Infrasound for Real-Time Volcano Monitoring

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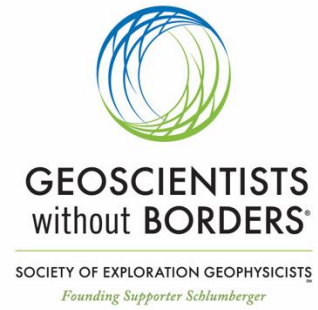

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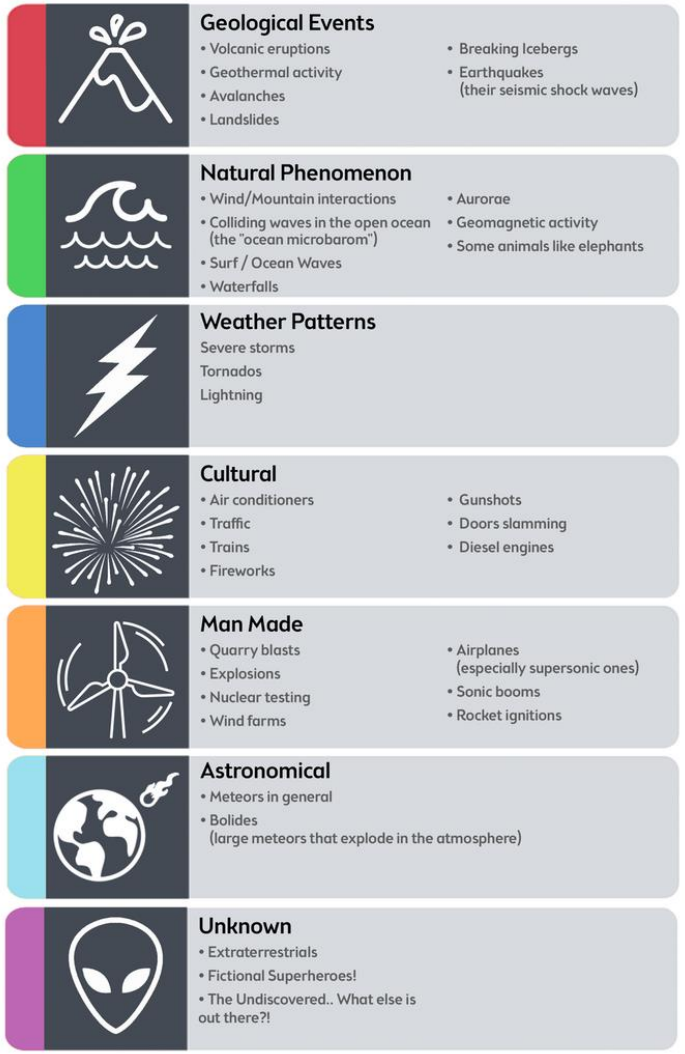
What is Infrasound?

- Definition:
  - Acoustic pressure waves <20Hz (generated by movement of atmospheric mass)
- Key properties and advantages/disadvantages:
  - Can travel very long distances minimally affected by attenuation
  - Available in Real-Time
  - Propagation affected by topography, wind, and temperature gradients
- Sources:
  - Natural: Volcanoes, Oceans, Avalanches, Earthquakes, …
  - Anthropogenic: Explosions, Rockets, Wind Turbines, …

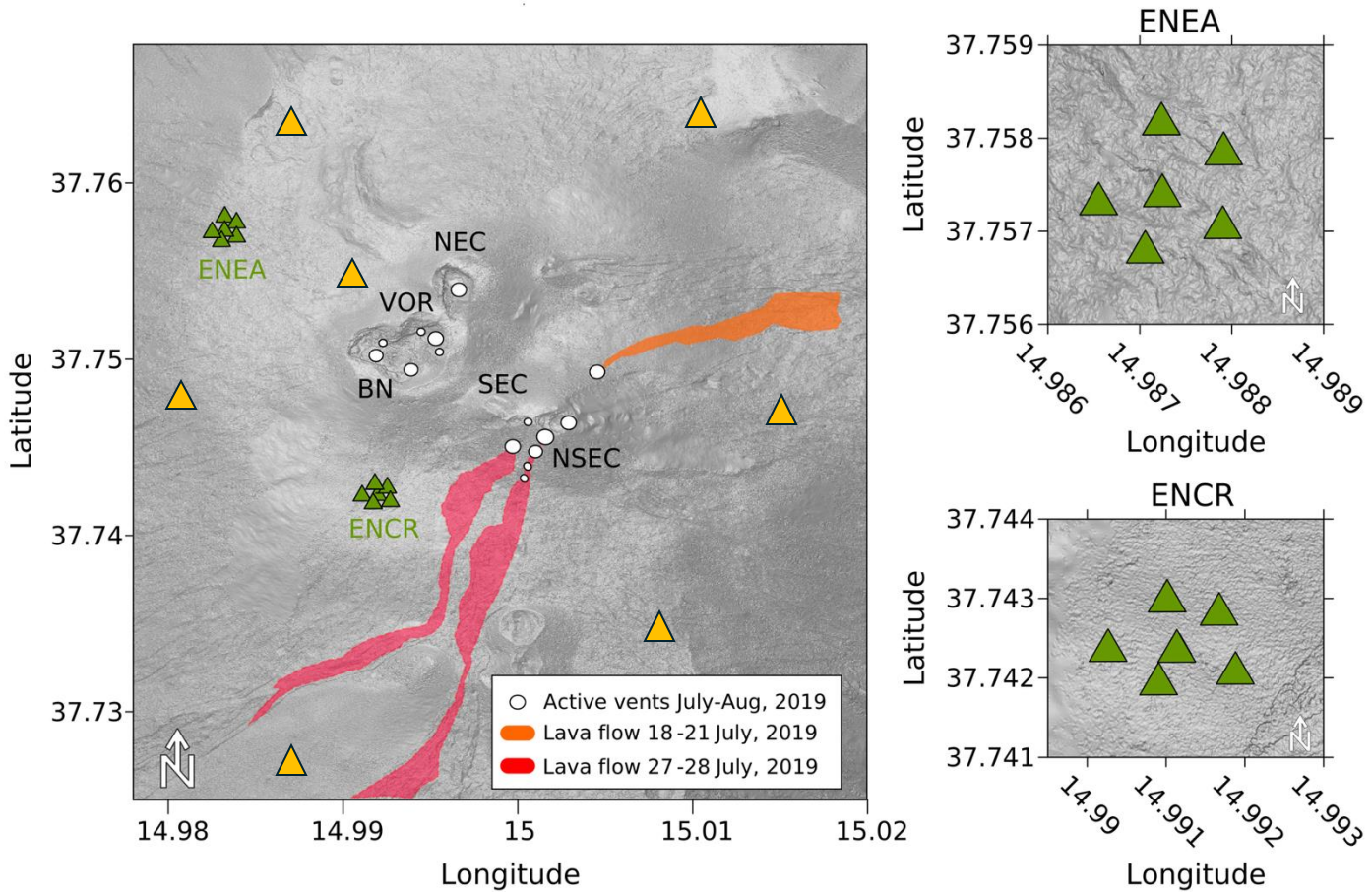


What can we do with infrasound?

- Unrest - Detection and location:
  - Real-time volcano (global), crater, vent (local) discrimination
- Style and intensity of eruptions:
  - Metrics (time and frequency domain) to qualify and quantify volcanic activity
- Eruption Source Parameters (ESP) and plume height:
  - Waveform inversion
  - Plume models (1D, 3D)
- Early Warning:
  - Detection Rates + Intensity to calibrate warnings

