# GeoAc

Numerical Tools to Model Acoustic Propagation in the Geometric Limit

*Author/Maintainer: Philip S. Blom (pblom@lanl.gov)*

# Contents

# 1 Introduction and Install

GeoAc is a numerical package written in C++ which solves the equations governing acoustic propagation through the atmosphere in the geometric limit using a RK4 algorithm. It contains multiple instances of said equation system and is able to model propagation in an azimuthal plane using the effective motionless medium approximation as well as in three dimensions using an inhomogeneous moving background medium. The three dimensional propagation scheme include methods to model propagation in a Cartesian coordinate system as well as a spherical coordinate system which incorporates the curvature of the earth.

In addition to the geometric propagation paths which are straightforward to compute, GeoAc uses auxiliary parameters as discussed in *Impulse Propagation in the Nocturnal Boundary Layer - Analysis of the Geometric Component* [Blom & Waxler; J. Acoust. Soc. Am., 2012, Vol.131(5), pp.3680-90] to calculate the Jacobian determinant and obtain a frequency independent amplitude coefficient describing the attenuation due to geometric spreading. The auxiliary parameters used to compute the amplitude coefficient have been found to provide an efficient means to identify eigenrays (propagation paths connecting a source and receiver at specific locations). Eigenray information provides a means to predict the characteristics of the various acoustic phases observed at a given receiver location for a known source and propagation medium.

For propagation through a horizontally varying medium, a multivariate interpolation scheme has been developed which uses a modified Keys bicubic interpolation algorithm as described in *Cubic Convolution Interpolation for Digital Image Processing* [IEEE Transactions on Signal Processing, Acoustics, Speech, and Signal Processing 29 (6): pp.1153-60]. In this case, the interpolation algorithm has been configured so that both first and second order derivatives of the medium are continuous between grid squares. This condition is required to generate smooth and continuous solutions for the auxiliary parameters.

**Installation**:

- Unarchive the package.
- Open a terminal and `cd` into the directory containing the un-archived GeoAc materials. Several options are now available:
  - For the default installation which builds and installs the executables to `/usr/local/bin`, type `make install` (this will likely also require using `sudo`).
  - For a custom installation, edit the `makefile` so that `INSTALL_DIR` is where you desire then run `make install` (may still require `sudo`).
  - To create the executables within the local directory, simply run `make all`.

The rest of this manual is divided up into the following sections: explanation of the usage of the individual executables are detailed in the Sect. 2, clarification of the amplitude computation and range dependent profile interpolation are summarized in Sect. 3, details of additional parameters available for all executables to customize propagation are given in Sect. 4. An overview of the changes made during each revision of the package are included in Sect. 5.

# 2 Using GeoAc

## 2.1 2D Stratified Cartesian Propagation

**Description**

The methods in `GeoAc2D` compute ray paths in an azimuthal plane using the effective sound speed approximation which defines $c_{\text{eff}}(z) = c(z) + \vec{v}(z) \cdot \hat{n}_\perp$, where $c(z) = \sqrt{\gamma R T(z)}$ is the adiabatic sound speed and $\vec{v}(z) \cdot \hat{n}_\perp$ is the component of the wind in the direction of propagation.

**Usage**

```
GeoAc2D [option] profile.met [parameters]
```

- Only one option can be applied for a given run. Possible options are:

  `-prop` Generate ray paths at a fixed azimuth using multiple inclination angles.
  `-interactive` Set a fixed source elevation and select individual ray paths to generate.

- The `profile.met` file is expected to contain columns describing the atmosphere in the format:

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

- Parameters are set using the format `parameter_name=value`, for example: `theta_step=1.0`. Possible parameters for each option are included below.

| **Parameters for propagation option** | | |
|---|---|---|
| Parameter | Description | Default Value |
| `theta_min` | Minimum inclination angle ($0^o$ = horizontal) | $0.5^o$ |
| `theta_max` | Maximum inclination angle ($0^o$ = horizontal) | $45.0^o$ |
| `theta_step` | Inclination step size | $0.5^o$ |
| `azimuth` | Azimuth angle (North = $0^o$, increases clockwise) | $-90.0^o$ |
| `bounces` | Maximum # of bounces to compute (integer $\geq 0$) | 2 |
| `z_src` | Elevation of the source | 0.0 km |

| **Parameters for interactive option** | | |
|---|---|---|
| Parameter | Description | Default Value |
| `z_src` | Elevation of the source | 0.0 km |

**Output**

`atmo.dat`
Contains the interpolate atmospheric profile. Columns are:

$$z\,[\text{km}] \vdots T(z)\,[\text{K}] \vdots u(z)\left[\frac{\text{m}}{\text{s}}\right] \vdots v(z)\left[\frac{\text{m}}{\text{s}}\right] \vdots \rho_0(z)\left[\frac{\text{g}}{\text{cm}^3}\right] \vdots p_0(z)\,[\text{mbar}] \vdots c_{\text{therm.}}(z)\left[\frac{\text{m}}{\text{s}}\right] \vdots c_{\text{eff}}(z,\phi_0)\left[\frac{\text{m}}{\text{s}}\right]$$

