Detecting geophysical signals and sources with large-scale network data

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Outline
Data Mining applied to the USArray

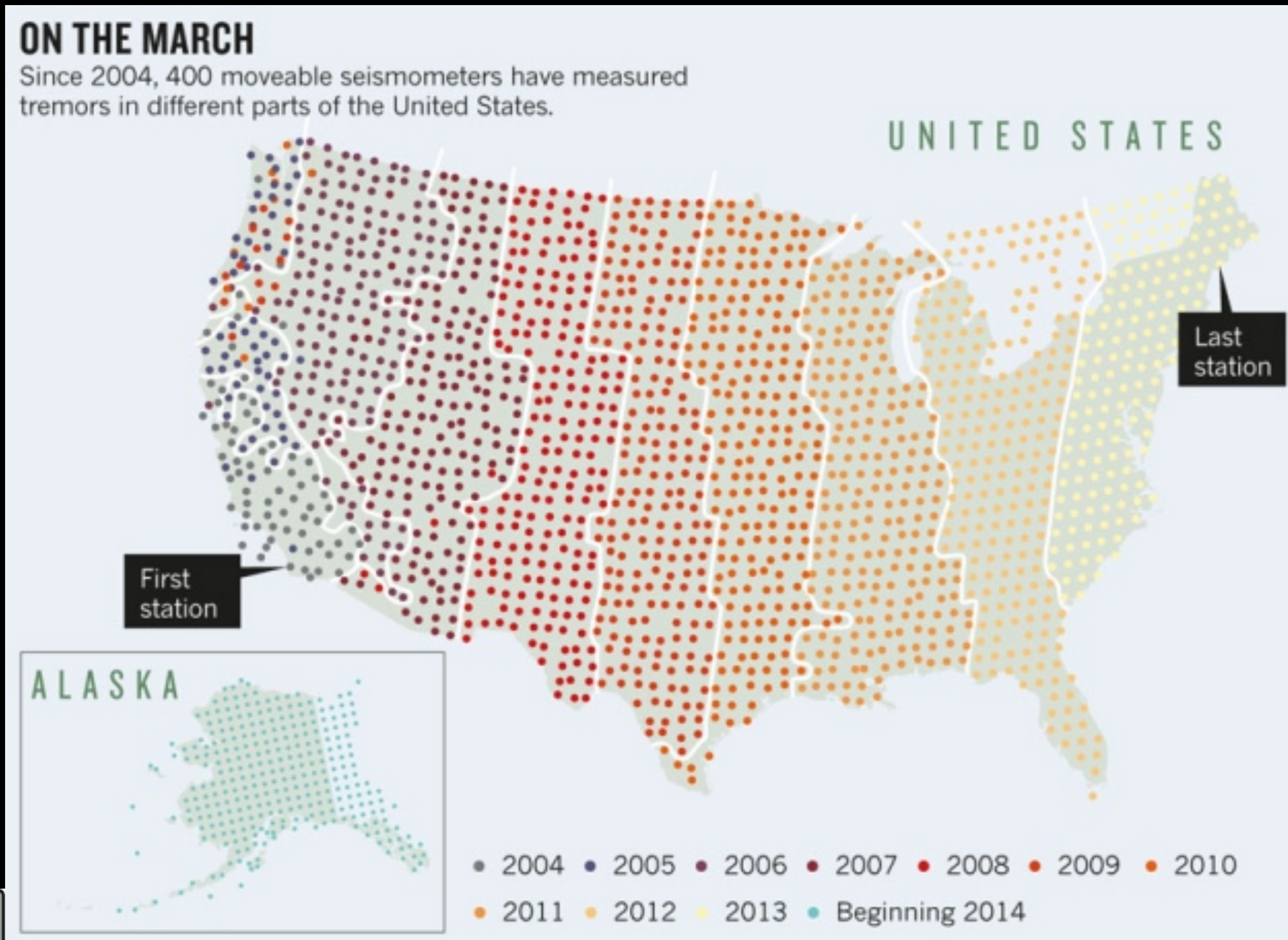
- The USArray
  - Installation history
  - sensors
- The AELUMA method

(Automated Event Location Using a Mesh of Arrays)
  - Signal detection
    - Applications to atmospheric gravity waves and seismic surface waves (coherent processing) and infrasound and seismic body waves (incoherent processing)
  - Source location
    - Combine related detections to locate events
    - Applications to infrasound, seismic surface waves and body waves

The USArray Transportable Array

Installation history

Stations spacing ~70 km in conterminous US, ~ 85 km in Alaska



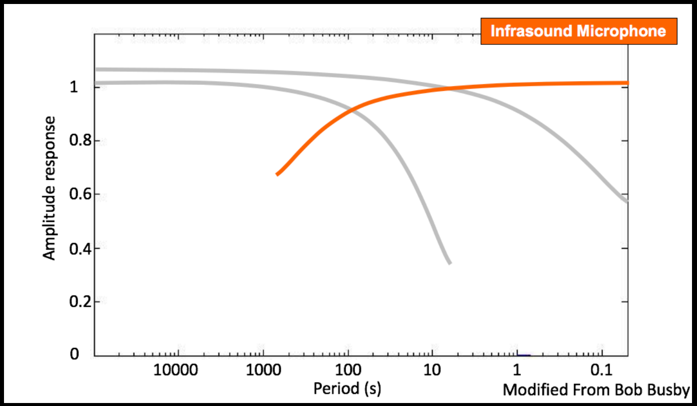
The USArray Transportable Array

Legacy stations

The USArray Transportable Array Sensors

Pressure Sensors
- 1 sps (Atmospheric Gravity Waves)
- 20 or 40 sps (infrasound)

3C seismic
- 1 sps (surface waves)
- 40 sps (seismic body waves)



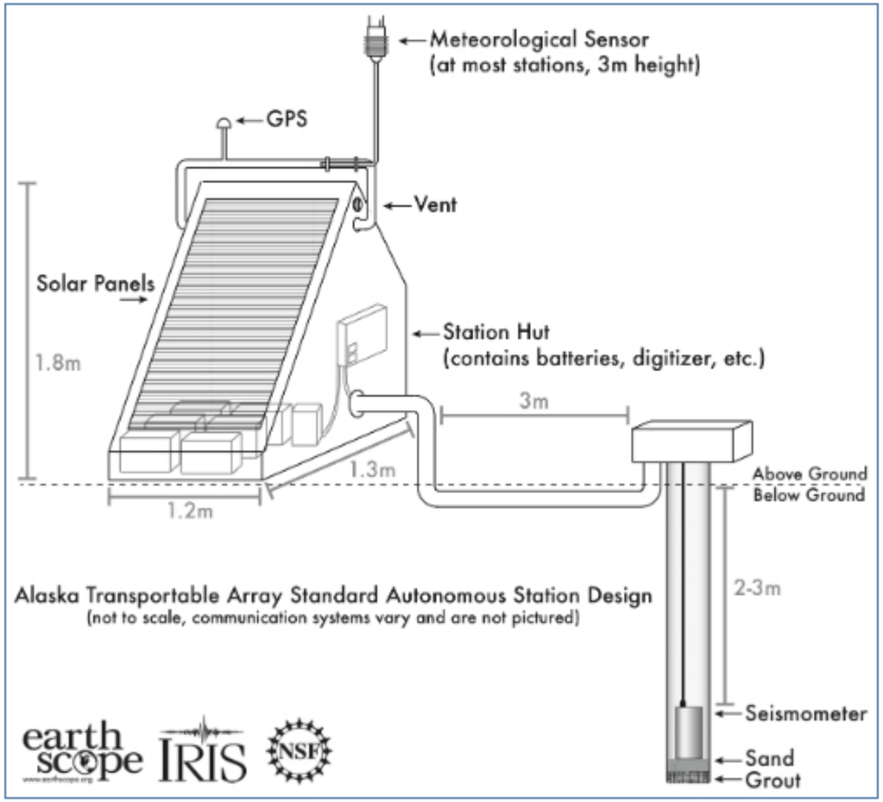


Figure 4: Schematic for an Alaska TA station, click to enlarge.

