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A Synthetic Study to Determine Adequate Infrasound Network Configurations for Resolving Source Directionality

Alexandra M. Iezzi, Robin S. Matoza, David Fee, and Keehoon Kim

Poster No. P1.1-264

POSTER

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ABSTRACT

Sources including volcanic eruptions and buried explosions have been shown to produce directional infrasound radiation. However, infrasound sensor deployments generally consist of instruments placed on the Earth's surface. Therefore, directional sampling of the radiated acoustic wavefield (especially at angles close to vertical incidence) is generally limited. This insufficient wavefield sampling may bias source size estimates, including mass flow rate for volcanic eruptions or explosion yield.

Here we conduct a synthetic study with local infrasound sensors placed around a directional acoustic explosion source to investigate the configuration of infrasound sensors required to uniquely recover a directional source mechanism estimate. We use finite-difference time-domain methods incorporating rigid topography to obtain the numerical Green's functions for each synthetic station. We invert these synthetics to determine if the prescribed directional source mechanism and source-time function can be retrieved for a variety of station configurations. We consider the influences of environmental factors (wind, temperature, noise), as well as the directionality strength and orientation. The optimal sensor configurations to best estimate acoustic directionality found in this synthetic study will help guide future deployment configurations around active volcanoes and anthropogenic explosions.

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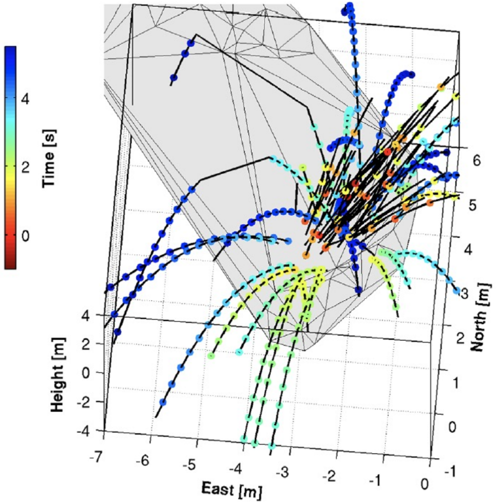
INTRODUCTION

- Sources including volcanic eruptions and buried explosions have been shown to produce directional infrasound radiation patterns
- Insufficient wavefield sampling (particularly in the vertical direction) of directional infrasound sources may bias source size estimates, including mass flow rate for volcanic eruptions or explosion yield for anthropogenic explosions
- Studying volcanic explosions can further the CTBT mission by improving the accuracy of infrasonic source characterization, which ultimately aids with validation of propagation modeling methods

3D reconstruction of ballistic trajectory during a volcanic explosion



[Gaudin et al., 2016]

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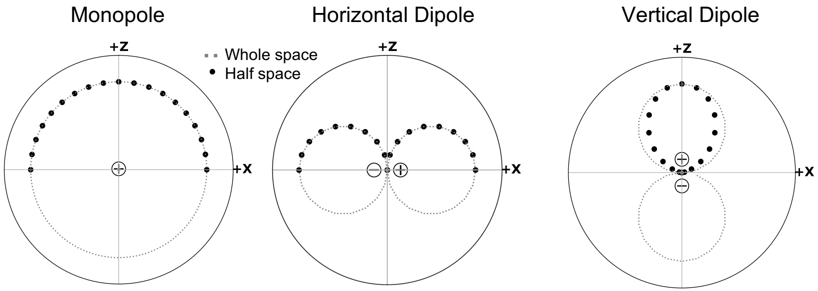
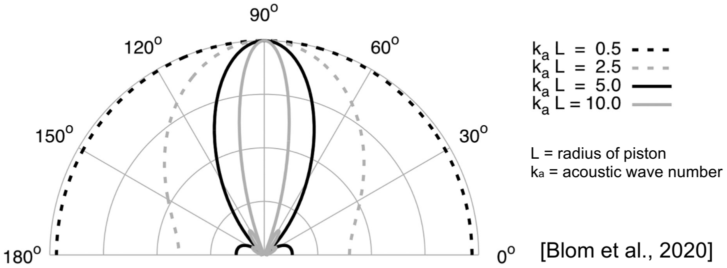
INTRODUCTION