`file_name_raypaths.dat`
Contains the ray path information. Columns are:

$$r[\text{km}] \vdots z[\text{km}] \vdots A_{\text{geo.}}[\text{dB}] \vdots A_{\text{atmo.}}[\text{dB}] \vdots t[\text{sec}]$$

`file_name_results.dat`
Contains the arrival information for each ground intercept

$$\theta[\text{deg}] \vdots \phi[\text{deg}] \vdots n_{\text{bnc}} \vdots r_0[\text{km}] \vdots t[\text{sec}] \vdots z_{\max}[\text{km}] \vdots \theta_{\text{inc.}}[\text{deg}] \vdots \phi_{\text{back}}[\text{deg}] \vdots A_{\text{geo.}}[\text{dB}] \vdots A_{\text{atmo.}}[\text{dB}]$$

**Amplitude Format**

The amplitude coefficient computed in the `GeoAc` methods is defined relative to spherical spreading at the source. That is, the amplitude approaches $\frac{1}{4\pi}\frac{1}{s}$ for $s \downarrow 0$. Assuming spherical spreading within 1 kilometer of the source, the amplitude in the far field relative to the amplitude 1 kilometer from the source is given by,

$$A_{\text{rel. 1 km}} = A_{\text{geo.}} + 20\log_{10}(4\pi) = A_{\text{geo.}} + 21.98 \text{ dB}.$$

## 2.2 3D Stratified Cartesian Propagation

**Description**

The methods in `GeoAc3D` compute ray paths in a three dimensional inhomogeneous moving medium. In this case, the atmosphere is assumed to vary only with altitude and be specified by a single file. Because of this horizontal symmetry, the source is assumed to be at the origin though its elevation above the ground can be modified.

**Usage**

`GeoAc3D [option] profile.met [parameters]`

- Only one option can be applied for a given run. Possible options are:

| | |
|---|---|
| `-prop` | Generate ray paths at a multiple azimuths and multiple inclination angles. |
| `-interactive` | Set a fixed source elevation and select individual ray paths to generate. |
| `-eig_search` | Search for all eigenray rays within a chosen inclination range connecting a source at $(0, 0, z_{\text{src}})$ to a receiver at $(x_{\text{rcvr}}, y_{\text{rcvr}}, z_{\text{grnd}})$. |
| `-eig_direct` | Search for a specific eigenray near estimated inclination and azimuth angles connecting a source at $(0, 0, z_{\text{src}})$ to a receiver at $(x_{\text{rcvr}}, y_{\text{rcvr}}, z_{\text{grnd}})$. |

- The `profile.met` file is expected to contain columns describing the atmosphere in the format:

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

- Parameters are set using the format `parameter_name=value`, for example: `theta_step=1.0`. Possible parameters for each option are included below.

| **Parameters for propagation option** | | |
|---|---|---|
| Parameter | Description | Default Value |
| `theta_min` | Minimum inclination angle ($0^o$ = horizontal) | $0.5^o$ |
| `theta_max` | Maximum inclination angle ($0^o$ = horizontal) | $45.0^o$ |
| `theta_step` | Inclination step size | $0.5^o$ |
| `phi_min` | Minimum azimuth angle (North = $0^o$, increases clockwise) | $-90.0^o$ |
| `phi_max` | Maximum azimuth angle (North = $0^o$, increases clockwise) | $-90.0^o$ |
| `phi_step` | Azimuth step size | $1.0^o$ |
| `azimuth` | Set a *single* azimuth (`phi_max` = `phi_min`) | – |
| `bounces` | Maximum # of bounces to compute (integer $\geq 0$) | 2 |
| `z_src` | Elevation of the source | 0.0 km |
| `WriteAtmo` | Boolean to write the atmosphere specifications | false |
| `WriteRays` | Boolean to write the ray paths | true |

| **Parameters for interactive option** | | |
|---|---|---|
| Parameter | Description | Default Value |
| `z_src` | Elevation of the source | 0.0 km |

| Parameters for eigenray search option | | |
|---|---|---|
| Parameter | Description | Default Value |
| `theta_min` | Minimum inclination angle ($0^o$ = horizontal) | $0.5^o$ |
| `theta_max` | Maximum inclination angle ($0^o$ = horizontal) | $45.0^o$ |
| `bnc_min` | Minimum # of bounces to consider (integer) | 0 |
| `bnc_max` | Maximum # of bounces to consider (integer) | 0 |
| `bounces` | Exact # of bounces (`bnc_min` = `bnc_max`) | 0 |
| `z_src` | Elevation of the source | 0.0 km |
| `x_rcvr` | Offset of receiver from source (E-W) | $-250.0$ km |
| `y_rcvr` | Offset of receiver from source (N-S) | 0.0 km |
| `Verbose` | Boolean to output details of the search | false |
| `azimuth_err_lim` | Maximum azimuth error for estimated eigenray | $2.0^o$ |
| `iterations` | Maximum number of iterations in eigenray search | 25 |

