

# The study of atmospheric phenomena using seismic networks

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# Outline

- ① A few words about infrasound; what it is and why we are interested
- ② Finding atmospheric events using seismic data
- ③ Probing the atmosphere using these events



# A little history (of infrasound)



US Civil War

If only General Grant knew more  
about how sound travels ...



Battle of Luca, September 19, 1862

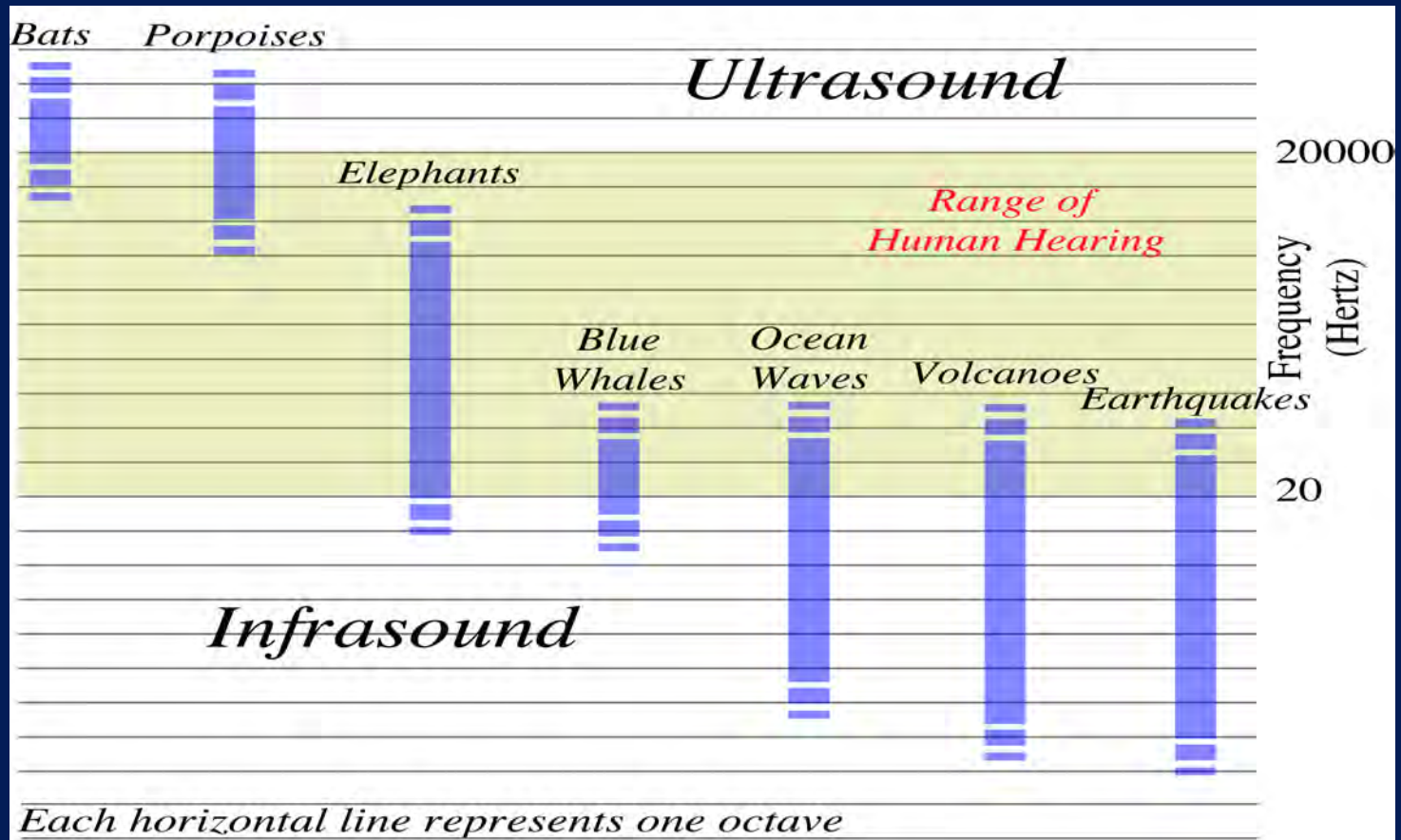
If only General Grant knew more  
about how sound travels ...



Battle of Iuka, September 19, 1862



# The Acoustic Spectrum



GAMMA RAYS

X - RAYS

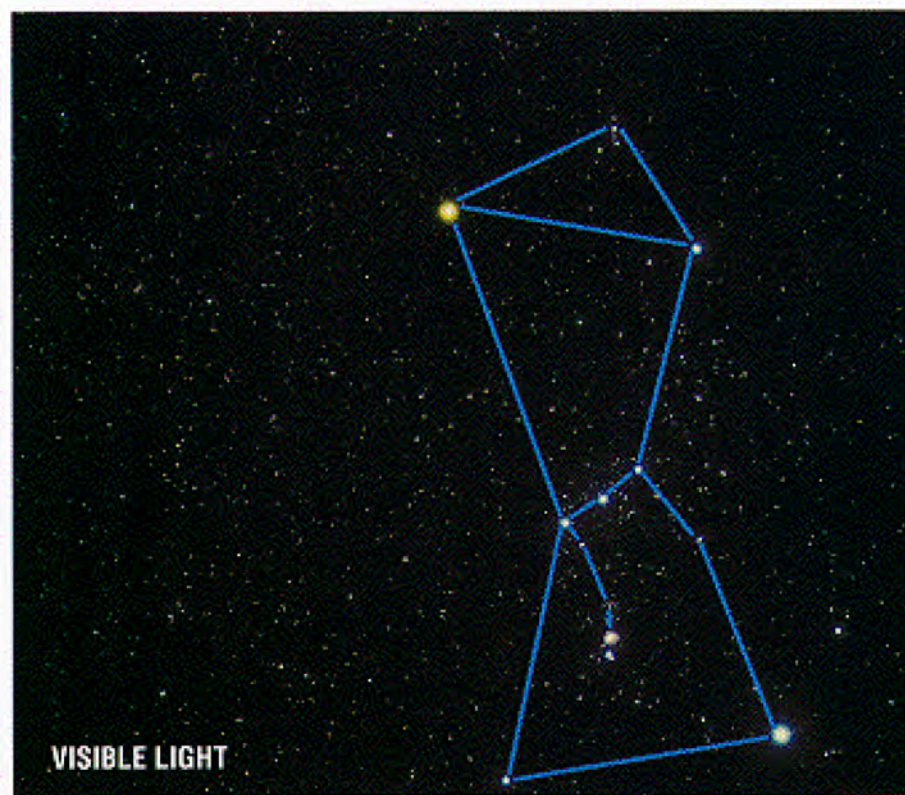
UV

VISIBLE

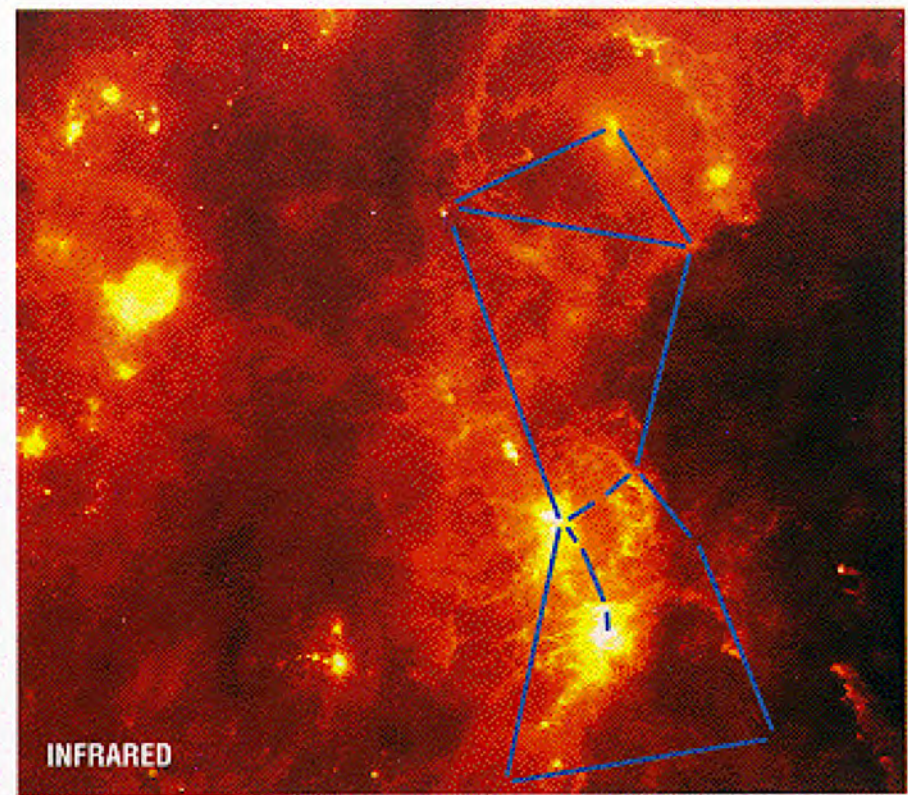
INFRARED

RADIO

# Orion



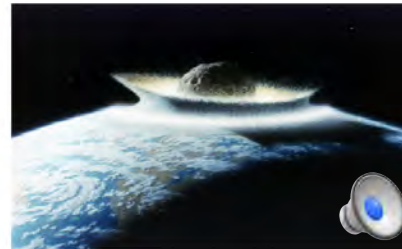
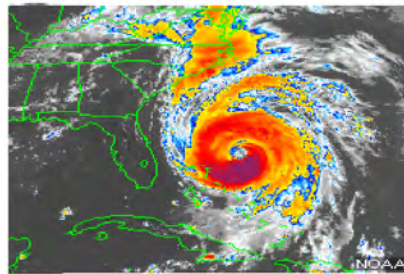
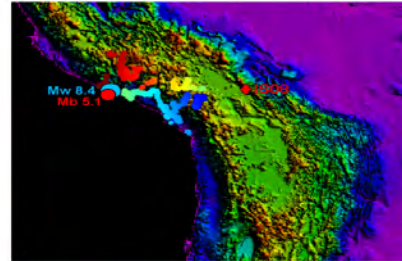
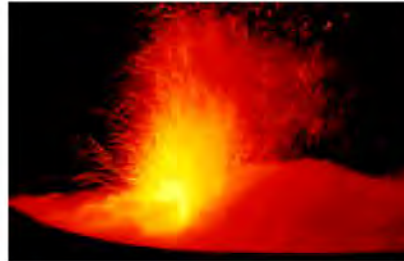
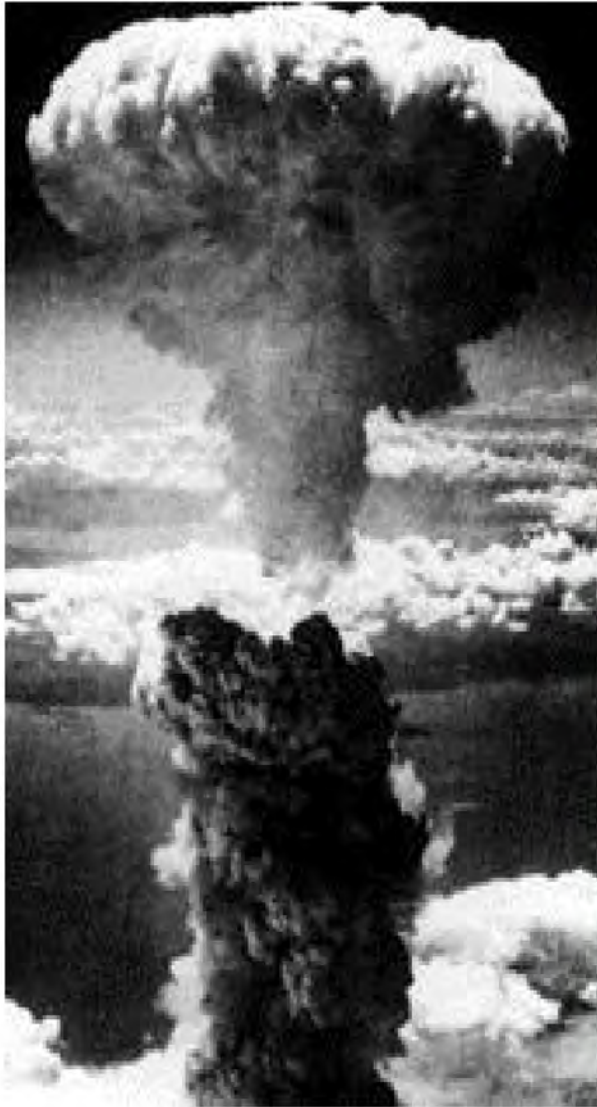
Visible light