- Acoustic waveform inversion has become a popular method for constraining the mass flow rate or yield of an explosion (monopole), as well as the potential directionality (represented by a dipole force in three dimensions)
- However, the cautions and limitations of applying these methods to complex sources and their ability to resolve the solution have not been investigated in detail
- In this study, we perform acoustic waveform inversions for a variety of idealized and realistic deployment scenarios and systematically vary the number and configuration of stations, degree of directionality, and noise level to investigate their impact on the ability to recover the input monopole and dipole source functions

Sub-Aerial Explosion Infrasound Radiation Patterns:



Buried Explosion Infrasound Radiation Pattern:
Rigid Piston



[Blom et al., 2020]

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METHODS

Waveform Modeling

- Finite-Difference Time-Domain (FDTD) following the methods of Kim and Lees [2014]
  - Grid-based differential numerical method that computes pressure and particle velocity in the time domain across topography
- FDTD yields the 3-D Green's functions resulting from a monopole (mass flow rate) and dipole force (Fx, Fy, and Fz) sources
- Synthetic data are created by the linear combination of Green's functions at a given station (each component can be scaled)

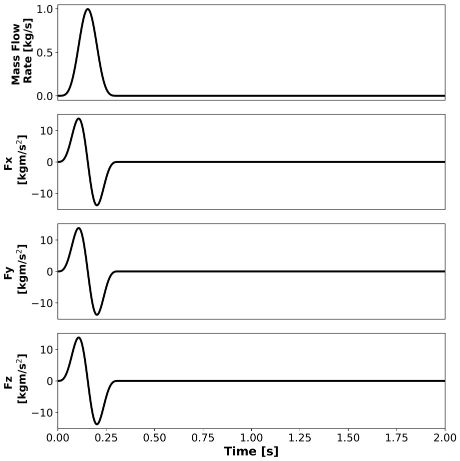
Input simple source time functions

Monopole

Dipole (x-component)

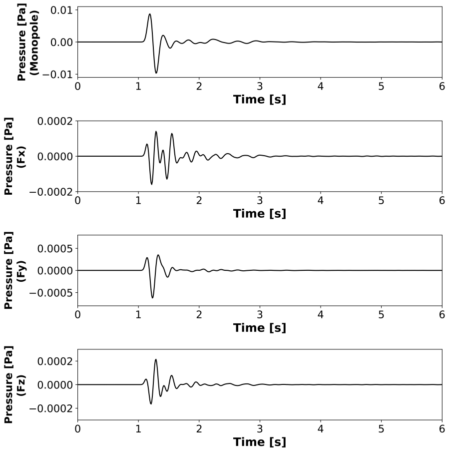
Dipole (y-component)

Dipole (z-component)

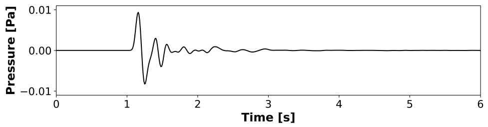


FDTD Waveform Modeling Across Topography

Output Green's functions for an example station



Synthetic data for an example station



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METHODS

Acoustic Source Inversions

- The Green's functions and synthetic data are used to invert for the source time functions for a variety of scenarios to determine if the input source functions can be resolved
- Linearized waveform inversion for the monopole [Kim et al., 2015] and multipole [Iezzi et al., 2019] sources

Monopole-Only

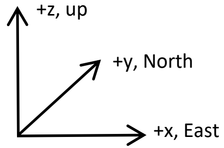
$$[G]\,[\dot{S}] = \mathbf{Gm} = \mathbf{d}$$