| Parameters for eigenray direct option | | |
|---|---|---|
| Parameter | Description | Default Value |
| `theta_est` | Estimated inclination angle ($0^o$ = horizontal) | $15.0^o$ |
| `phi_est` | Estimated azimuth angle (North = $0^o$, increases clockwise) | atan2 (`y_rcvr`, `x_rcvr`) |
| `bounces` | Exact # of bounces to consider (integer $\geq 0$) | 0 |
| `z_src` | Elevation of the source | 0.0 km |
| `x_rcvr` | Offset of receiver from source (E-W) | $-250.0$ km |
| `y_rcvr` | Offset of receiver from source (N-S) | 0.0 km |
| `Verbose` | Boolean to output details of the search | false |
| `iterations` | Maximum number of iterations in eigenray search | 25 |

**Output**

`atmo.dat`
Contains the interpolate atmospheric profile. Columns are:

$$z\,[\mathrm{km}] \vdots T(z)\,[\mathrm{K}] \vdots u(z)\left[\frac{\mathrm{m}}{\mathrm{s}}\right] \vdots v(z)\left[\frac{\mathrm{m}}{\mathrm{s}}\right] \vdots \rho_0(z)\left[\frac{\mathrm{g}}{\mathrm{cm}^3}\right] \vdots p_0(z)\,[\mathrm{mbar}] \vdots c_{\mathrm{therm.}}(z)\left[\frac{\mathrm{m}}{\mathrm{s}}\right] \vdots c_{\mathrm{eff}}\,(z,\phi_0)\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$$

`file_name_raypaths.dat`
`file_name_eigenray-#.dat`
Contains the ray path information. Columns are:

$$x[\mathrm{km}] \vdots y[\mathrm{km}] \vdots z[\mathrm{km}] \vdots A_{\mathrm{geo.}}[\mathrm{dB}] \vdots A_{\mathrm{atmo.}}[\mathrm{dB}] \vdots t[\mathrm{sec}]$$

`file_name_results.dat`
Contains the arrival information for each ground intercept for the `-prop` option:

$$\theta[\mathrm{deg}] \vdots \phi[\mathrm{deg}] \vdots n_{\mathrm{bnc}} \vdots x_0[\mathrm{km}] \vdots y_0[\mathrm{km}] \vdots t[\mathrm{sec}] \vdots z_{\mathrm{max}}[\mathrm{km}] \vdots \theta_{\mathrm{inc.}}[\mathrm{deg}] \vdots \phi_{\mathrm{back}}[\mathrm{deg}] \vdots A_{\mathrm{geo.}}[\mathrm{dB}] \vdots A_{\mathrm{atmo.}}[\mathrm{dB}]$$

Contains the run summary and arrival information for each eigenray for the `-eig_search` option:

```
Eigenray-#.  [ ] bounce(s).
       theta, phi = [ ].
       Travel Time = [ ].
       Celerity = [ ].
       Amplitude (geometric) = [ ].
       Atmospheric attenuation =  [ ].
       Arrival inclination =  [ ].
       Azimuth to source = [ ].
       Back azimuth of arrival = [ ].
       Azimuth deviation = [ ] .
```

## 2.3 3D Stratified Global Propagation

**Description**

The methods in `GeoAcGlobal` compute ray paths in a three dimensional inhomogeneous moving medium using spherical coordinates. Currently, the earth is assumed to be spherical with a fixed radius of 6,370 kilometers (a future update to the methods will include topography and allow for variable radius with latitude and longitude). The atmosphere is assumed to be stratified and specified by a single file. The latitude and longitude of the source can be specified to produce results for specific geographic locations without requiring coordinate shifts.

**Usage**

```
GeoAcGlobal [option] profile.met [parameters]
```

- Only one option can be applied for a given run. Possible options are:

| | |
|---|---|
| `-prop` | Generate ray paths at a multiple azimuths and multiple inclination angles. |
| `-interactive` | Set a fixed source elevation and select individual ray paths to generate. |
| `-eig_search` | Search for all eigenray rays within a chosen inclination range connecting a source at $(\text{lat}_{\text{src}}, \text{lon}_{\text{src}}, z_{\text{src}})$ to a receiver at $(\text{lat}_{\text{rcvr}}, \text{lon}_{\text{rcvr}}, z_{\text{grnd}})$. |
| `-eig_direct` | Search for a specific eigenray near estimated inclination and azimuth angles connecting a source at $(\text{lat}_{\text{src}}, \text{lon}_{\text{src}}, z_{\text{src}})$ to a receiver at $(\text{lat}_{\text{rcvr}}, \text{lon}_{\text{rcvr}}, z_{\text{grnd}})$. |

- The `profile.met` file is expected to contain columns describing the atmosphere in the format:

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

- Parameters are set using the format `parameter_name=value`, for example: `theta_step=1.0`. Possible parameters for each option are included below.

| **Parameters for propagation option** | | |
|---|---|---|
| Parameter | Description | Default Value |
| `theta_min` | Minimum inclination angle ($0^o$ = horizontal) | $0.5^o$ |
| `theta_max` | Maximum inclination angle ($0^o$ = horizontal) | $45.0^o$ |
| `theta_step` | Inclination step size | $0.5^o$ |
| `phi_min` | Minimum azimuth angle (North = $0^o$, increases clockwise) | $-90.0^o$ |
| `phi_max` | Maximum azimuth angle (North = $0^o$, increases clockwise) | $-90.0^o$ |
| `phi_step` | Azimuth step size | $1.0^o$ |
| `azimuth` | Set a *single* azimuth (`phi_max` = `phi_min`) | – |
| `bounces` | Maximum # of bounces to compute (integer $\geq 0$) | 2 |
| `lat_src` | Latitude of the source | $30.0^o$ |
| `lon_src` | Longitude of the source | $0.0^o$ |
| `z_src` | Elevation of the source | 0.0 km |
| `WriteAtmo` | Boolean to write the atmosphere specifications | false |
| `WriteRays` | Boolean to write the ray paths | true |

| **Parameters for interactive option** | | |
|---|---|---|
| Parameter | Description | Default Value |
| `lat_src` | Latitude of the source | $30.0^o$ |
| `lon_src` | Longitude of the source | $0.0^o$ |
| `z_src` | Elevation of the source | 0.0 km |

| Parameters for eigenray search option | | |
|---|---|---|
| Parameter | Description | Default Value |
| theta_min | Minimum inclination angle ($0^o$ = horizontal) | $0.5^o$ |
| theta_max | Maximum inclination angle ($0^o$ = horizontal) | $45.0^o$ |
| bnc_min | Minimum # of bounces to consider (integer) | 0 |
| bnc_max | Maximum # of bounces to consider (integer) | 0 |
| bounces | Exact # of bounces (bnc_min = bnc_max) | 0 |
| lat_src | Latitude of the source | $30.0^o$ |
| lon_src | Longitude of the source | $0.0^o$ |
| z_src | Elevation of the source | 0.0 km |
| lat_rcvr | Latitude of the receiver | $30.0^o$ |
| lon_rcvr | Longitude of the receiver | $-2.5^o$ |
| Verbose | Boolean to output details of the search | false |
| azimuth_err_lim | Maximum azimuth error for estimated eigenray | $2.0^o$ |
| iterations | Maximum number of iterations in eigenray search | 25 |

| Parameters for eigenray direct option | | |
|---|---|---|
| Parameter | Description | Default Value |
| theta_est | Estimated inclination angle ($0^o$ = horizontal) | $15.0^o$ |
| phi_est | Estimated azimuth angle (North = $0^o$, increases clockwise) | atan2 (y_rcvr, x_rcvr) |
| bounces | Exact # of bounces to consider (integer $\geq 0$) | 0 |
| lat_src | Latitude of the source | $30.0^o$ |
| lon_src | Longitude of the source | $0.0^o$ |
| z_src | Elevation of the source | 0.0 km |
| lat_rcvr | Latitude of the receiver | $30.0^o$ |
| lon_rcvr | Longitude of the receiver | $-2.5^o$ |
| Verbose | Boolean to output details of the search | false |
| iterations | Maximum number of iterations in eigenray search | 25 |

**Output**

atmo.dat

Contains the interpolate atmospheric profile. Columns are:

$$z\,[\mathrm{km}] \vdots T(z)\,[\mathrm{K}] \vdots u(z)\left[\frac{\mathrm{m}}{\mathrm{s}}\right] \vdots v(z)\left[\frac{\mathrm{m}}{\mathrm{s}}\right] \vdots \rho_0(z)\left[\frac{\mathrm{g}}{\mathrm{cm}^3}\right] \vdots p_0(z)\,[\mathrm{mbar}] \vdots c_{\mathrm{therm.}}(z)\left[\frac{\mathrm{m}}{\mathrm{s}}\right] \vdots c_{\mathrm{eff}}\left(z,\varphi_0\right)\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$$

file_name_raypaths.dat

file_name_eigenray-#.dat

Contains the ray path information. Columns are:

$$z[\mathrm{km}] \vdots \mathrm{Lat}\ [\mathrm{deg}] \vdots \mathrm{Lon}\ [\mathrm{deg}] \vdots A_{\mathrm{geo.}}[\mathrm{dB}] \vdots A_{\mathrm{atmo.}}[\mathrm{dB}] \vdots t[\mathrm{sec}]$$

file_name_results.dat

Contains the arrival information of each ground intercept for the -prop option:

$$\theta[\mathrm{deg}] \vdots \phi[\mathrm{deg}] \vdots n_{\mathrm{bnc}} \vdots \mathrm{Lat}_0[\mathrm{km}] \vdots \mathrm{Lon}_0[\mathrm{km}] \vdots t[\mathrm{sec}] \vdots \nu\left[\frac{\mathrm{km}}{\mathrm{s}}\right] \vdots z_{\max}[\mathrm{km}] \vdots \theta_{\mathrm{inc.}}[\mathrm{deg}] \vdots \phi_{\mathrm{back}}[\mathrm{deg}] \vdots A_{\mathrm{geo.}}[\mathrm{dB}] \vdots A_{\mathrm{atmo.}}[\mathrm{dB}]$$