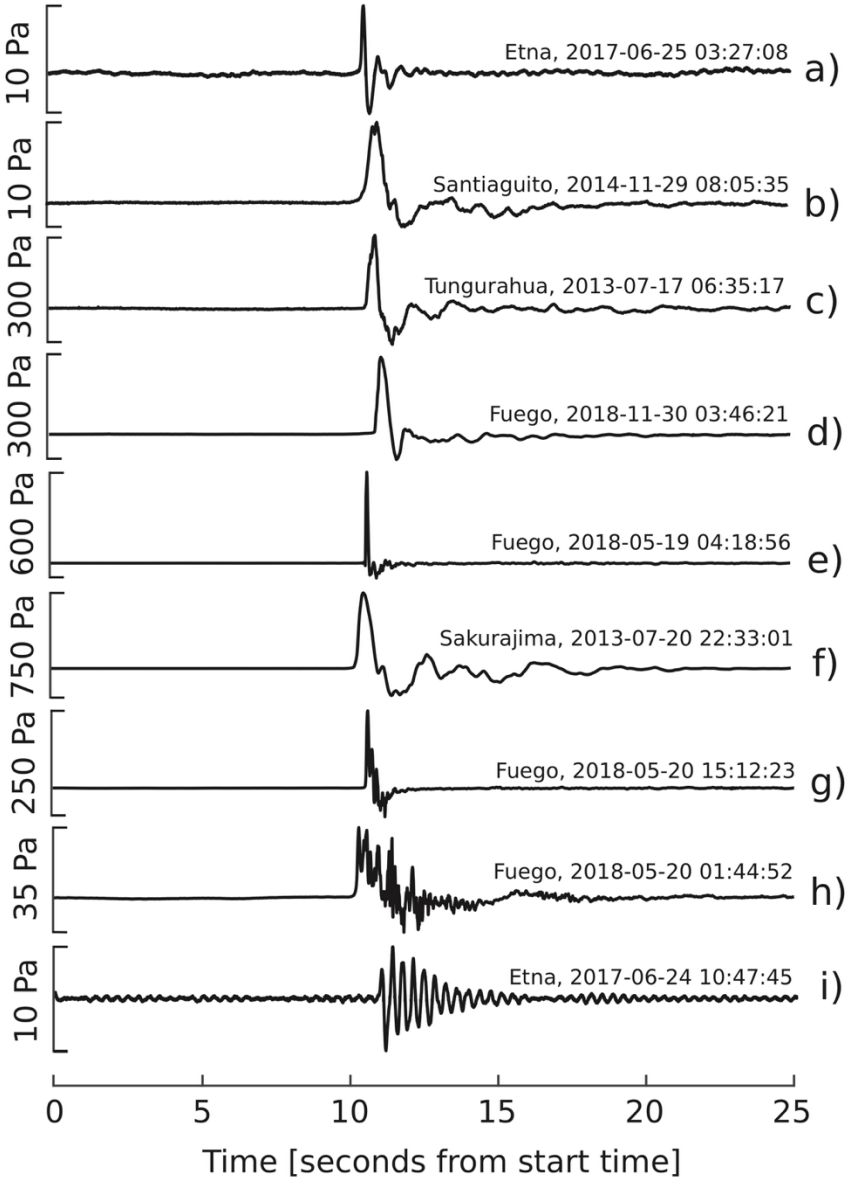
Infrasound arrays and networks (local scale)

- Local Infrasound:
  - <15-20km from the
  - Rich variety of signals
- Networks vs Arrays
  - Networks: sensors distributed around active vents (1-20km aperture)
  - Arrays: Tight clusters of>3 sensors (spacing 30-100m)



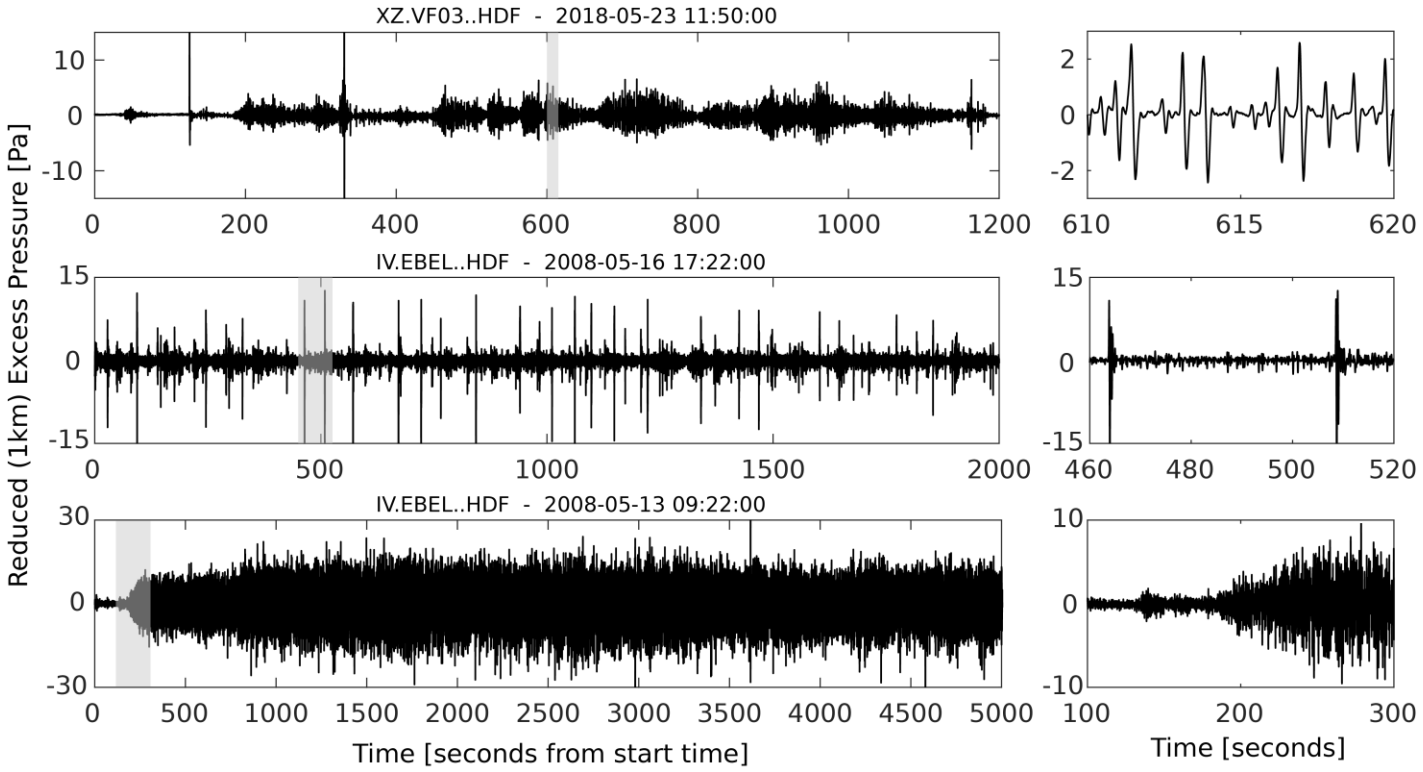
Impulsive sources

- Impulsive sources
  - Short duration Source Time Functions (associated with transient activity)



Sustained sources

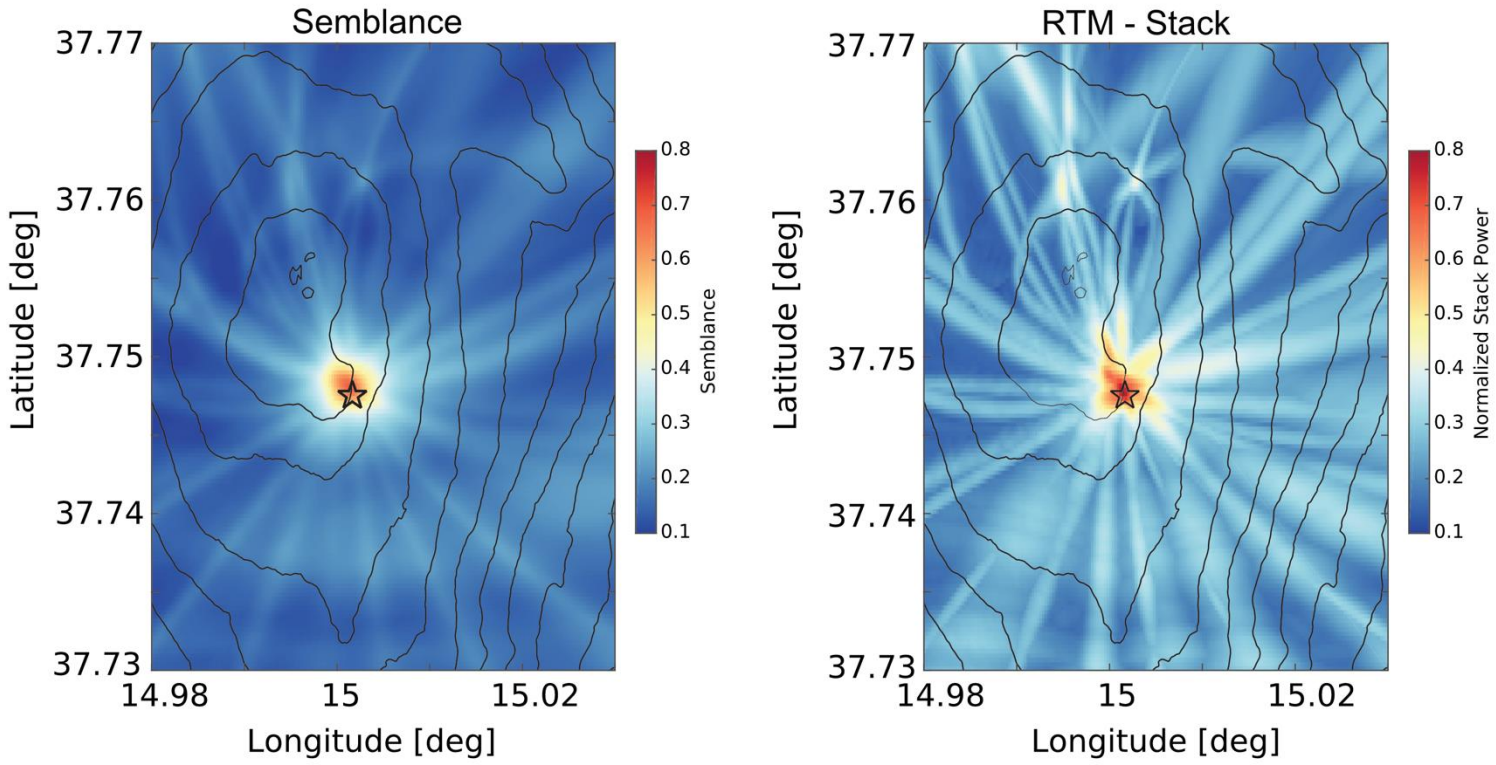
- Sustained sources
  - Longer duration Source Time Functions (associated with sustained activity)



