Comparison of 2-D and 3-D Finite-Difference Simulations for Infrasound Propagation in the Atmosphere

Keehoon Kim (kim84@llnl.gov)
Lawrence Livermore National Laboratory

November 6 , 2024

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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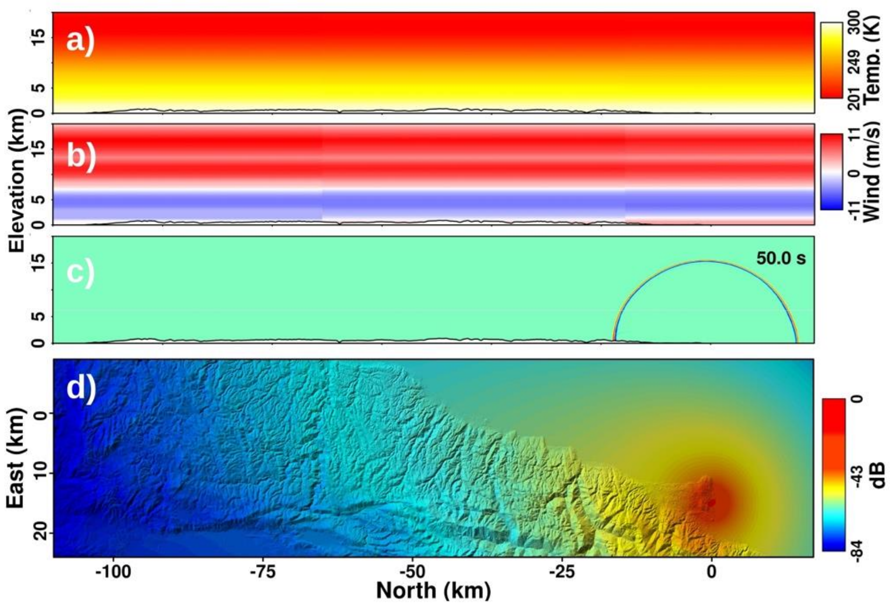
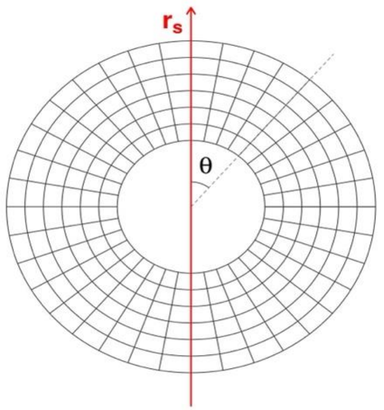
Full 3D Finite-Difference Methods for Acoustics

- Finite-Difference Applications
  - Computational fluid dynamics
  - Computational aeroacoustics
  - Computational seismology/acoustics
- Advantages
  - Flexible for complex sources and media (topography, turbulence)
- Limitation
  - Computationally expensive

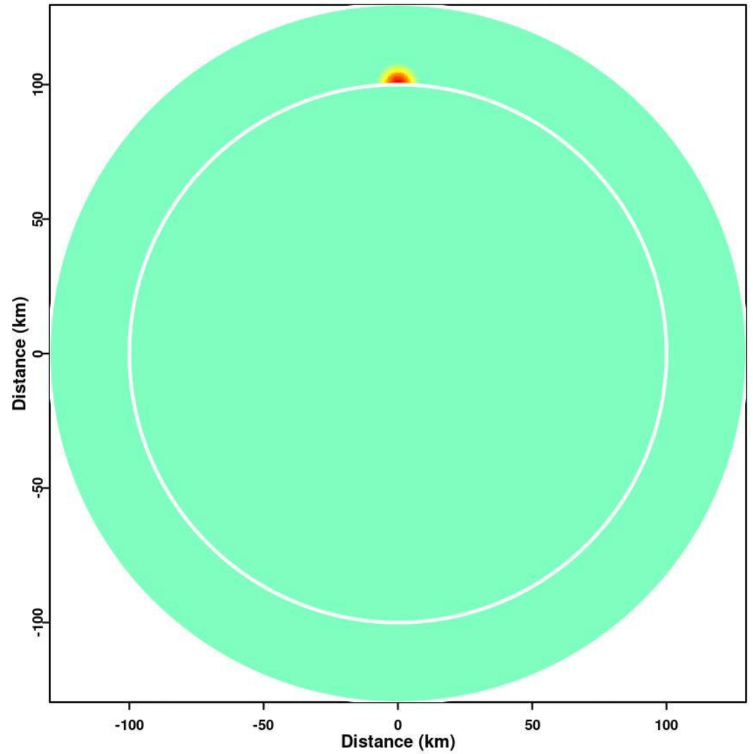


Full 3-D infrasound propagation simulations from an explosive source (Kim and Pasyanos, 2022)

2D Acoustic Codes in Spherical Coordinates (AC2Dr)

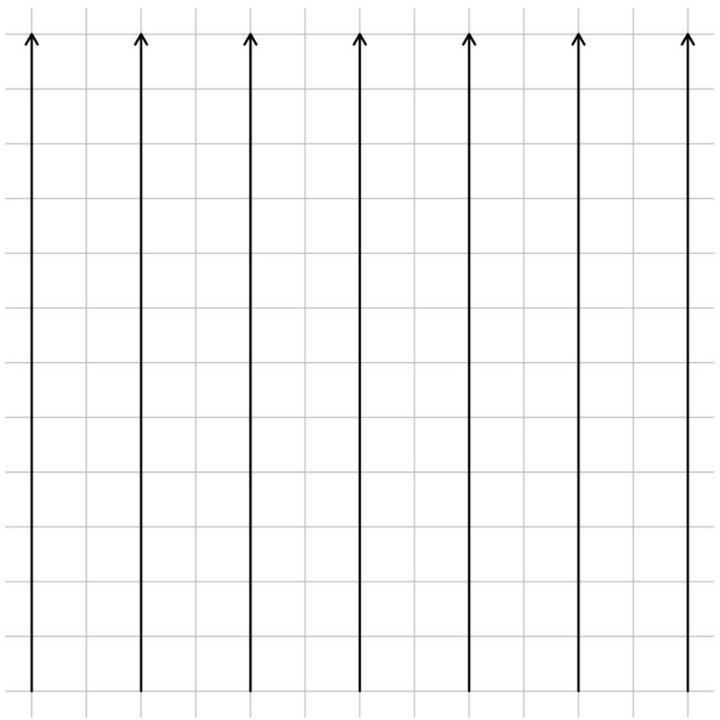


- Axisymmetric spherical coordinates for spherical spreading of acoustic waves
- High-order finite-difference discretization
  - 6 order central finite difference in space (7-point approximation for spatial derivatives)
  - 4 order Runge-Kutta time integration
- Approximate 3-D infrasound propagation by 2-D simulations?
  - Spherical source geometry can be approximated well

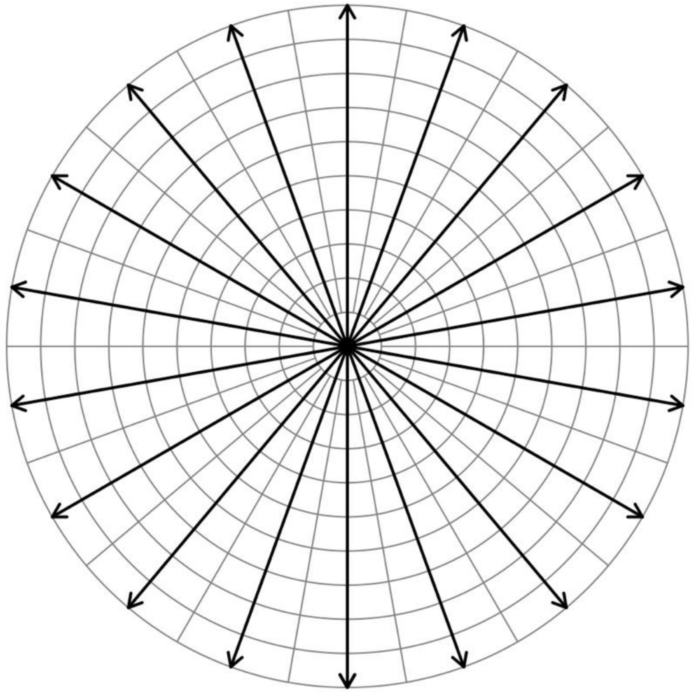


2D Approximation of Wind Field

Translation Wind in 3D



Radial in Axisymmetric 2D



- Translational wind field can be approximated by the 2-D in the far distances, but near the symmetric axis, only radial wind field can be represented by the 2-D.

2D Acoustic Codes in Spherical Coordinates (AC2Dr)

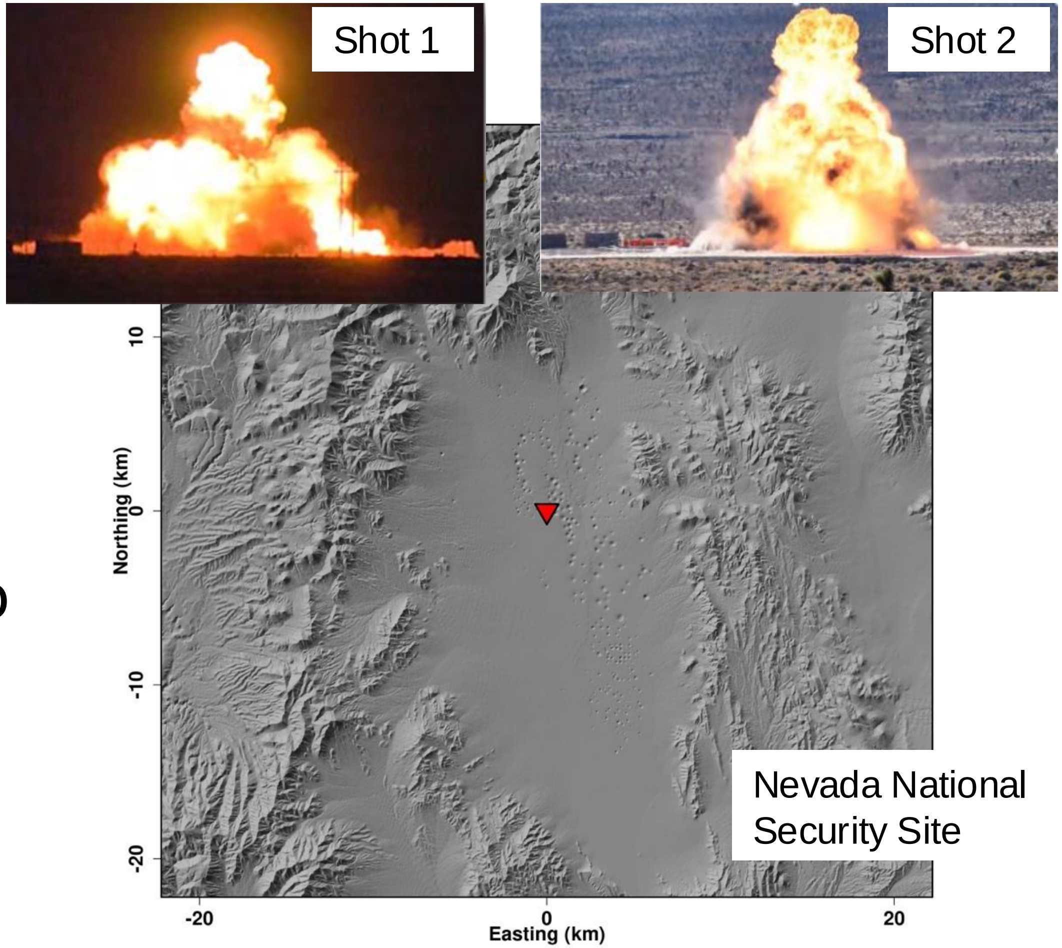
- 2-D finite-difference codes solving linear acoustic wave equations for pressure (p) and particle motions (u) with background mean flows (û)

$$\frac{\partial \mathbf{u}}{\partial t} + (\hat{\mathbf{u}} \cdot \nabla)\mathbf{u} + (\mathbf{u} \cdot \nabla)\hat{\mathbf{u}} + \frac{1}{\hat{\rho}}\nabla p = \mathbf{f}_{\mathbf{u}},$$

$$\frac{\partial p}{\partial t} + (\hat{\mathbf{u}} \cdot \nabla)p + \hat{\rho}\hat{c}^2\nabla \cdot \mathbf{u} = f_p.$$

Large Surface Explosion Coupling Experiment (LSECE)

- LSECE conducted at Nevada National Security Site in support of Defense Threat Reduction Agency in October 2020.
- Two shots (992 tons TNT equivalent) executed at dawn (06:37 local) and in the afternoon (15:35 local) to collect acoustic (infrasonic) data under two different atmospheric conditions.
- Local and regional infrasound signals were analyzed (Kim and Pasyanos, 2022; Blom, 2023)