Contains the run summary and arrival information for each eigenray for the -eig_search option (identical to 3D Stratified case)

## 2.4 3D Range Dependent Cartesian Propagation

**Description**

The methods in `GeoAc3D.RngDep` are identical to those in `GeoAc3D` with the modification that the atmosphere is no longer assumed to be stratified. The atmosphere is now specified by a grid of vertical profiles, $f_{i,j}(z) = f(x_i, y_j, z)$, which are interpolated to produce a continuous function for the specifications.

**Usage**

```
GeoAc3D.RngDep [option] profile_prefix nodes-x.loc nodes-y.loc [parameters]
```

- Options, parameters, and output are identical to those for `GeoAc3D`. for `-prop` and `-interactive`, however the inputs for the eigenray methods allow variable source and receiver locations (no longer assumes the source is at $x = 0$, $y = 0$).

| **Parameters for eigenray search option** | | |
|---|---|---|
| Parameter | Description | Default Value |
| `theta_min` | Minimum inclination angle ($0^o$ = horizontal) | $0.5^o$ |
| `theta_max` | Maximum inclination angle ($0^o$ = horizontal) | $45.0^o$ |
| `bnc_min` | Minimum # of bounces to consider (integer) | 0 |
| `bnc_max` | Maximum # of bounces to consider (integer) | 0 |
| `bounces` | Exact # of bounces (`bnc_min` = `bnc_max`) | 0 |
| `x_src` | $x$ location of the source | Midpoint of `nodes-x.loc` file |
| `y_src` | $y$ location of the source | Midpoint of `nodes-x.loc` file |
| `z_src` | Elevation of the source | 0.0 km |
| `x_rcvr` | $x$ location of the receiver | Midpoint of `nodes-x.loc` file + 250 km |
| `y_rcvr` | $y$ location of the receiver | Midpoint of `nodes-y.loc` file |
| `Verbose` | Boolean to output details of the search | false |

| **Parameters for eigenray direct option** | | |
|---|---|---|
| Parameter | Description | Default Value |
| `theta_est` | Estimated inclination ($0^o$ = horizontal) | $15.0^o$ |
| `phi_est` | Estimated azimuth (North = $0^o$, increases clockwise) | atan2 (`y_rcvr`, `x_rcvr`) |
| `bounces` | Exact # of bounces to consider (integer $\geq 0$) | 0 |
| `x_src` | $x$ location of the source | Midpoint of `nodes-x.loc` file |
| `y_src` | $y$ location of the source | Midpoint of `nodes-x.loc` file |
| `z_src` | Elevation of the source | 0.0 km |
| `x_rcvr` | $x$ location of the receiver | Midpoint of `nodes-x.loc` file + 250 km |
| `y_rcvr` | $y$ location of the receiver | Midpoint of `nodes-y.loc` file |
| `Verbose` | Boolean to output details of the search | false |

- Each `profile_prefix#.met` file is expected to contain columns describing the atmosphere in the same format as `GeoAc3D`.

  The `.loc` files are expected to contain the $x$ and $y$ locations of the individual atmosphere specifications.

## 2.5 3D Range Dependent Global Propagation

**Description**

The methods in `GeoAcGlobal.RngDep` are identical to those in `GeoAcGlobal` with the modification that the atmosphere is no longer assumed to be stratified. The atmosphere is now specified by a grid of vertical profiles, $f_{i,j}(z) = f(r_e + z, \theta_i, \phi_j)$, which are interpolated to produce a continuous function for the specifications.

**Usage**

```
GeoAcGlobal.RngDep [option] profile_prefix nodes-lat.loc nodes-lon.loc [parameters]
```

- Options, parameters, and output are identical to those for `GeoAcGlobal` with the following additions.
- Each `profile_prefix#.met` file is expected to contain columns describing the atmosphere in the same format as `GeoAcGlobal`.

  The `.loc` files are expected to contain the latitude and longitude locations of the individual atmosphere specifications.