(Photo credit: AP)

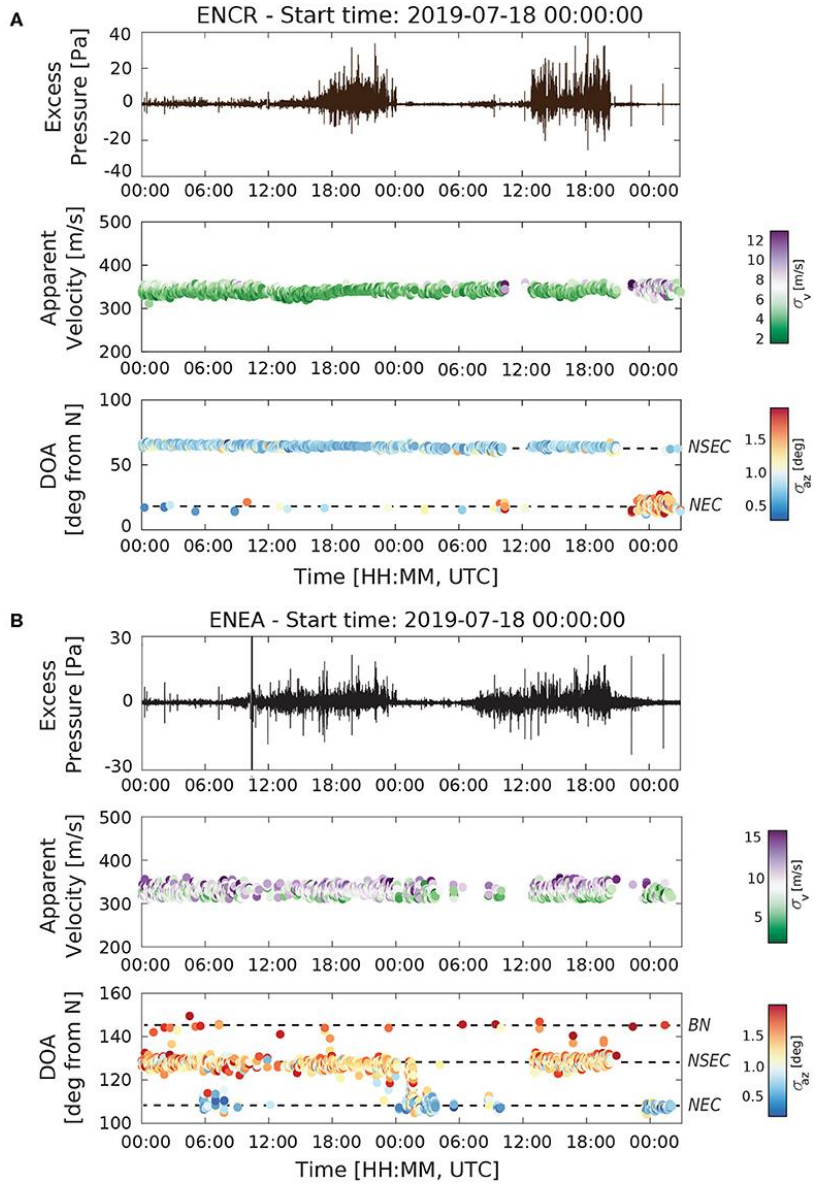
Infrasound location – Network

- Network locations
  - Grid search methods (sometimes RTM/back-projection) commonly used
  - Waveform corrected for travel-time from candidate sources
  - Detector function evaluated to find the best location (semblance, stack)



Infrasound location – Arrays

- Least Trimmed Squared Slowness Inversion
  - Can handle data outliers better than ordinary least squares
  - Include uncertainty estimates from error propagation theory



Infrasound sources

- Linear Acoustics
  - Small density (pressure) fluctuation, valid only for the sub-sonic regime
- Infrasound generated by fluctuations in fluid flow. Three types of sound sources:
  - Monopoles: mass and heat fluctuations (linked to acceleration of atmospheric mass)
  - Dipoles: pressure fluctuations at solid boundaries or due to non-point sources (generally represent ‘directivity’ of the acoustic field, link to perturbations of the flow)
  - Quadrupoles: turbulence and viscous stress effects (internal stresses due to deformation during flow)

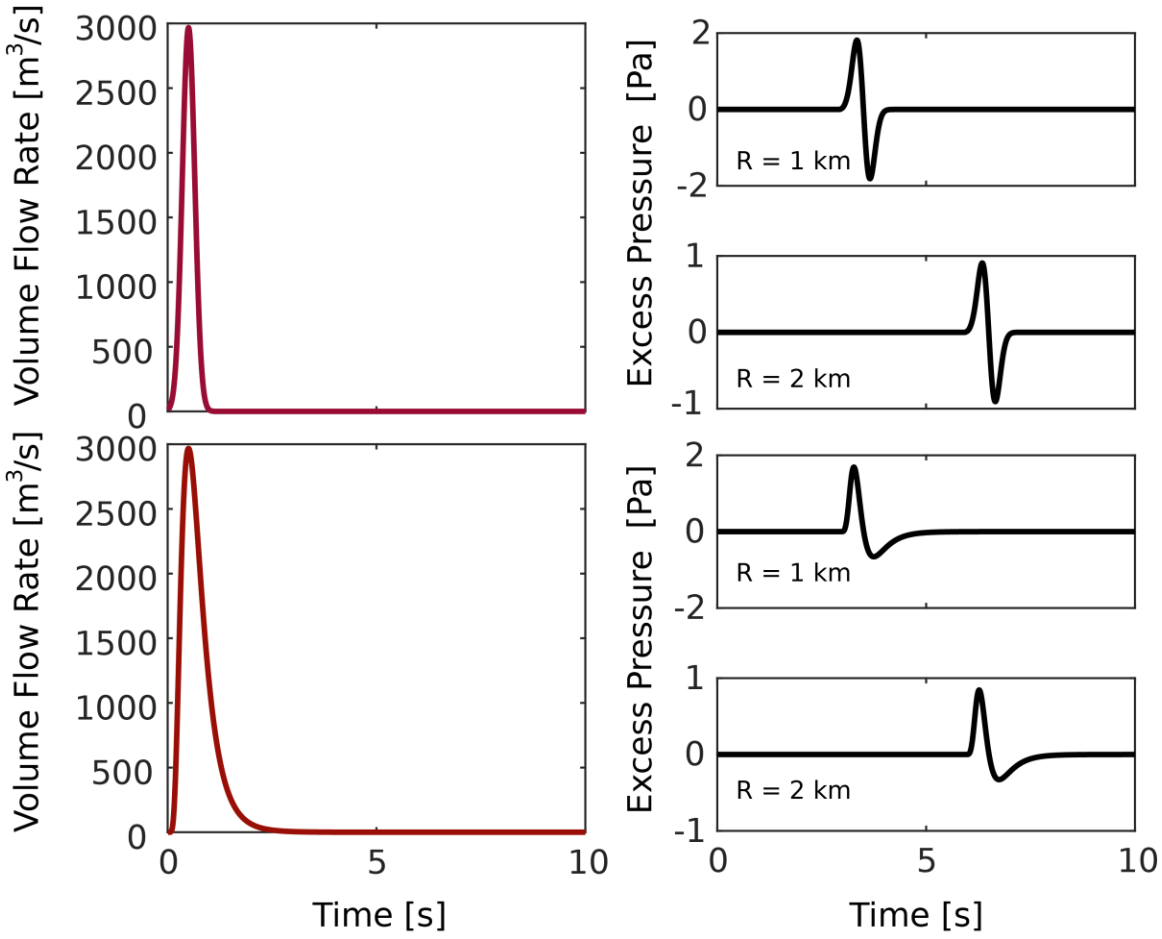
$$p(t) = G_m(t) * \dot{M}(t) + G_d(t) * D(t) + G_q(t) * Q(t)$$