Signal detection

- We need efficient data mining algorithms to handle the massive quantities of data
- Algorithms must be applicable to
  - coherent signals (wavelengths > sensor spacing)
  - Incoherent signals (wavelengths << sensor spacing)

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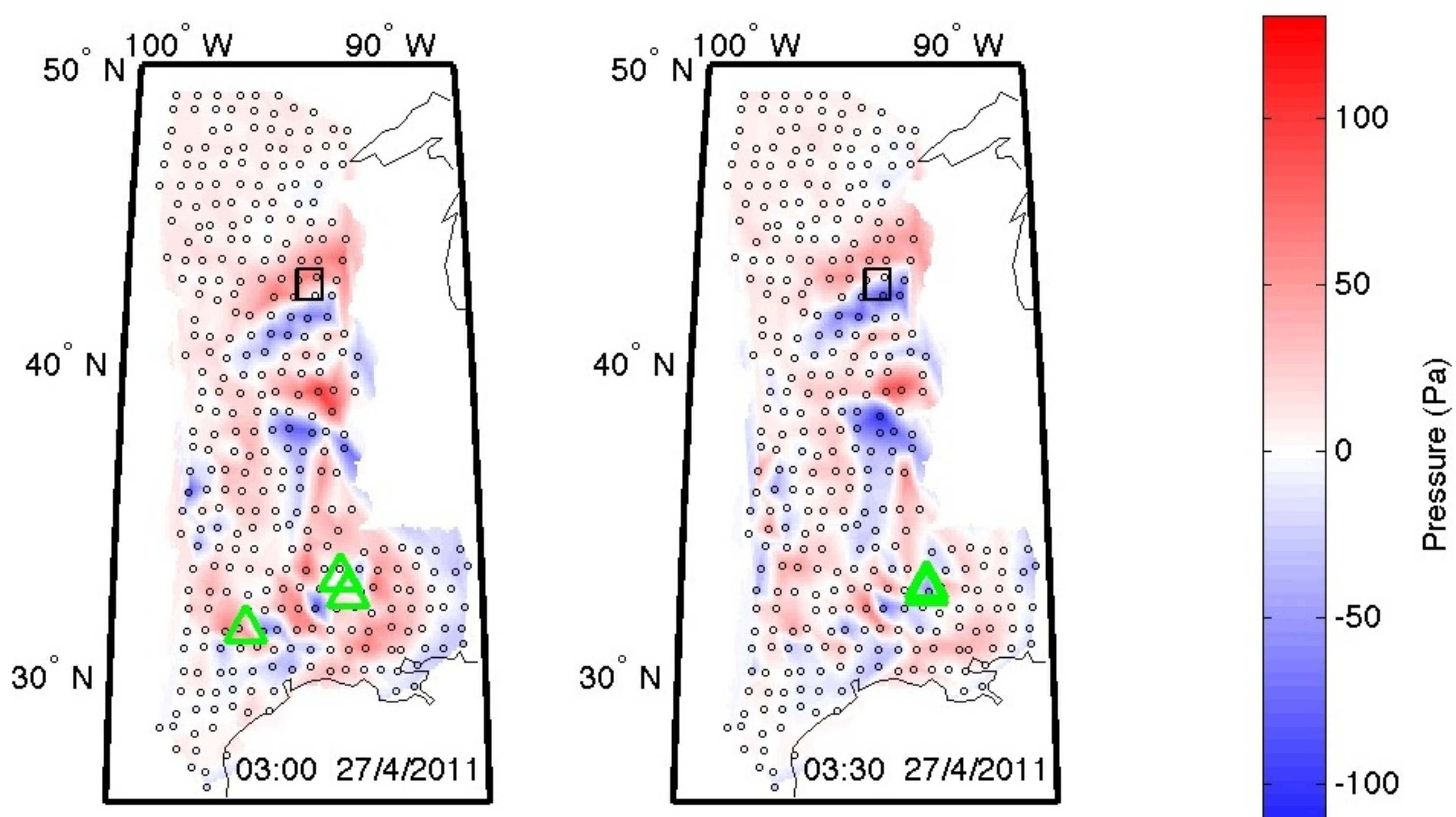
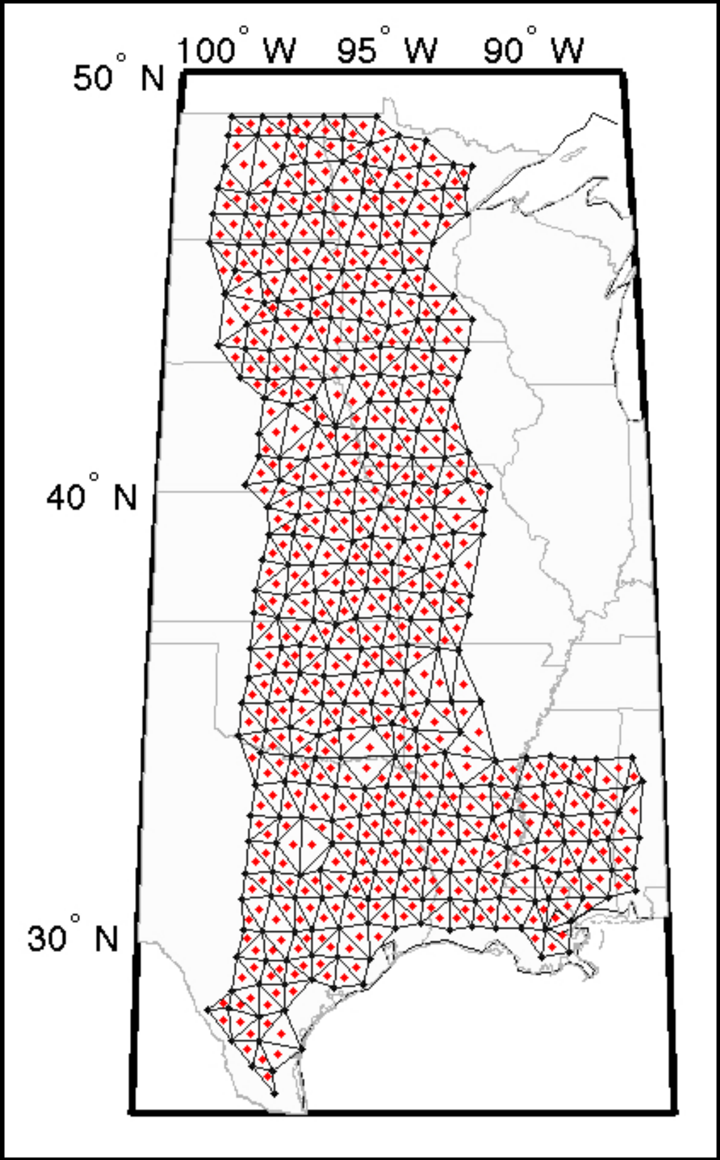
Coherent signals at Earth's surface



Green triangles are tornado locations

de Groot-Hedlin et al., EPSL, 2014

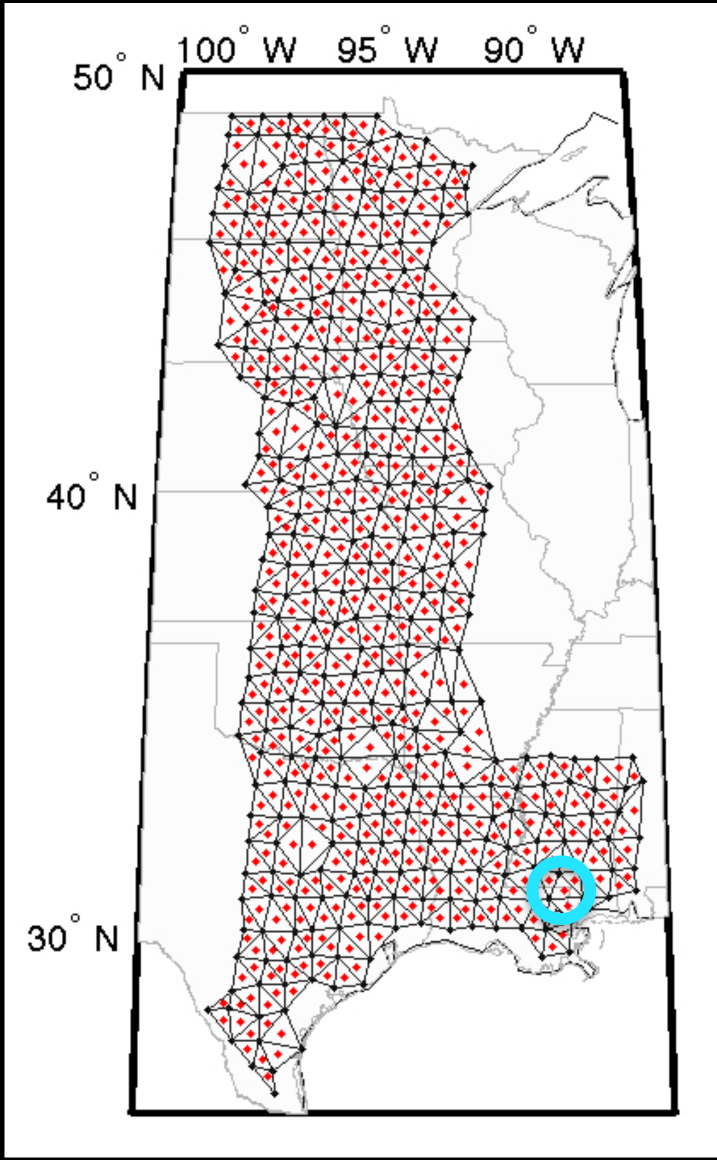
Delauney triangulation → a mesh of arrays