# 3 Clarifications

## 3.1 Amplitude Format

The amplitude coefficient computed in the `GeoAc` methods is defined relative to spherical spreading at the source. That is, the amplitude approaches $\frac{1}{4\pi}\frac{1}{s}$ for $s \downarrow 0$. Assuming spherical spreading within 1 kilometer of the source, the amplitude in the far field relative to the amplitude 1 kilometer from the source is given by,

$$A_{\text{rel. 1 km}} = A_{\text{geo.}} + 20\log_{10}(4\pi) = A_{\text{geo.}} + 21.98 \text{ dB}.$$

## 3.2 Range Dependent Profile Interpolation

The range dependent interpolation scheme uses profiles specified by the definition

$$f_n(z) = f(x_i, y_j, z), \quad \text{with} \;\; n = i + n_x j.$$

For the global case, replace $x$ with latitude and $y$ with longitude. The multivariate interpolation scheme pre-computes vertical splines at each horizontal grid node and stores them in memory. The 3D interpolation is then evaluated using a bicubic interpolation in the horizontal which has been modified to guarantee continuous second order derivatives required for the continuity of the differential equations governing propagation. This interpolation scheme runs at approximately $\frac{1}{10}$ the speed of the stratified counterpart.

# 4 Additional Parameters

In addition to those listed in the previous section, a number of global parameters can be used to modify the propagation scheme. These include `freq`, `z_grnd`, and `profile_format`. Additionally, while a Python script is included to convert G2S .bin files into range dependent files, a summary of the details of the expected inputs is presented here. Lastly, boolean values control the output of caustic points in the `-prop` option and the computation of amplitudes in the `-prop` and `-interactive` options.

## 4.1 Propagating Specific Frequencies

The default frequency used to calculate attenuation is 0.1 Hz. By entering `freq=VALUE` other frequencies can be used. The amplitude coefficient currently calculated is a frequency-independent geometric spreading factor and Sutherland-Bass attenuation with variable scaling value of to control decrease the attenuation in the thermosphere. The absorption coefficient defaults to 0.3 but can be modified by `abs_coeff=VALUE`. Future modifications to the code are planned to include the non-linear transport coefficient which produces more physical realistic results.

## 4.2 Modifying the Ground Elevation

G2S profiles define $z = 0$ at sea level. This often produces temperature and wind values extrapolated below ground level. For propagation at a known (average) elevation, one can modify the ground level with `z_grnd=VALUE`. Given such an option, the numerics will automatically set the source elevation to the specified ground level unless some higher elevation is entered. The methods automatically adjust the source height to ground level to satisfy `z_src` $\geq$ `z_grnd` so that a source on elevated ground need only specify `z_grnd`.

## 4.3 Modifying the Profile Format

The expected format can be modified with the parameter statement `profile_format=TYPE`. Current options include the default, `zTuvdp`, and the NCPA format, `zuvwTdp`. As one might expect, this alternate profile format expects files with columns containing,

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

Additional profile formats may be introduced in future versions but as of v1.0.2 only these two formats are available.

## 4.4 Writing the Caustic Points to File

When using the `-prop` option, an additional parameter is available: `WriteCaustics`. This is defaulted to `false` but when set to `true` will create a number of files entitled `file_name_caustics-path#.dat`. These files contain the locations at which the Jacobian determinant changes sign which indicates passage through a caustic. The numerical value indicates the path between reflection `#` and `#+1`. Columns of the file contain:

$$x[\text{km}] \vdots y[\text{km}] \vdots z[\text{km}] \vdots t[\text{sec}]$$

## 4.5 Disabling the Calculation of Amplitudes

Computation of the Jacobian terms requires solving a number of additional equations. When the amplitude is not needed, disabling this computation increases the ray path computation speed by a factor of at least 3 (since many second order derivative terms are no longer calculated as well). To disable the computation of the Jacobian coefficients, set `CalcAmp=False` in the command line parameter list. This is only available in the `-prop` and `-interactive` modes.

## 4.6 Modifying the Propagation Region

In some cases, it is useful to modify the extent of the propagation region. In the case of a stratified atmosphere, the default propagation region extends to the upper limit of the interpolated atmosphere file and to a range of 10,000 kilometers. In many cases, in addition to limiting the number of ground reflections, limiting the propagation range and altitude can be an efficient way to improve computation time. Listed in the table below are available options in each method to modify the propagation region. In the case of range dependent propagation, the default horizontal limits are set by the interpolated atmosphere grid.

| **Propagation Region Modifications** | | | | | |
|---|---|---|---|---|---|
| | `2D` | `3D` | `3D.RngDep` | `Global` | `Global.RngDep` |
| `alt_max` | ✓ | ✓ | ✓ | ✓ | ✓ |
| `rng_max` | ✓ | ✓ | | ✓ | |
| `x_min` | | | ✓ | | |
| `x_max` | | | ✓ | | |
| `y_min` | | | ✓ | | |
| `y_max` | | | ✓ | | |
| `lat_min` | | | | | ✓ |
| `lat_max` | | | | | ✓ |
| `lon_min` | | | | | ✓ |
| `lon_max` | | | | | ✓ |

## 5 Plotting the Results

Included here are several short gnuplot scripts which are useful for displaying results. In all cases, you'll need to attached the appropriate prefix to the raypath.dat and results.dat files to be plotted.