Infrared

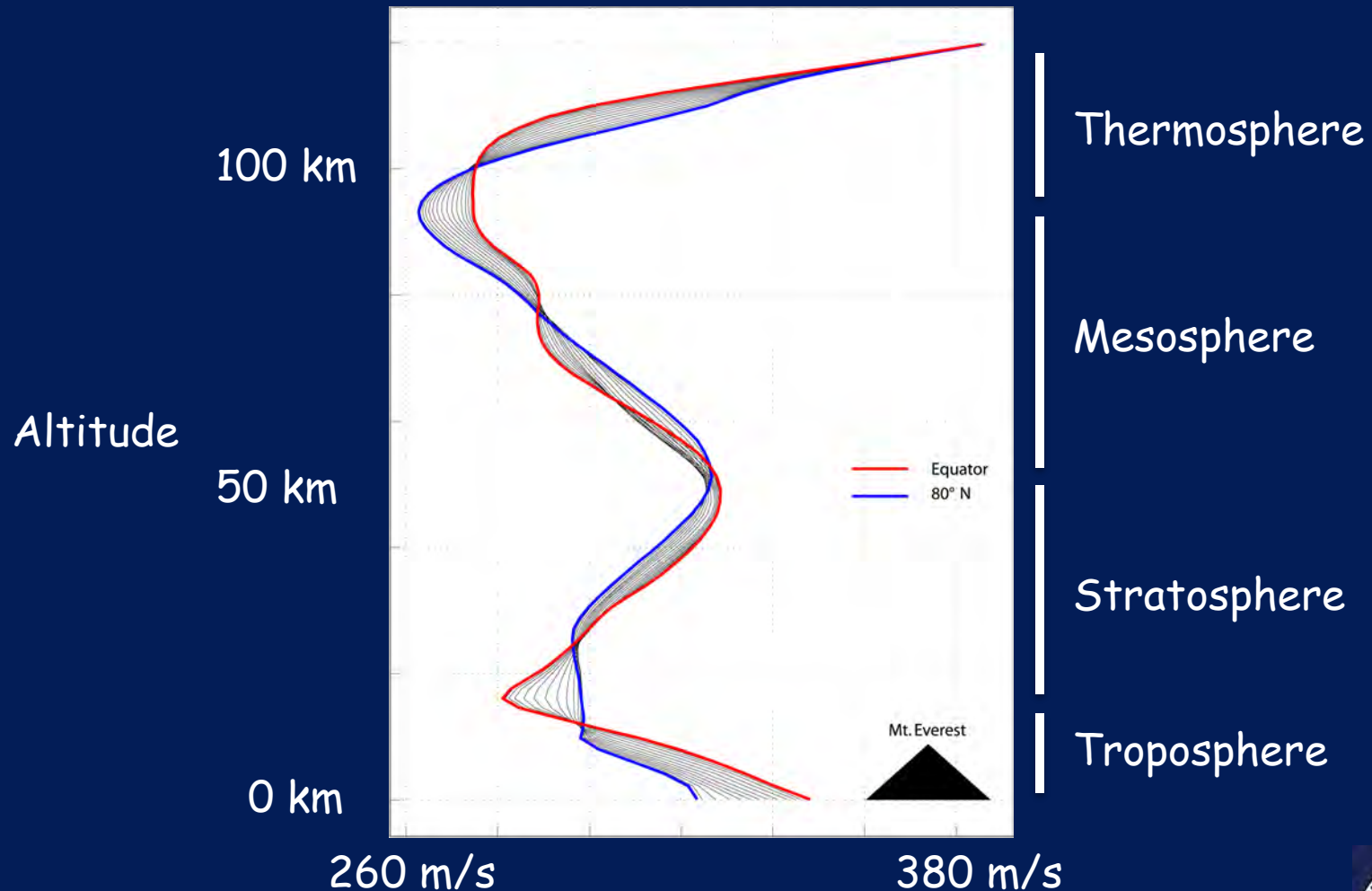


# *Some Infrasound Sources*

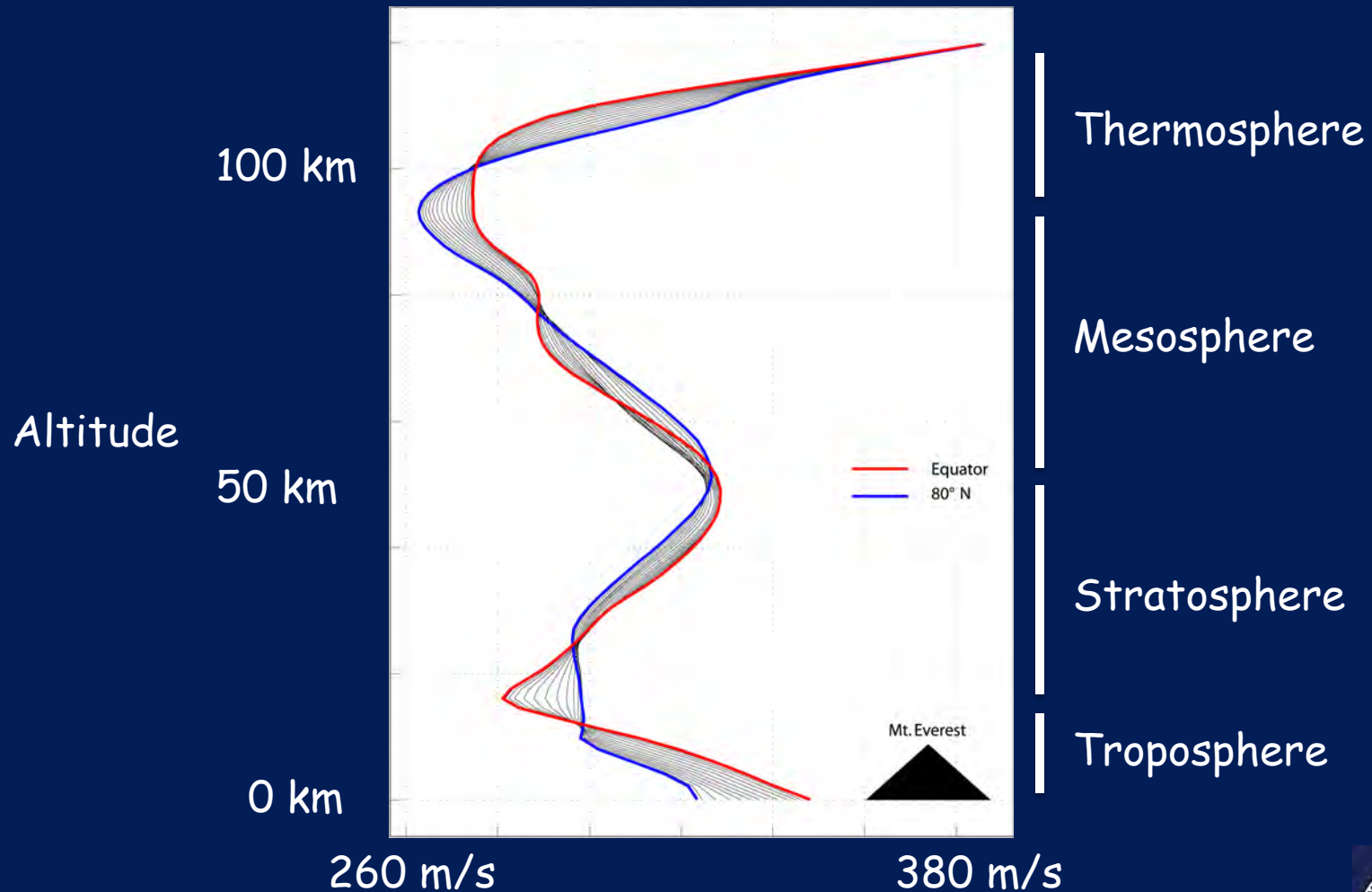




# *The speed of sound*

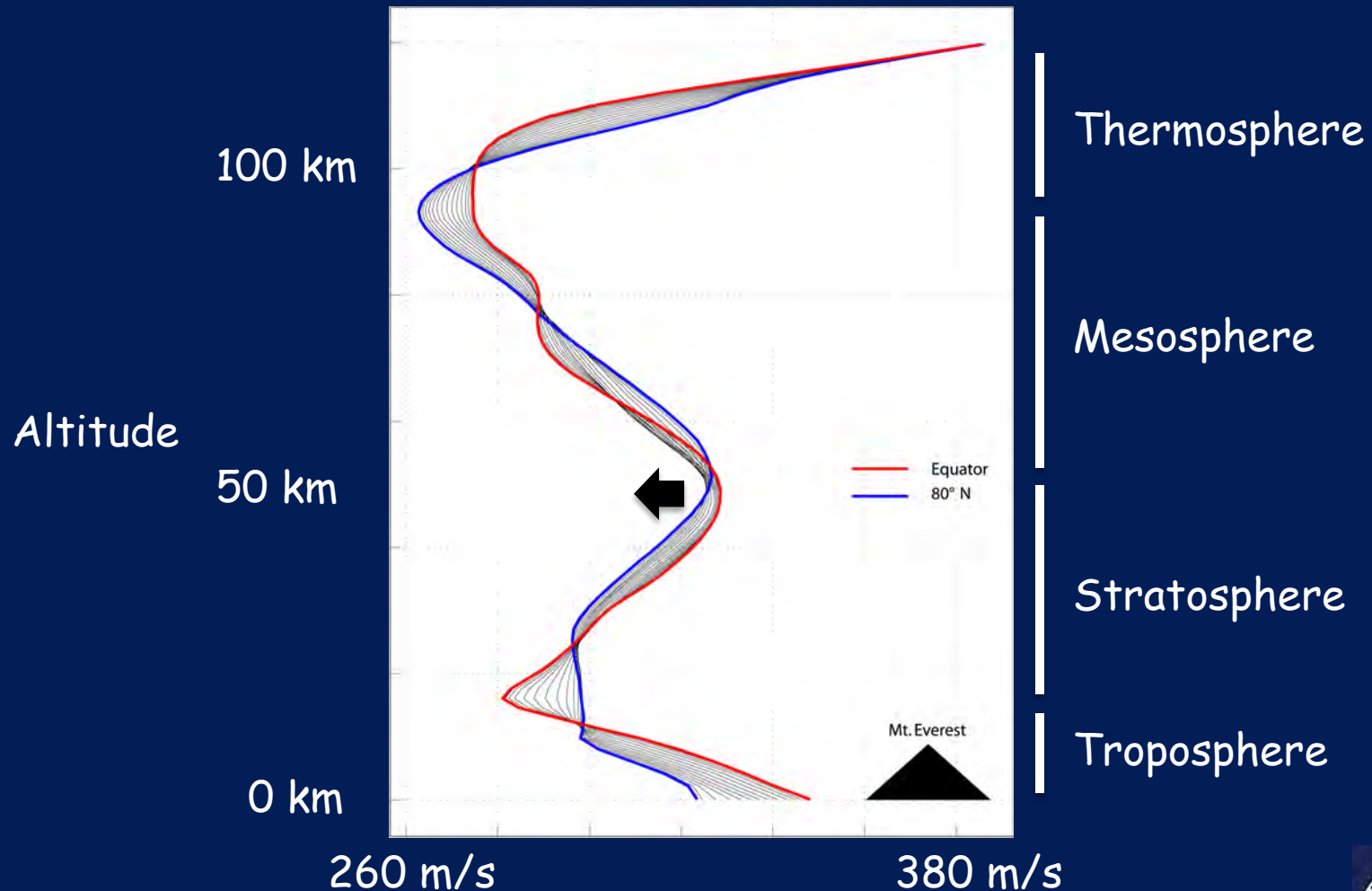


# *The speed of sound*



$$c = 20.05 \sqrt{T + \vec{v} \cdot \hat{k}}$$

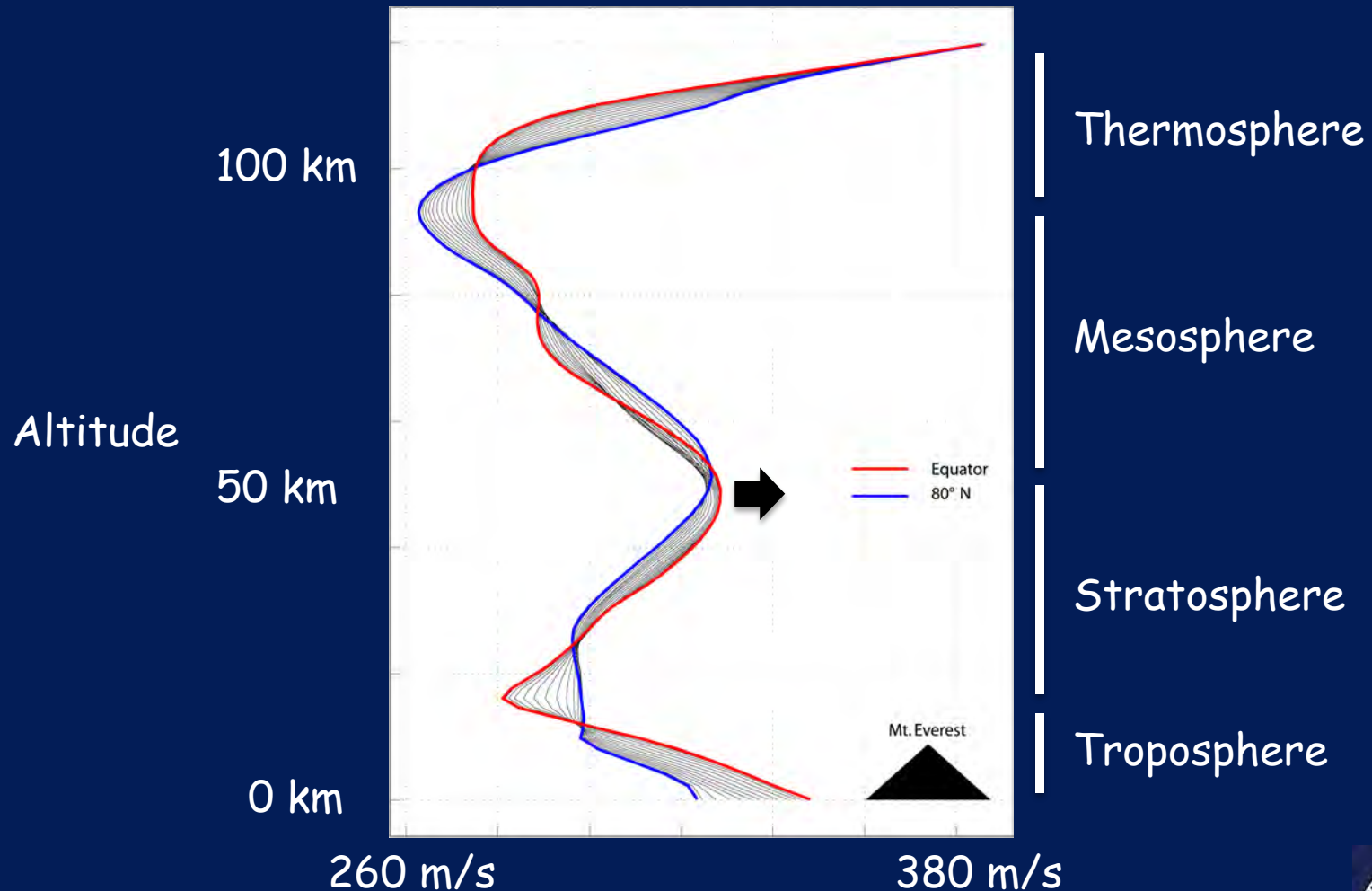
# *The speed of sound*



$$c = 20.05 \sqrt{T} + \vec{v} \cdot \hat{k}$$

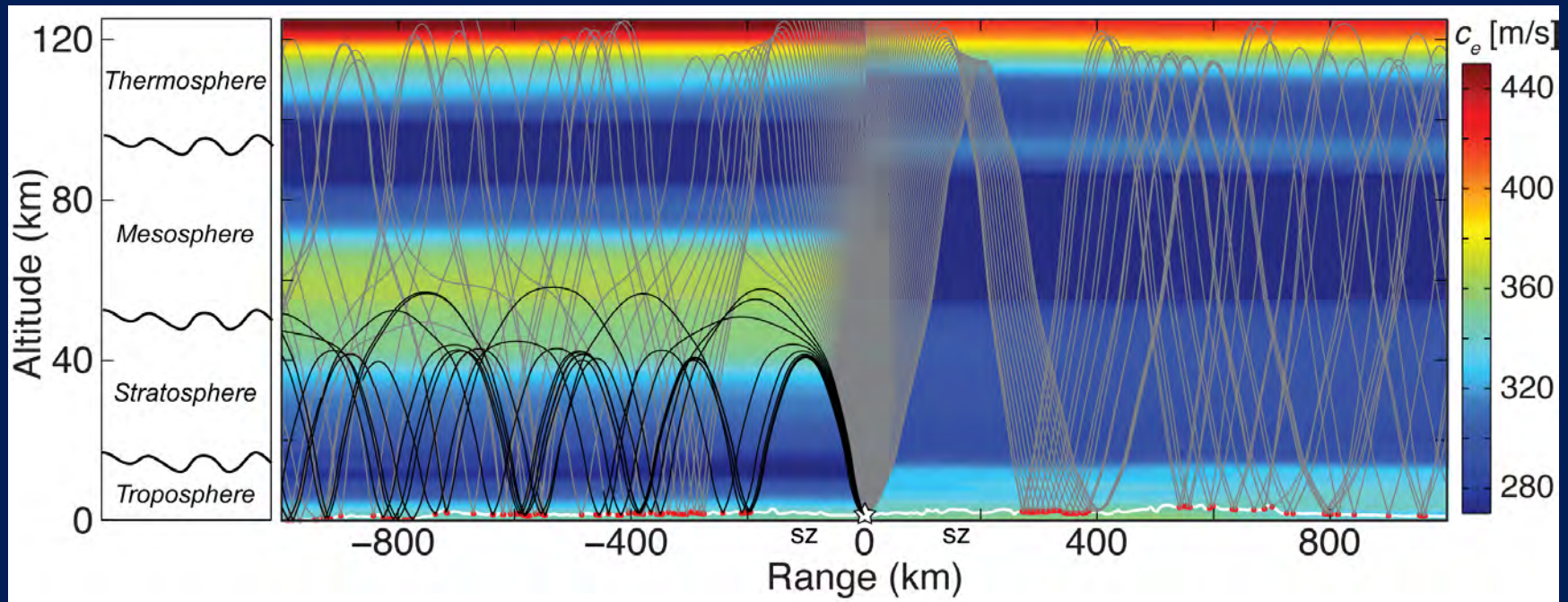


# *The speed of sound*



$$c = 20.05 \sqrt{T + \vec{v} \cdot \hat{k}}$$

# Sound speed is anisotropic



← West

Source

East →

Summertime in Utah



# The global infrasound network



*Good for nuclear monitoring, less useful for research*



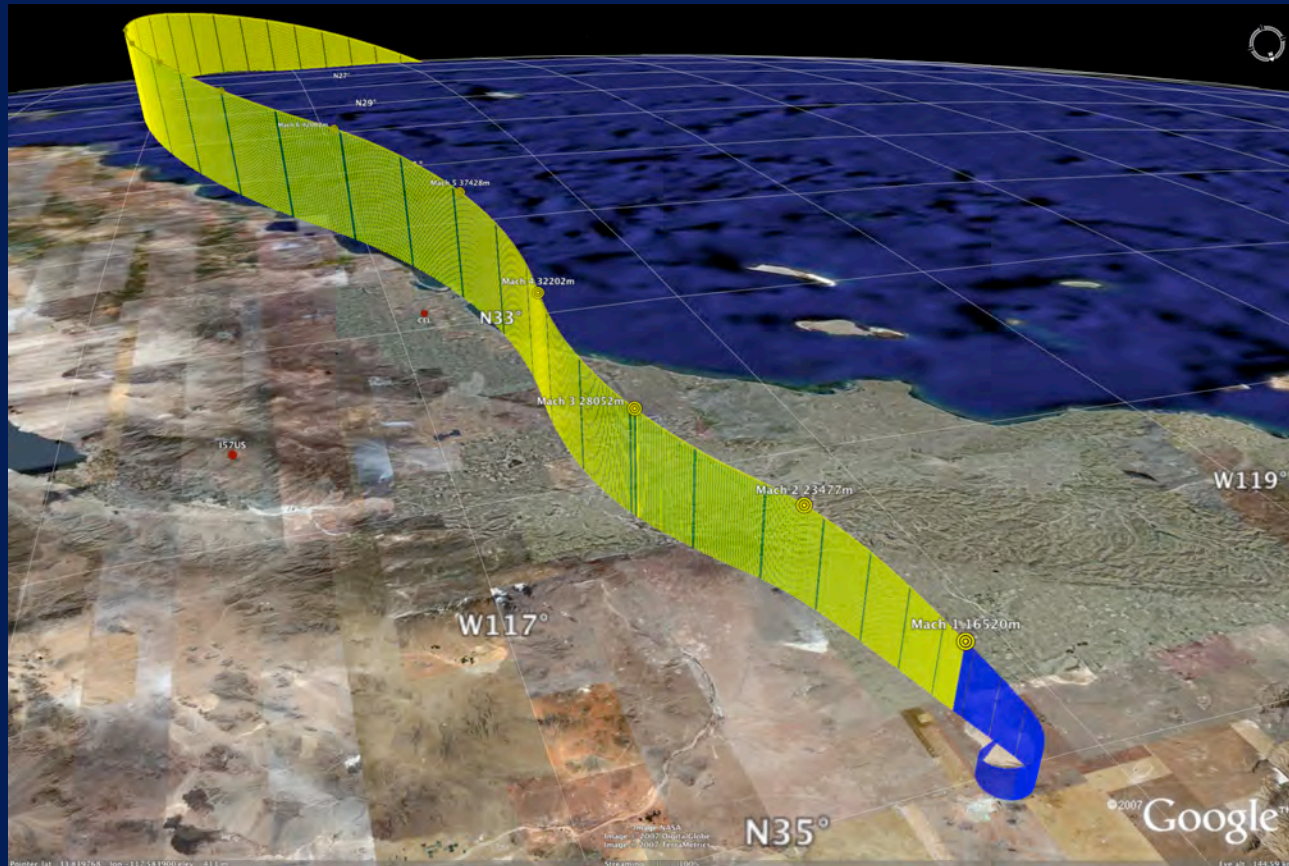


# Seismic studies of the atmosphere

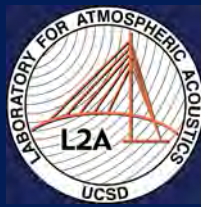
- Atmospheric pressure waves convert to seismic
- Over 10,000 seismic stations worldwide