Divide network into non-overlapping triangles = triads

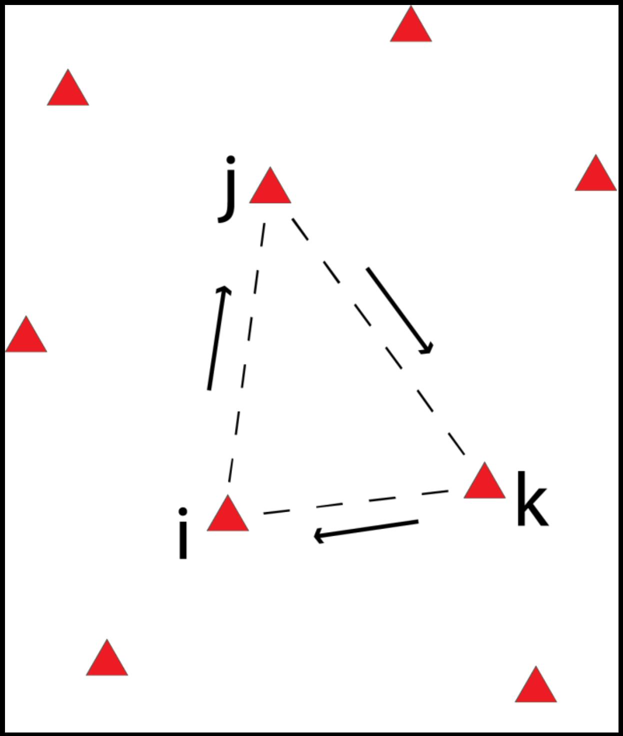
de Groot-Hedlin et al., EPSL, 2014

Signal detection at each triad



Each triad is an individual array

Check for coherent detections

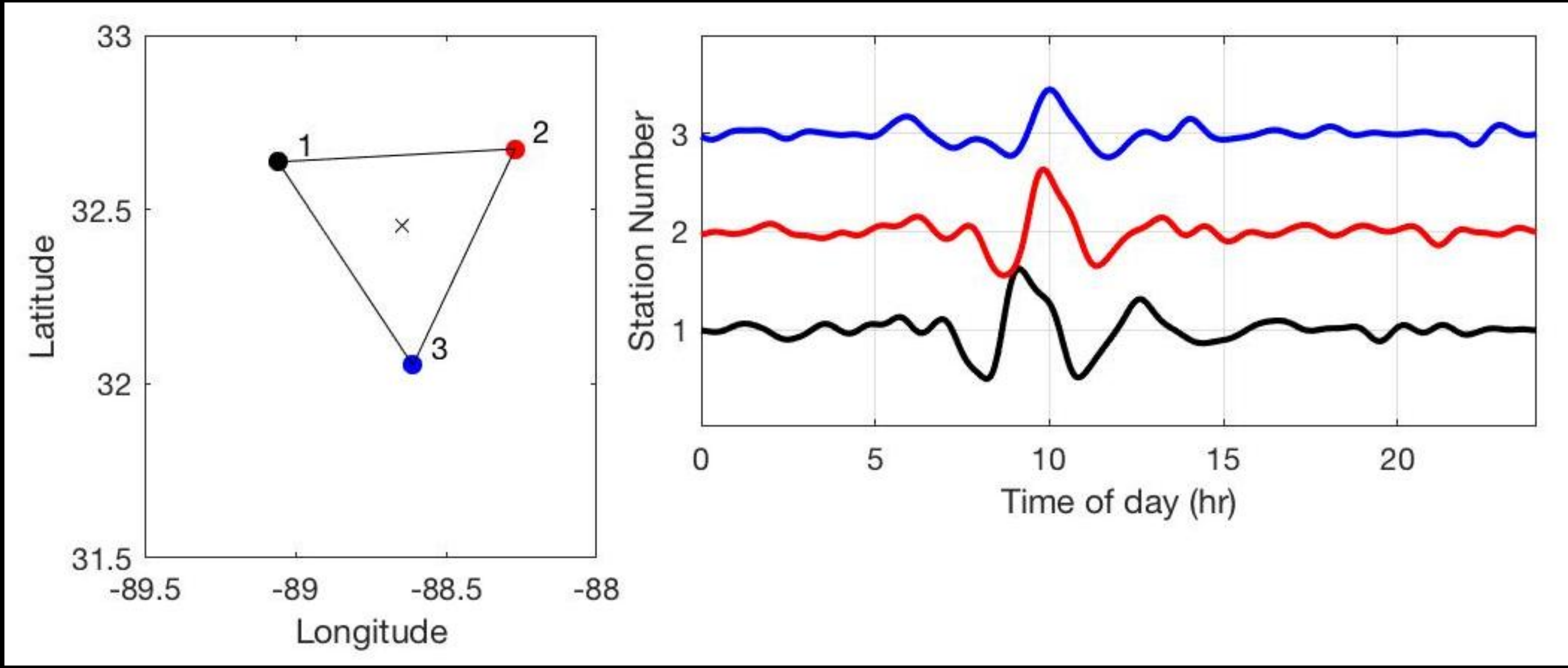


Consistency criterion

$$\tau_{ij} + \tau_{jk} + \tau_{ki} < \tau_{res}$$

Compute time delays between stations, then apply the consistency criterion to each time window, for each triad

Coherent signal – Gravity wave example



Compute cross-correlations to find the time delays between stations

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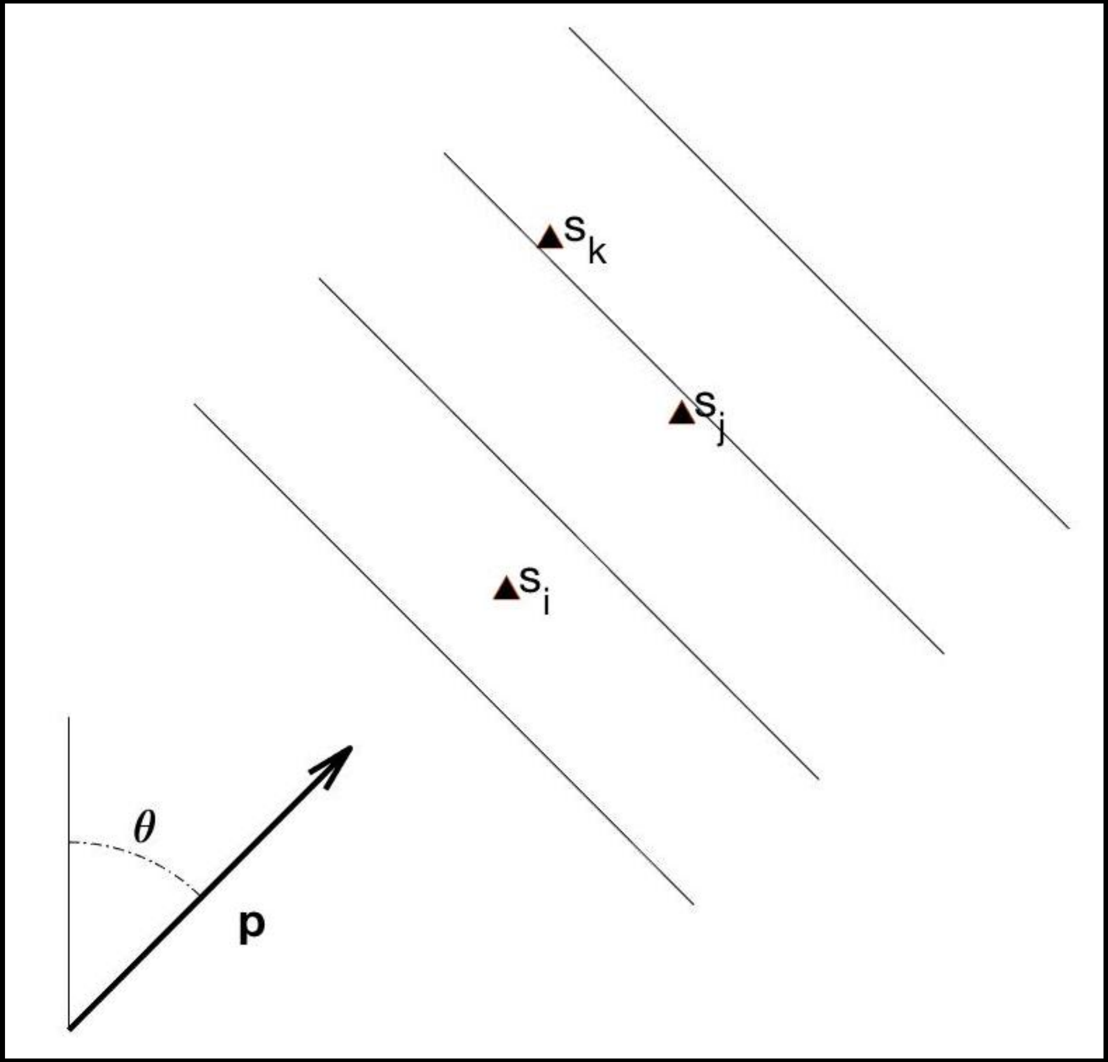
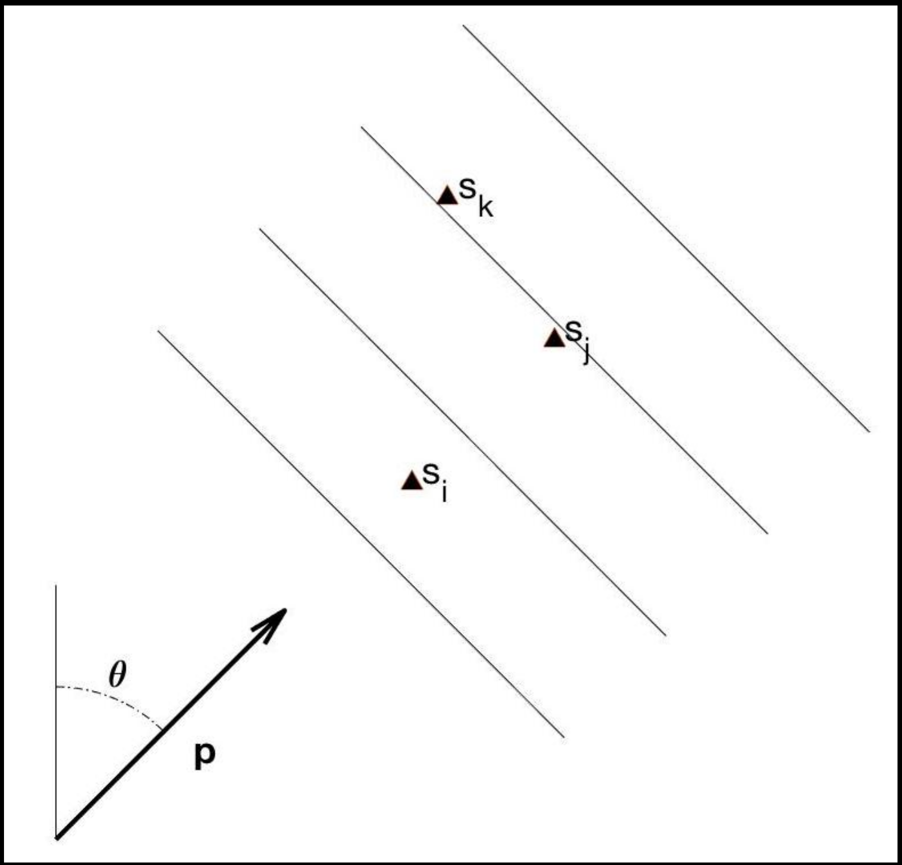
Assume plane propagation across each triad