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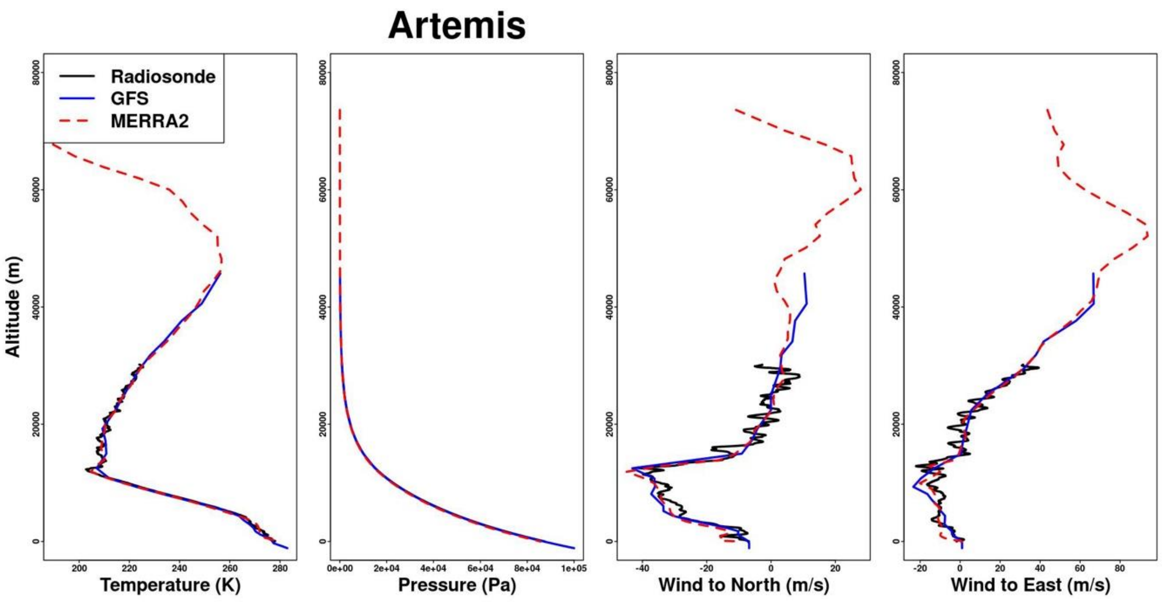
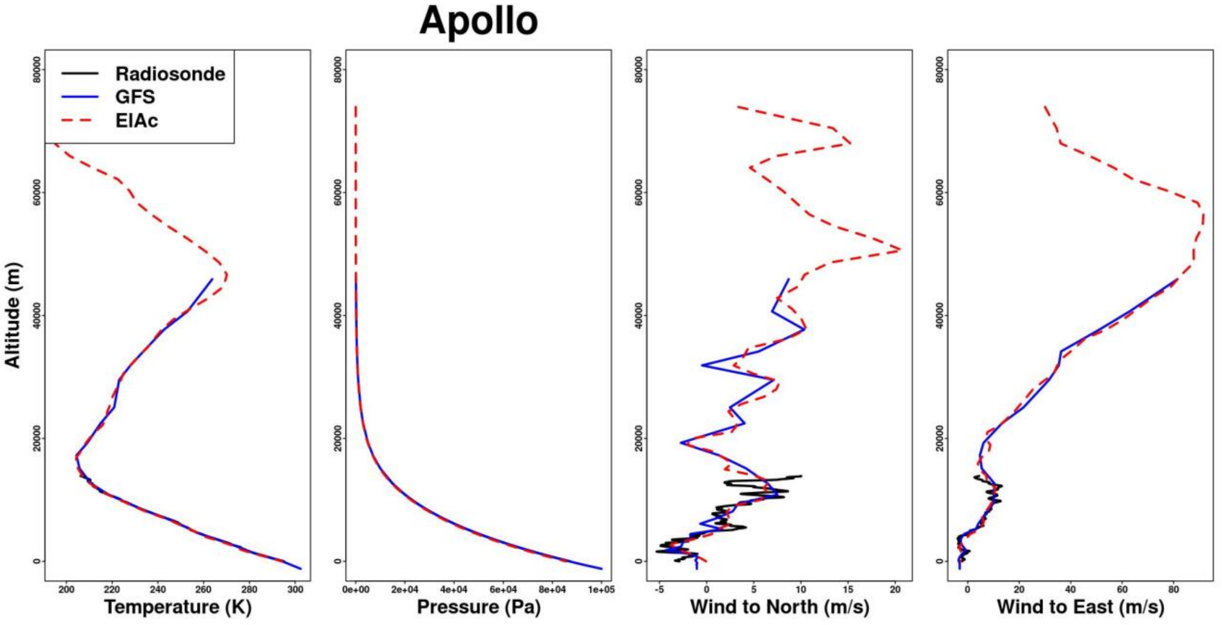
Weather Model Specification

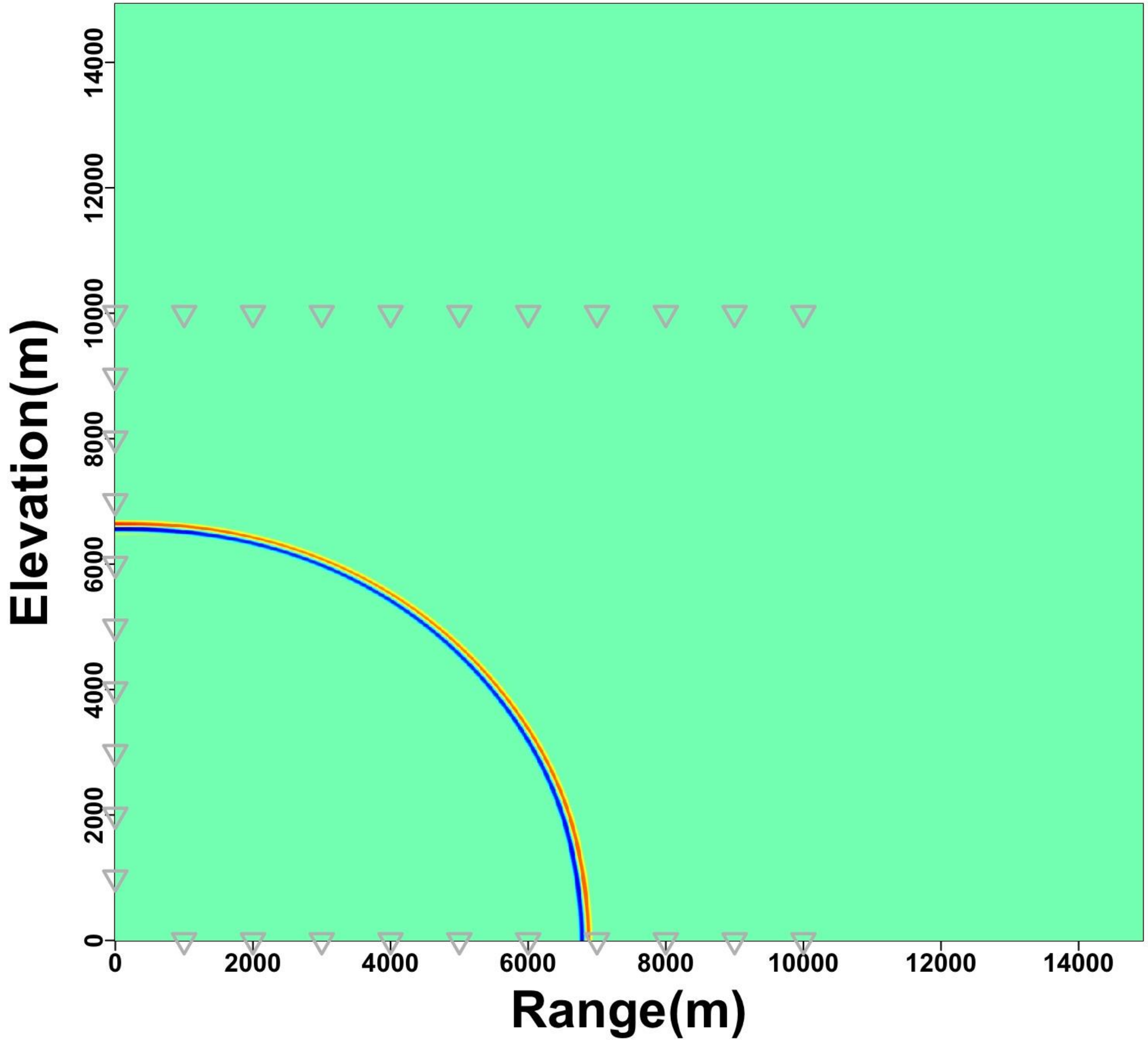




Comparison of 2-D and 3-D Simulations

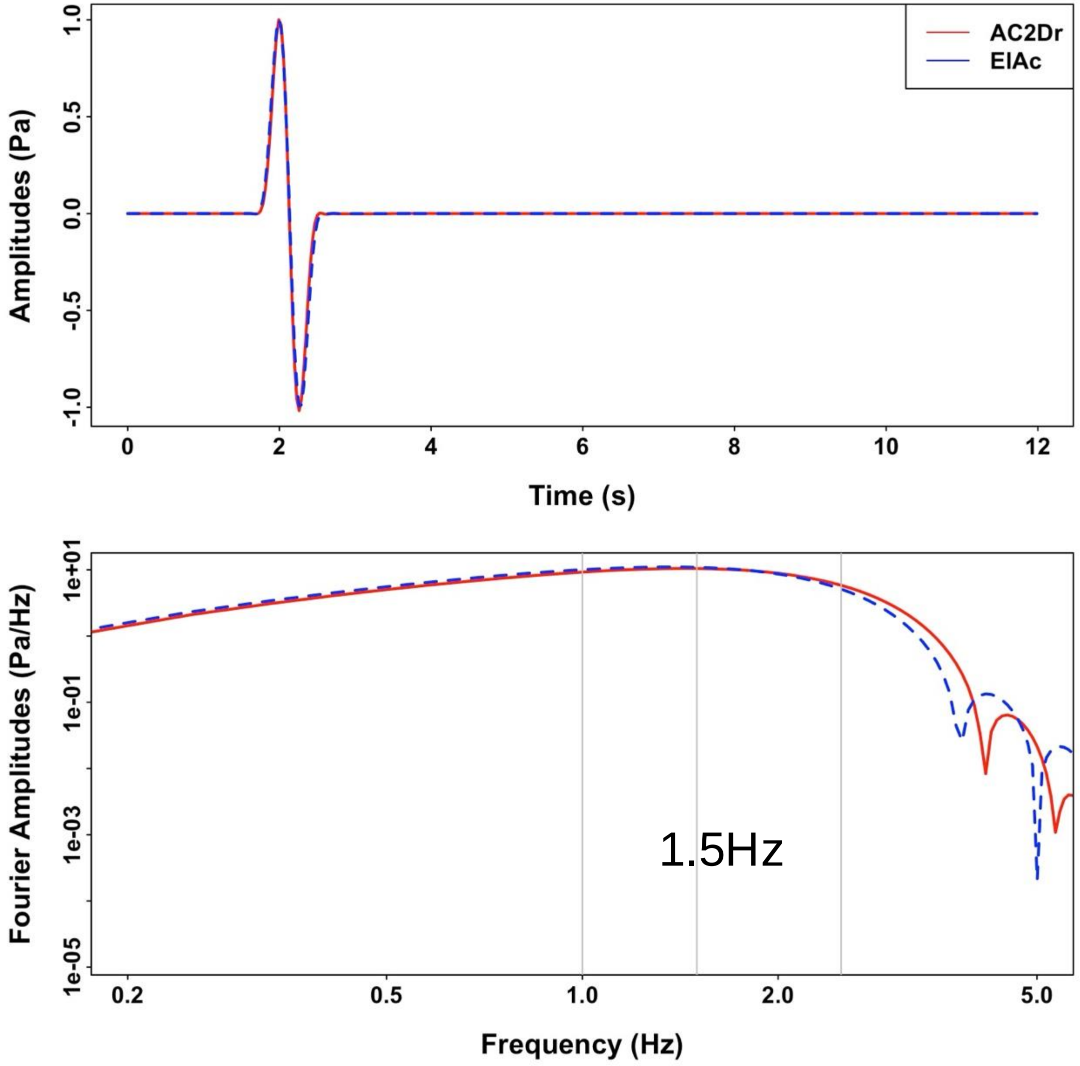
	3-D	2-D
Source Code	ElAc (Cartesian Coord.)	AC2Dr (Spherical Coord)
Spatial Discretinzation	6th order finite difference	6th order finite difference
Temporal Discretization	4th order Runge Kutta	4th order Runge Kutta
Absorbing Boundary	Super-grid	Super-grid

Local Infrasound Propagation



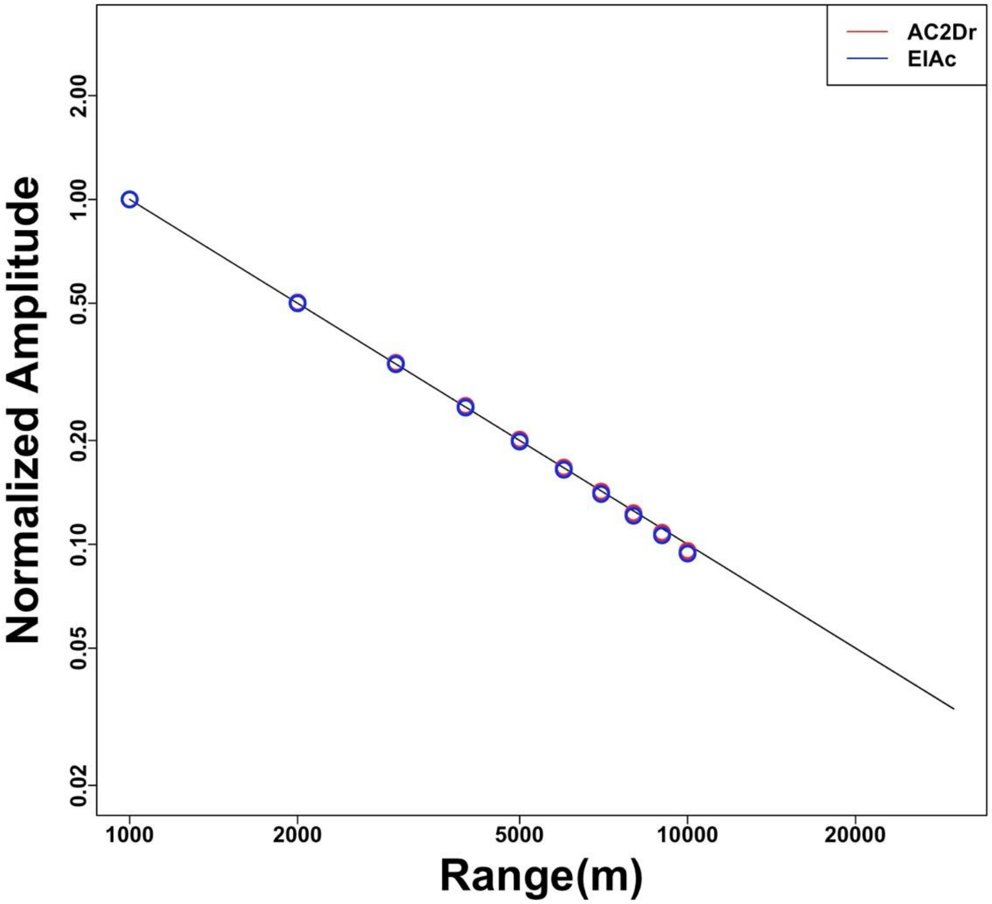
Source Characteristics	Shape	Peak Frequency	Corner Frequency
3-D (ElAc)	Gaussian (point)	1.0 Hz	2.0 Hz
2-D (AC2Dr)	Gaussian (initial field)	1.0 Hz	2.0 Hz