Acoustic monopole

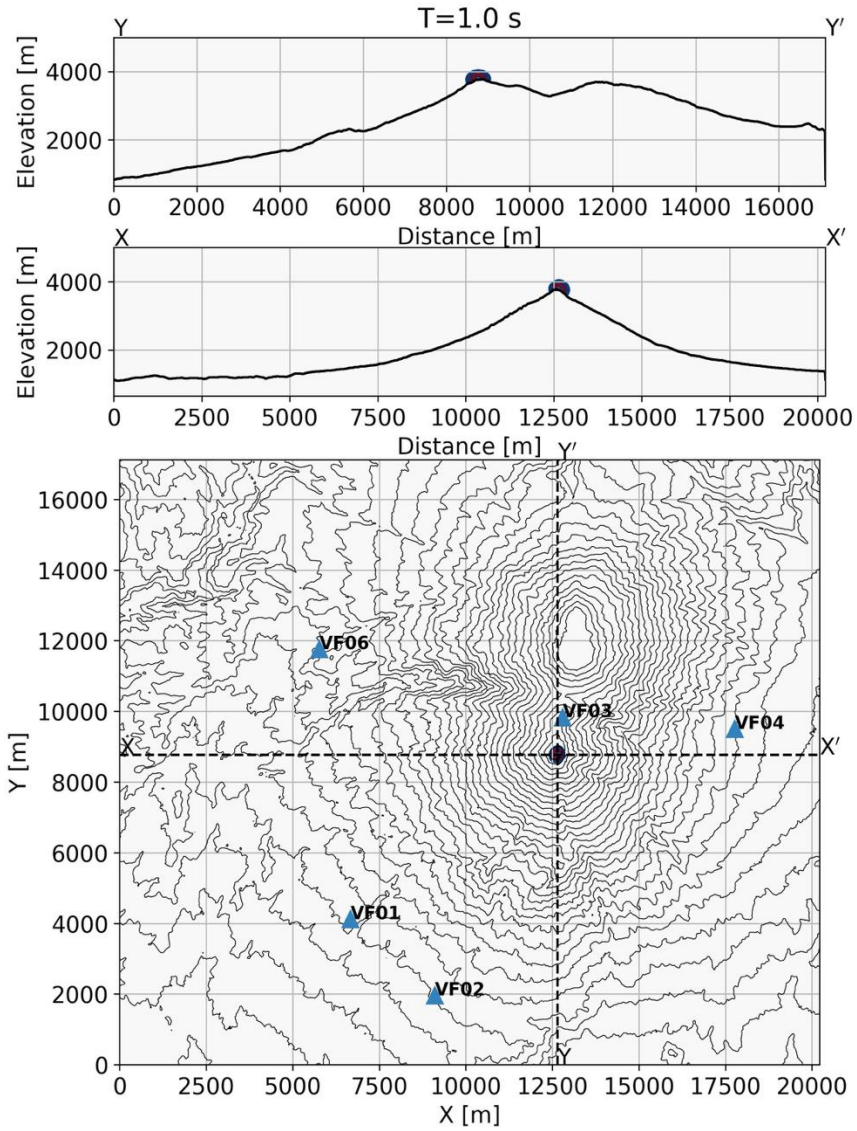
Homogeneous and isotropic (windless) atmosphere bounded by a flat horizontal surface

- Acoustic monopole
  - Flow velocity (or volume flow rate) linked to the integral of the pressure time series

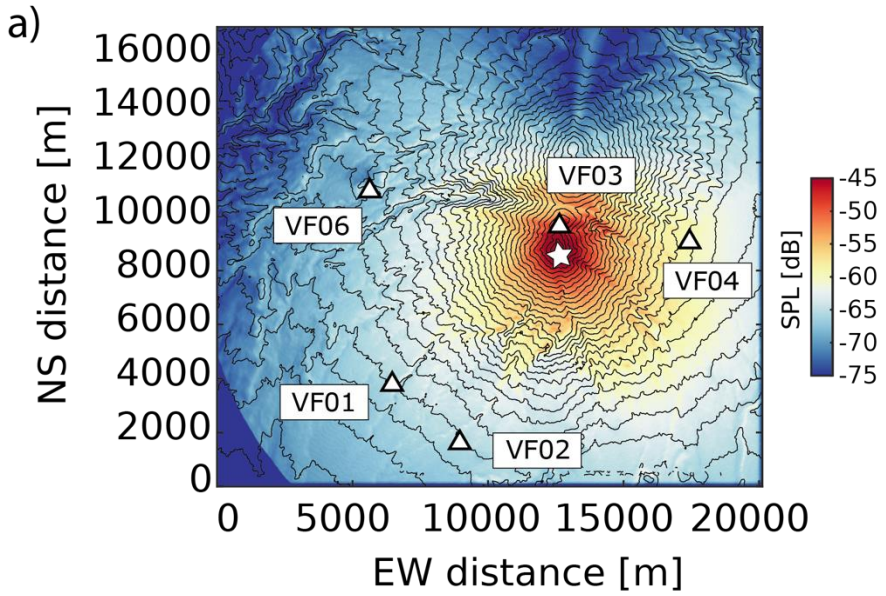
$$\dot{V}(t) = \frac{2\pi r}{\rho_{atm}} \int \Delta p(\tau) d\tau$$