Solve using either
1) beam-forming (delay & sum)
2) Tau-p (time domain)
3) f-k decomposition

Hedlin et al., Geop. Res. Lett., 2018

The Tau-p solution



$$\tau_{ij} = p_x(x_j - x_i) + p_y(y_j - y_i)$$

where **p** = [px,py] is the horizontal slowness

$$\boldsymbol{\tau} = \boldsymbol{X} \cdot \boldsymbol{p}$$

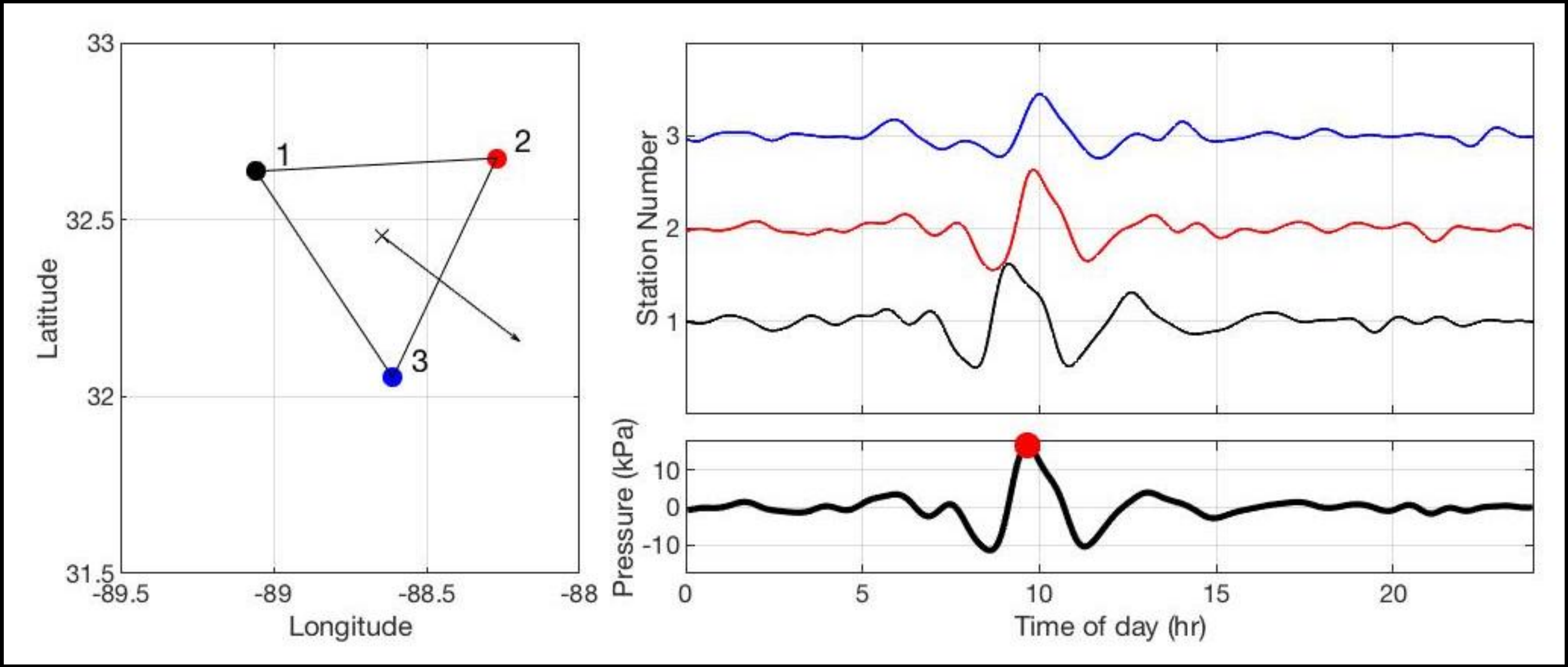
Solve for slowness **p** and derive azimuth and phase velocity as

$$\theta = tan^{-1}\,(p_x/p_y)$$

and

$$|v| = \sqrt{1/(p_x^2 + p_y^2)}$$

Beam-formed solution-coherent signal



The tau-p solution yields the direction of propagation & phase velocity. The maximum amplitude of the beam-formed result is taken as the signal arrival time.