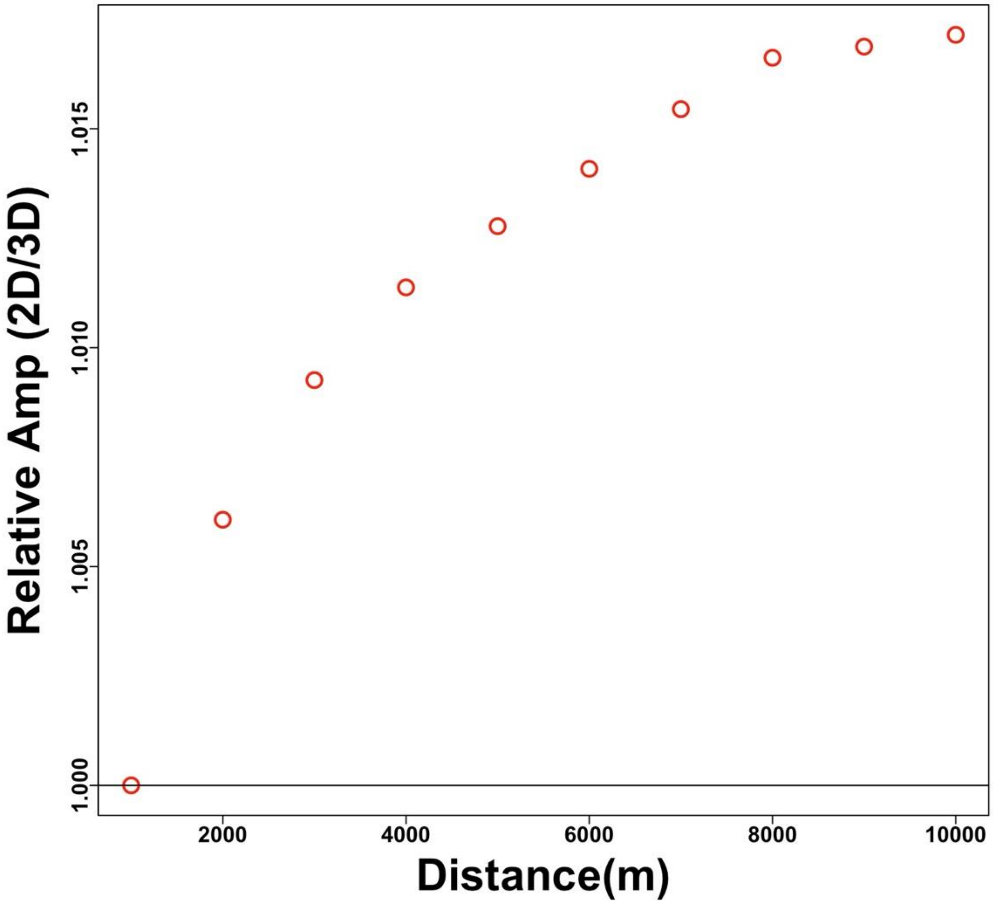
Local Propagation (Artemis)



1km (on the ground)

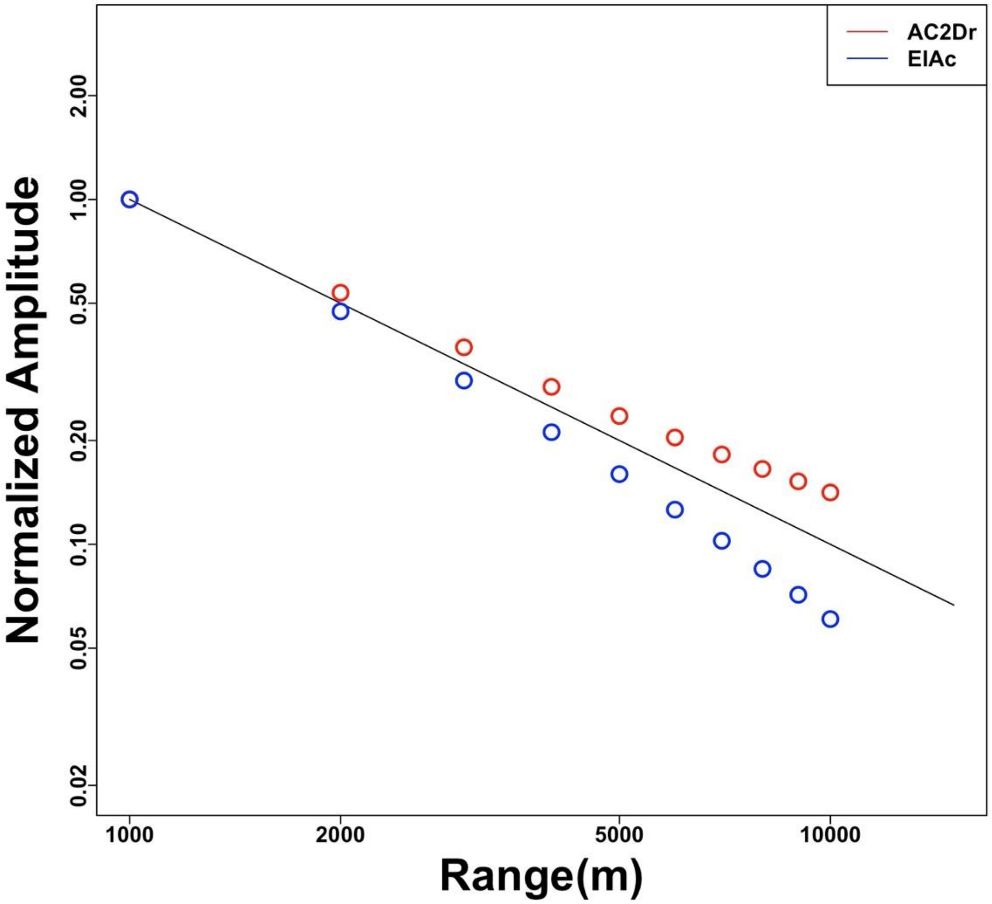
Local Propagation (Artemis)

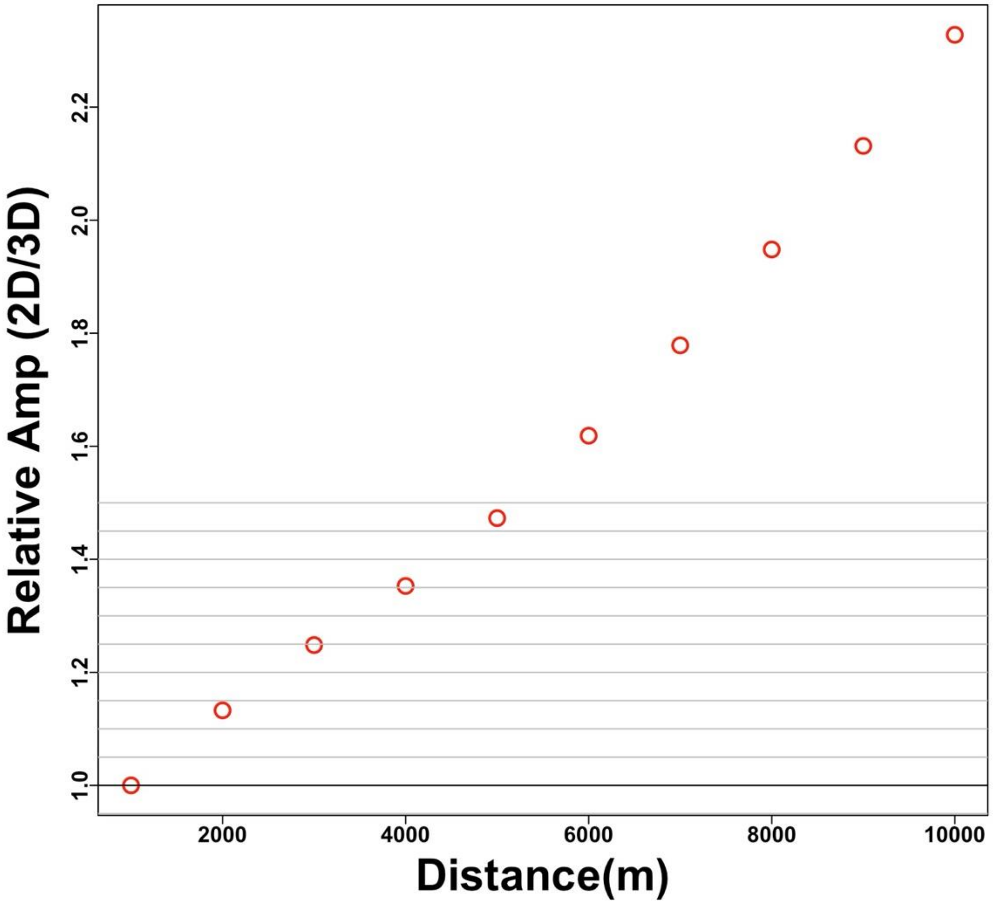




On the ground

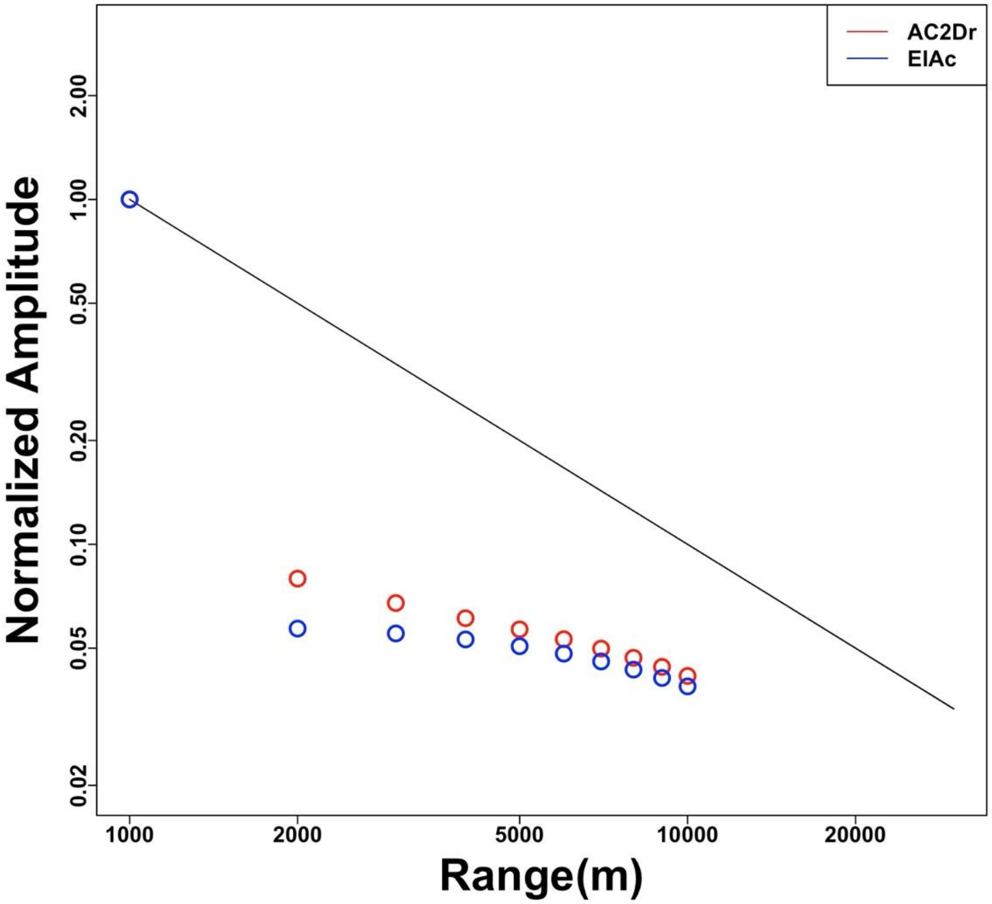
Local Propagation (Artemis)