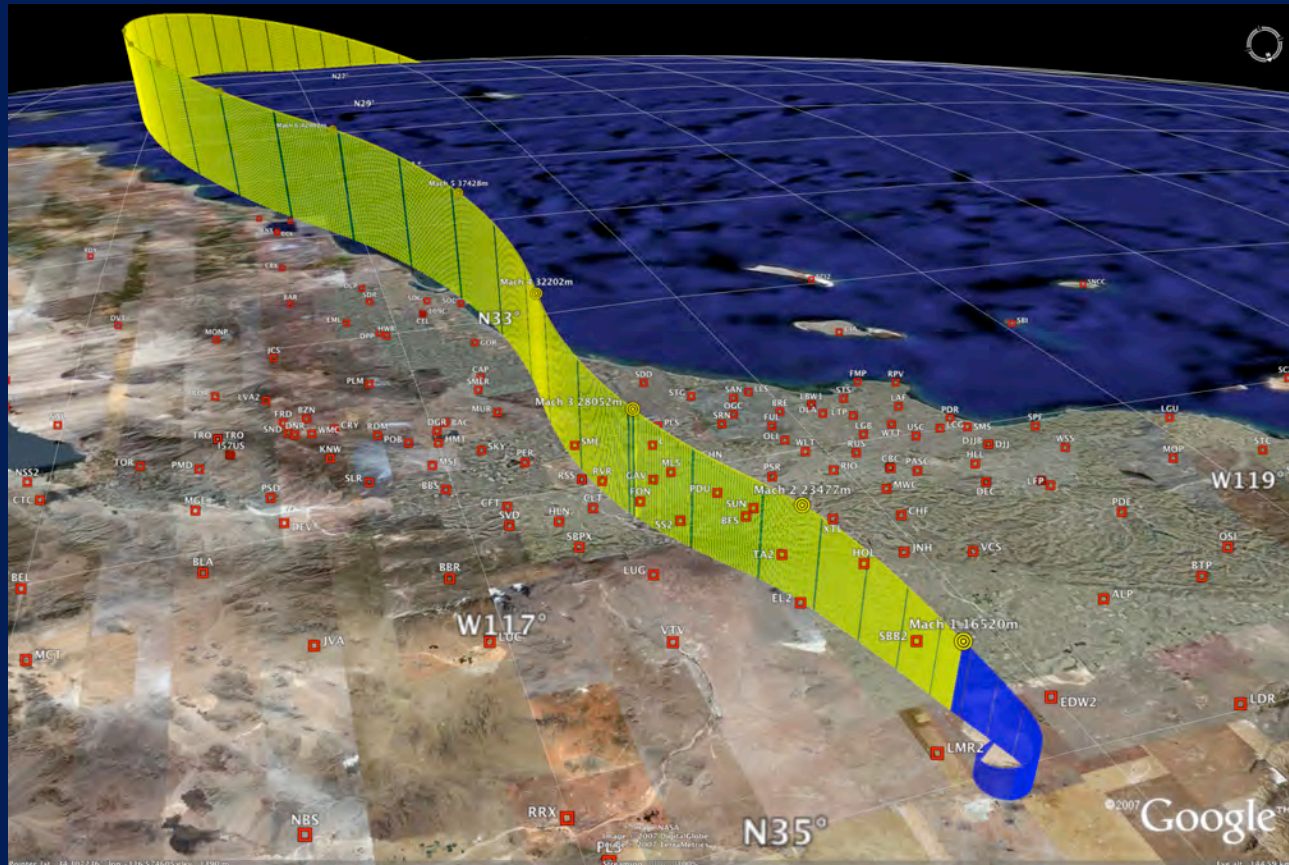
# Shuttle Atlantis: example signal



June, 2007



# Shuttle Atlantis: example signal

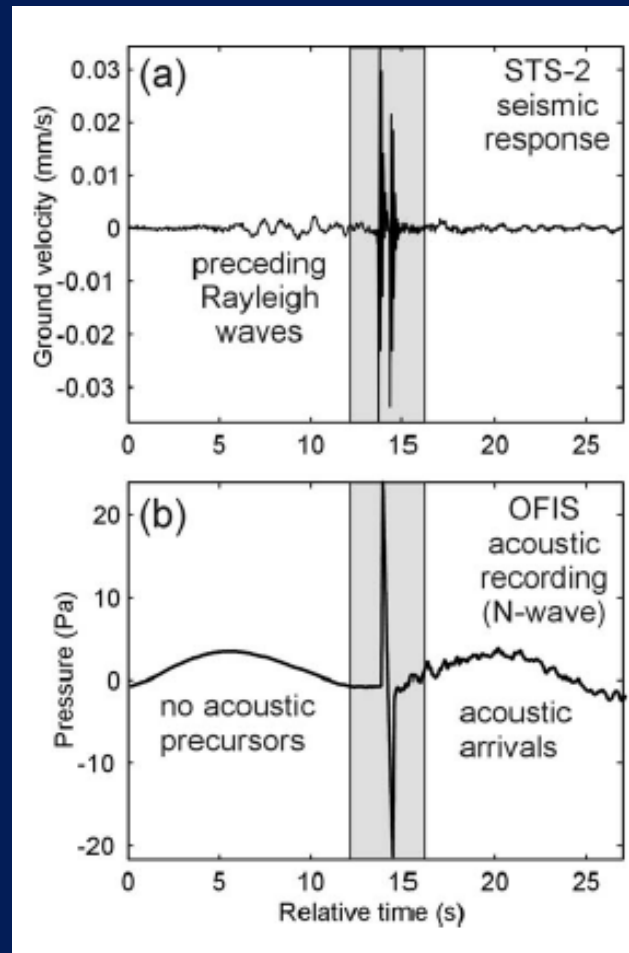


June, 2007





# Shuttle Atlantis: example signal



Seismic signal

Infrasonic signal

From seismic station in southern California



# USArray Transportable Array





# February, 2006



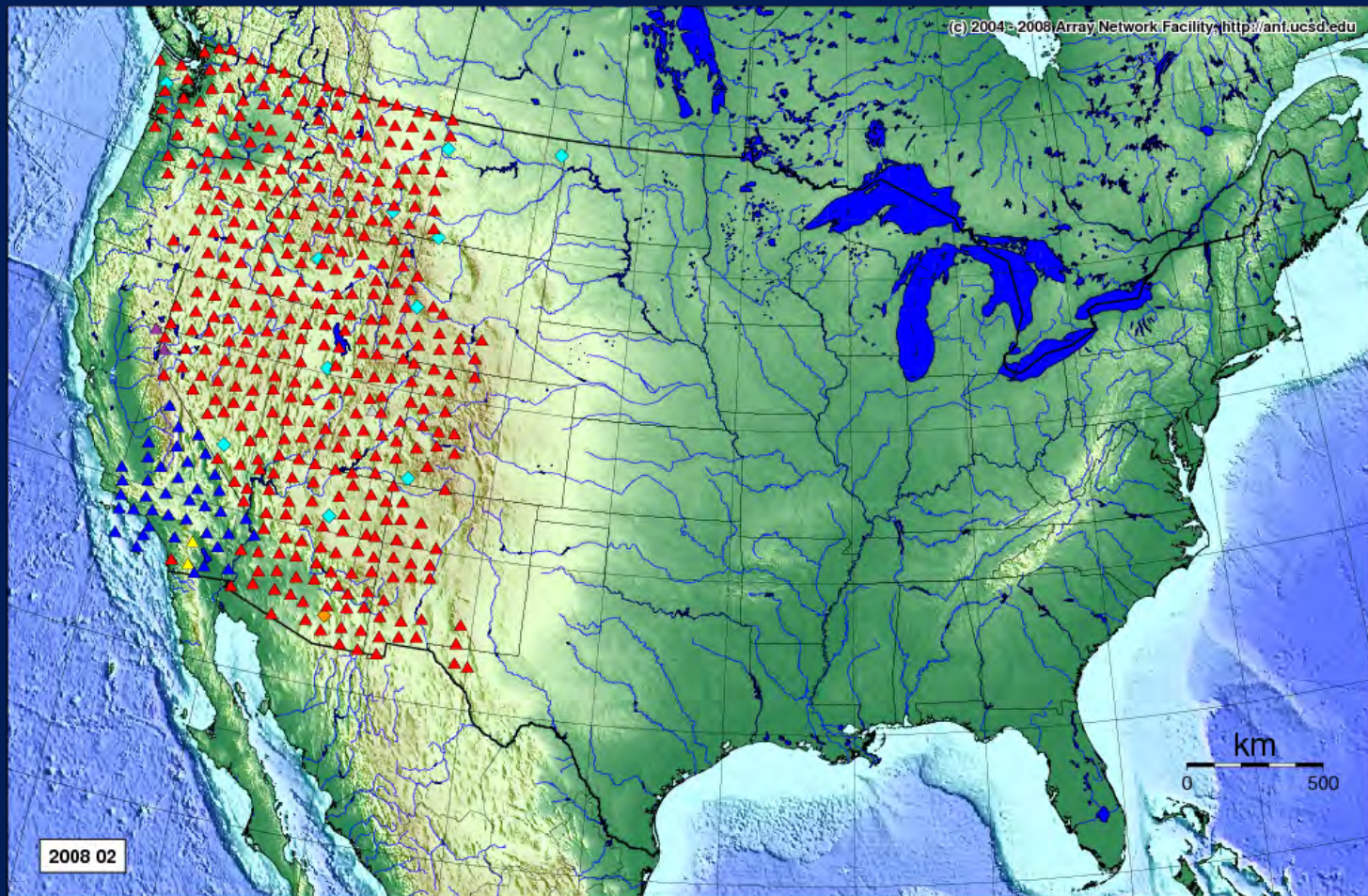


# February, 2007



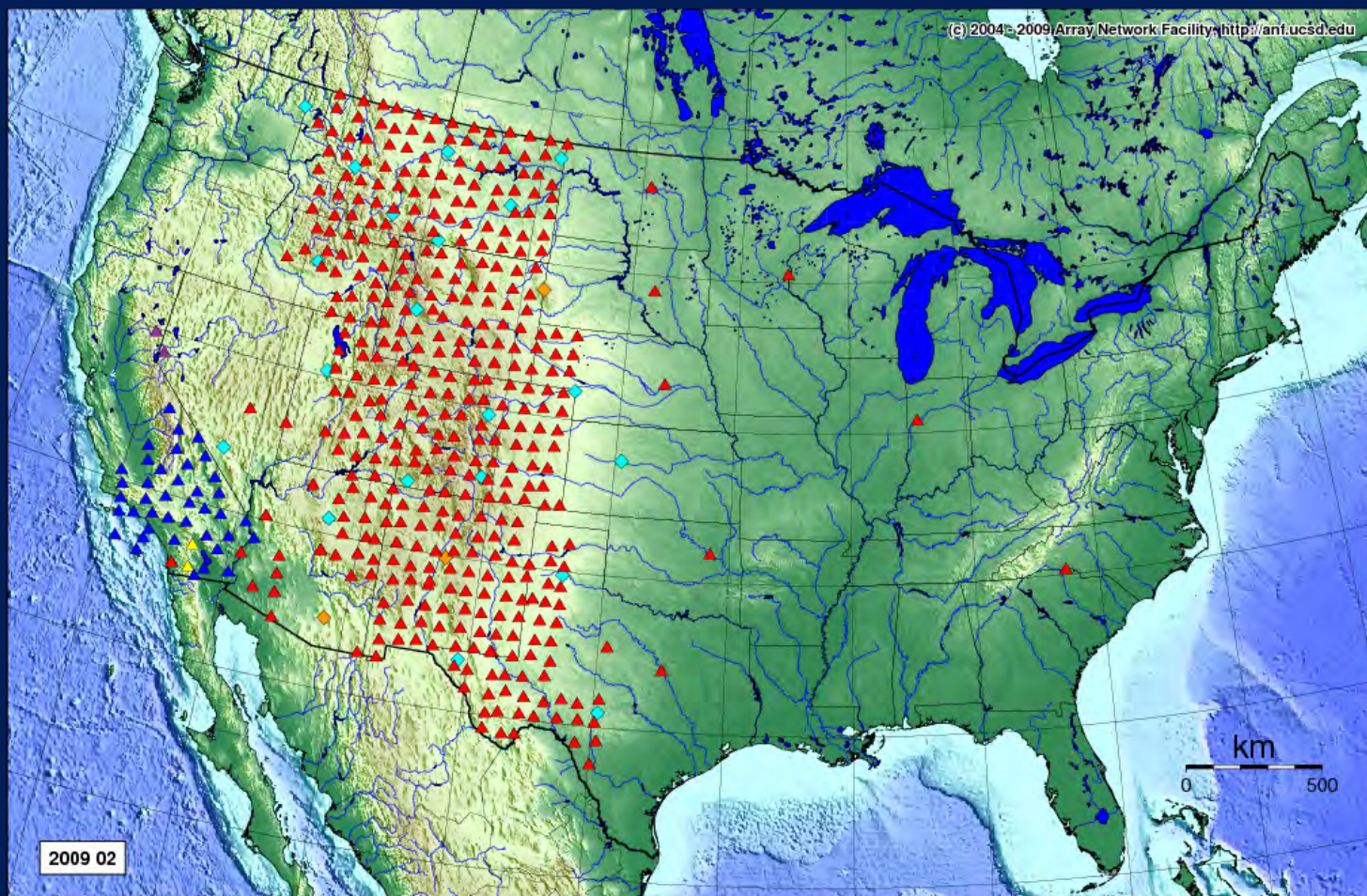


# February, 2008





# February, 2009



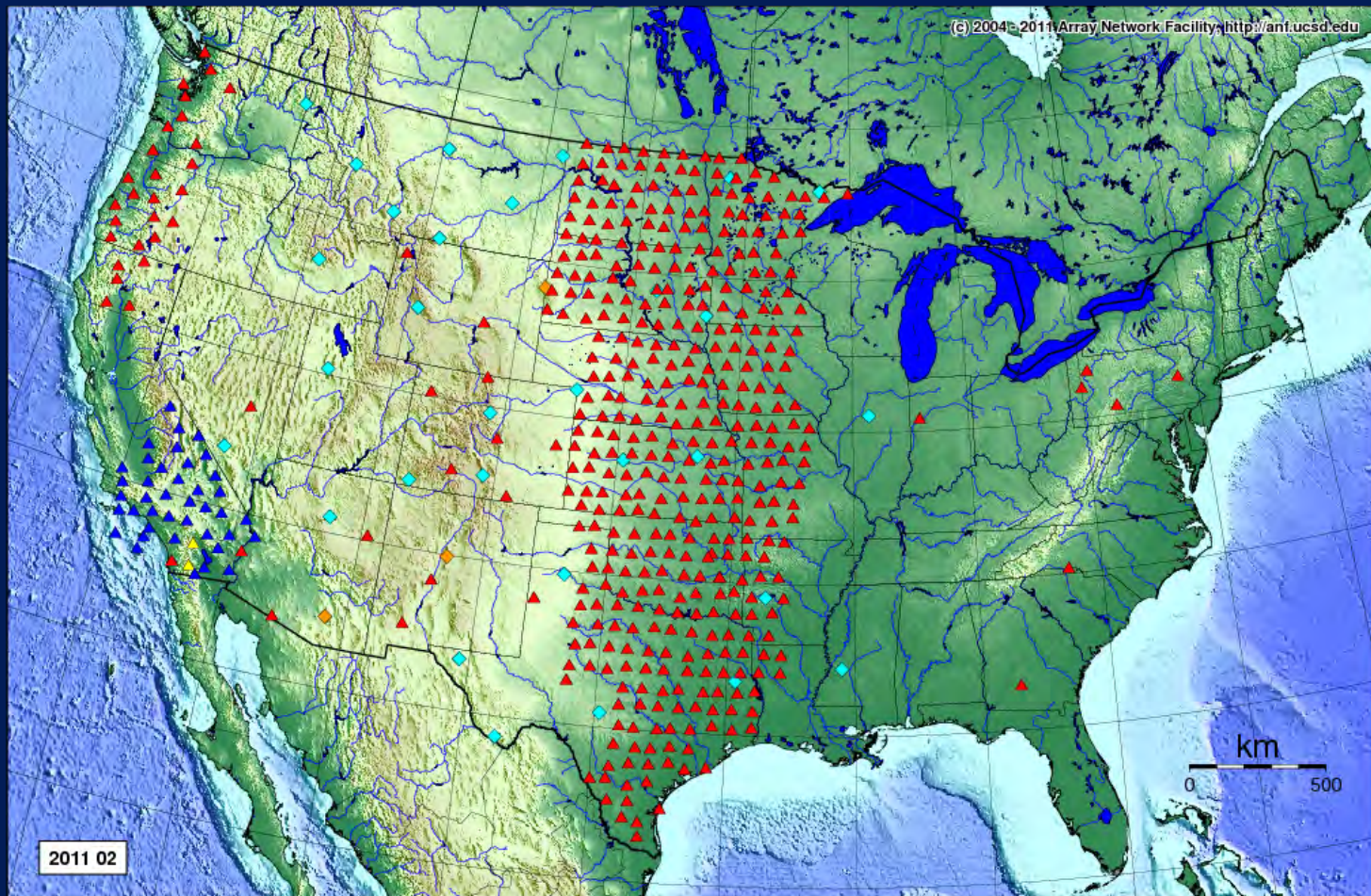


# February, 2010





# February, 2011





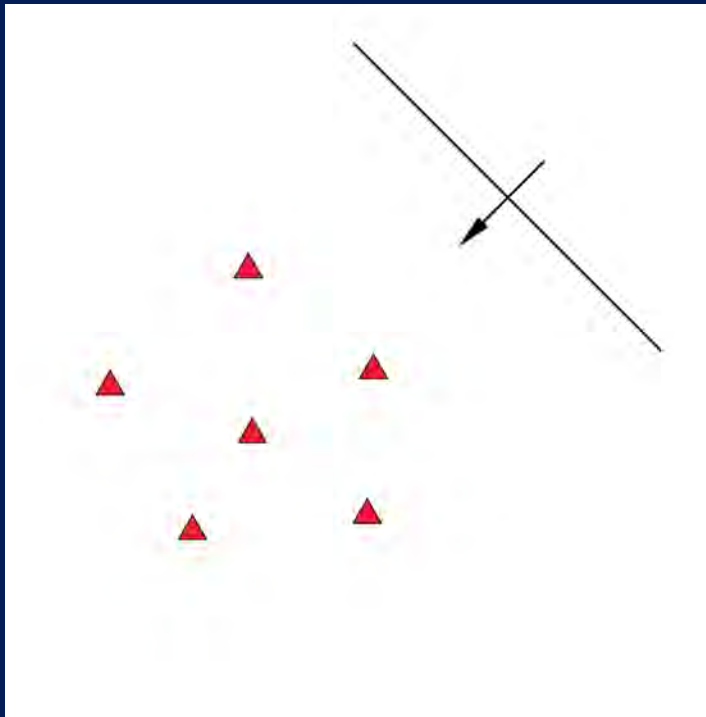
# February, 2011 (with IMS stations)



First: how do we find sources  
in the atmosphere  
using seismometers?