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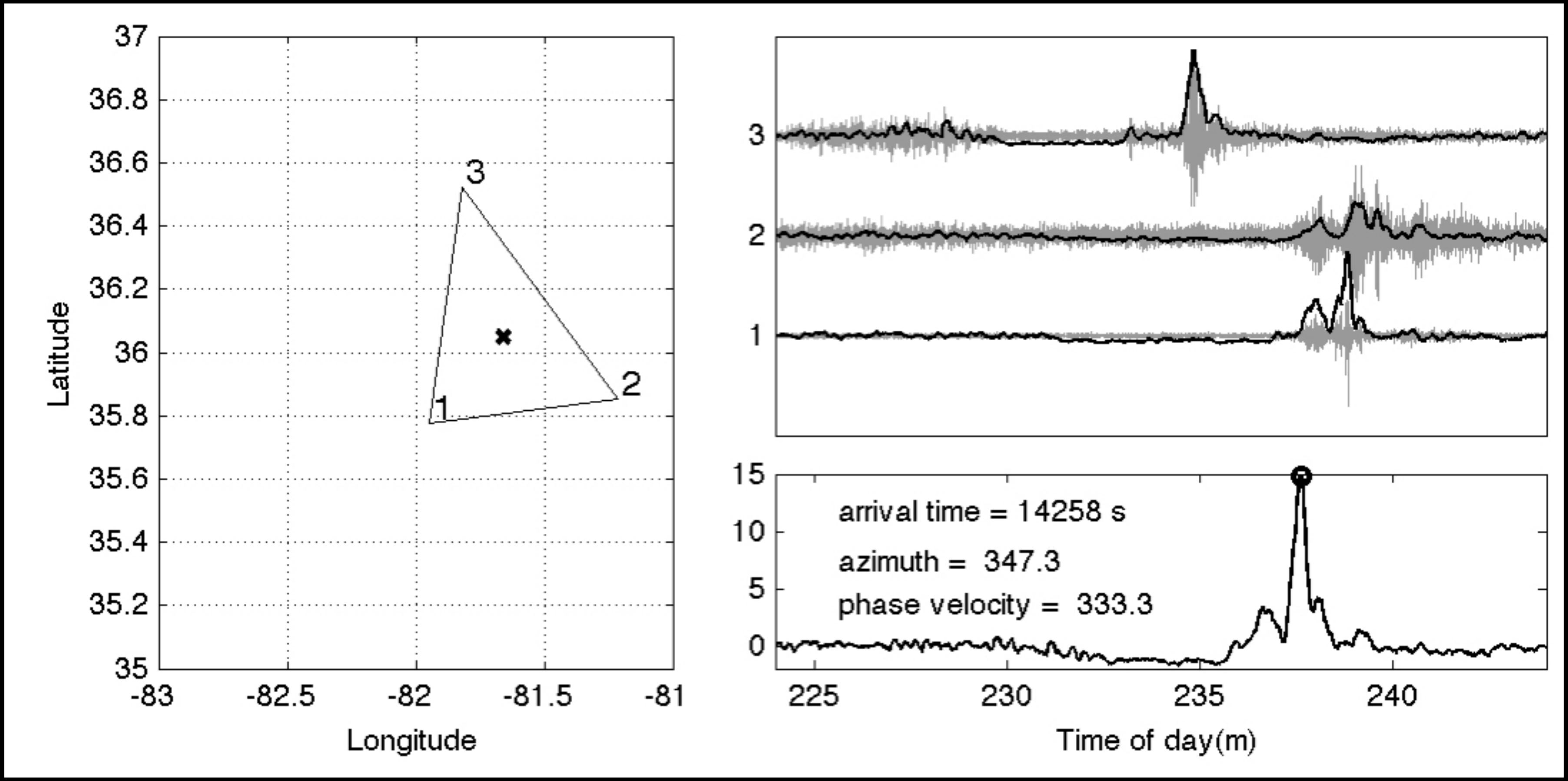
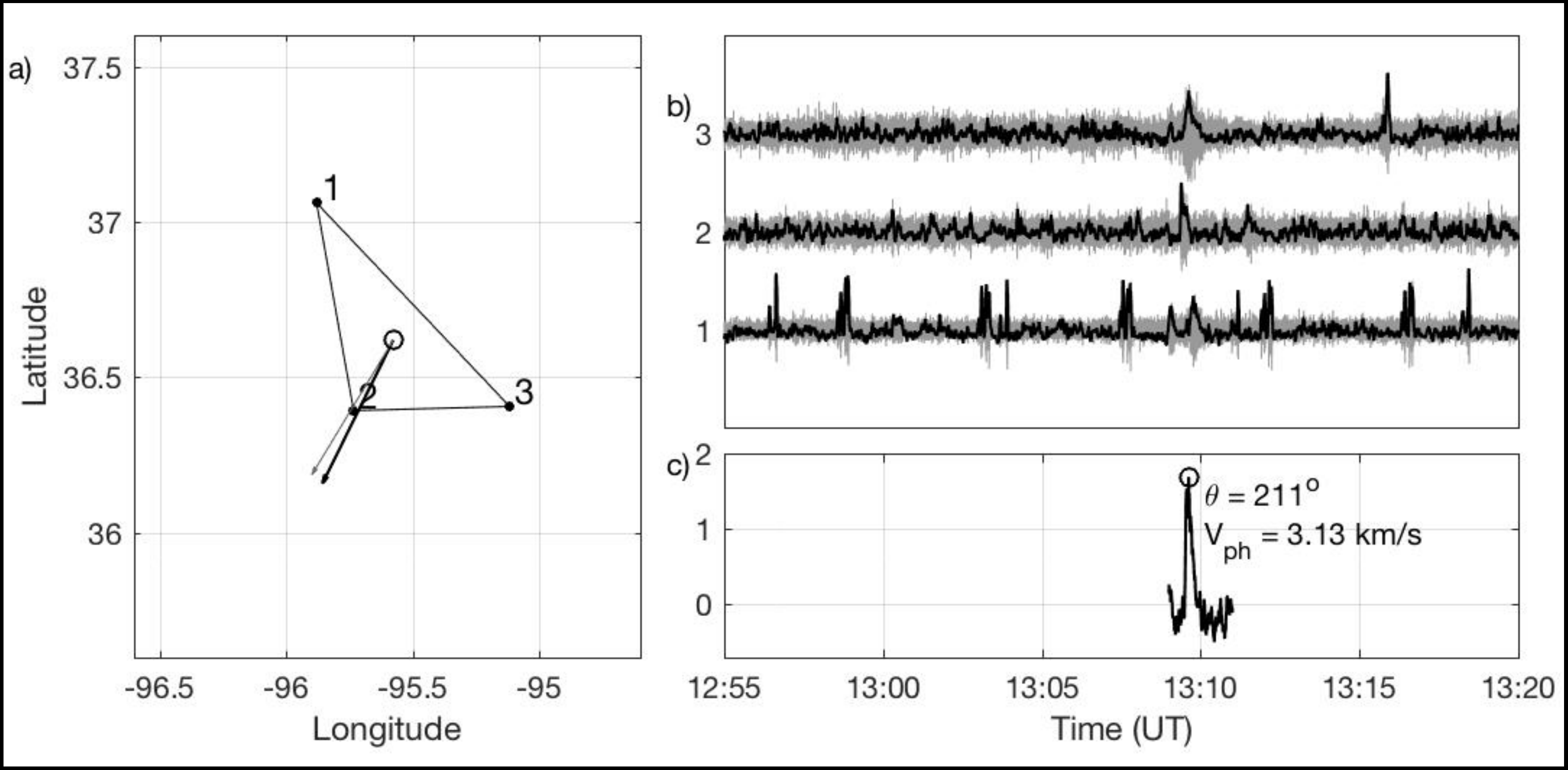
Signal detection – incoherent arrivals



de Groot-Hedlin et al., GJI, 2015

Infrasound signals – wavelength << station spacing

Signal detection – incoherent arrivals

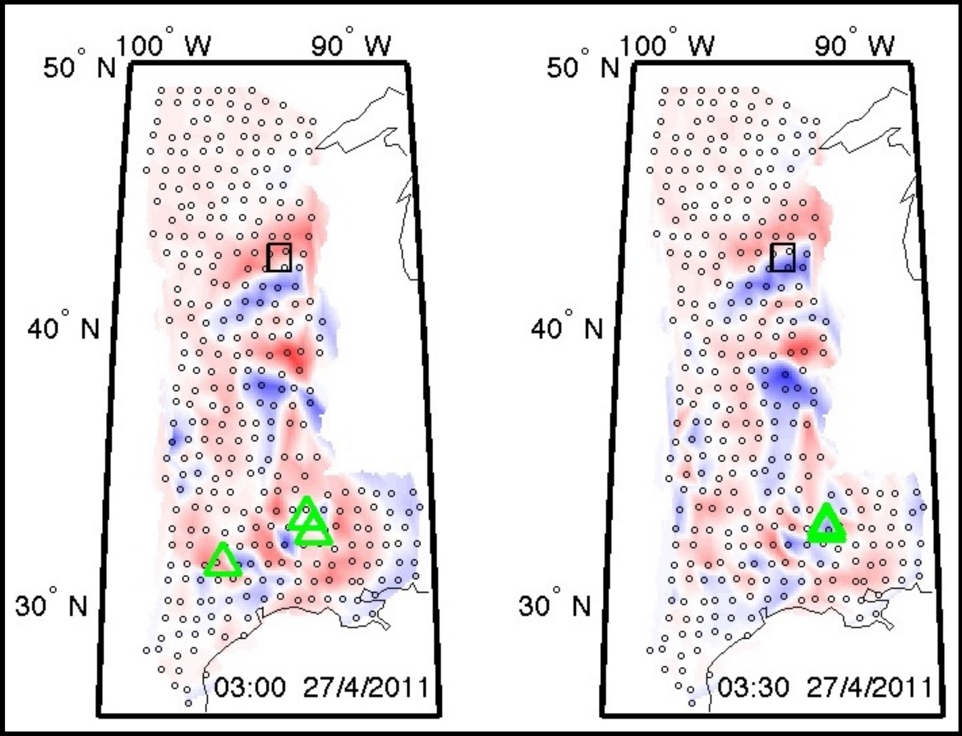


de Groot-Hedlin et al., BSSA, 2018

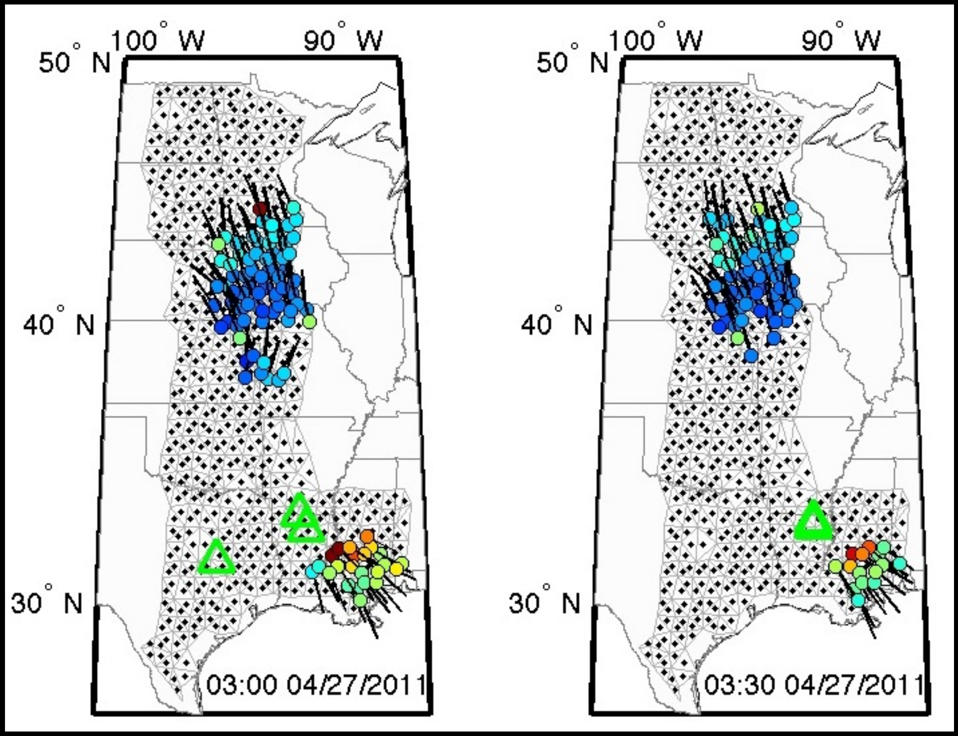
Seismic body waves – wavelength << station spacing
Effective signal detection even for noisy data