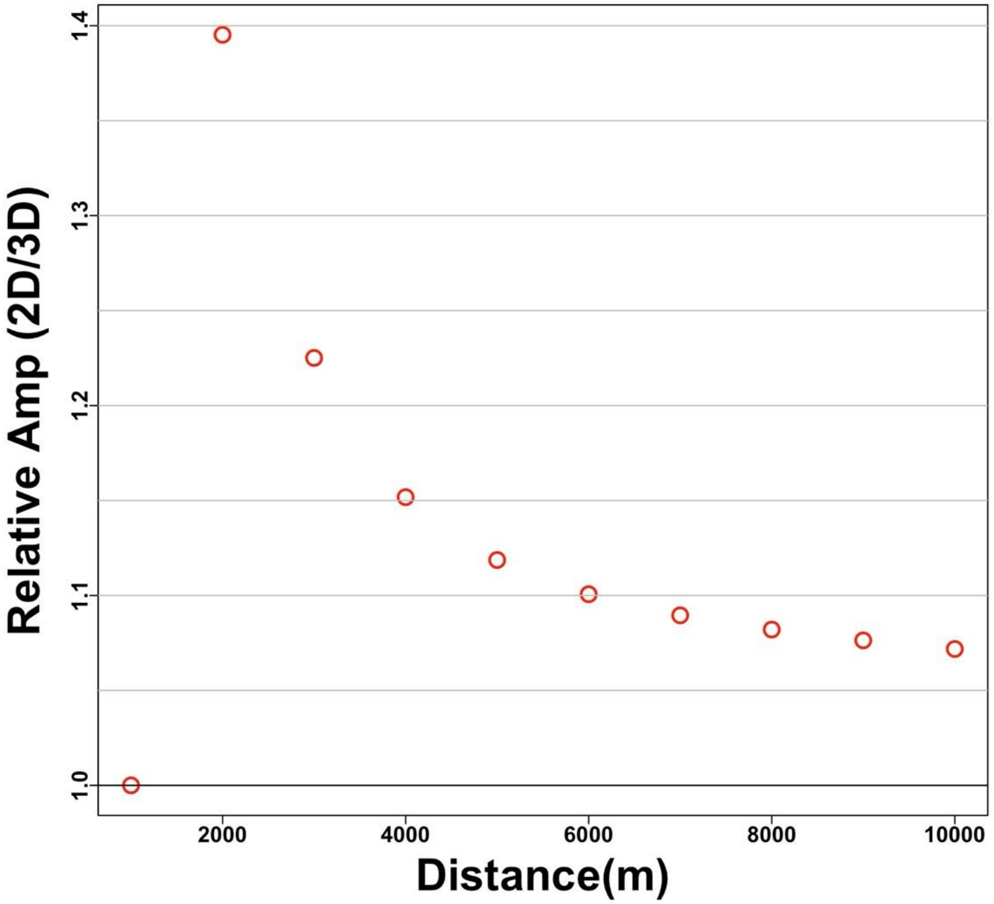




On the symmetric axis

Local Propagation (Artemis)



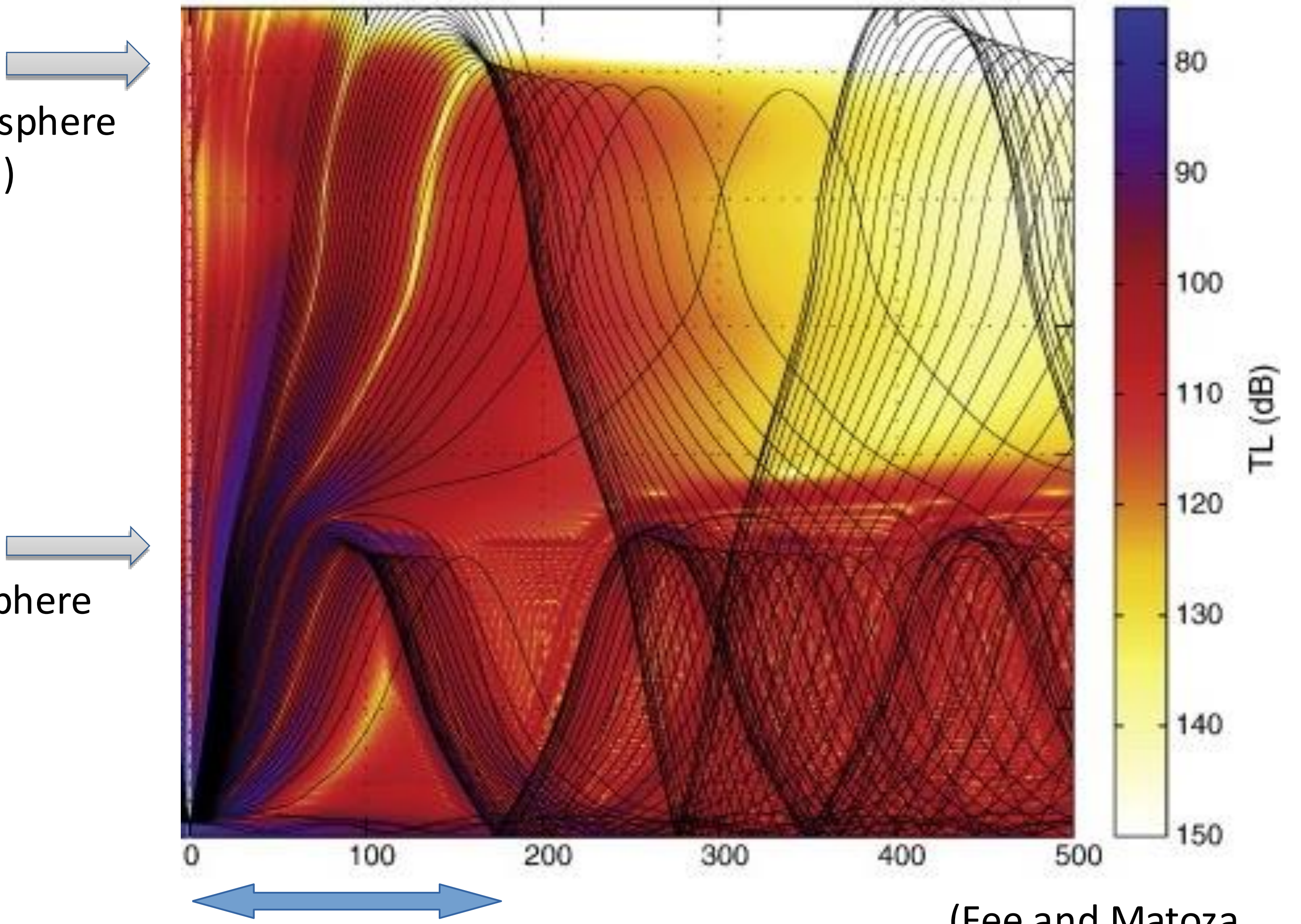


At 10 km elevation

Regional Infrasound Propagation

Thermosphere (120 km)

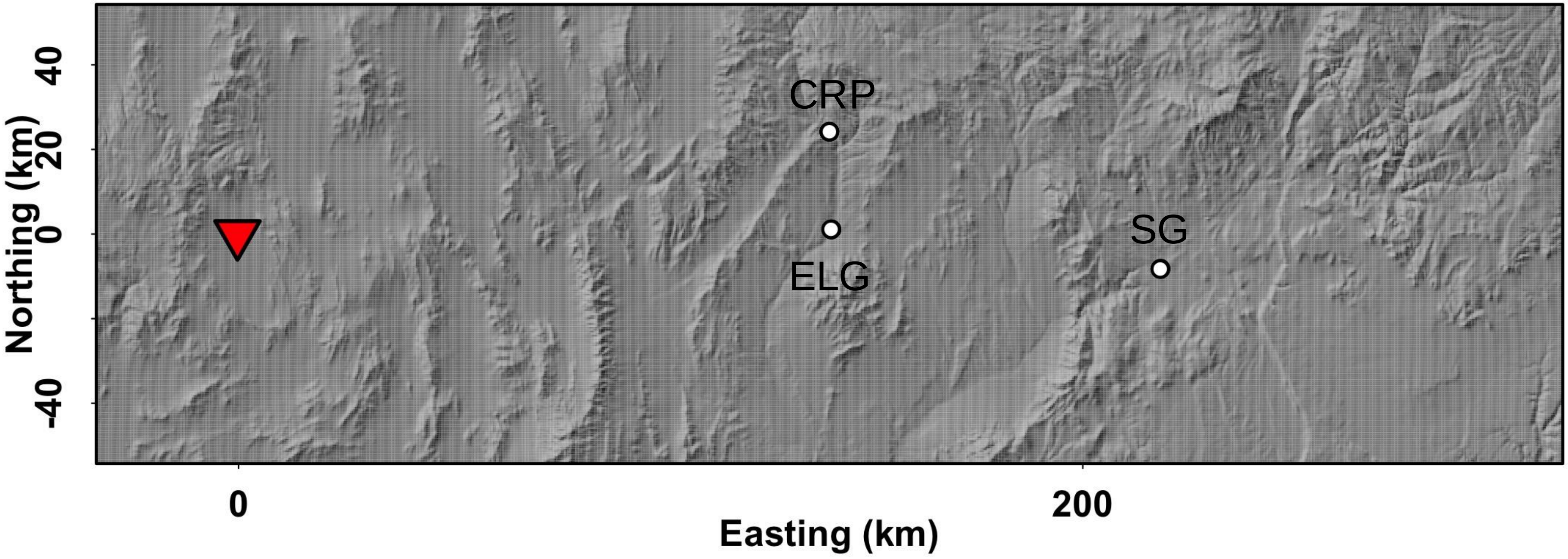
Stratosphere (40 km)



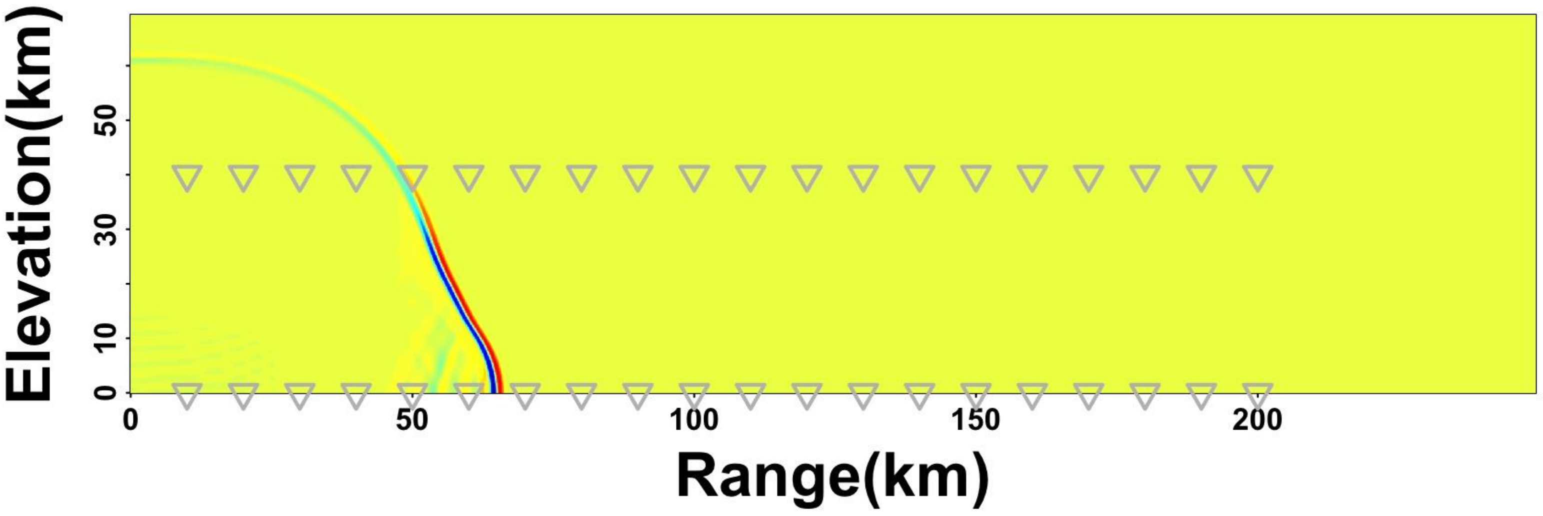
Infrasound shadow zone on the ground

(Fee and Matoza, 2013, JVGR)