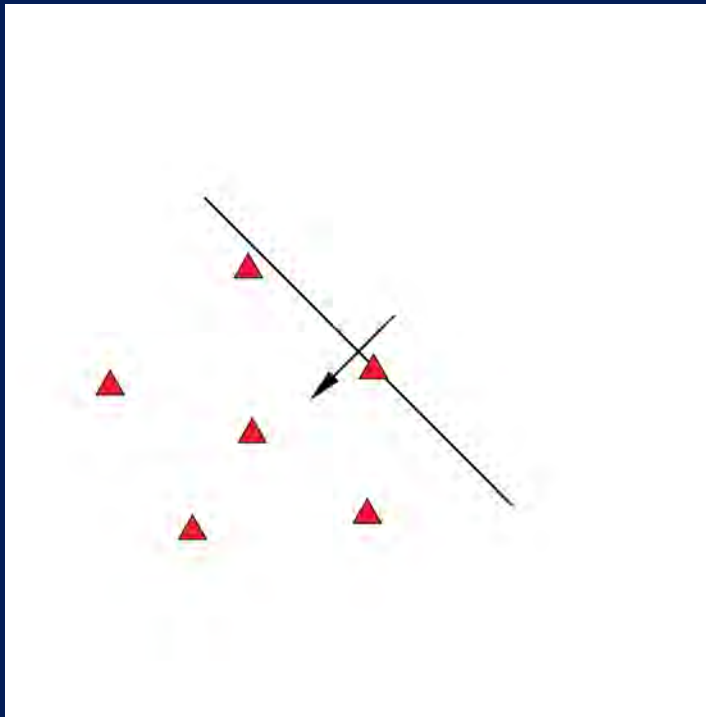


# Simple delay and sum beamforming

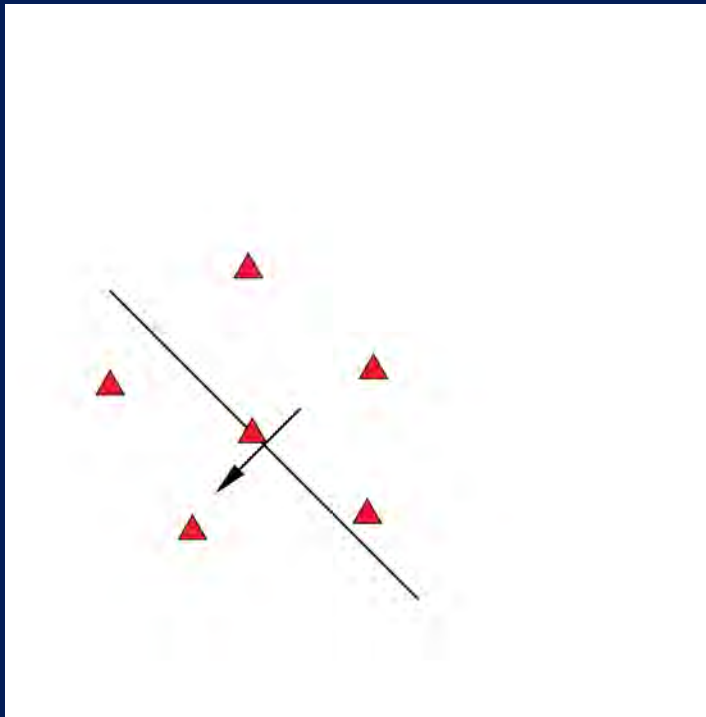




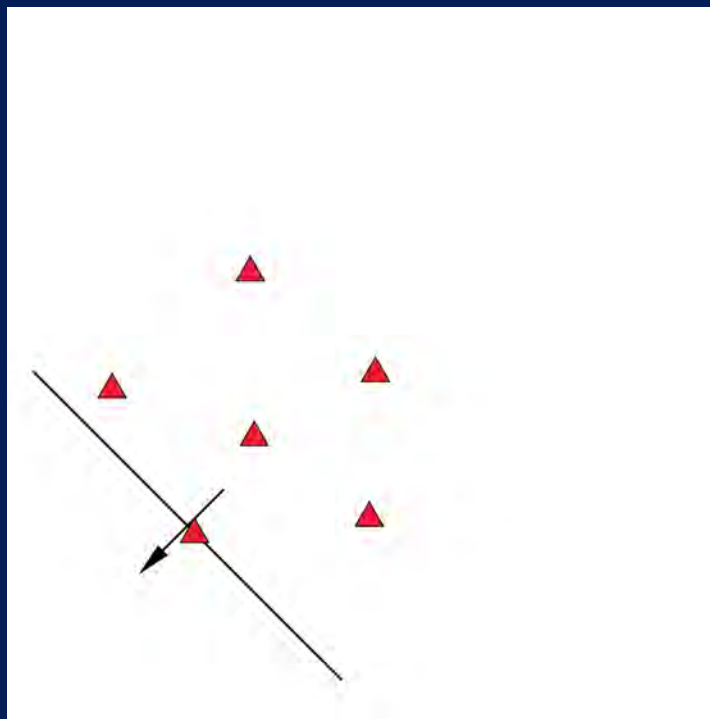
# Simple delay and sum beamforming



# Simple delay and sum beamforming



# Simple delay and sum beamforming



Have  $n$  stations

Want to stack recordings to enhance incoming signal

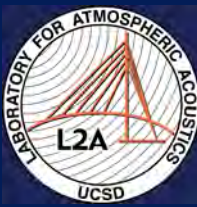
Beam function ( $B$ )