Gravity wave detections

Gravity waves at Earth’s surface



Gravity waves detections
-showing direction of propagation



de Groot-Hedlin et al., EPSL, 2014

Gravity Waves: Wavelength >> Station spacing

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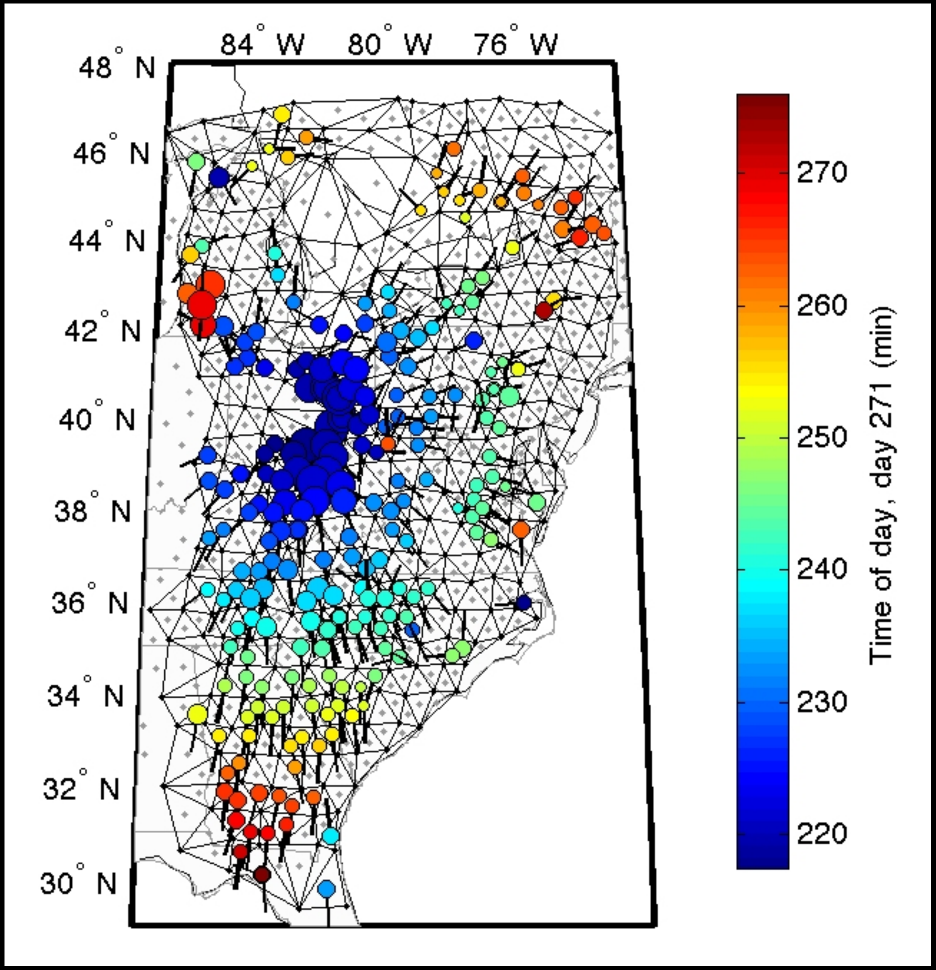
Source Location

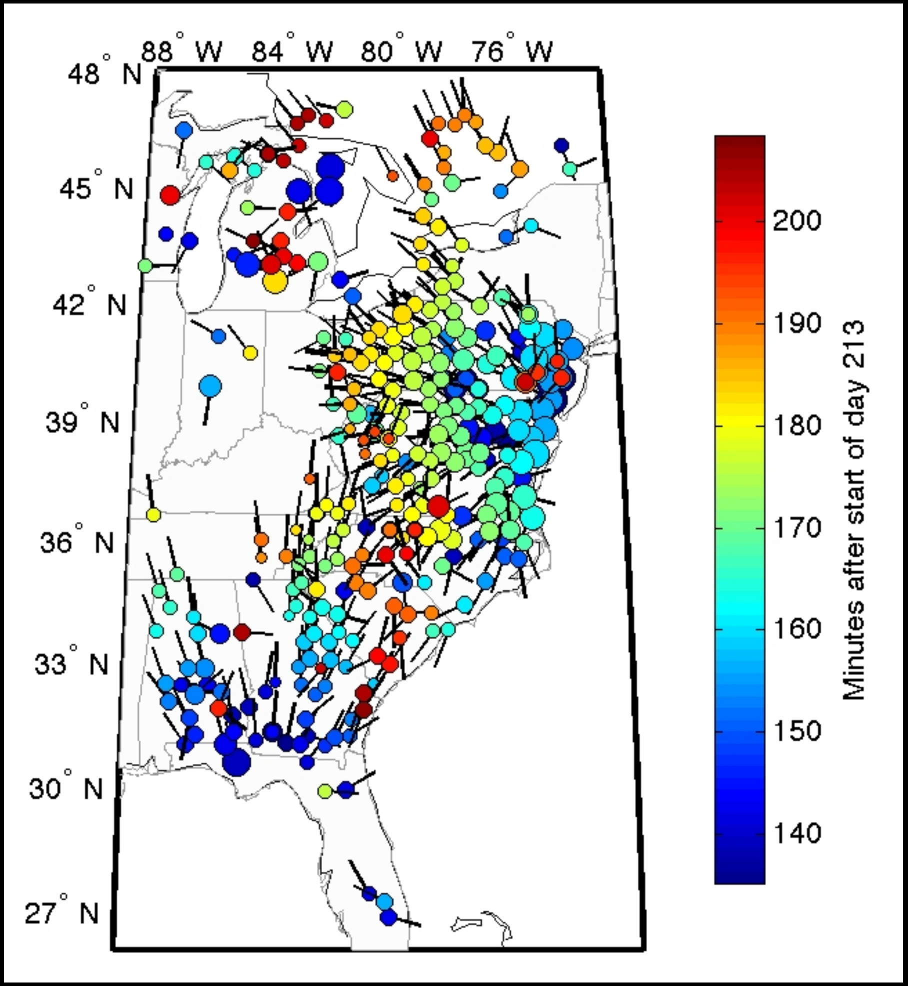
Infrasound detections from a large bolide



Detections over 1 hour - All detected signals are associated with 1 source

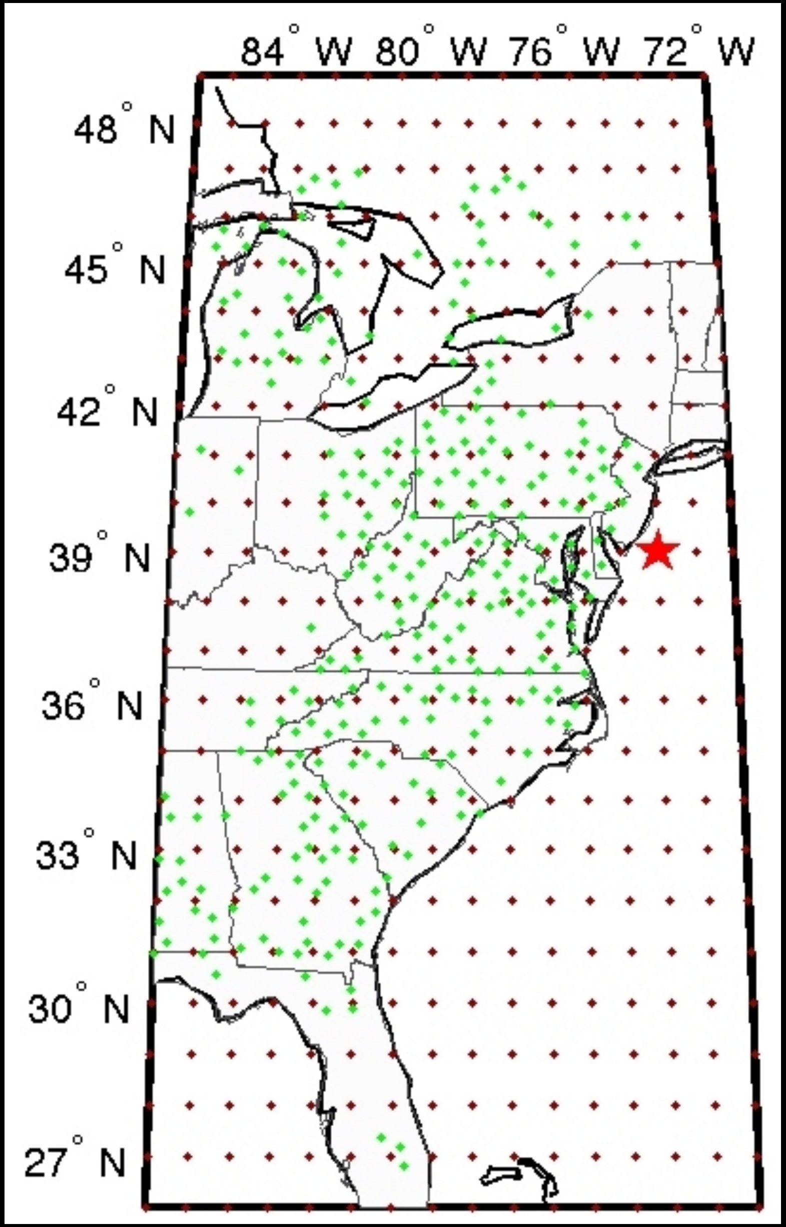
de Groot-Hedlin et al., GJI, 2015

More common example – nearly simultaneous signal arrivals



Detections within 75 minutes - Separate detections into clusters, each associated with a single event