Regional Infrasound Stations

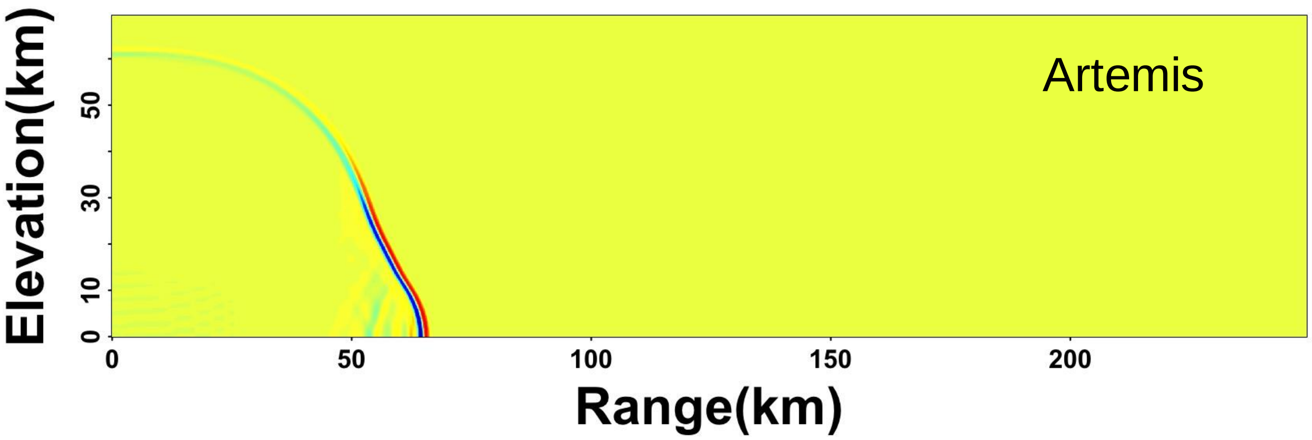


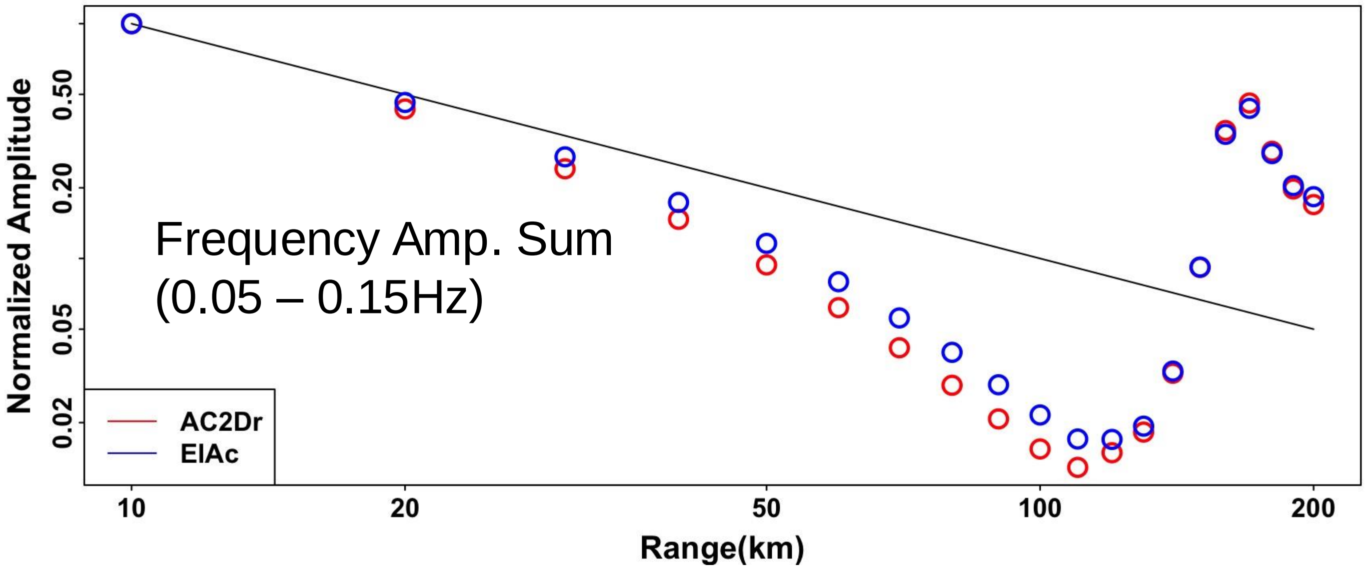
Regional Simulation Comparison



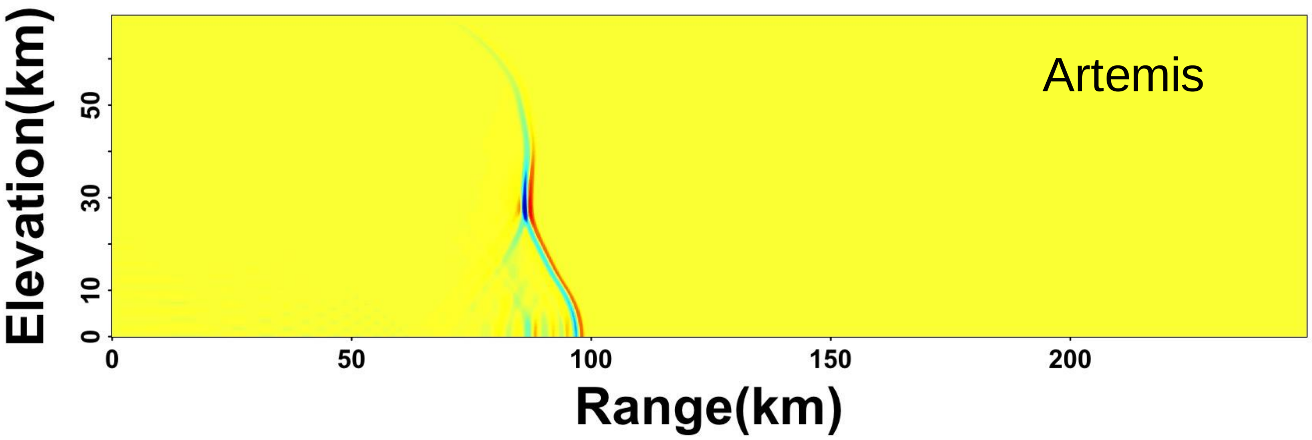
Model Domain	Peak Frequency	Grid Spacing / point-per-wavelength	Speed of Sound	Air Density	Computation Time (CPU hr)
Height: 70 km Radial Distance: 200 km	0.1 Hz	100 m / 10 ppw	1-D profile (MERRA2)	1-D profile (MERRA2)	3D: 22k hr 2D: 8 hr

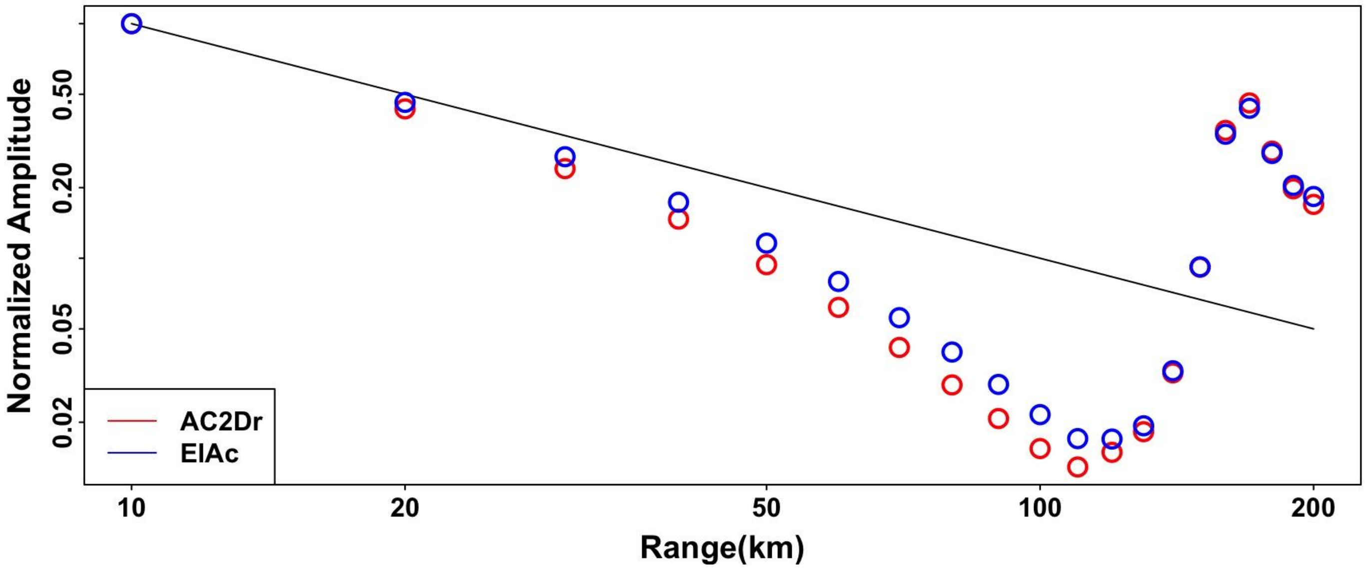
AC2Dr Simulations



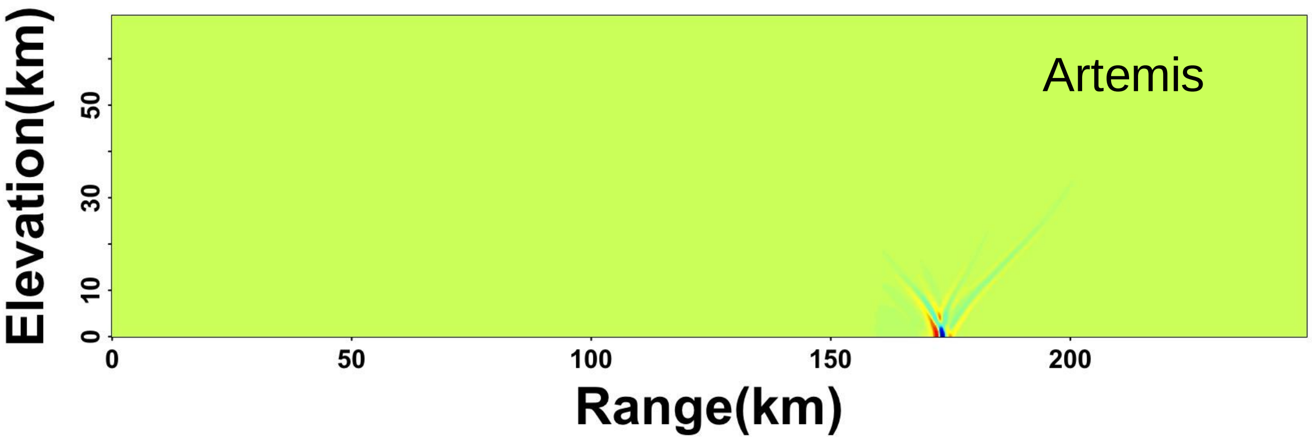


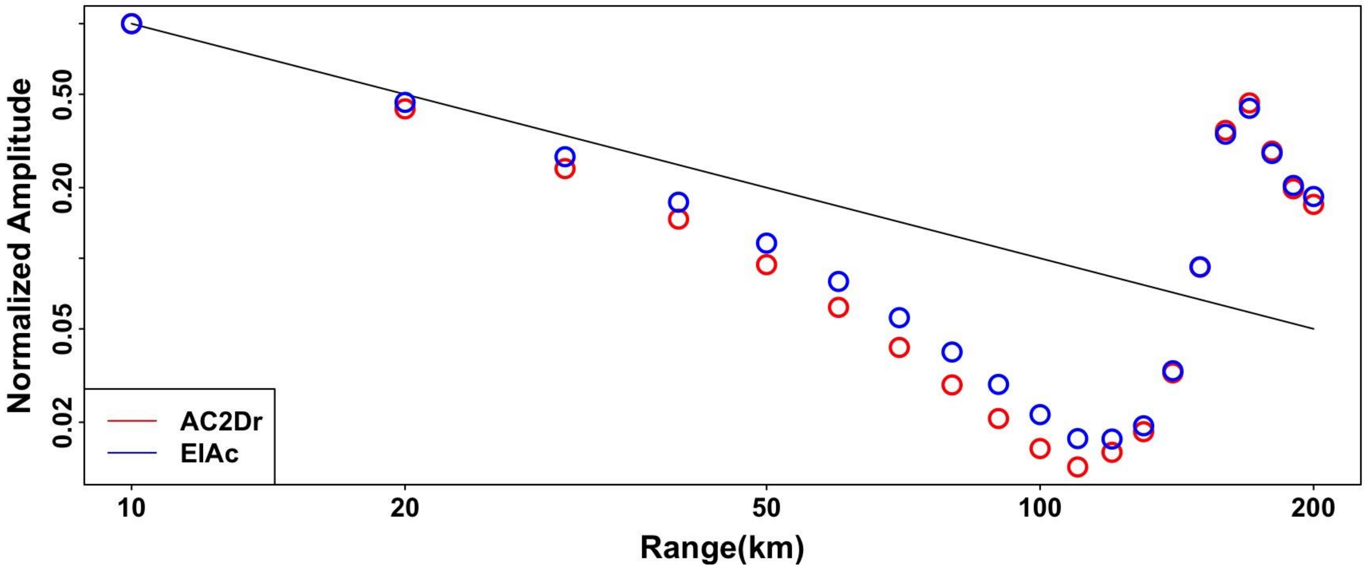
AC2Dr Simulations





AC2Dr Simulations

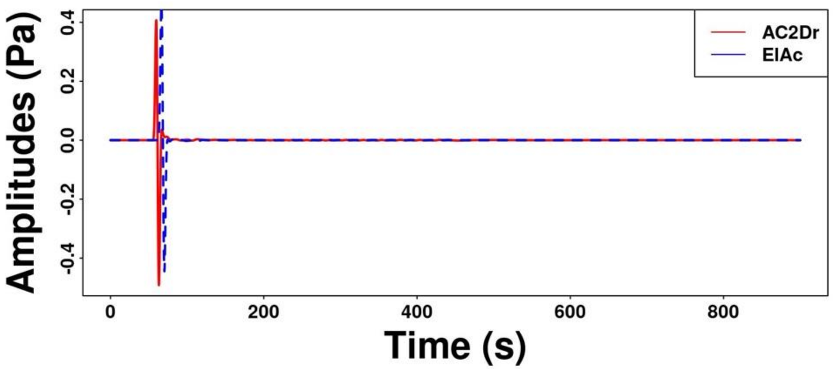


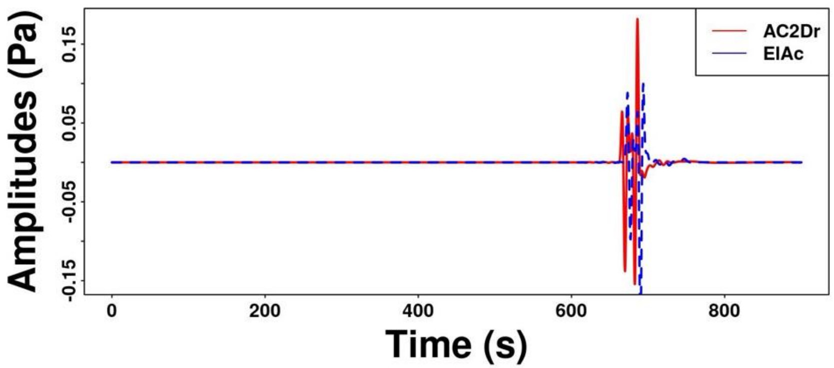


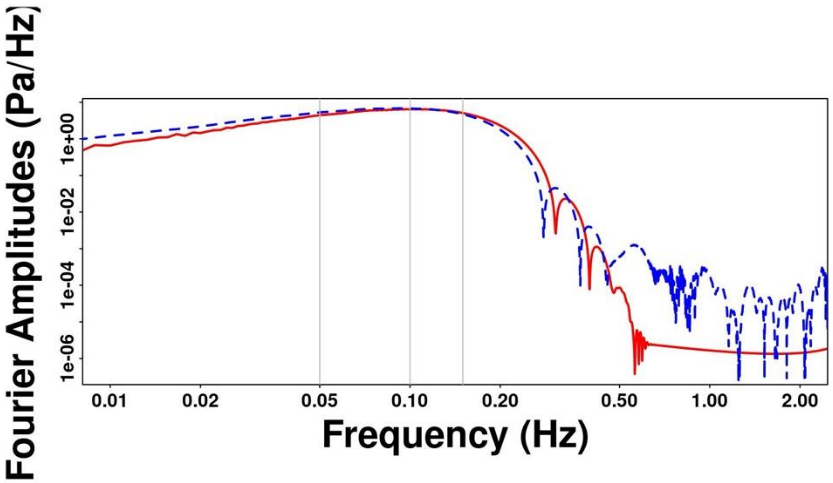
Waveform Comparison (Artemis)