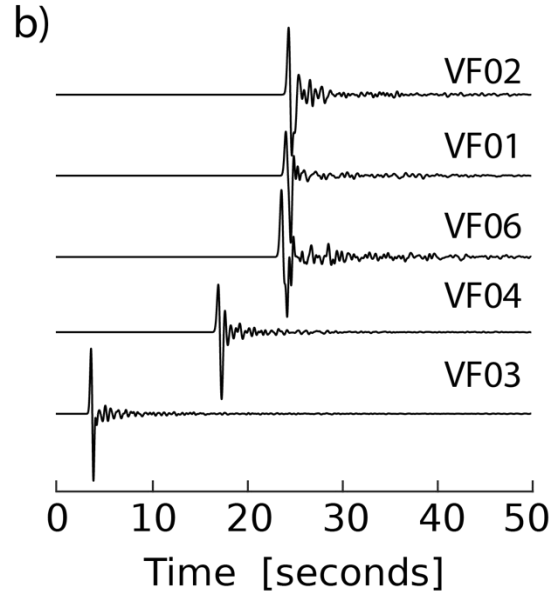


Numerical models – Acoustic wavefield

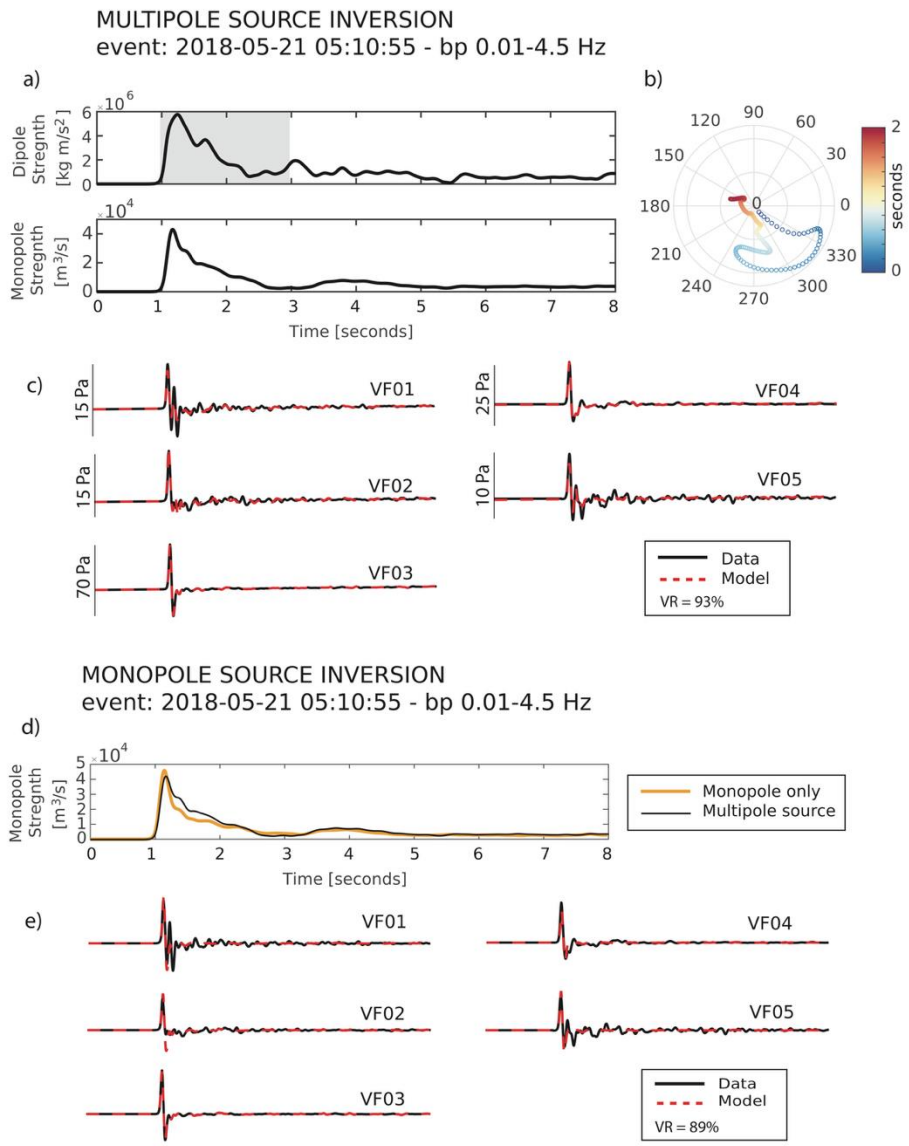


- Numerical models (multipole sources)
  - 3D Finite Difference Time Domain (GPU)
  - Include effects of stratified and windy atmosphere and topography





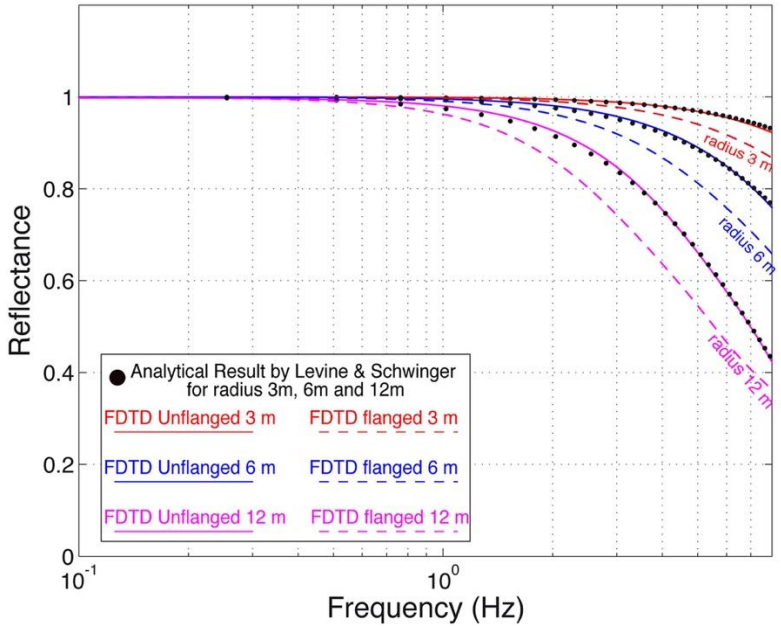
Multipole Inversion

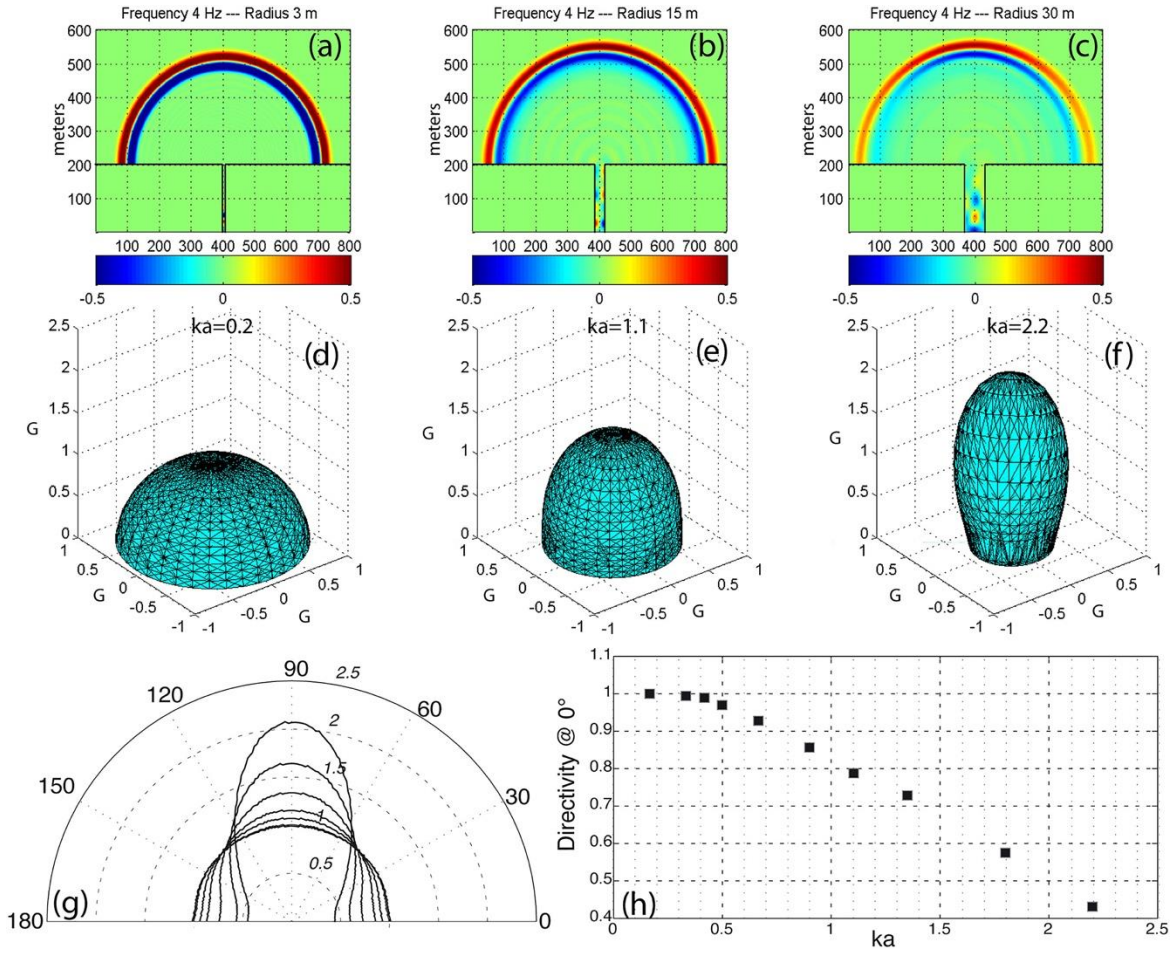


- Multipole waveform inversion
  - Dipole azimuth ‘unstable’ over the STF function. Does it reflect source directivity?
  - Dipole strength small
  - Inclusion of dipole improves model-to-data waveform fit but does not change estimates of flow rates significantly

