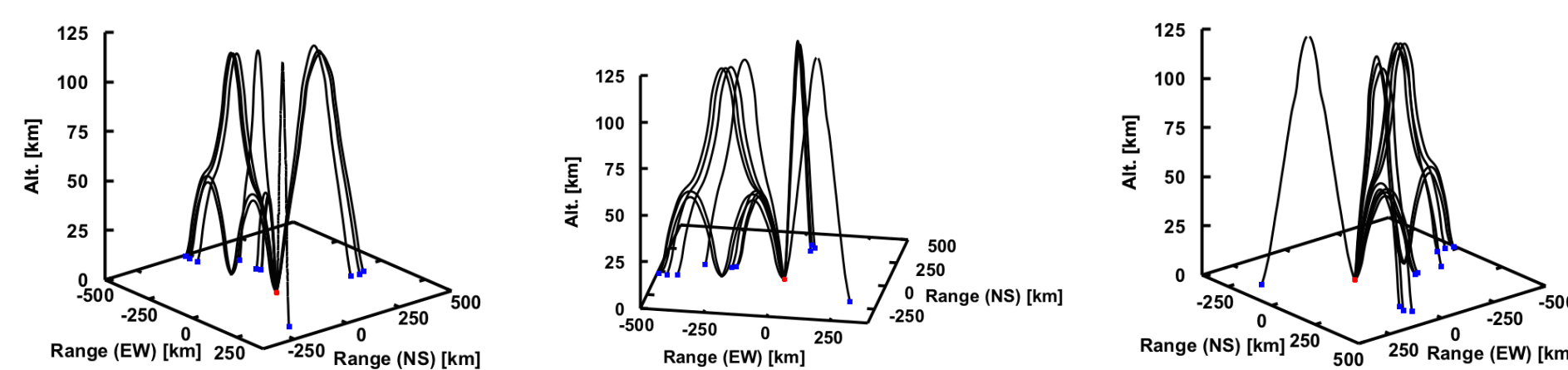


Figure 6 : Eigenrays from a single source to a number of regional infrasound arrays. Propagation characteristics along this set of eigenrays is useful in acoustic tomography applications.

Weakly Non-Linear Waveforms

- ▶ Methods developed by Lonzaga *et al.* (2015) detailed a method to compute waveforms along individual ray paths including weakly non-linear effects as shown in Fig. 7.
- ▶ The weakly non-linear waveform calculation method is being implemented and compared with that available through the NCPA propagation software package. It will be included in a future update to *InfraGA/GeoAc*.