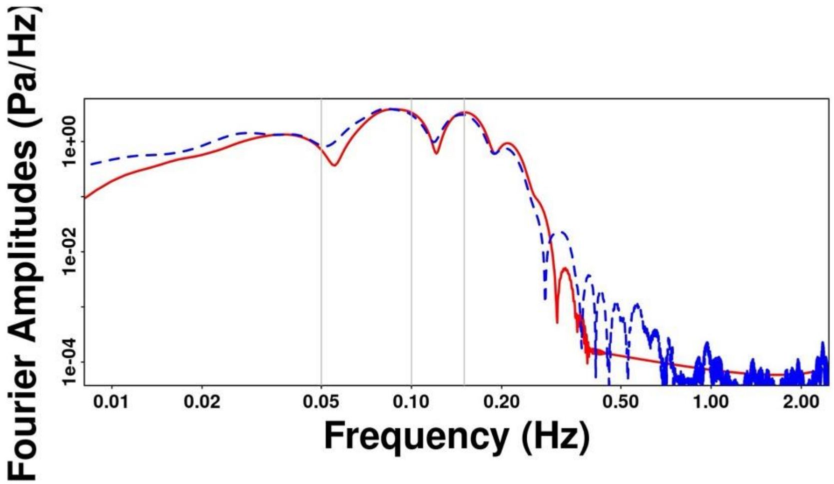
20 km

200 km



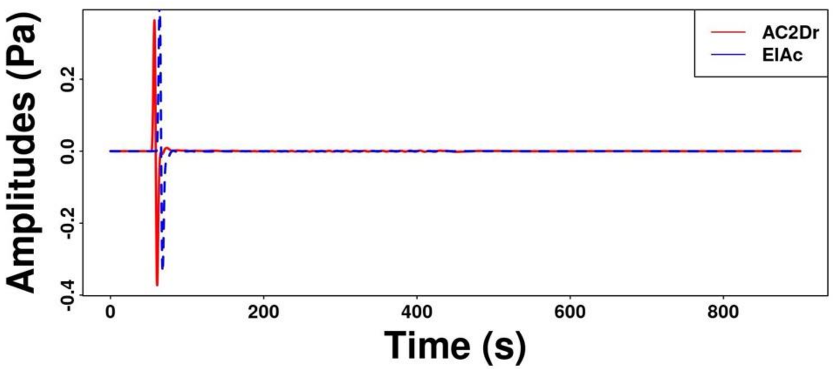


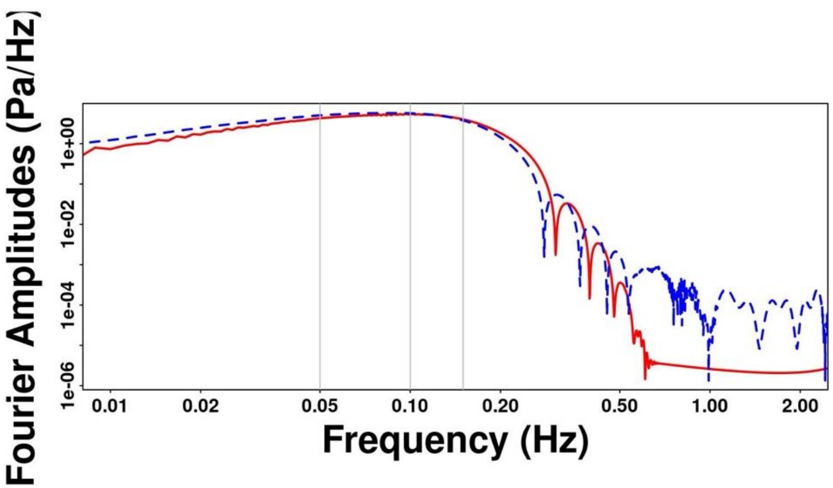




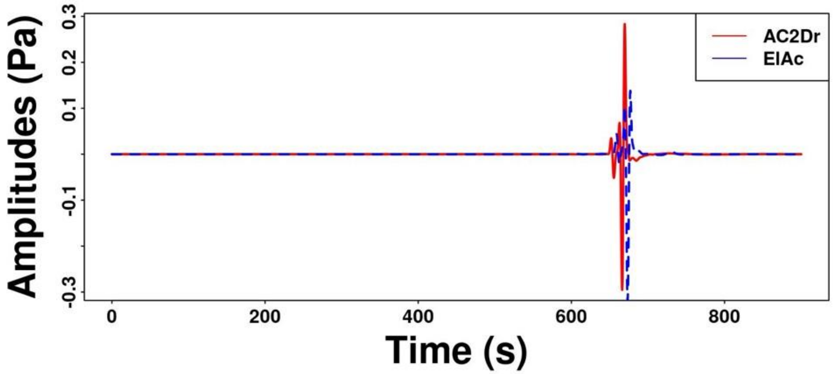
Waveform Comparison (Apollo)

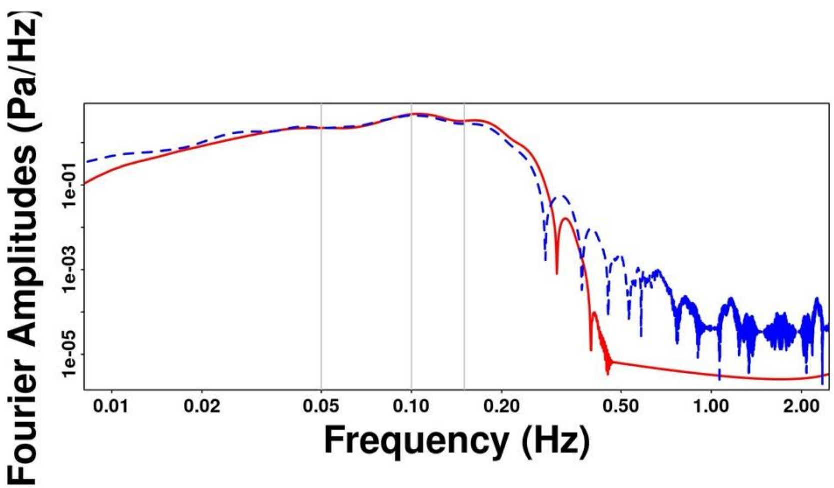
20 km



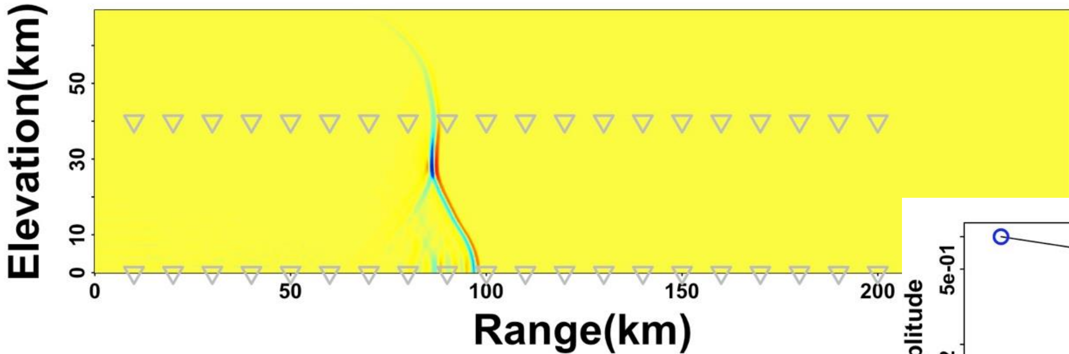


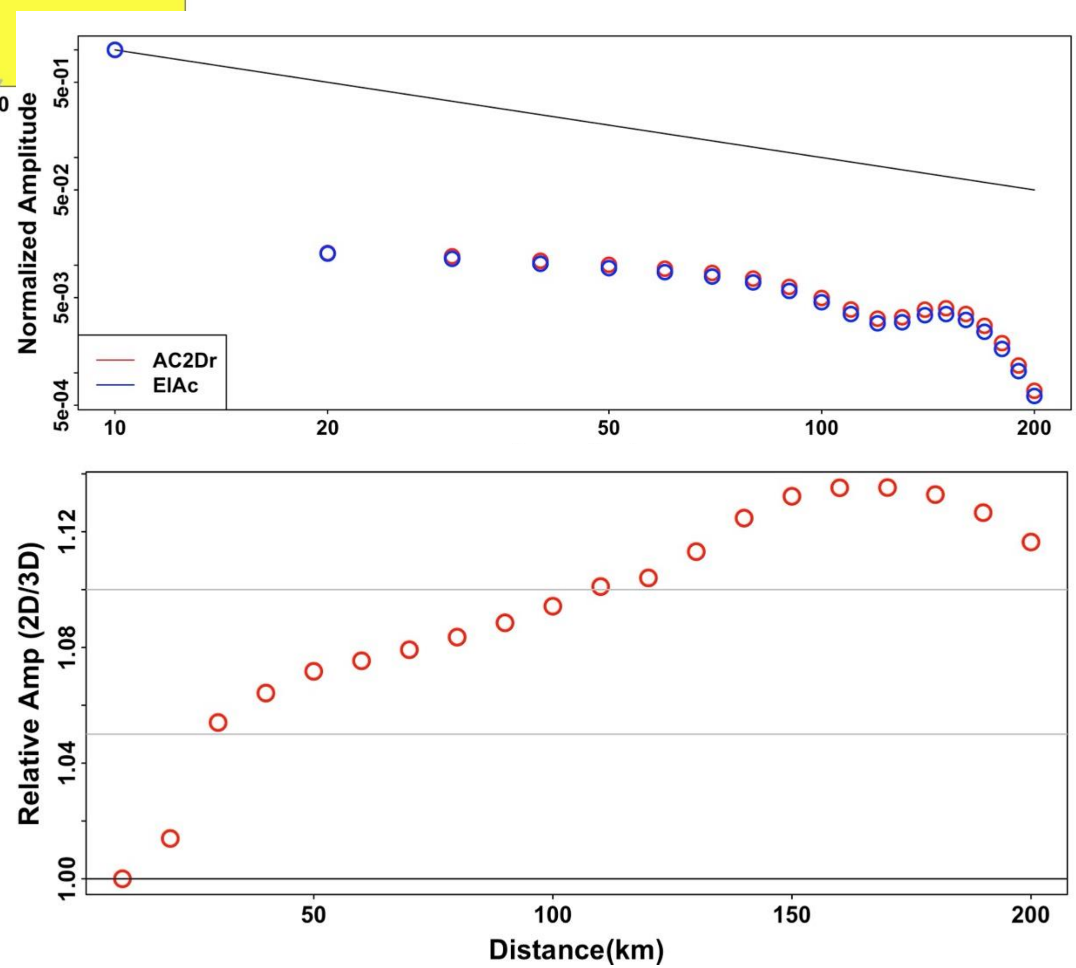
200 km





Amplitudes Comparison within Stratospheric Duct

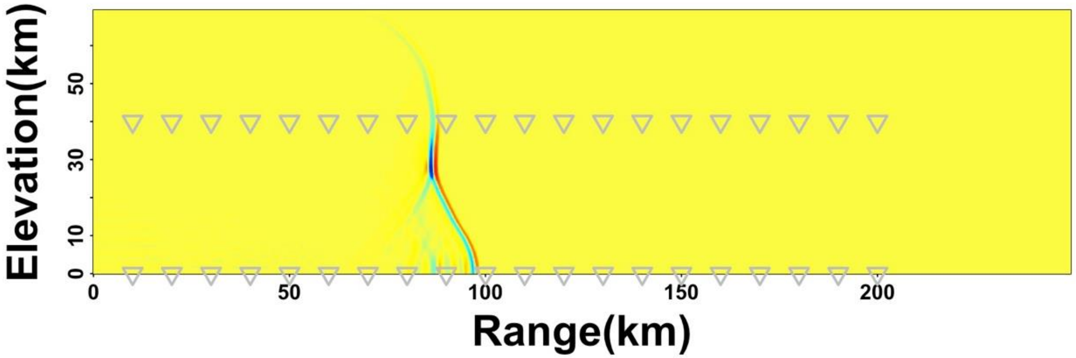




Artemis

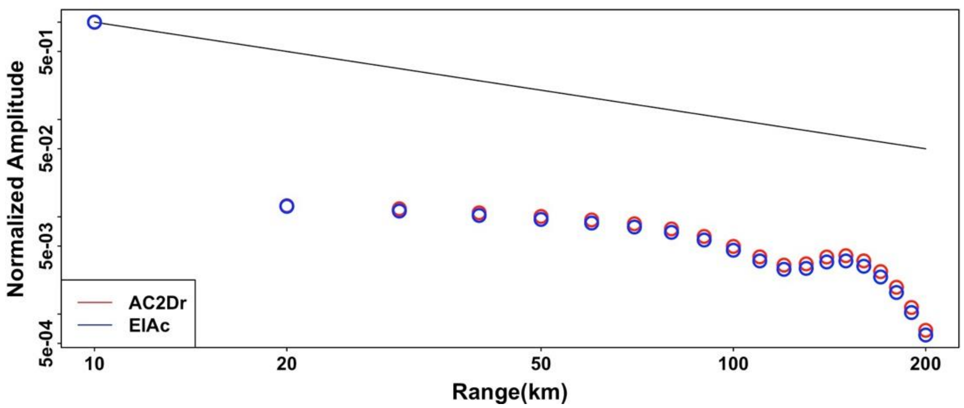
- Acoustic energy (0.05 – 0.15Hz) in the stratospheric duct shows good agreement between 2D and 3D
- Stratospheric return can be represented well by 2D even in longer distances than 200km