$$B(t, \theta, \nu) = \sum_i^n a_i(t + t_0(\theta, \nu, r_x, r_y))$$

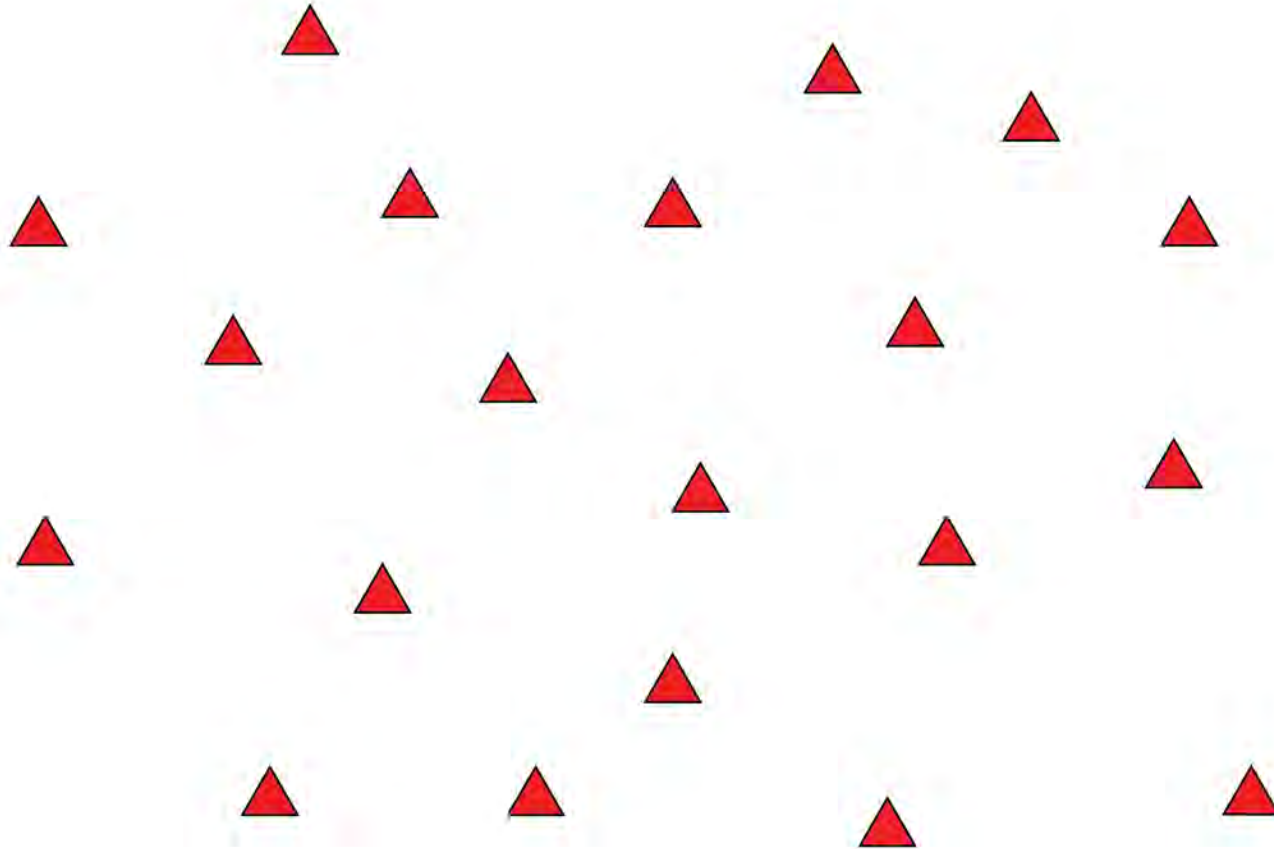


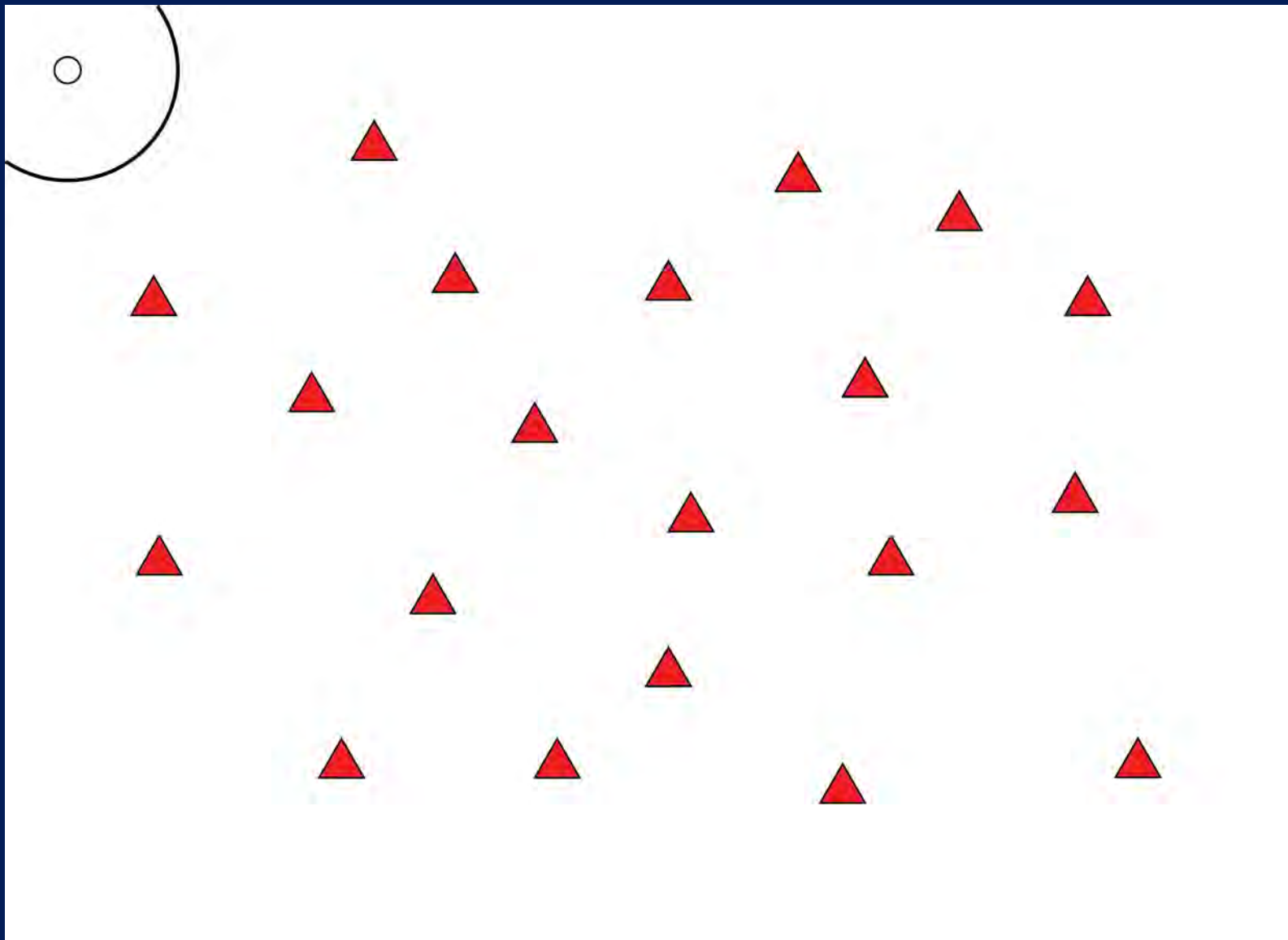
# Reverse Time Migration

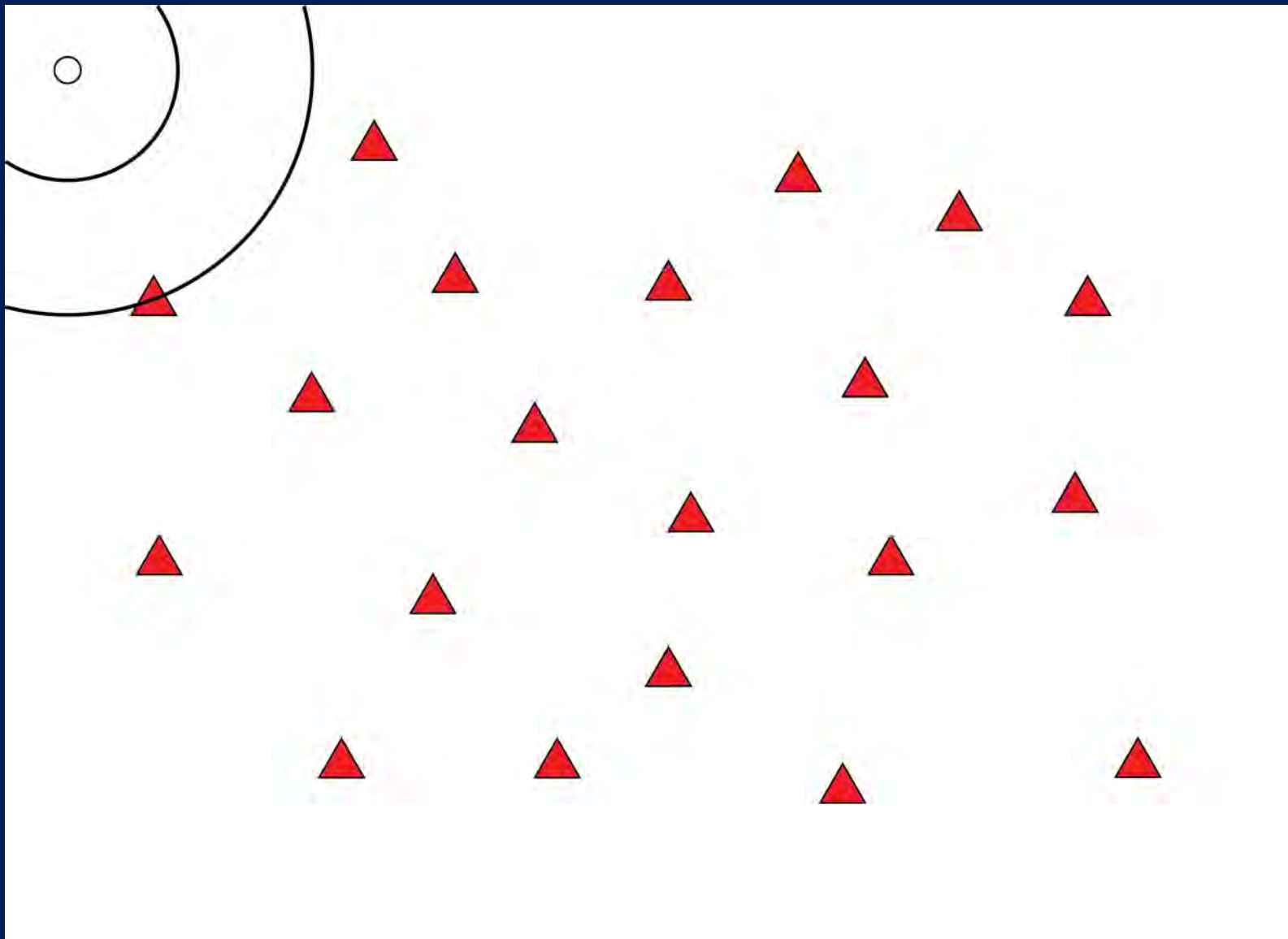
- Used to illuminate sources of energy that propagate to many receivers
  - e.g. secondary sources such as reflectors
  - e.g. primary sources such as explosions