Numerical models – Acoustic wavefield

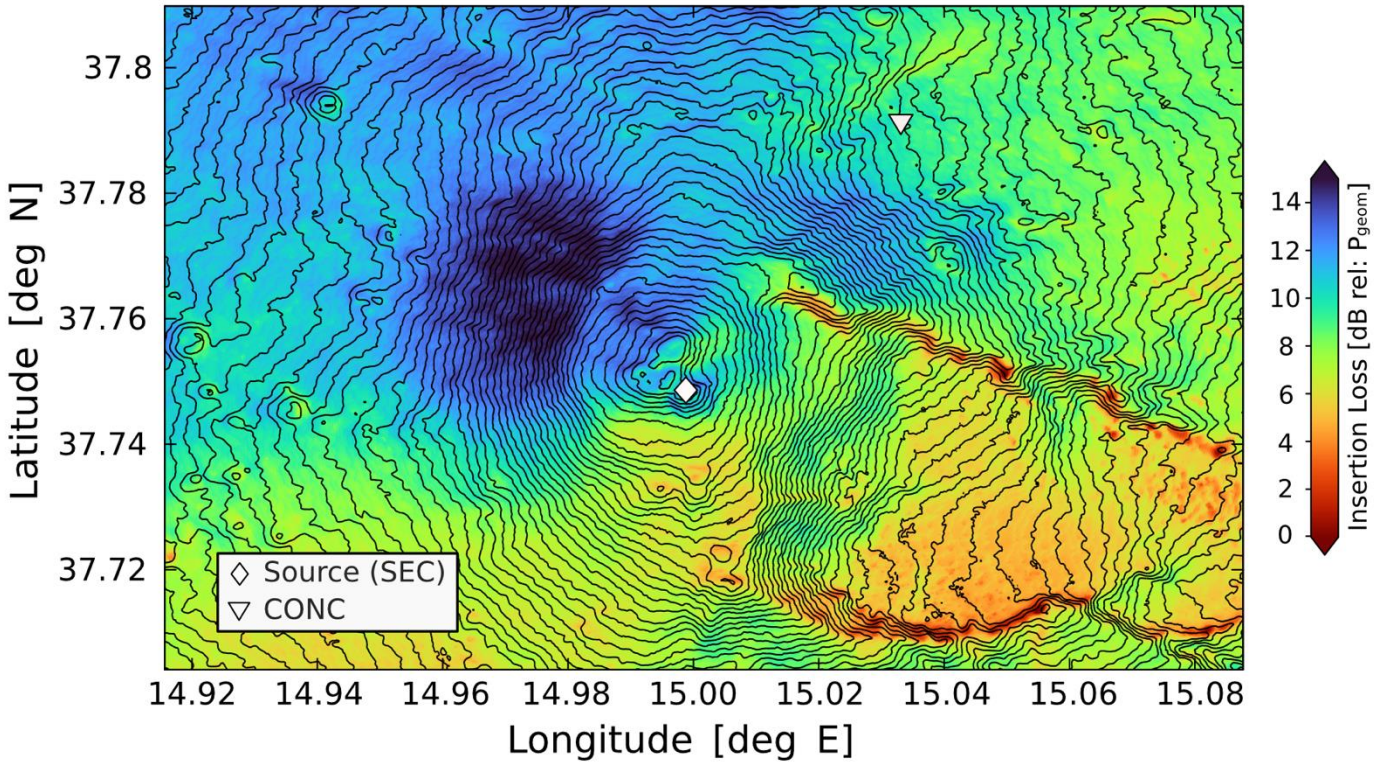
- Monopole-only reduces complexity
  - Good approximation for Ka < 0.5
  - Consider reflectivity at the source atmosphere boundary and effect of vent geometry





Numerical models – Attenuation

- Numerical models
  - Estimate true wavefield attenuation relative to simple geometrical spreading
  - Provide corrections for the simple monopole model



$$IL = 20 * log(\frac{P_t}{P_{geom}})$$

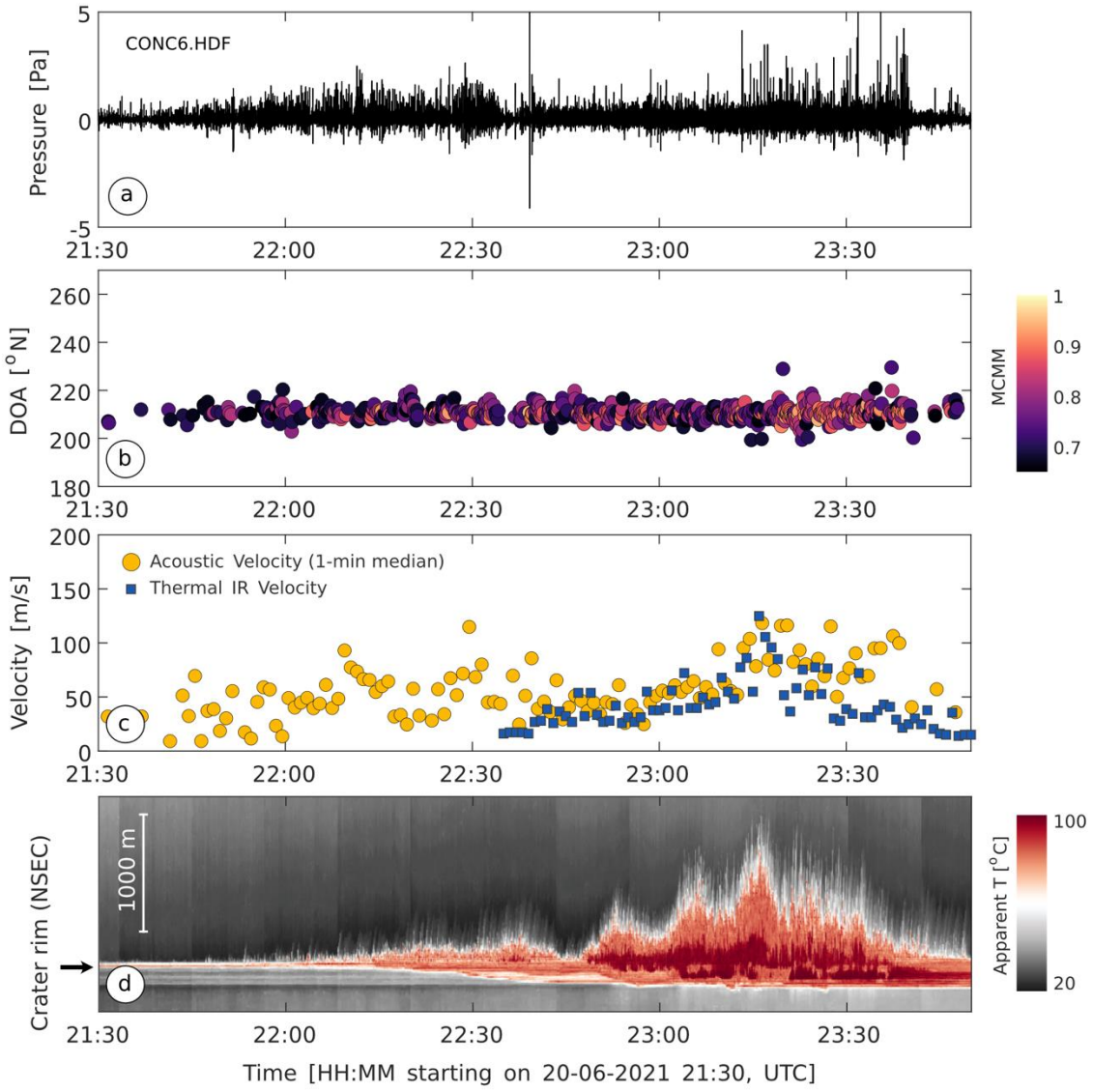
Flow velocity – Volume Flow Rate

$$\dot{V}(t) = \frac{2\pi r}{\rho_{atm}} \int \Delta p(\tau) d\tau$$

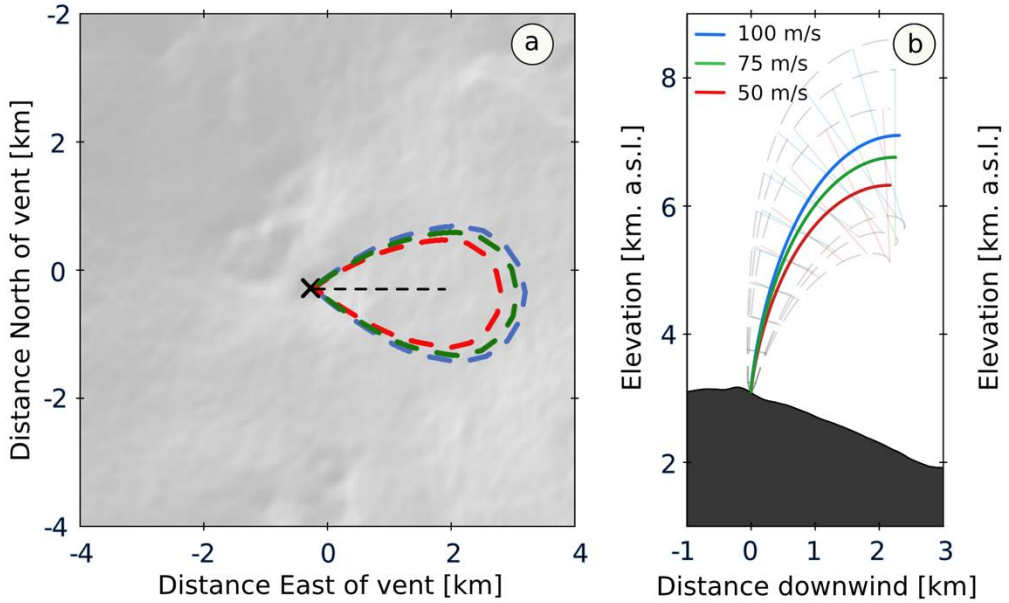
Accounting for reflectivity and true attenuation

$$\dot{V}(t) = \frac{2\pi r}{(1 + |R|)\rho_{atm} 10^{IL/20}} \int \Delta p(\tau) d\tau$$