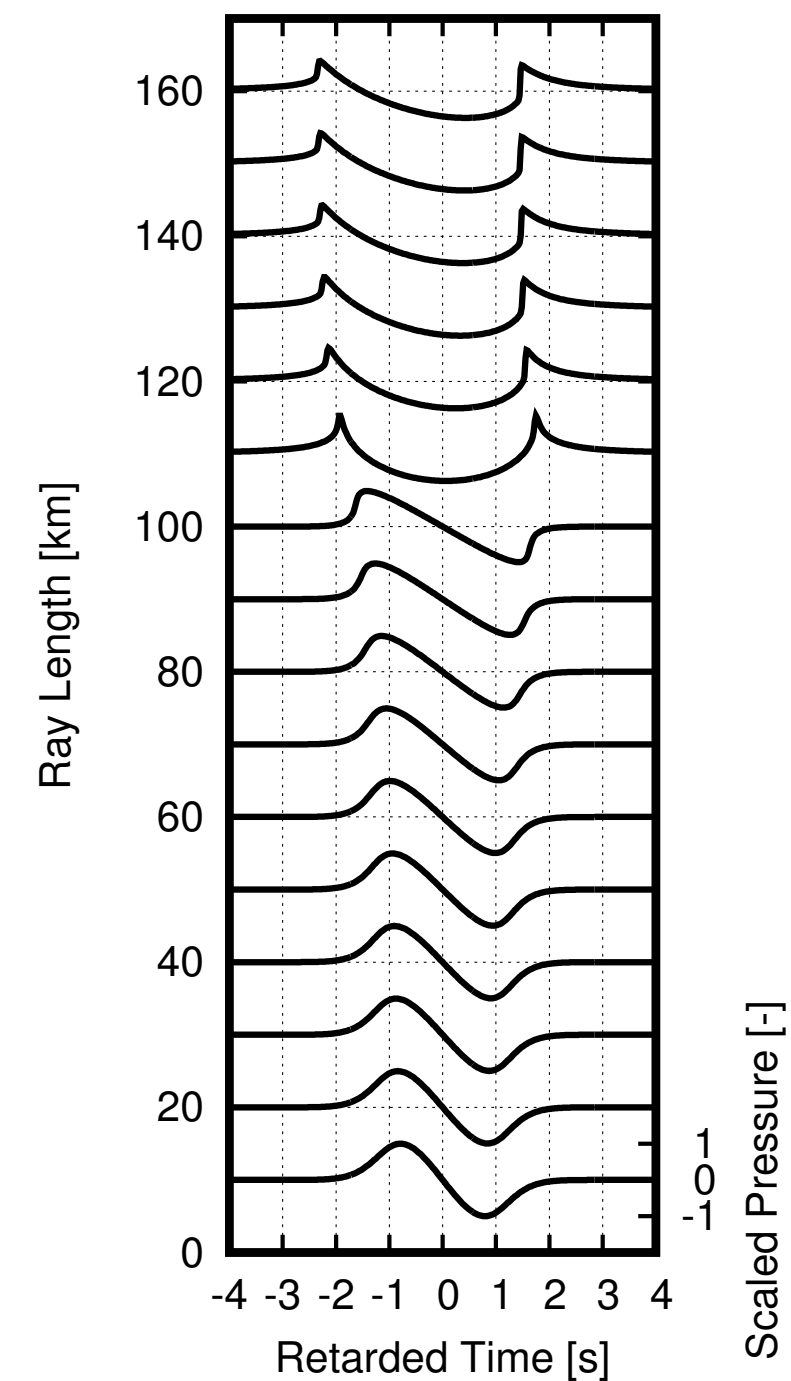


Figure 7 : Example of weakly non-linear waveform calculations.

Accelerated

- ▶ Ray tracing is easily applied to multiprocessor computing since each ray path can be computed independently.
- ▶ A parallelized version of the ray tracing code is being developed that will allow for accelerated ray calculation and will be included in a future update to *InfraGA/GeoAc*.

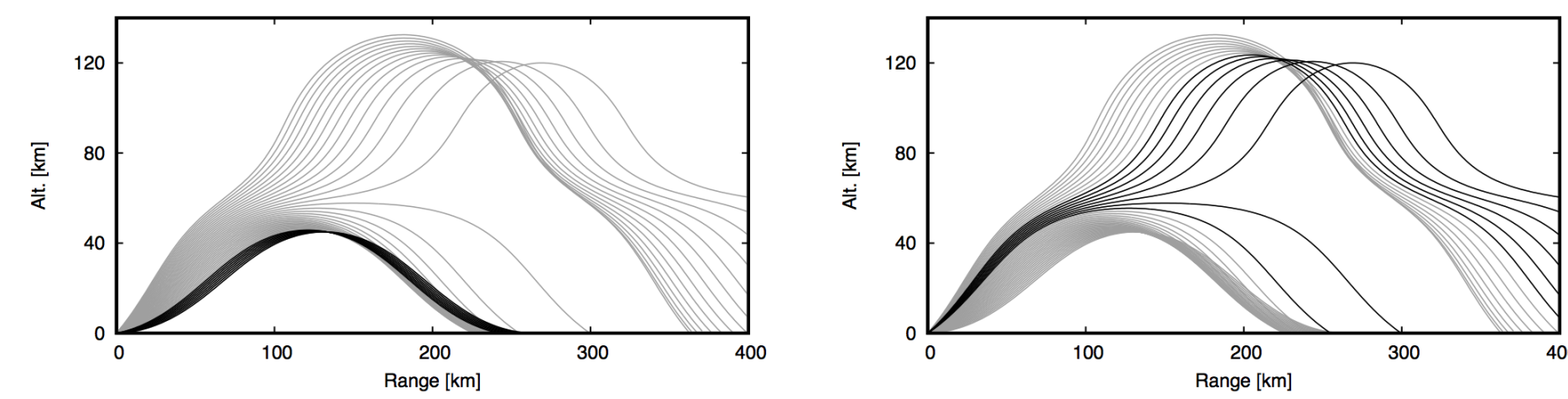


Figure 8 : Sets of ray paths can be simultaneously calculated using parallelization.

Summary

- ▶ *InfraGA/GeoAc* is a robust numerical tool that allows for simulation of infrasound propagation through the atmosphere available on the [LANL Seismoacoustics GitHub repository](#).
- ▶ Auxiliary parameters utilized in the algorithm enables calculation of the attenuation due to geometric spreading along individual ray paths.
- ▶ Eigenray analysis leveraging the auxiliary parameters allows for efficient identification of arrivals even in the case of 3D propagation through a moving medium.
- ▶ Weakly non-linear waveform calculation and acceleration of computations through parallelization are planned for future inclusion.

References and Supplemental Reading

1. Blom, Philip, and Roger Waxler. "Modeling and observations of an elevated, moving infrasonic source: Eigenray methods." *The Journal of the Acoustical Society of America* 141(4) (2017): 2681-2692. doi: 10.1121/1.4980096.
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4. Blom, Philip, and Roger Waxler. "Impulse propagation in the nocturnal boundary layer: Analysis of the geometric component." *The Journal of the Acoustical Society of America* 131(5) (2012): 3680-3690. doi: 10.1121/1.3699174.

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