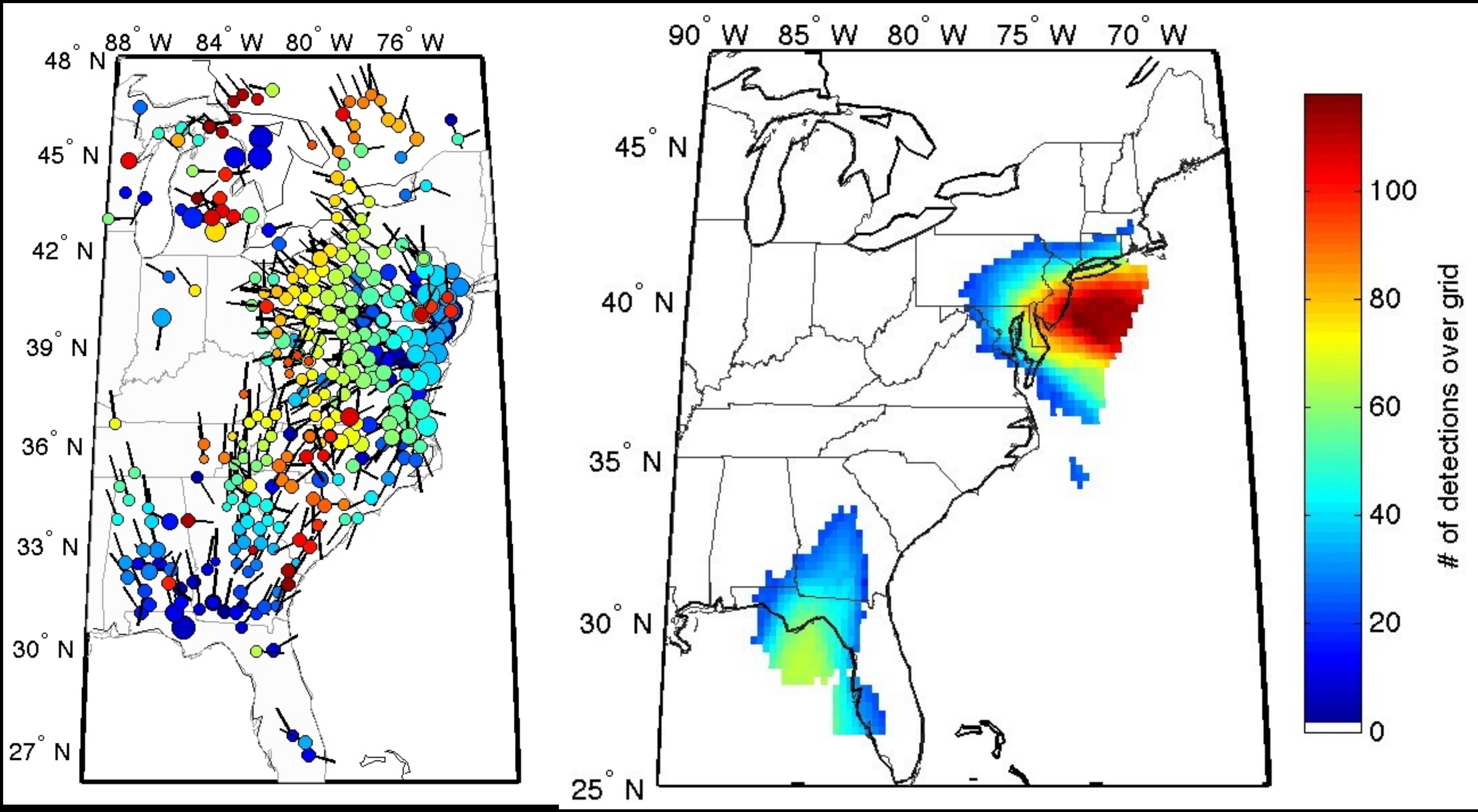
Infrasound data

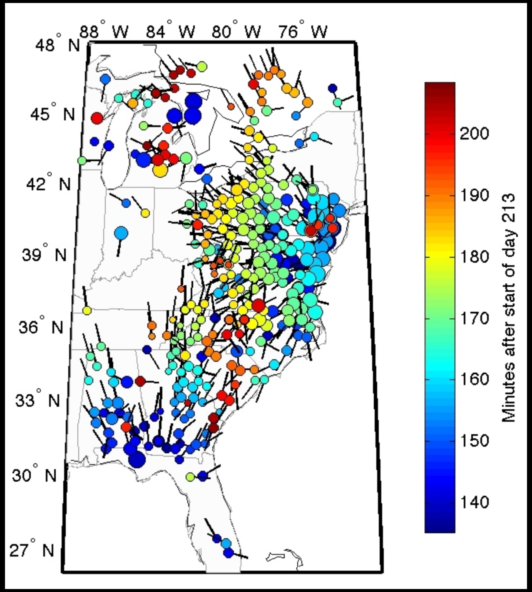


Source search

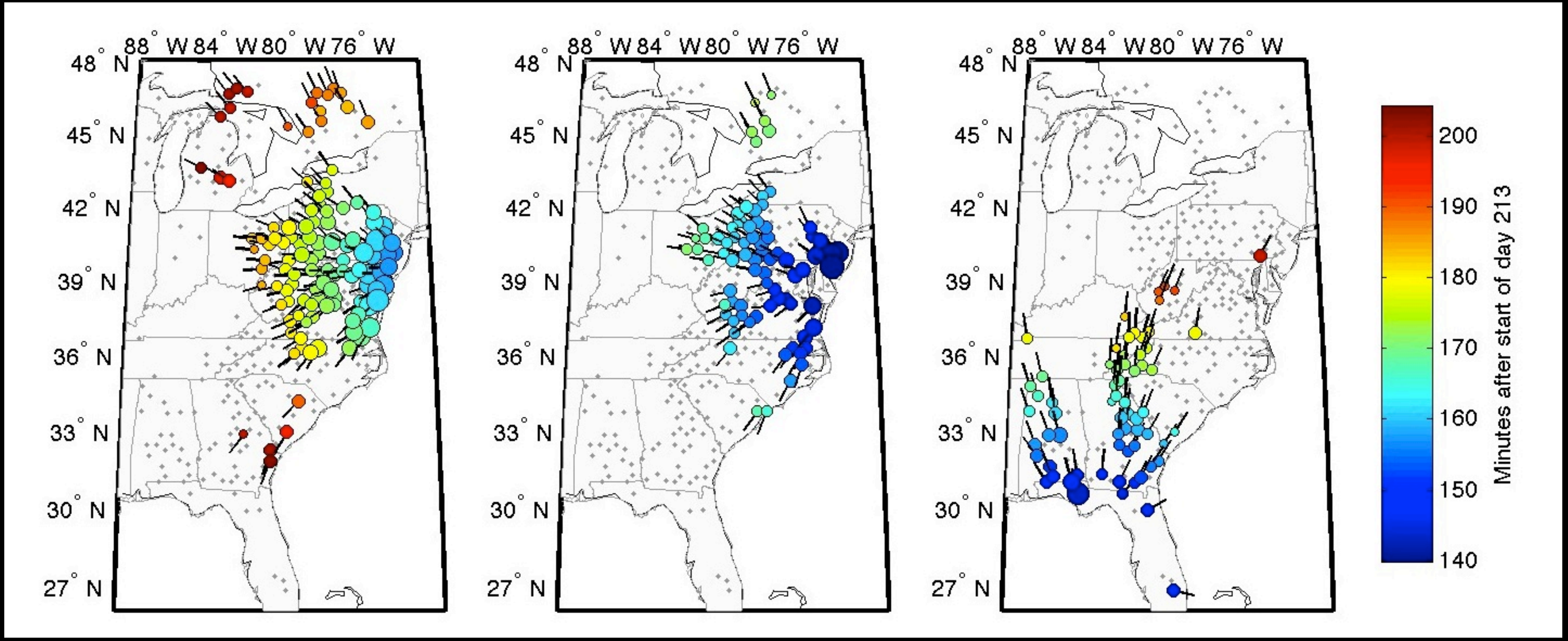
- Define a grid of hypothetical sources
- For each grid point, find detections with a consistent azimuth and travel time
- Find the grid point consistent with largest subset of the detections
- Each detection cluster is removed from population
- For each cluster, a finer grid of hypothetical sources is used to refine each source location