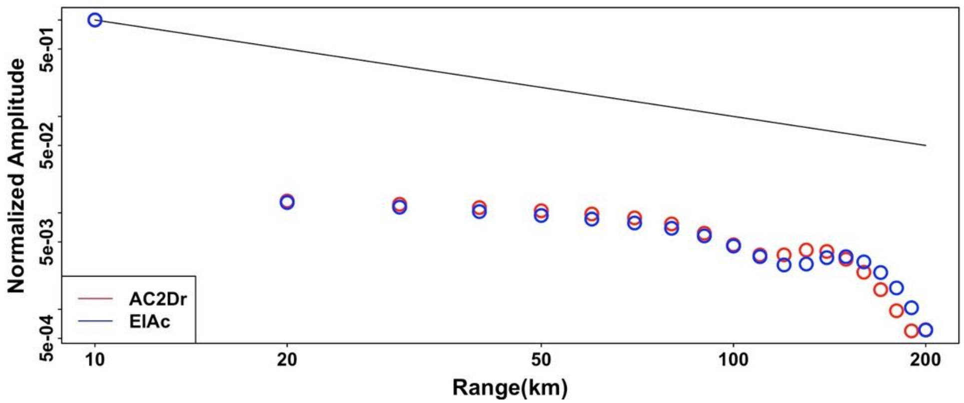
Comparison with Effective Sound Speed (Artemis)



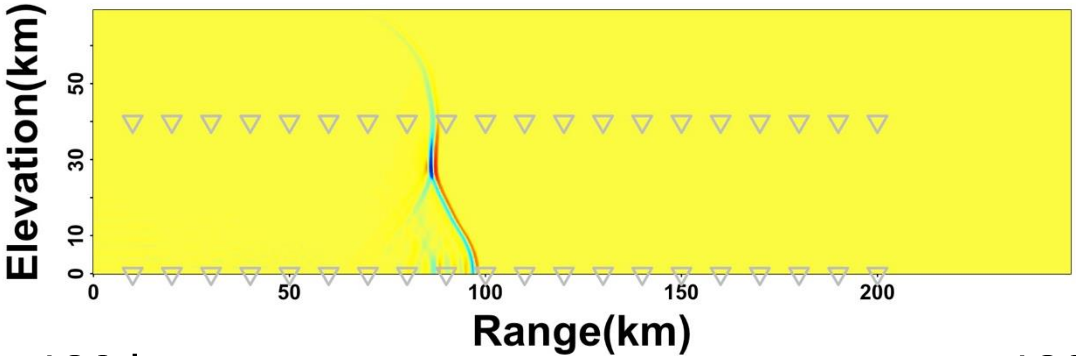
Advective Wind

Effective sound speed / density





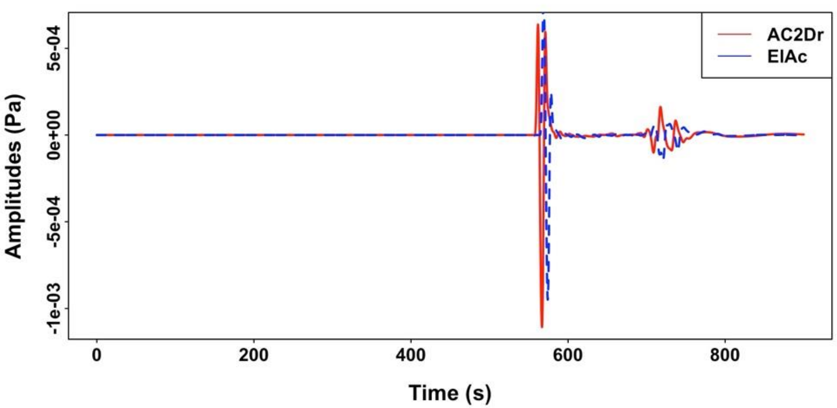
Comparison with Effective Sound Speed (Artemis)