**2D Raypaths**

```
set pm3d map
set palette defined (0 "white", 1 "blue", 2 "green", 3 "yellow", 4 "red")
set cbrange[-150:-50]
splot '{...}_raypaths.dat' u 1:2:($3 + $4 > -150 ? $3 + $4 : 1/0) w lines lw 1 palette
```

**2D Results**

```
set pm3d map
set palette defined (0 "white", 1 "blue", 2 "green", 3 "yellow", 4 "red")
set cbrange[-100:-50]
splot '{...}_results.dat' u ($5 - $4/0.35):4:($8+$9) with points pt 7 ps 0.75 palette
```

---

**3D Raypaths**

```
rng(x,y)=sqrt(x**2+y**2)
set pm3d map
set palette defined (0 "white", 1 "blue", 2 "green", 3 "yellow", 4 "red")
set cbrange[-140:-40]
splot '{...}_raypaths.dat' u (rng($1,$2)):3:($4 +$5 > -140 ? $4 + $5 : 1/0) w lines lw 1 palette
```

**3D Results**

```
rng(x,y)=sqrt(x**2+y**2)
set pm3d map
set palette defined (0 "white", 1 "blue", 2 "green", 3 "yellow", 4 "red")
set cbrange[-100:-50]
splot '{...}_results.dat' u 3:4:($5+$6) with points palette
splot '{...}_results.dat' u ($7-rng($3,$4)/0.350):(rng($3,$4)):($5+$6) w points palette

set palette defined (0 "red", 12 "red", 15 "green", 70 "green", 80 "blue", 140 "blue")
set cbrange[0:140]
splot '{...}_results.dat' u 3:4:8 with points palette
```

---

**Global Raypaths**

```
set pm3d map
set palette defined (0 "white", 1 "blue", 2 "green", 3 "yellow", 4 "red")
set cbrange[-140:-40]
splot '{...}_raypaths.dat' u 3:1:($4 +$5 > -140 ? $4 +$5 : 1/0) w lines lw 1 palette
splot '{...}_raypaths.dat' u 2:1:($4 +$5 > -140 ? $4 +$5 : 1/0) w lines lw 1 palette
```

**Global Results**

```
set pm3d map
set palette defined (0 "white", 1 "blue", 2 "green", 3 "yellow", 4 "red")
set cbrange[-100:-50]
splot '{...}_results.dat' u 3:4:($5+$6) w points palette

set palette defined (0 "red", 12 "red", 15 "green", 70 "green", 80 "blue", 140 "blue")
set cbrange[0:140]
splot '{...}_results.dat' u 3:4:9 with points palette
```

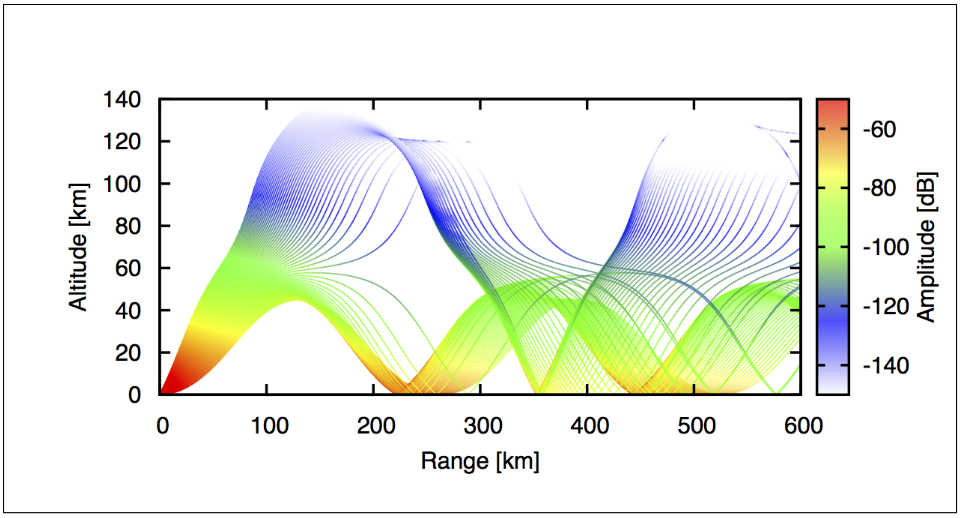


Figure 1: Example ray path figure generated with GNUPlot commands.

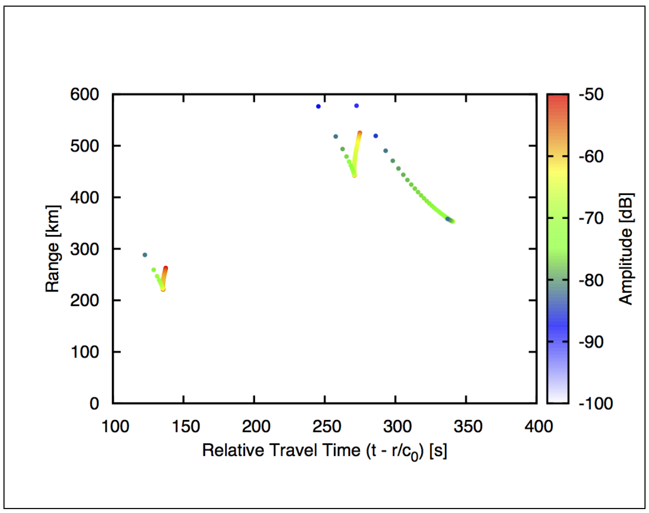


Figure 2: Relative travel time figure generated with GNUPlot commands.