More common example



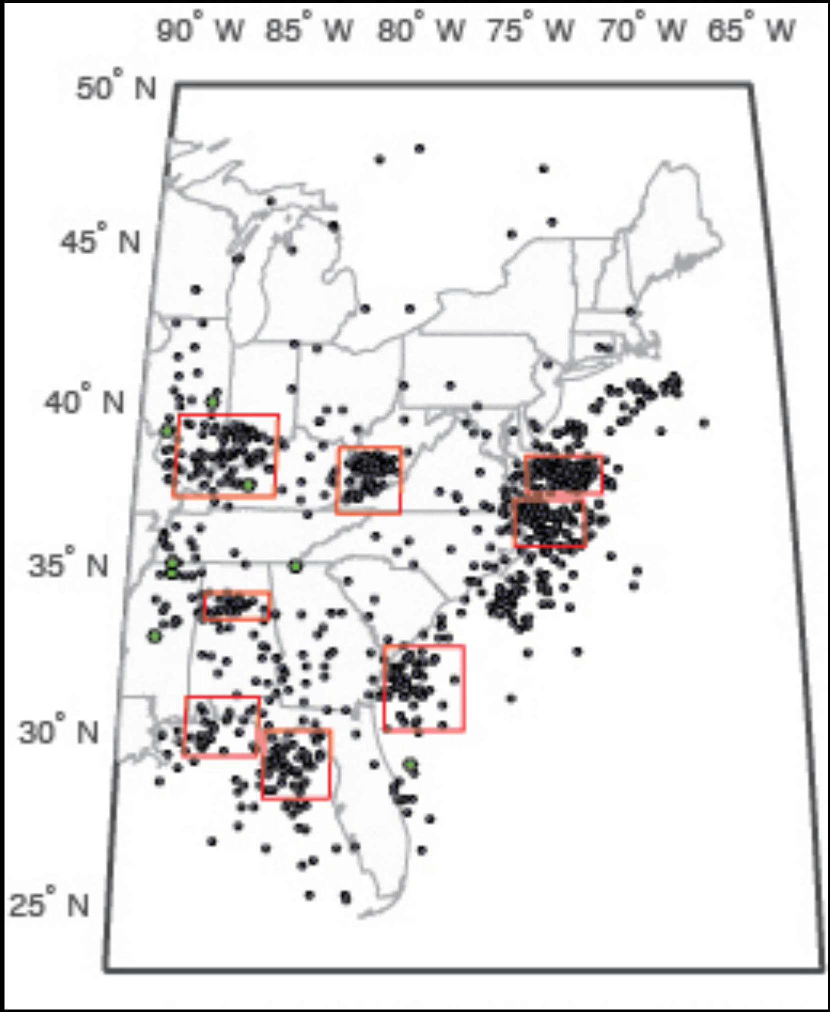


Detections divided into separate clusters



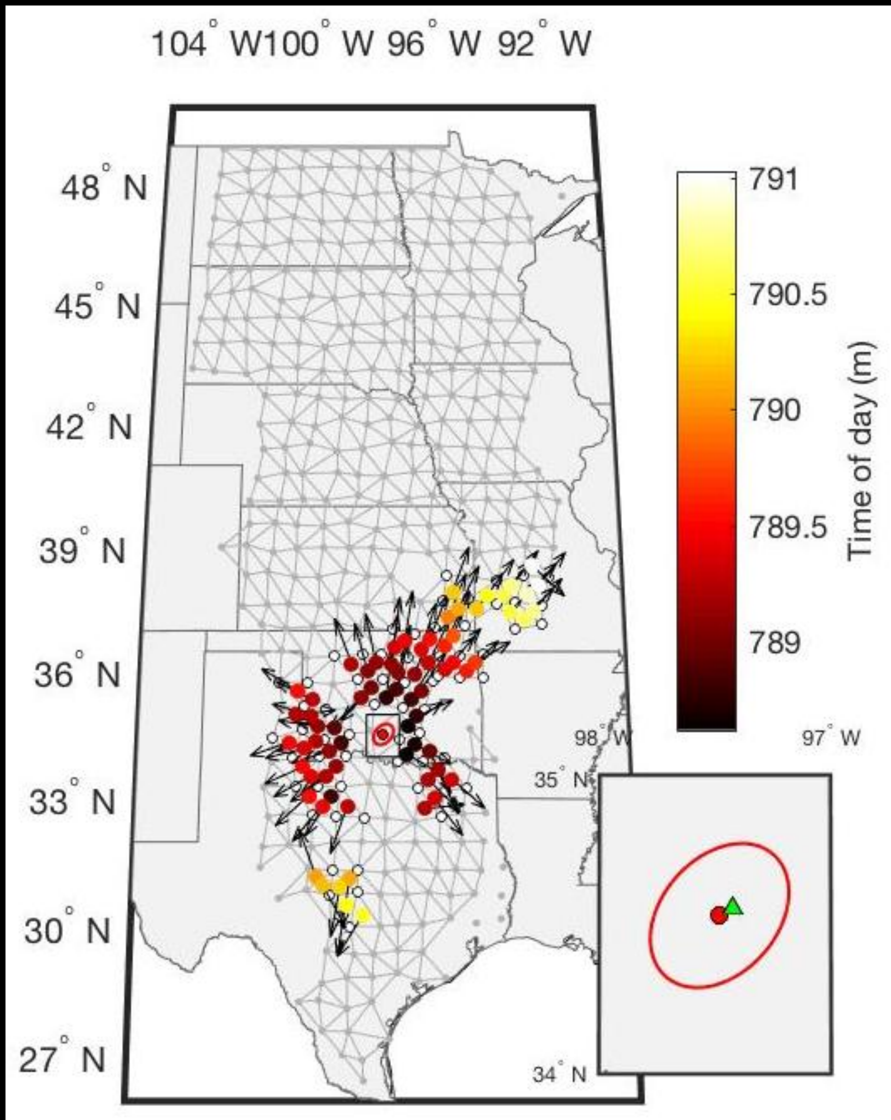
de Groot-Hedlin et al., GJI, 2015

Example output catalog



- Identified clusters of infrasound events offshore and onshore largely due to mining

Source location uncertainty



(Seismic body wave example)

- Each source location is associated with an error ellipse (shown in inset)

de Groot-Hedlin et al., BSSA, 2018

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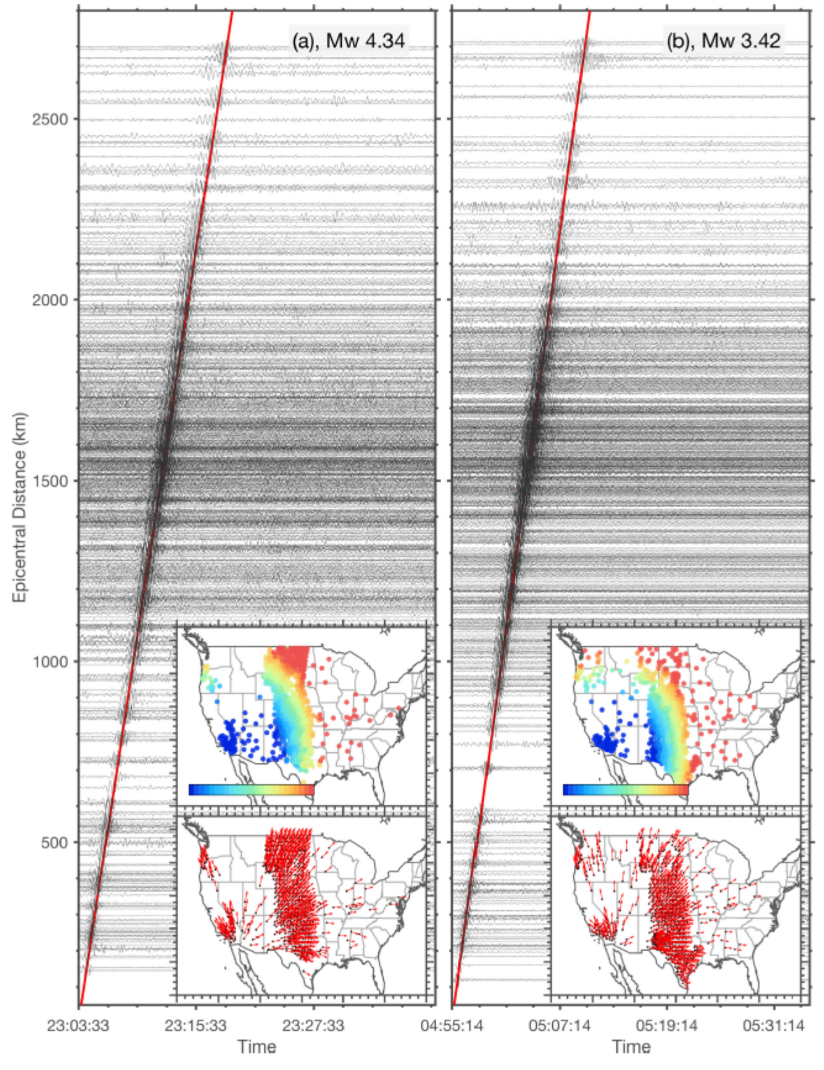
Coherent signal detections



Seismic surface waves – wavelength << station spacing

Color-coding: time of arrival

Direction of propagation

Fan et.al (2018) Geop. J. Int

Concluding remarks

- Dense sensor networks are becoming common, increasing the need for efficient data mining algorithms
- Detect infrasound, seismic body, seismic surface, gravity waves
- The AELUMA method detects (without analyst oversight)
  - Both coherent & incoherent signals
  - Does not rely on knowledge of velocity structure
- AELUMA has been used to create source catalogs for
  - Infrasound
  - Seismic body waves
  - Surface waves
- The catalogs reveal previously undetected sources

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