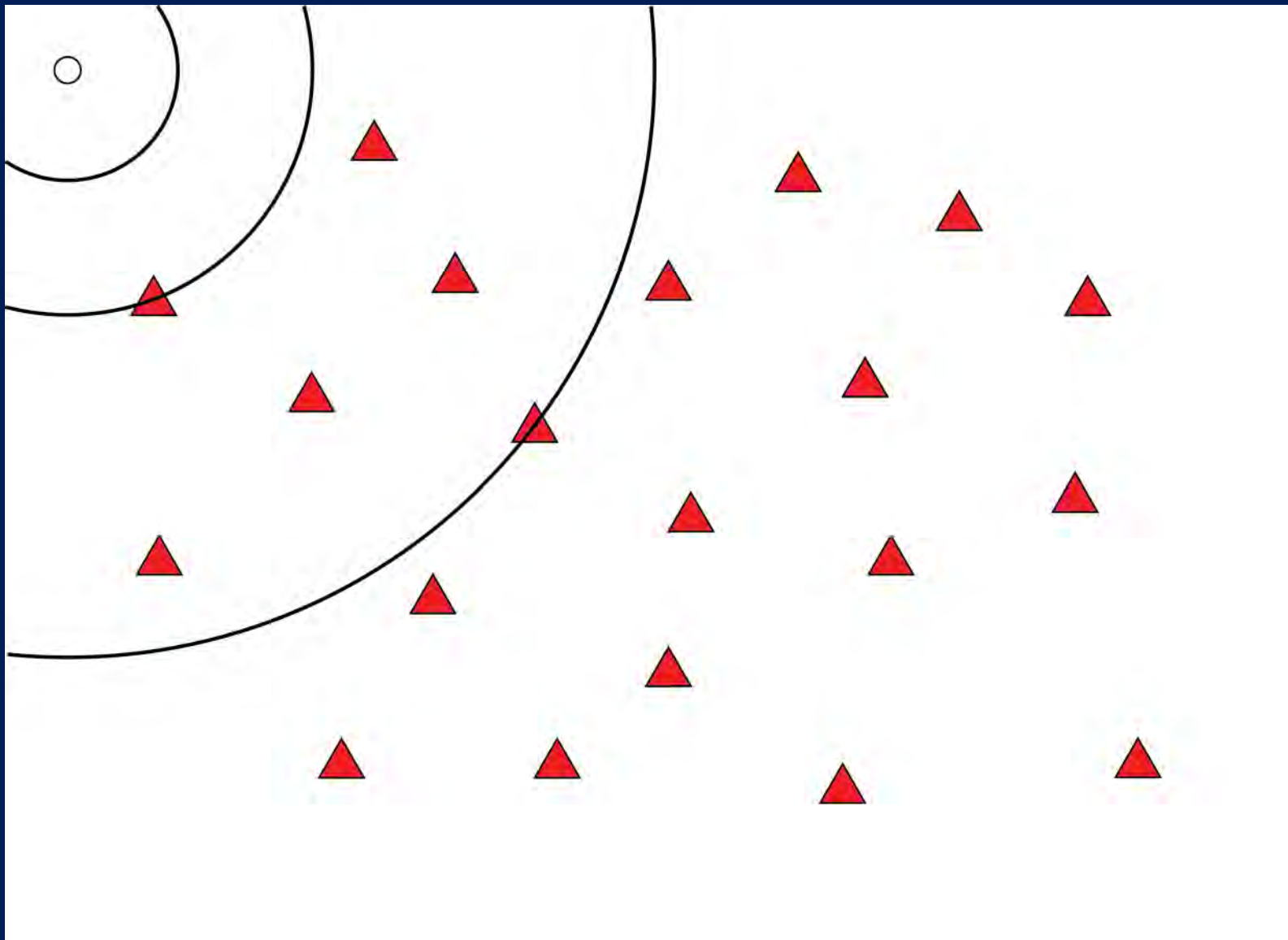


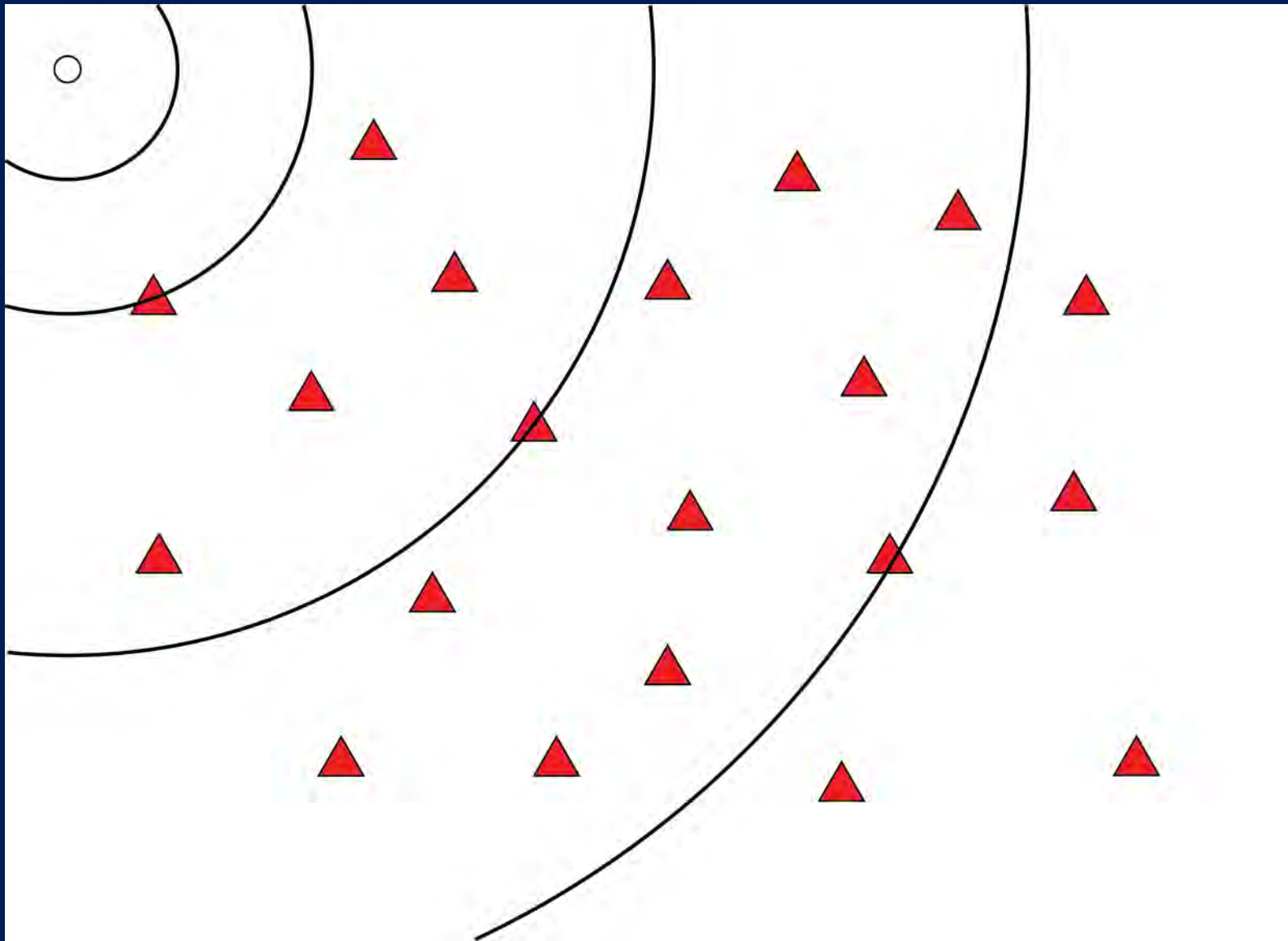


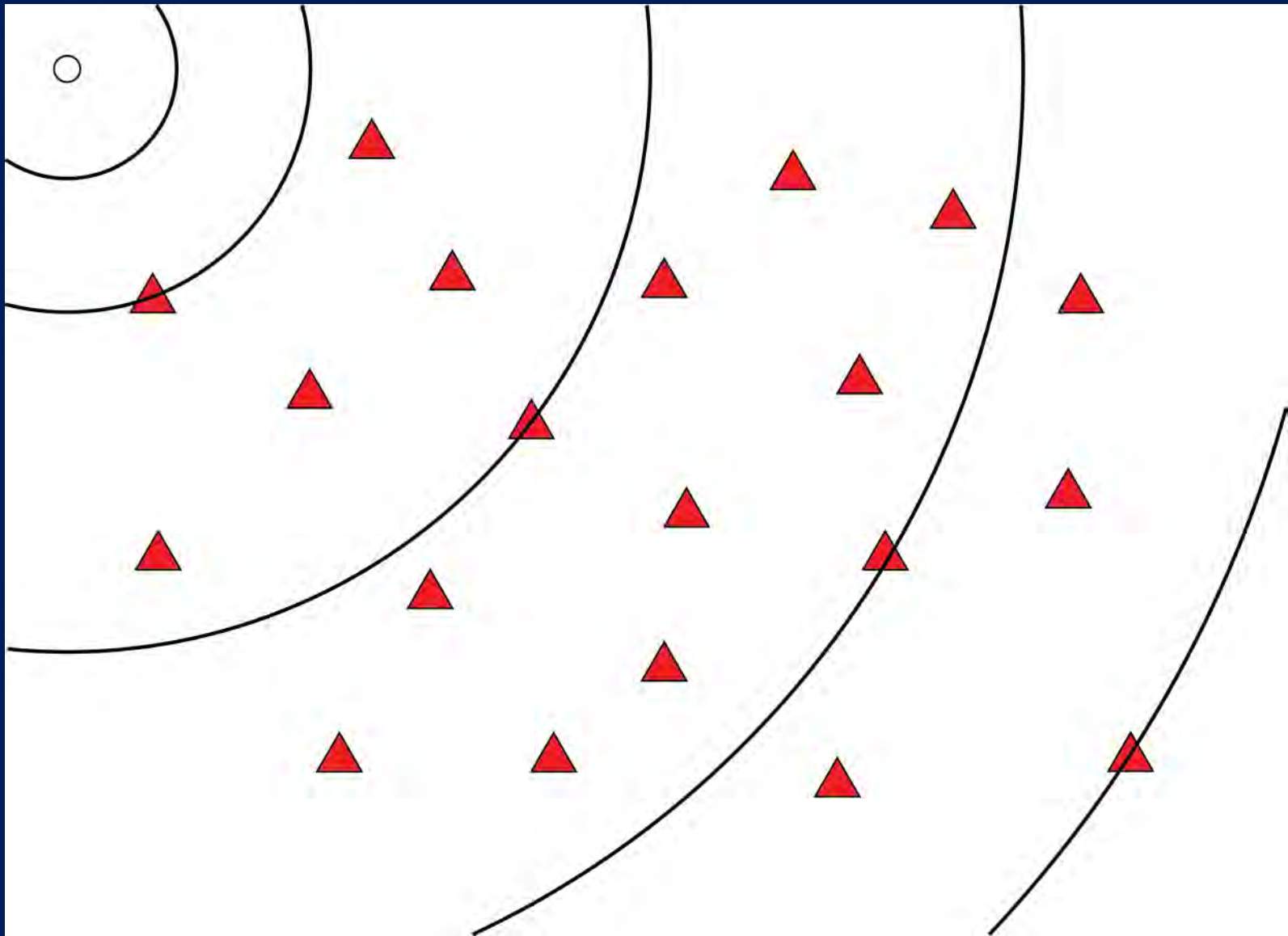


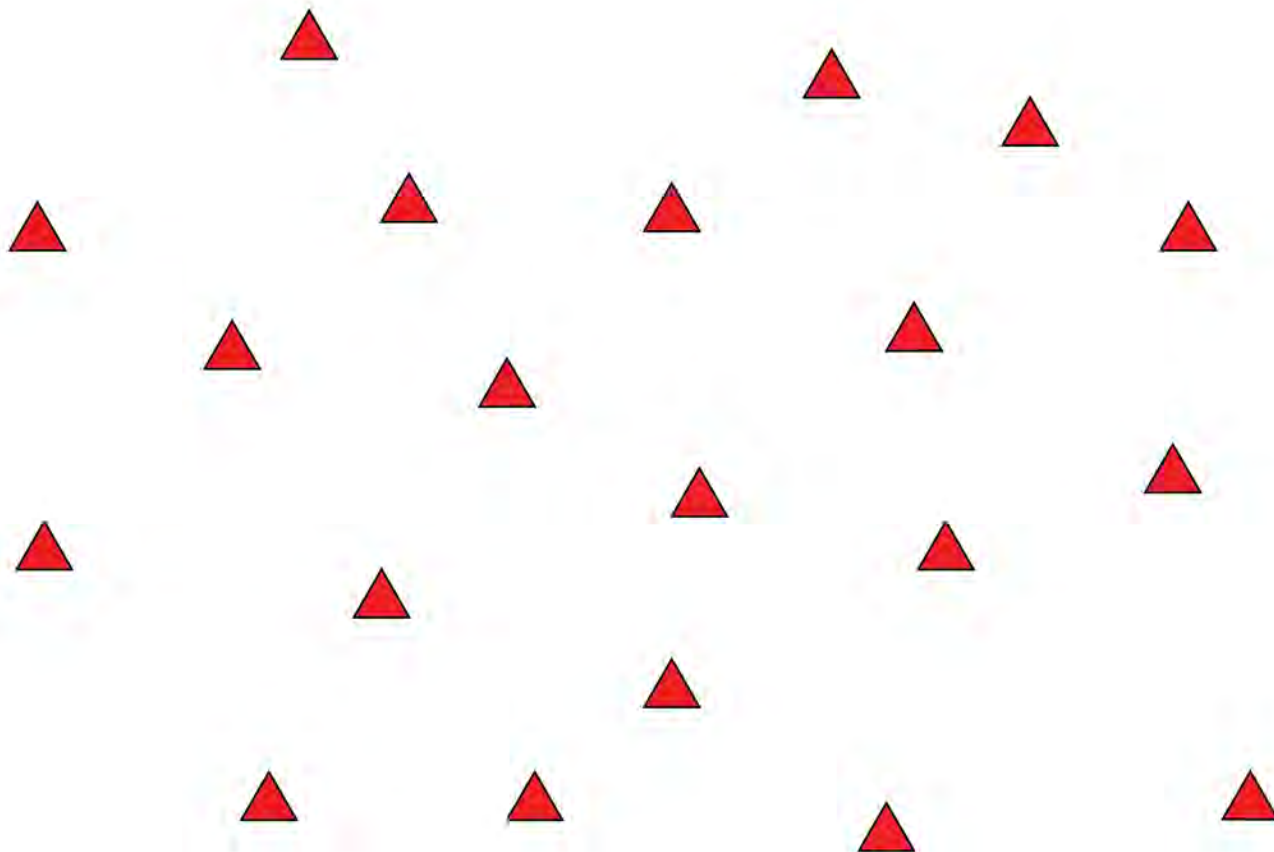




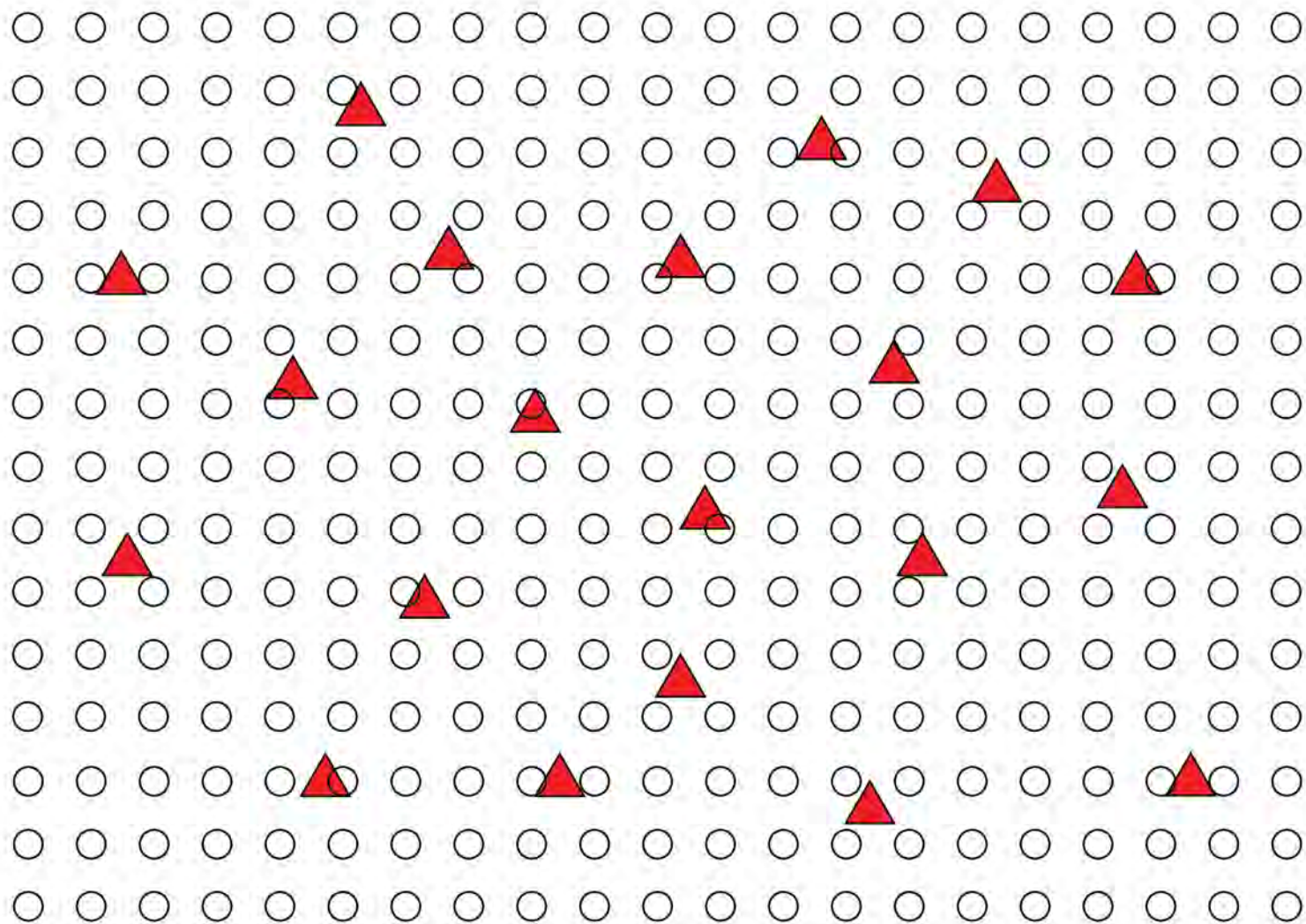












# Reverse Time Migration (RTM)

Beamforming at the source

$$B(t, s_x, s_y) = \sum_i^n a_i(t + t_0(s_x, s_y, r_x, r_y))$$



# Reverse Time Migration (RTM)

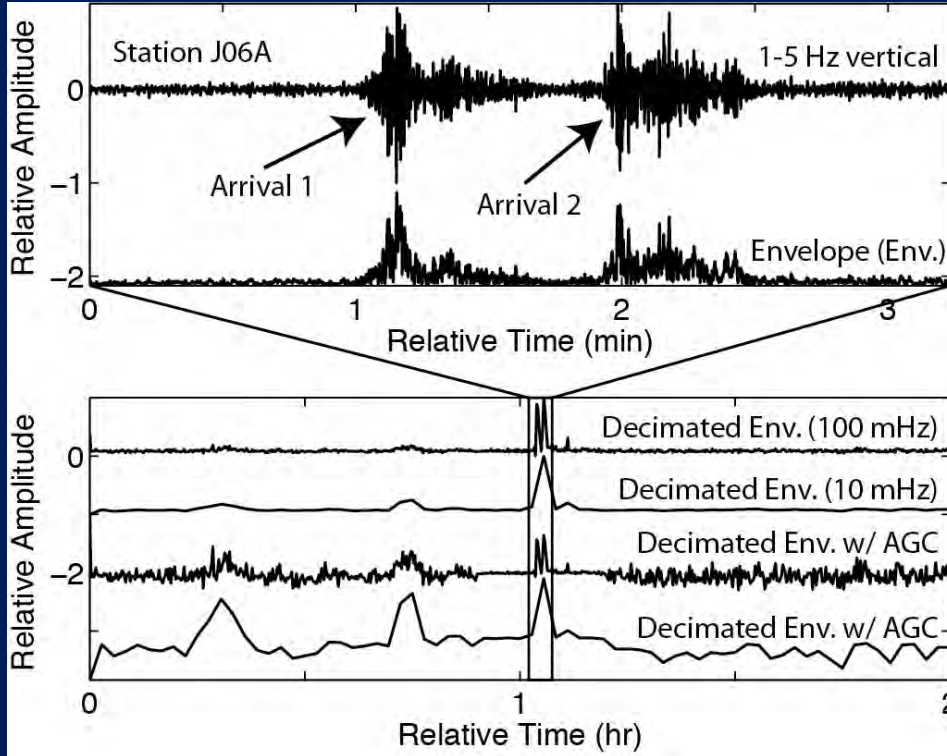