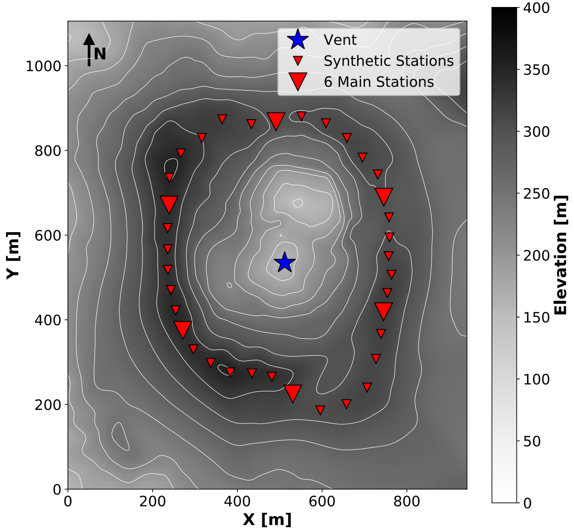
Multipole (Monopole + Dipole)

$$\underbrace{\begin{bmatrix} G & D_x & D_y & D_z \end{bmatrix}}_{\text{Green's functions that account for 3D topography}} \underbrace{\begin{bmatrix} \dot{S} \\ F_x \\ F_y \\ F_z \end{bmatrix}}_{\text{Source terms that we solve for}} = \mathbf{Gm} = \underbrace{\mathbf{d}}_{\text{Synthetic data}}$$

- The solution ***m*** is solved for by minimizing the waveform misfit (*R*, residual) using the iterative solver LSQR [Paige and Saunders, 1982]

$$R = \frac{(\mathbf{d}-\mathbf{Gm})^T(\mathbf{d}-\mathbf{Gm})}{\mathbf{d}^T\mathbf{d}}$$





Synthetic station map with example topography of Yasur volcano, Vanuatu (contour interval 25 m)

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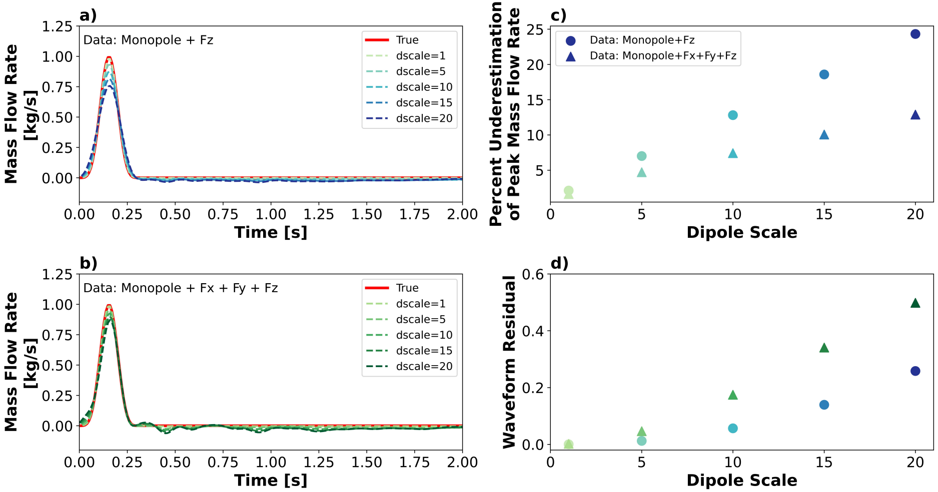
RESULTS

Ideal Inversions (No Noise):

Monopole Inversions with Increasing Data Dipole Strength

- We perform inversions for the monopole-only source but use data created from a directional source for increasing degree of directionality (dipole scale)
- Source Type Inverted For:
  - Monopole-only
- Data Type Used:
  - 6 stations spaced equally in azimuth around the source
  - Panel a) Monopole + Fz
  - Panel b) Monopole + Fx + Fy + Fz



Results and Interpretations:

- The peak mass flow rate of the inversion solution decreases for increasing dipole strength relative to the monopole (panels a and b)
- The mass flow rate inversion solution for data created from the monopole and vertical-only dipole has a higher percent underestimation of the peak mass flow rate relative to the inversions where data are created using all three dipole components (panel c)
- The waveform residual increases with increasing dipole strength for both scenarios (panel d)
  - For data created using monopole and vertical only dipole force, the residual remains under 0.10 for dipole scales less than 10 (~100 kg m/s^2 compared with 1 kg/s)

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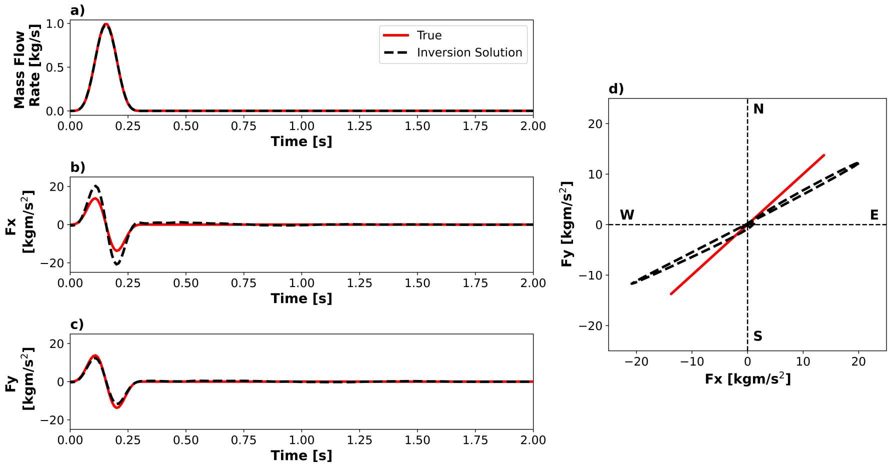
RESULTS

Ideal Inversions (No Noise):

Monopole and Horizontal Dipole Inversions

- We perform inversions for the monopole and horizontal dipole components, but use data created from multipole data
- Source Type Inverted For :
  - Monopole + Fx + Fy
- Data Type Used:
  - 6 stations spaced equally in azimuth around the source
  - Monopole + Fx + Fy + Fz



Results and Interpretations:

- A dipole solution with the correct azimuth quadrant can be obtained, but the amplitude and exact direction of the dipole may not be correct if there is a substantial vertical dipole (Fz) component
- The mass flow rate (panel a) and Fy components (panel c) are recovered well for this example, however, the peak Fx (panel b) is overestimated by 47.4%, yielding a dipole azimuth of 58.6°, a 13.6° deviation from true (panel d)
- Caution is advised when performing multipole acoustic inversions using only sensors placed on the ground surface, even if only the horizontal dipole source components are used in the inversion

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RESULTS

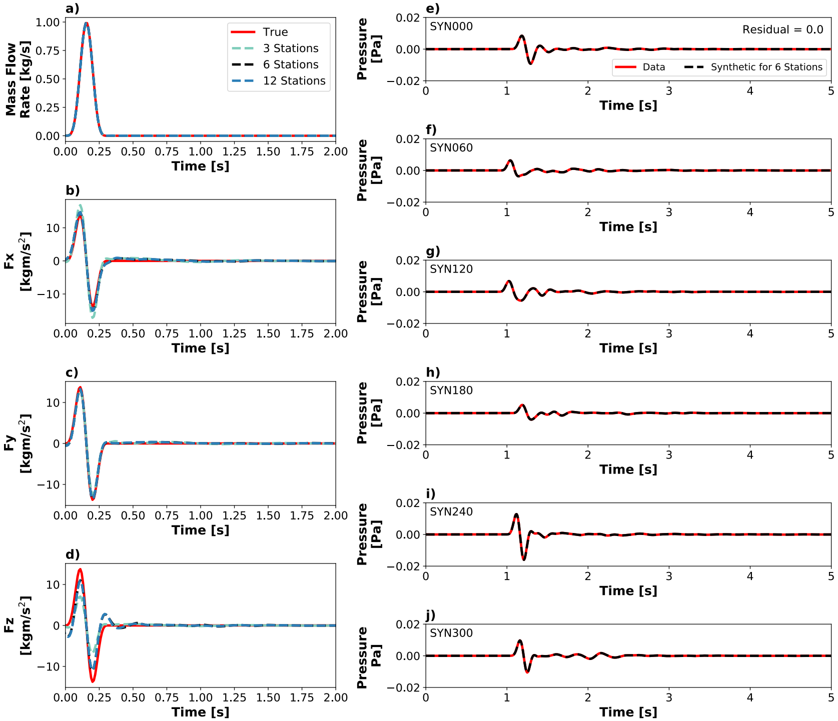
Ideal Inversions (No Noise):