Flow velocity – Volume Flow Rate – Plume Height

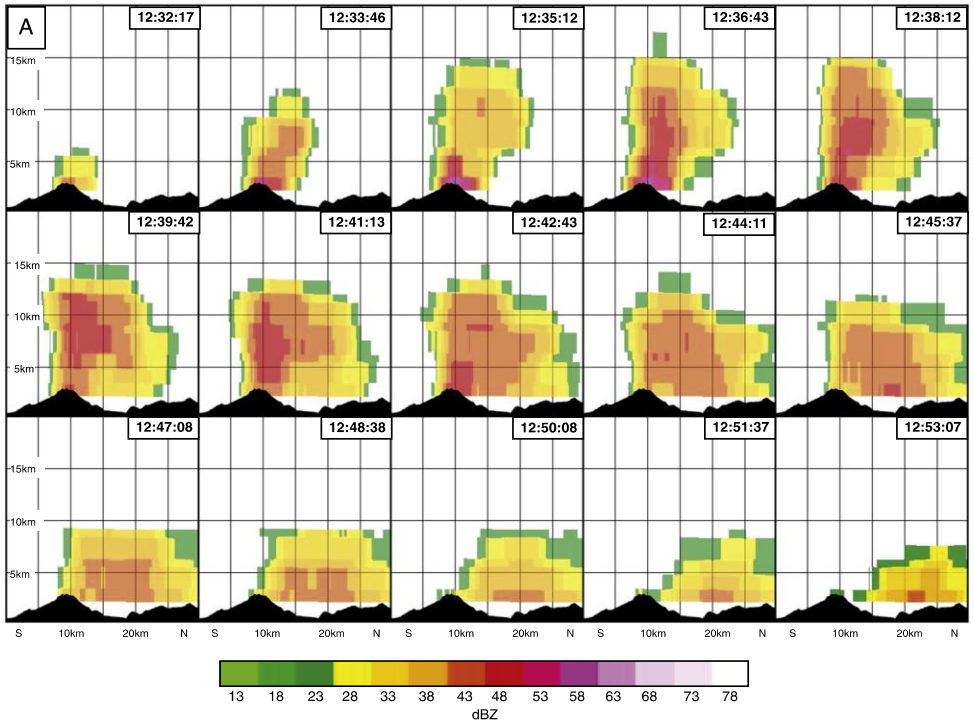


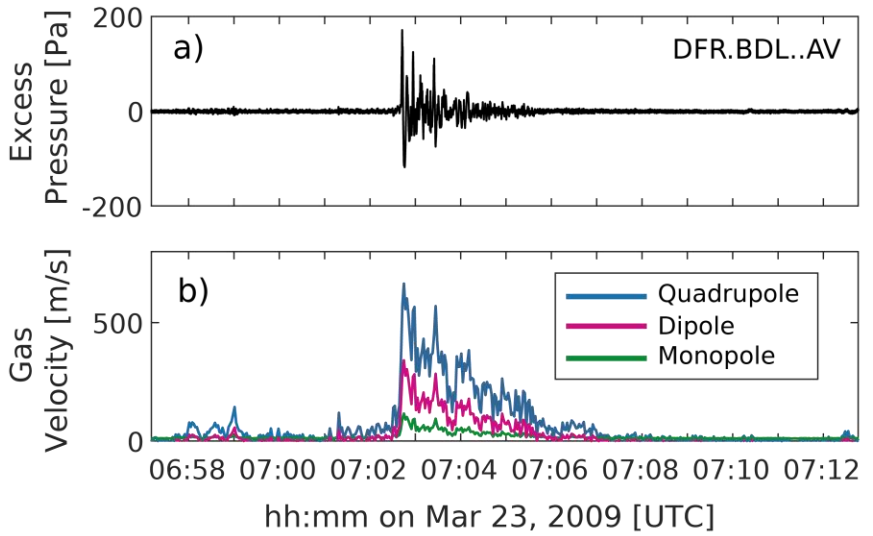
- Rapid estimates of ash plume height
  - Non-empirical. Flow velocity into a numerical plume model (atmosphere considered)
  - Low-latency
  - Range of conditions

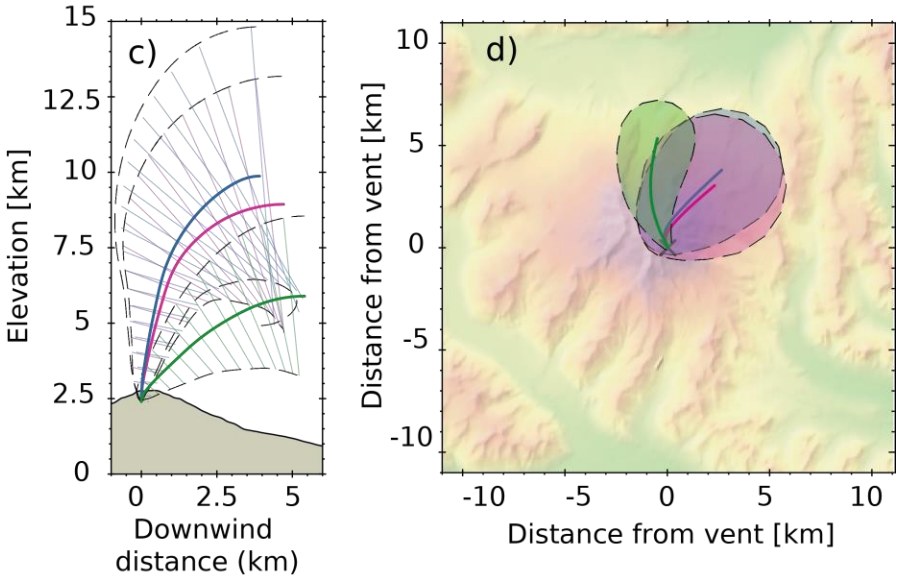


Flow velocity – Volume Flow Rate – Plume Height

- Ash plume height validated
  - Ground-based radar measurements
  - Satellite remote sensing estimates
  - Optical camera estimates