Sound speed is unknown *a priori*

$$B(t, s_x, s_y, v_g) = \sum_i^n a_i(t + d(s_x, s_y, r_x, r_y)/v_g)$$



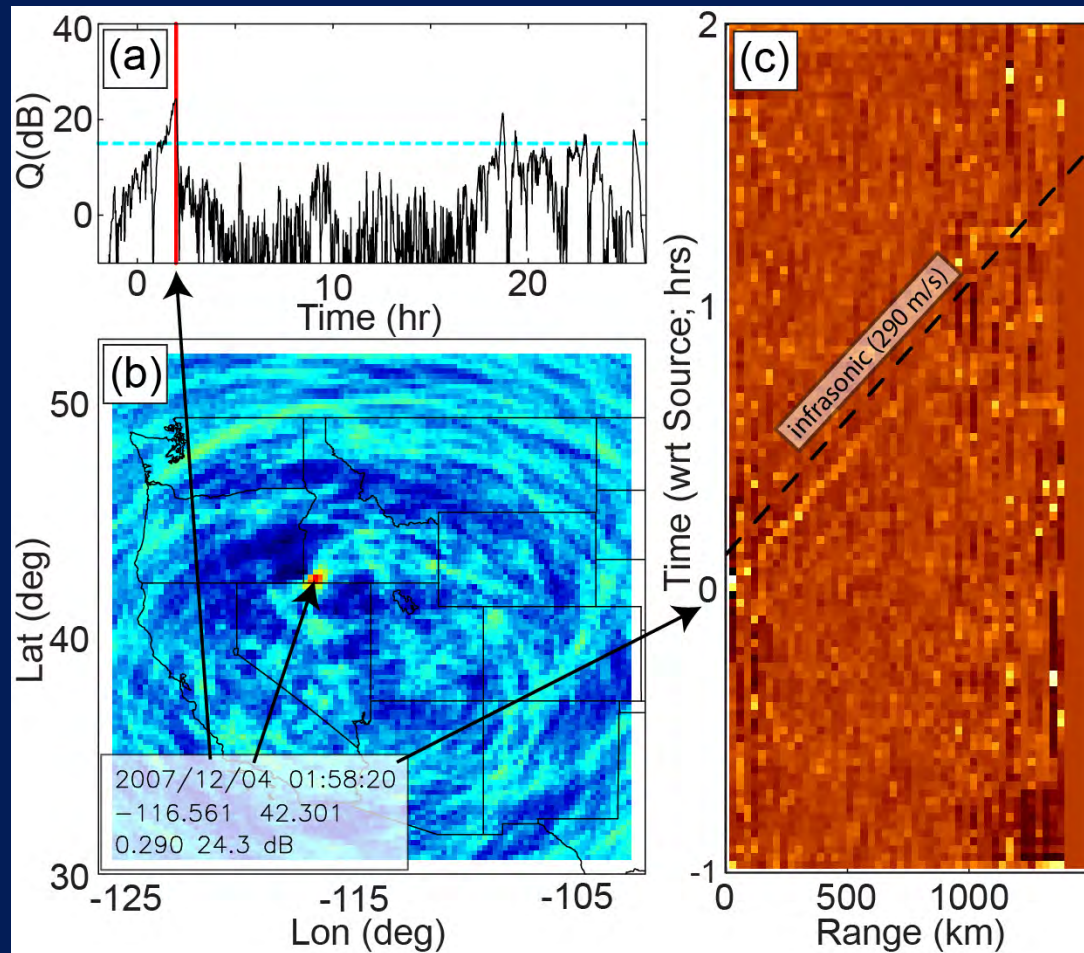


# Additional processing



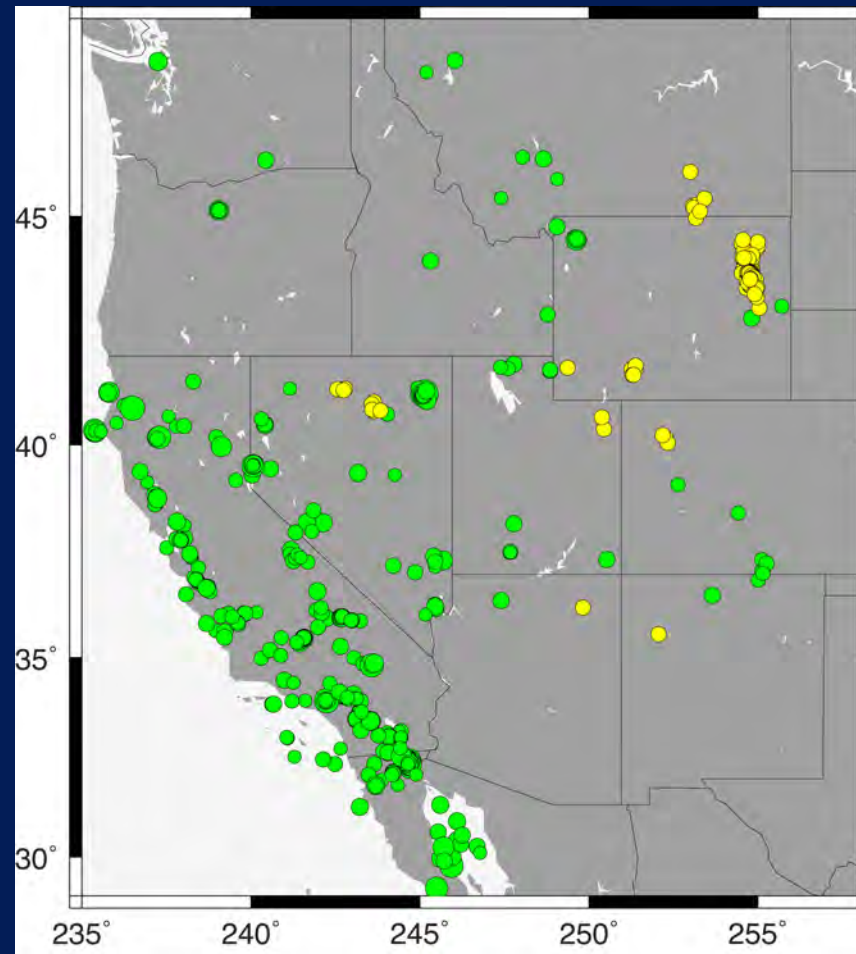
- Filter
- RTM requires phase coherence  $\therefore$  convert to envelope
- Decimate
- Apply automatic Gain Control (AGC)
- Weight based on station density

# Example detection

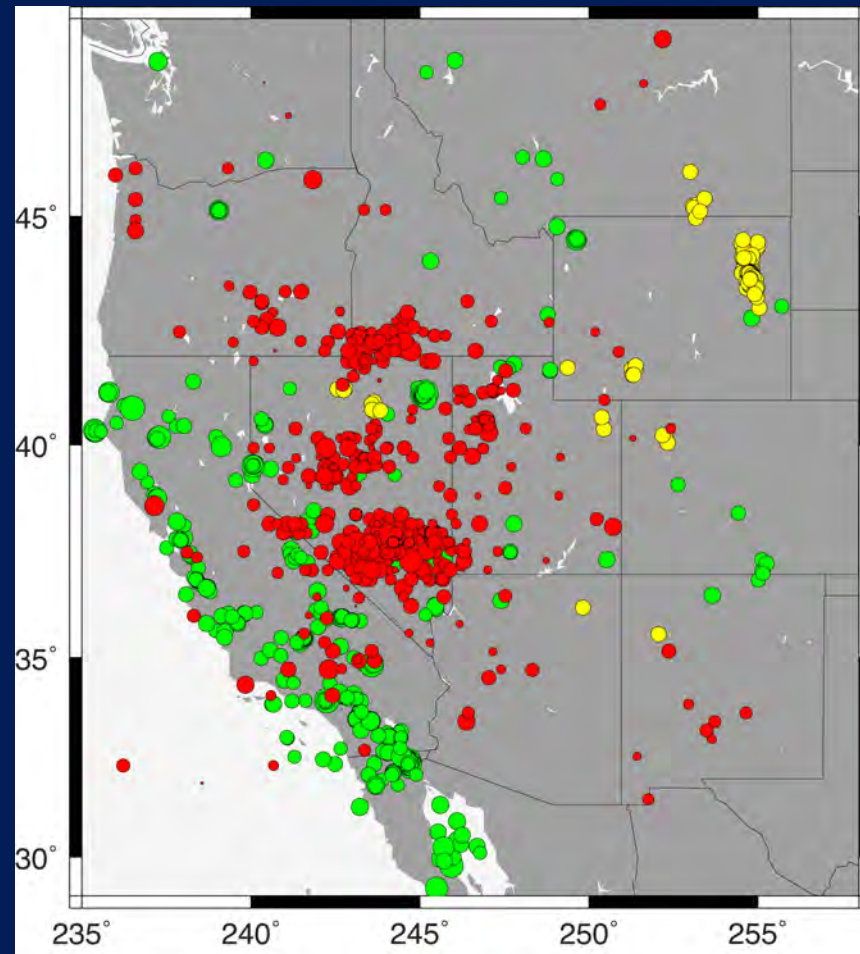