Multipole Inversions with Increasing Number of Stations

- We perform inversions for an increasing number of stations (3 to 12) located on the ground
- Source Type Inverted For :
  - Monopole + Fx + Fy + Fz
- Data Type Used:
  - 3-12 stations spaced equally in azimuth around the source
  - Monopole + Fx + Fy + Fz

Results and Interpretations:

- The mass flow rate solution vector (panel a) can be resolved regardless of the number of stations around the source
- The dipole solution vectors (panels b-d) are not fully resolved even in the absence of noise with up to 12 stations
- The vertical dipole component is the most difficult to resolve due to sensors being placed on the ground (panel d)
- While the data can be fit perfectly with a residual of 0.0 for the inversion with 6 stations (panels e-j), the correct solution (panels a-d) may not be recovered due to the inversion being ill-posed



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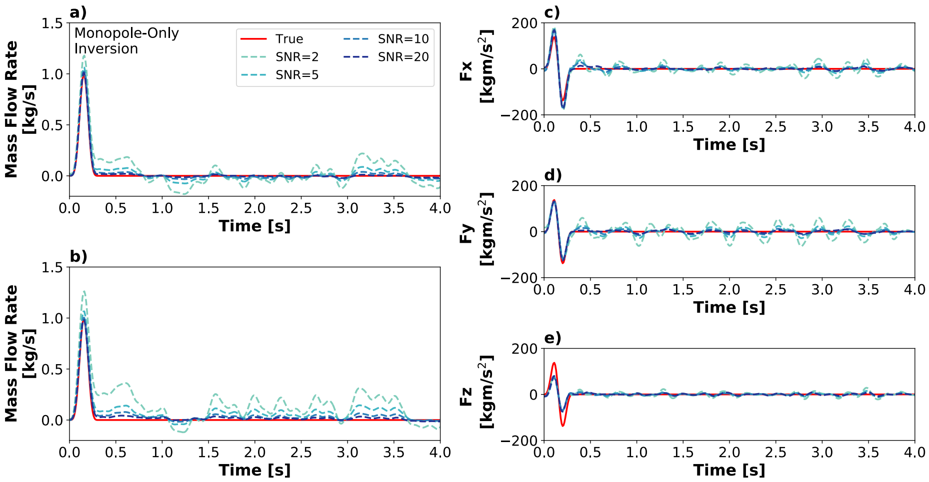
RESULTS

Realistic Scenarios:
Add Noise to the Data

- We perform inversions for an increasing signal to noise ratio (SNR) added to the data prior to inversion
- Source Type Inverted For :
  - Panel a) Monopole-only
  - Panels b-e) Monopole + Fx + Fy + Fz
- Data Type Used:
  - 6 stations spaced equally in azimuth around the source
  - Panel a) Monopole-only
  - Panels b-e) Monopole + Fx + Fy + Fz



Results and Interpretations:

- Inversions that include data with a SNR of 5 or greater produce reasonable source solutions for both the monopole-only (panel a) and multipole inversions (panels b-d), with the exception of the vertical dipole component (panel e)
- The source vector inversion solutions for all components approach the true source vectors for increasing SNR (panels b-d), with the exception of the vertical dipole component (panel e)