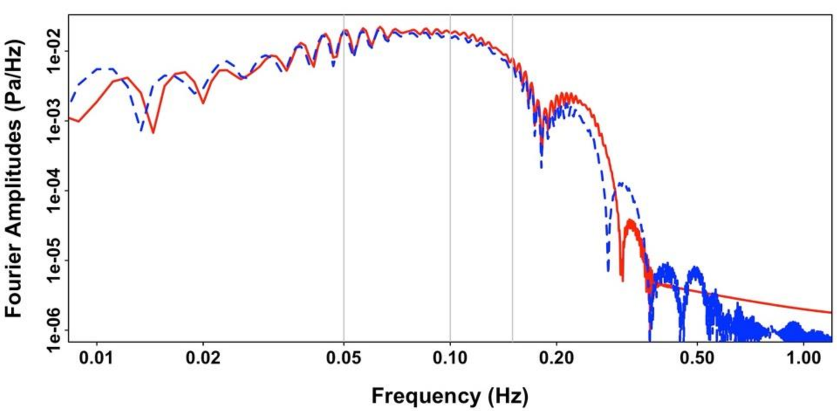


Advective Wind

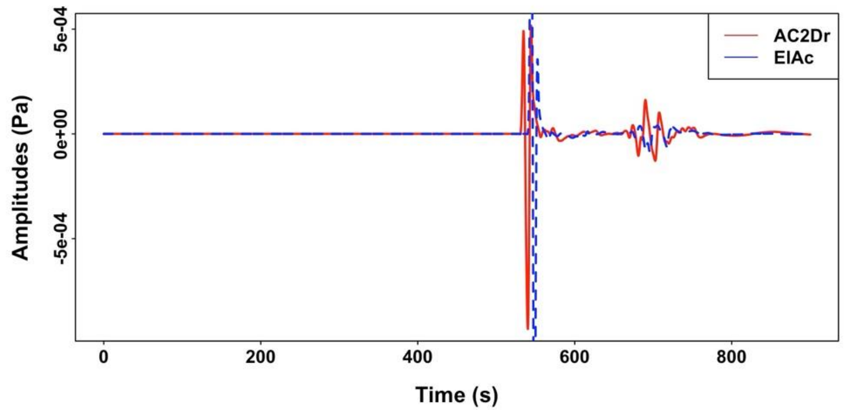
Effective sound speed / density

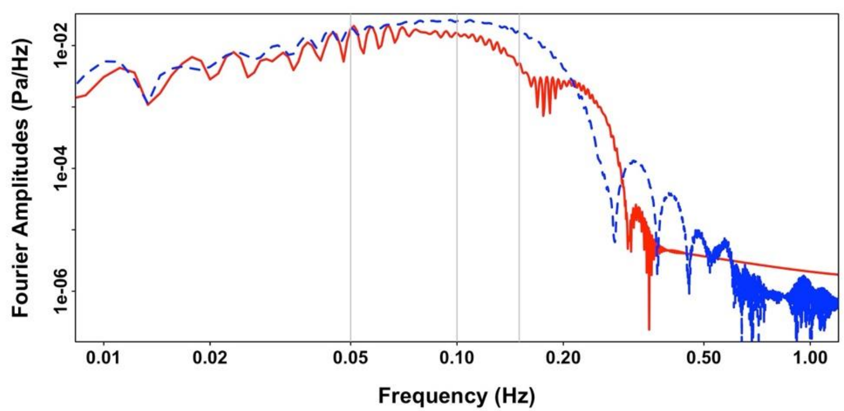
180 km



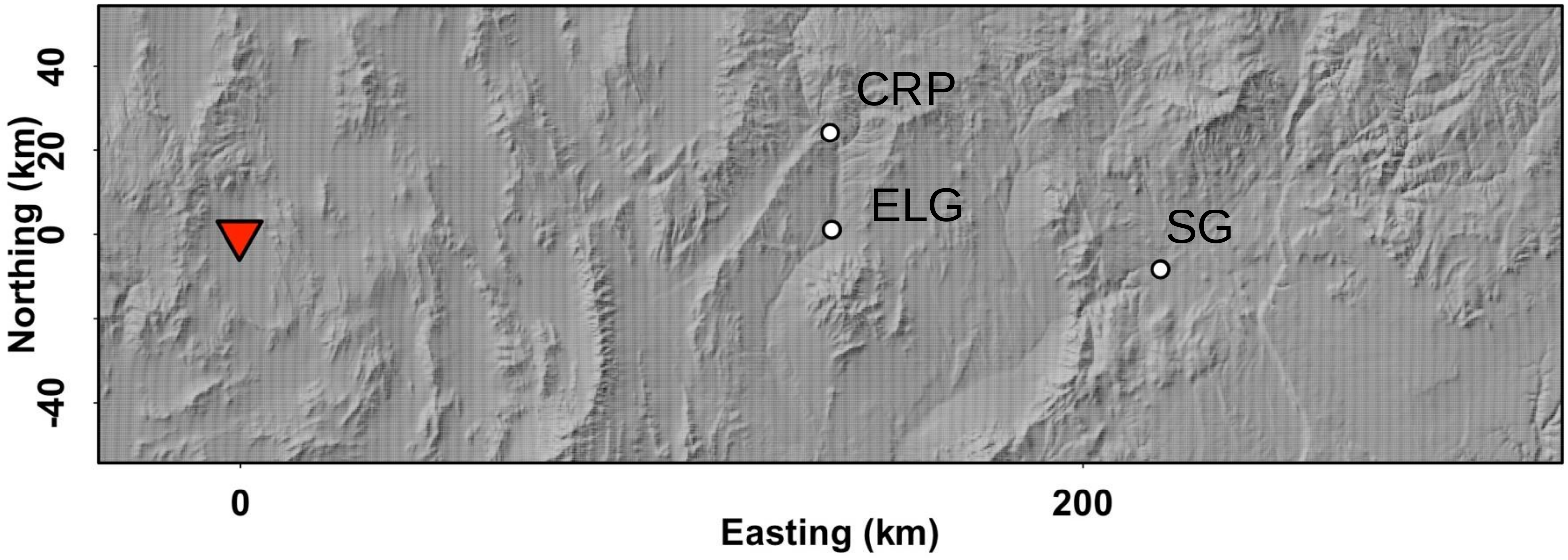


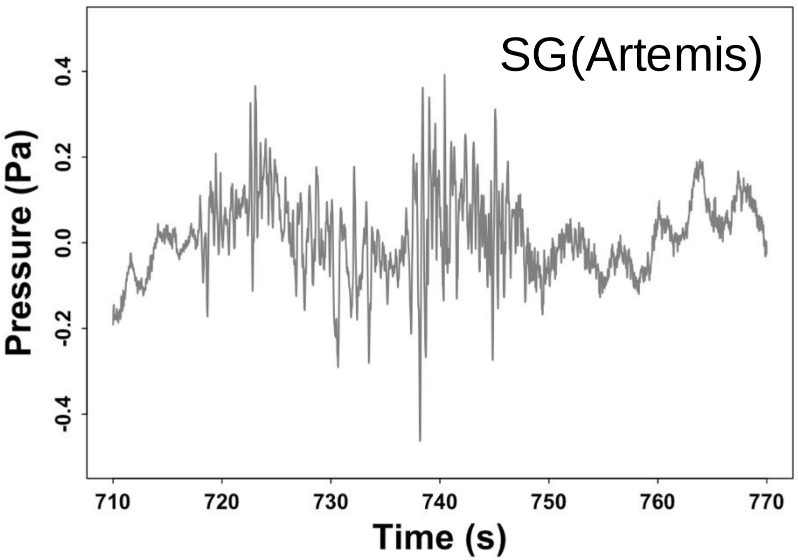
180 km

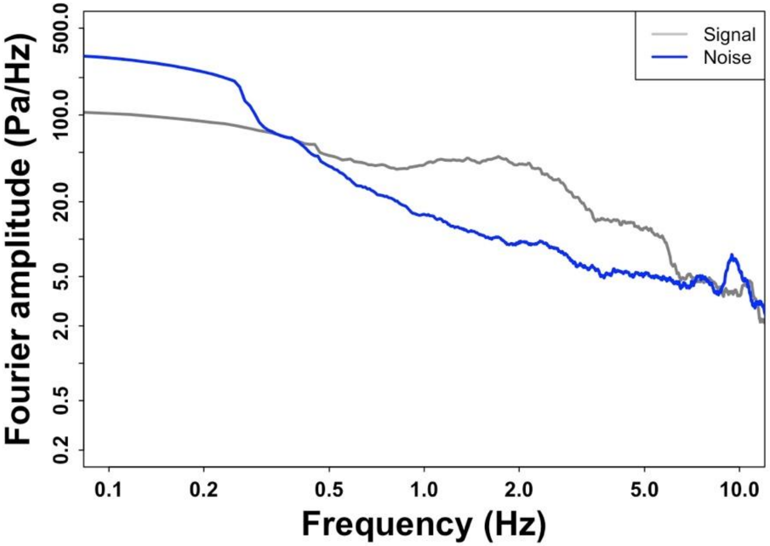




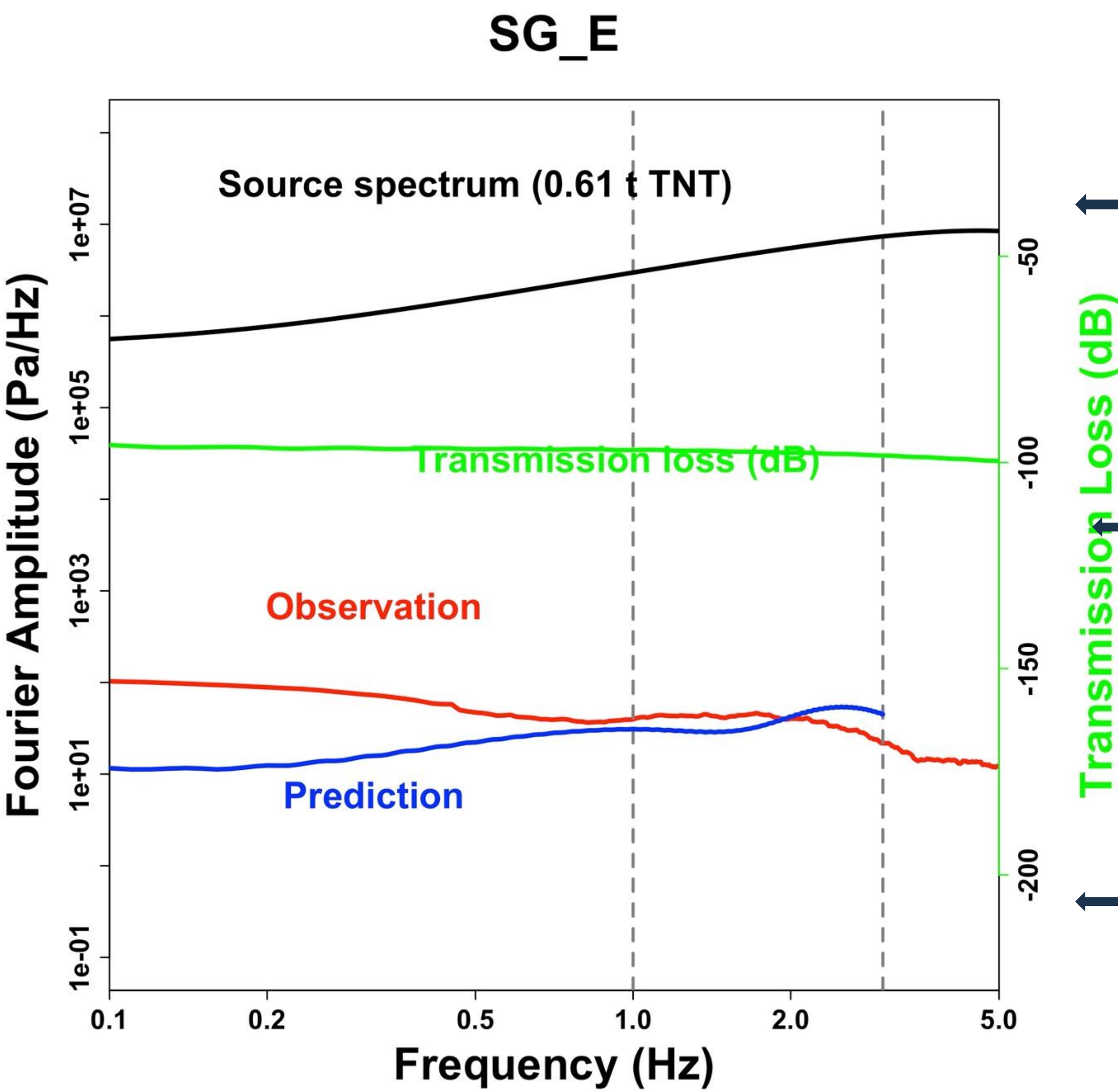
Regional Infrasound Observations

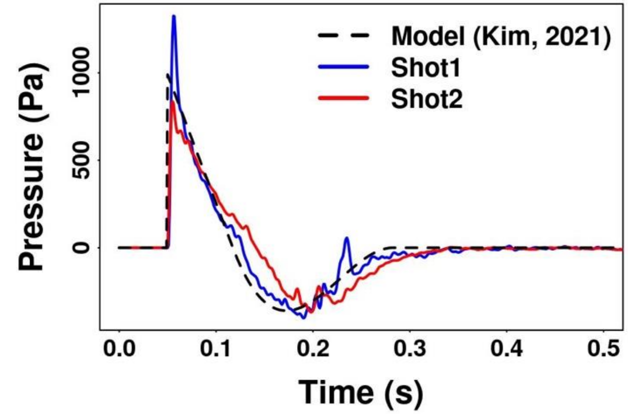


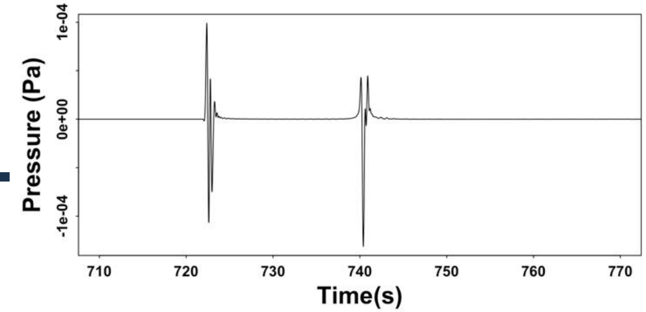


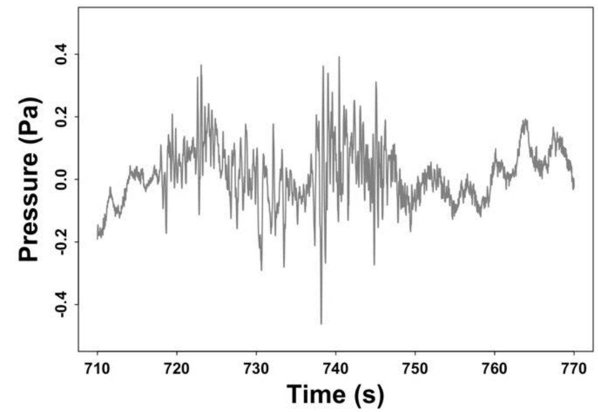


Explosion Yield Estimation (Artemis)

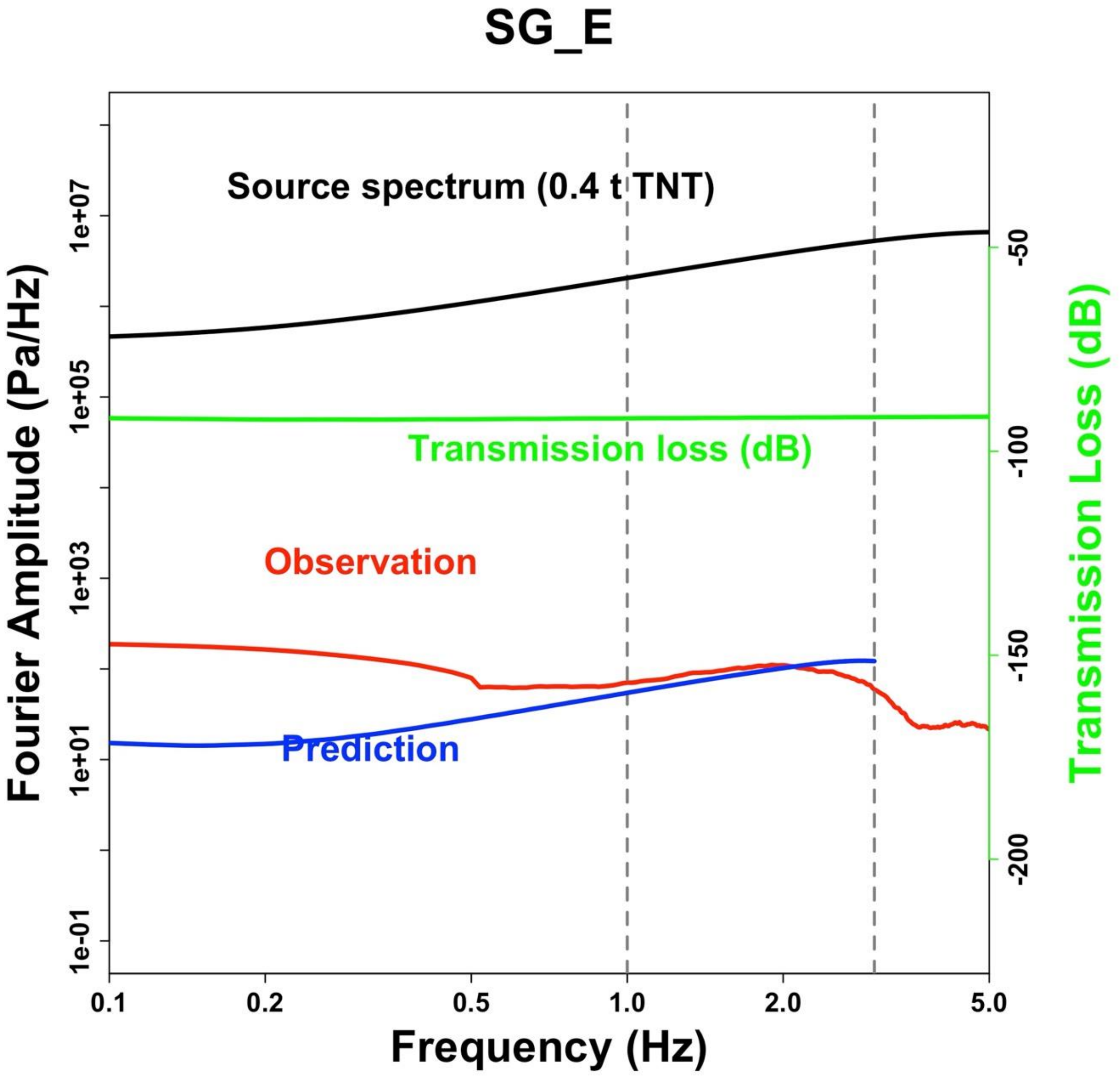






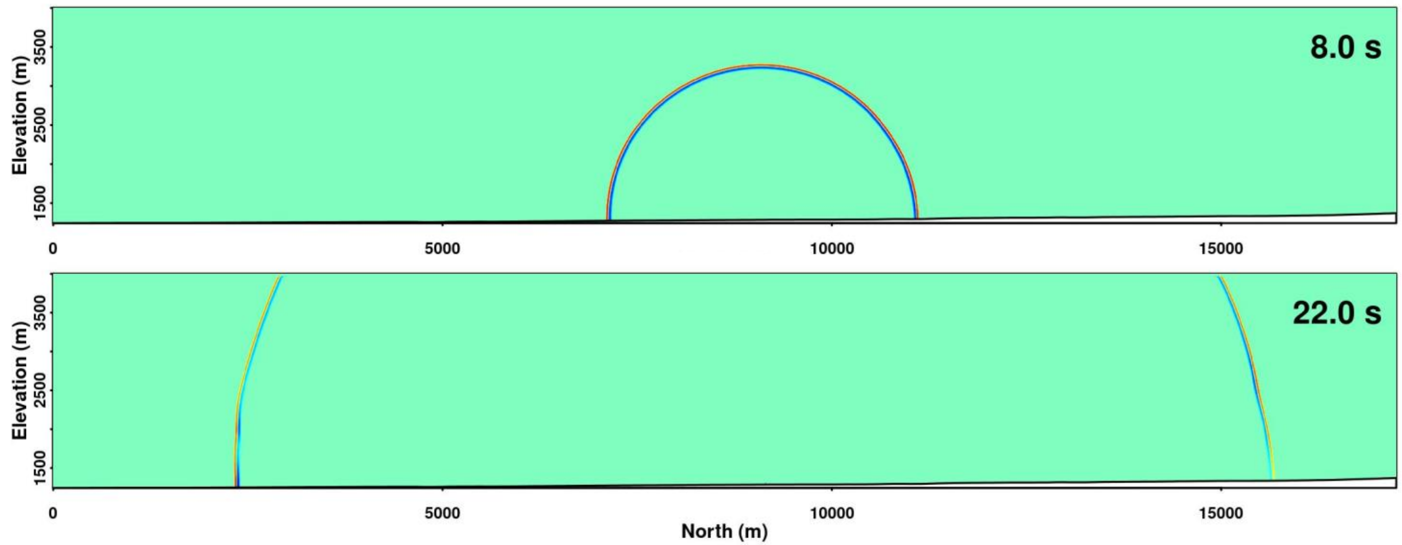


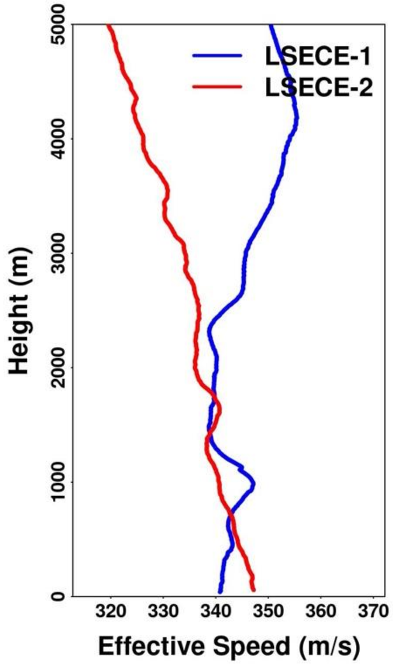
Explosion Yield Estimation (Apollo)



Yield Estimation by Local Infrasound

- Local infrasound prediction with full waveform simulations by finite-difference methods (Kim and Pasyanos, 2022)





- Explosion yields were estimated as

Data	Artemis	Apollo
Local (< 10 km)	1200kg	550kg
Regional (~ 200 km)	610kg	410kg

AC2Dr is available in public repo

- **https://github.com/LLNL/AC2Dr**

Summary

- 2-D Acoustic codes (AC2Dr) in spherical coordinates are developed, and its accuracy is verified by the comparison with full 3-D finite-difference modelings and data.
- Axisymmetric coordinates cannot represent translational wind field near the axis, producing deformed wavefield along the axis.
- However, laterally propagating waves and resultant stratospheric waveguides can be reasonably approximated by the 2-D approach.

References

Kim, K., & Pasyanos, M. E. (2022). Yield Estimation of the August 2020 Beirut Explosion by Using Physics-Based Propagation Simulations of Regional Infrasound. Geophysical Research Letters, e2022GL101118

Kim, K., & Pasyanos, M. E. (2023). Seismoacoustic explosion yield and depth estimation: Insights from the large surface explosion coupling experiment. *Bulletin of the Seismological Society of America*, *113*(4), 1457-1470.

Blom, P. (2023). Regional infrasonic observations from surface explosions–influence of atmospheric variations and realistic terrain. *Geophysical Journal International*, *235*(1), 200-215.