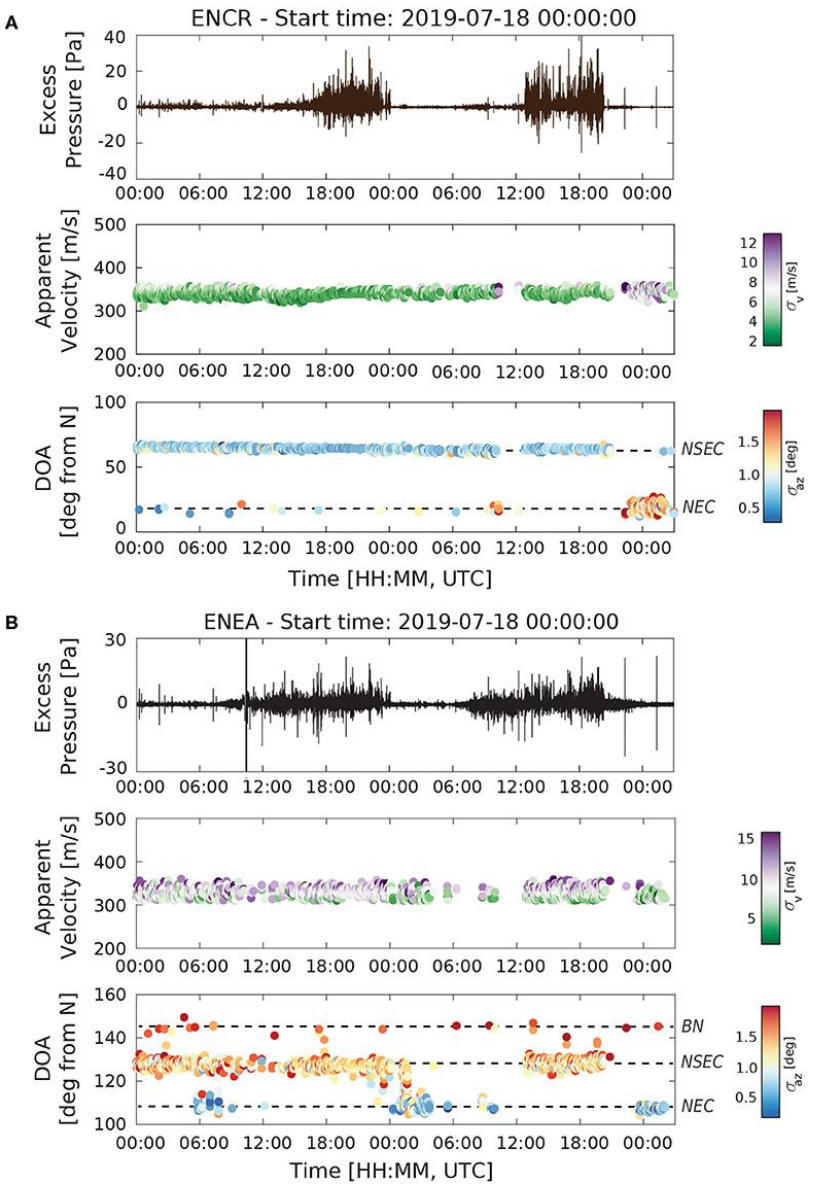




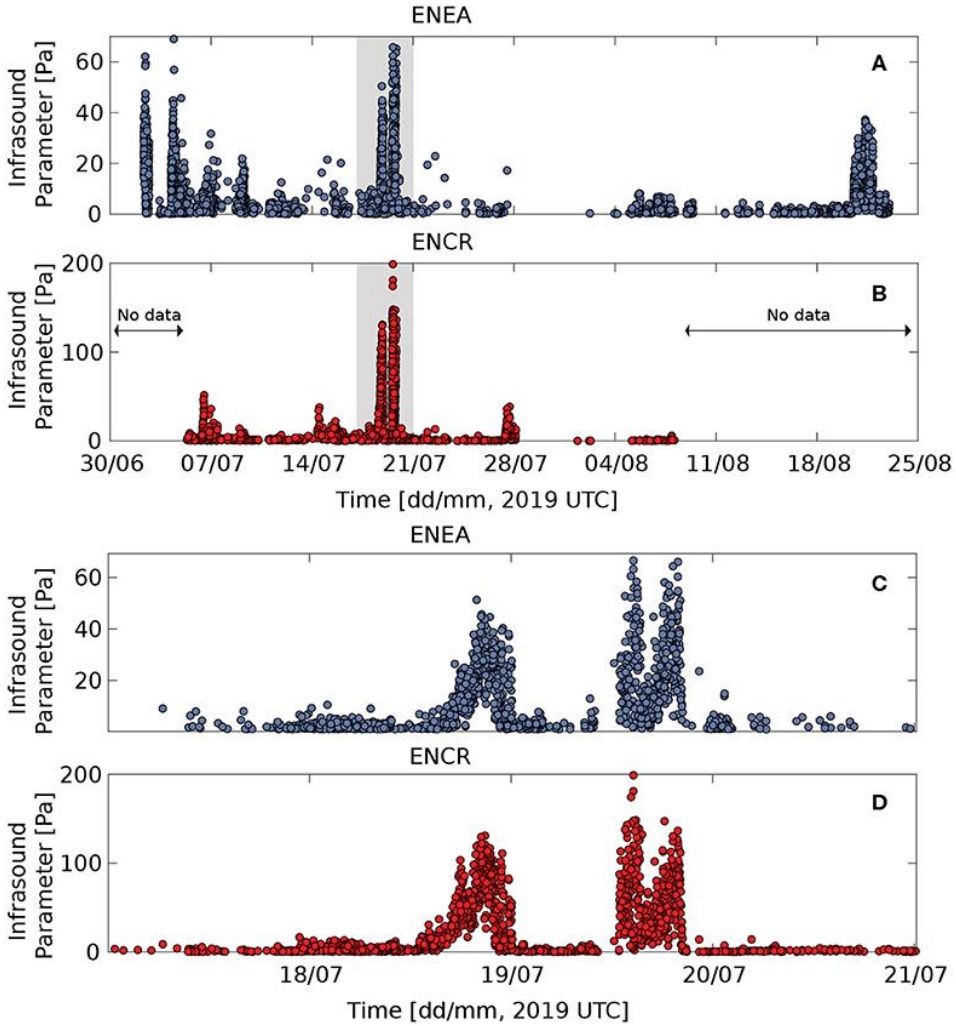
Operational monitoring

- Operational implementation
  - Ash dispersal scenarios generated daily corresponding to atmospheric models, for a plausible range of plume heights
  - Acoustic array detects activity
  - On-the-fly inversion using corrected monopole scheme provides range of eruption rate values
  - Maximum plume height modelled with Gaussian Plume model and maximum height estimated
  - Most likely dispersal scenario confirmed

Early Warning



$$IP = A_p \cdot N_p$$

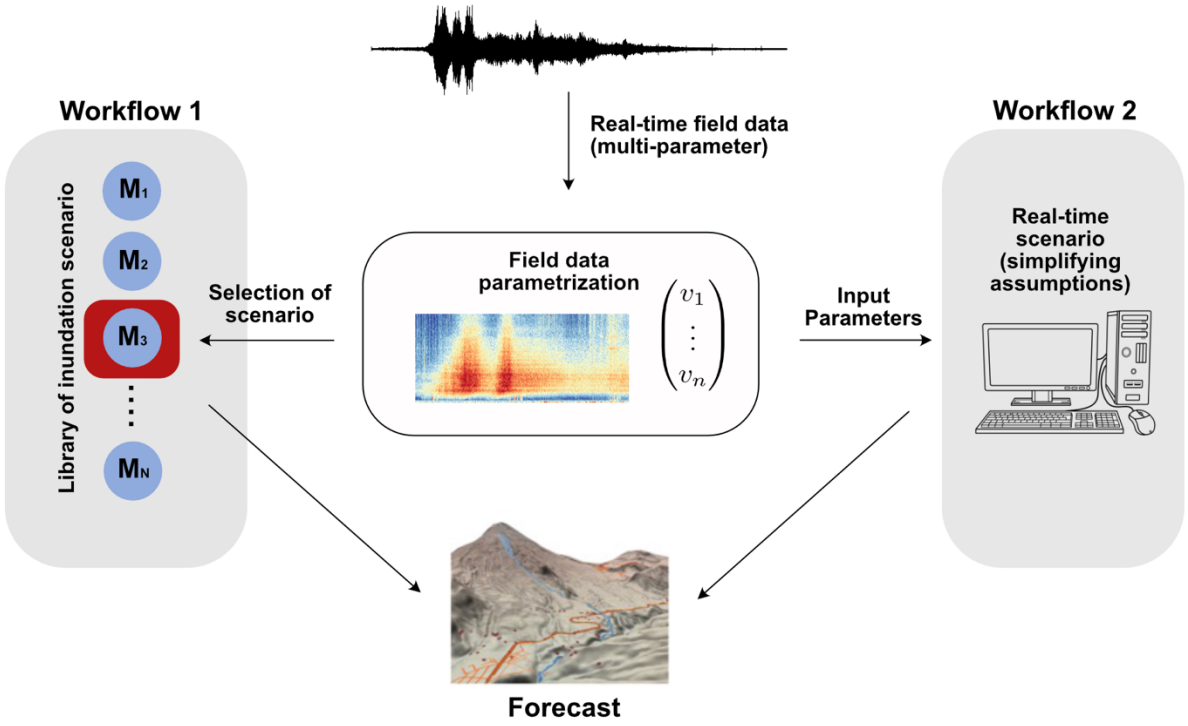


Take home points

- Unrest - Detection and location:
  - Real-time detections/locations array allow vent discrimination
  - Ideally multiple arrays for cross-beam approach
- Style and intensity of eruptions:
  - Waveform inversion allows estimates of flow velocity
  - Signal characterization can help detect the style of eruption (e.g., ash-rich vs ga-rich)
- Eruption Source Parameters (ESP) and plume height:
  - Flow velocity used to estimate plume height with numerical models (1D, 3D)
- Early Warning:
  - Detection Rates + Intensity to calibrate warnings

Thank you

Lahar detection and early warning using infrasound



- Infrasound for lahar early warning
  - Lahar detection, tracking and characterization with infrasound arrays
  - Estimates of flow parameters to inform lahar flow models and selection of inundation scenarios