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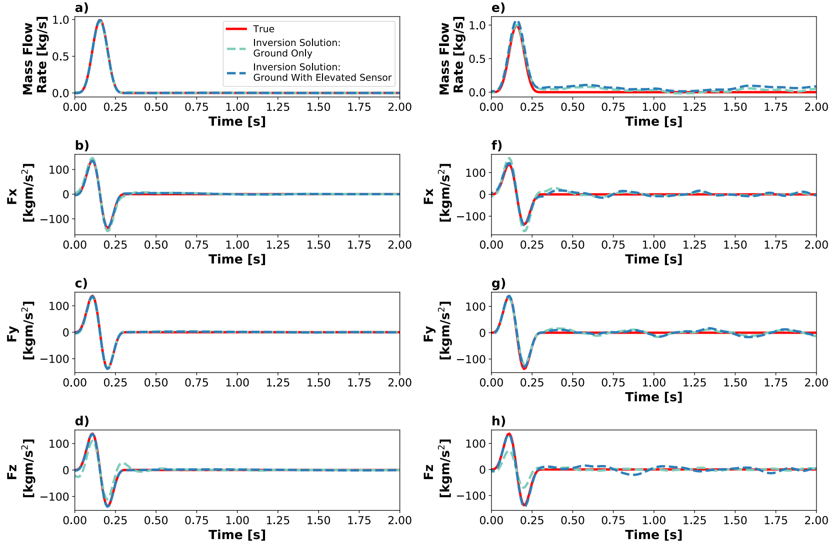
RESULTS

Enhanced Vertical Coverage:

Include a Sensor Floated Above the Source

- We perform inversions using stations on the ground only (light blue) and including a station floated above the source (dark blue) with (right) and without (left) noise added to the data prior to inversion
- Source Type Inverted For :
  - Monopole + Fx + Fy + Fz
- Data Type Used:
  - 6 stations spaced equally in azimuth around the source (+1 floated above the source)
  - Monopole + Fx + Fy + Fz



Results and Interpretations:

- No noise (panels a-d): We find that adding a single elevated station directly above the source to the 6 stations placed on the crater rim allows for all four multipole source vectors to be resolved, including the vertical dipole component
- Noise with SNR of 10 added to the data (panels e-h): The multipole source vectors for the initial explosion (0-0.3 s) can be resolved, however, the true solution is not fully resolved as there are minor fluctuations in all four solution source vectors after 0.3s

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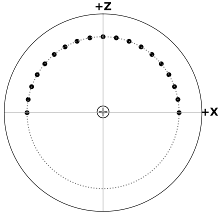
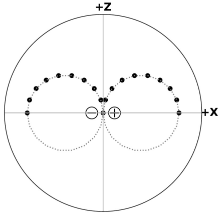
CONCLUSIONS

- The infrasound radiating from sub-aerial and buried explosions can be directional and a detailed knowledge of the radiation pattern is required to accurately characterize source properties
- Acoustic source inversion methods are a popular method for constraining the mass flow rate or yield of an explosion (monopole), as well as the potential directionality (represented by a dipole force in three dimensions)
- A monopole inversion with a ground-based network yields information that may be good enough for practical purposes, even for multipole sources as long as the dipole component is relatively small
- If multipole inversions are to be performed, care should be taken in interpreting the results
- Studies such as this using typical sensor configurations can help quantify the uncertainty and place bounds on how much information may be missing, including the likely source mass flow rate underestimate
- While we chose to use a volcanic explosion as the example source in this study, we note that for this type of study the input source characteristics and topography are less important than our ability to recover the input source time functions for a given scenario

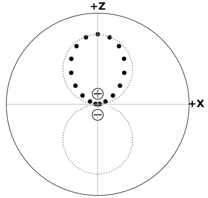
Monopole



Horizontal Dipole



Vertical Dipole



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