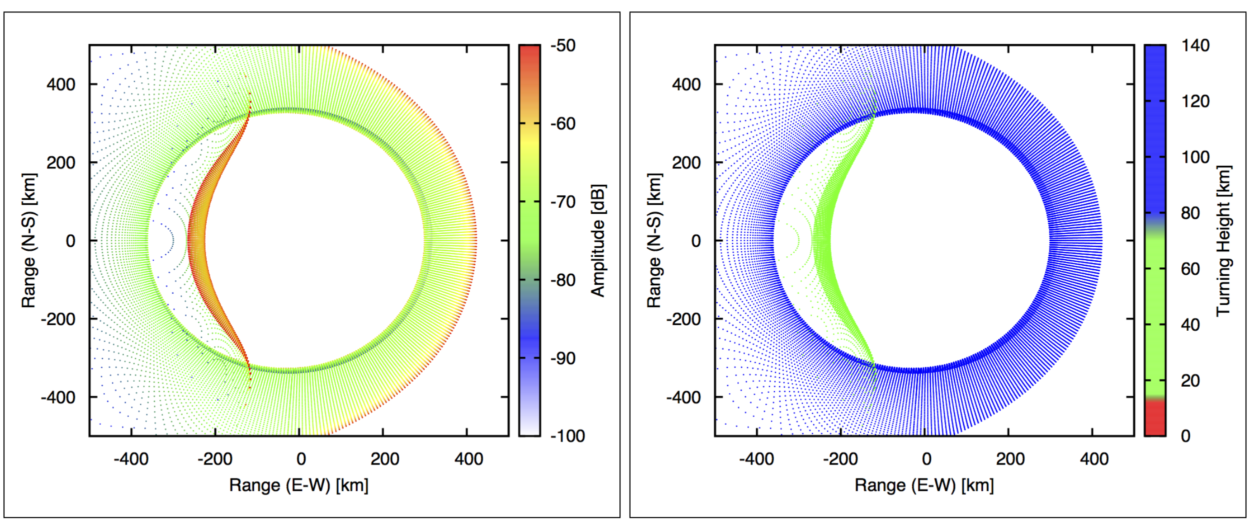


Figure 3: Arrival amplitudes and turning heights for 3D propagation. Similar results for global case.

# 6 Version History

**Development -** 2007 through 2013

- The original implementation of this coding package was developed during graduate research performed at the National Center for Physical Acoustics (NCPA), University of Mississippi between the summer of 2007 and the spring of 2013.
- The 2D (effective sound speed) implementation was developed for studying propagation in the nocturnal boundary layer as discussed in *Impulse Propagation in the Nocturnal Boundary Layer - Analysis of the Geometric Component* [Blom & Waxler; J. Acoust. Soc. Am., 2012, Vol.131(5), pp.3680-90].
- The 3D implementation was developed following this and has been extended to allow for range dependent media as detailed in *Interaction of the cyclonic winds with the infrasonic signal generated by a large maritime storm* [Blom; Ph.D. thesis, University of Mississippi, 2013].
- The eigenray methods were developed at the NCPA during the spring of 2013, then implemented and tested at Los Alamos National Laboratory (LANL) during the fall of the same year.
- The spherical coordinate (global) formulation was developed and implemented at LANL during the fall of 2013.

---

**v1.0.0 -** February, 2014

- Sharable (Academic and Government Use Only) version of GeoAc established and licensed by Los Alamos National Laboratory.

**v1.0.1 -** March, 2014

- Corrected eikonal vector differential equations to correctly account for variable unit vectors in spherical coordinates (global instances).

**v1.0.2 -** August, 2014

- Added output of number of bounces in results files.
- Added output of ray path inclination to allow computation of trace velocity in the range dependence and global cases.
- Changed order of columns in the results output for clarity.
- Corrected output of turning height. Previous versions didn't reset the height until the end of a full ray path. Now outputs between each pair of bounces (applicable for range dependent media).
- Added command line option to turn off amplitude calculation. Increases the speed of the computations by approximately a factor of 3 for cases in which amplitudes are not of interest.

**v1.1.0 -** November, 2014

- Re-licensed as an Open Source product for easier sharing within the infrasound research community.

**v1.1.1 -** January, 2015

- Included a run summary for eigenray search methods and added variables for minimum and maximum ground reflections. Corrected a bug that would occasionally cause the eigenray search methods to repeatedly identify the same eigenray.
- Corrected units in `atmo.dat` output.
- Included command line options to modify the propagation region.