Detector function  $Q(t) = \text{maximum of } B(t) \text{ across } s_x, s_y, v_g$

# Seismic Activity in 2008



# 2008: Seismic and Acoustic events



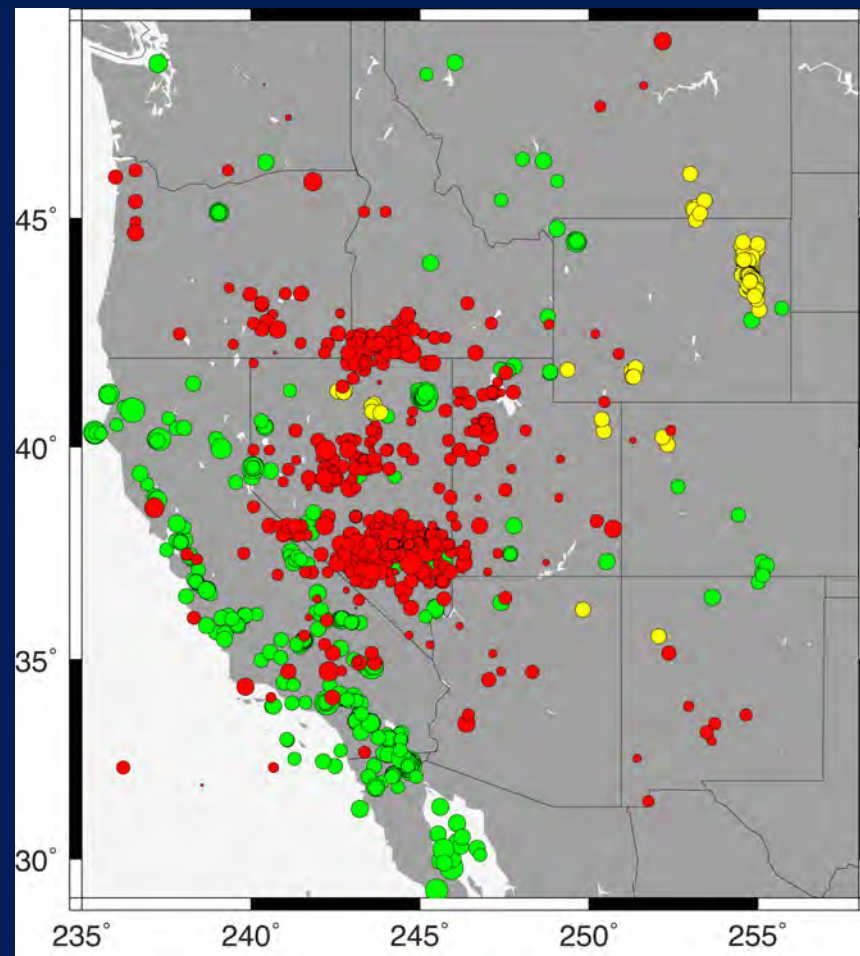
Infrasonic hotspots

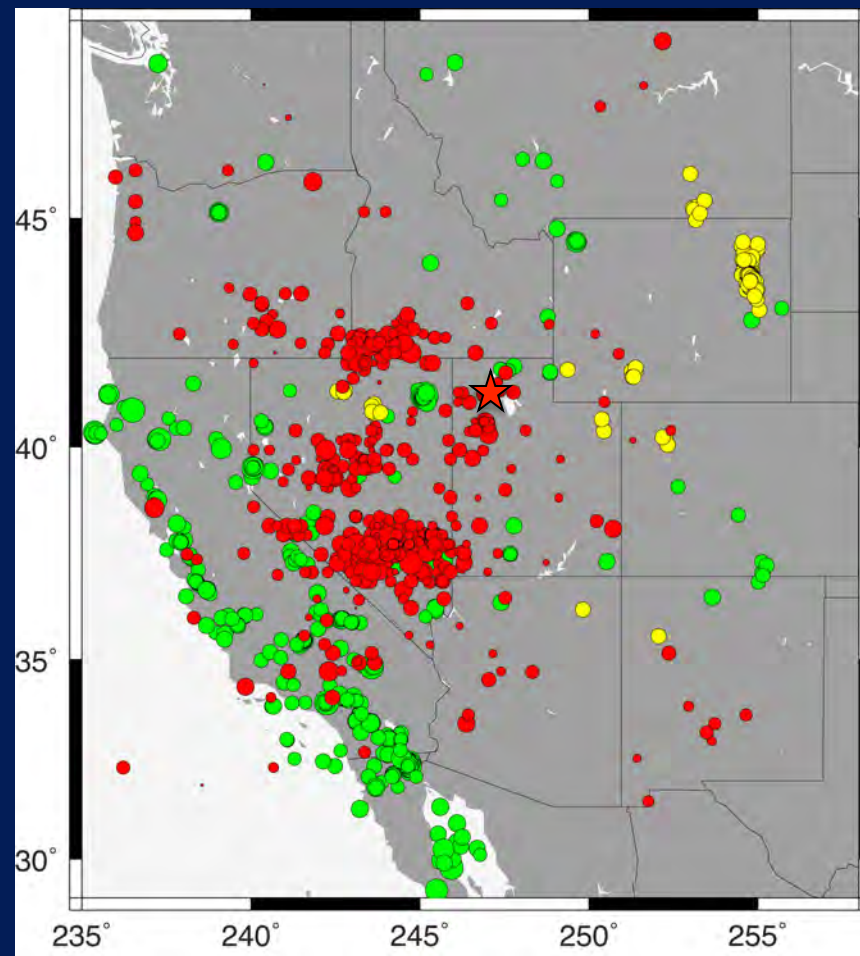




Second: What can we learn  
from these events?

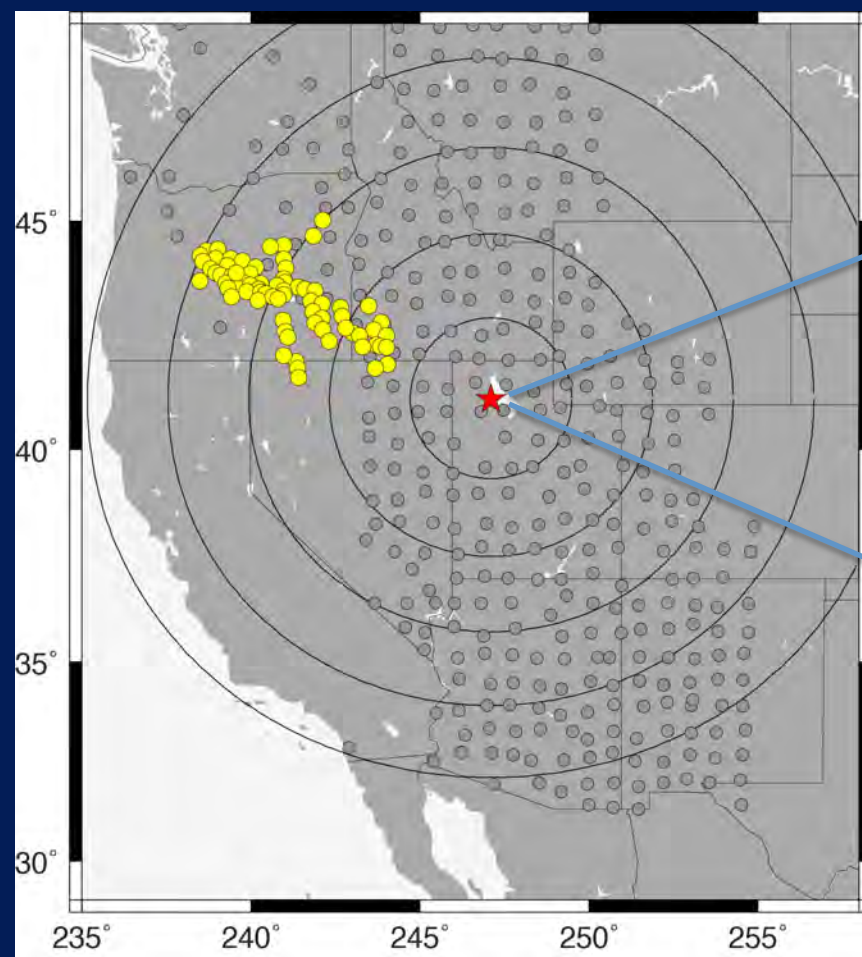








# Sound from an explosion at the Utah Test and Training Range

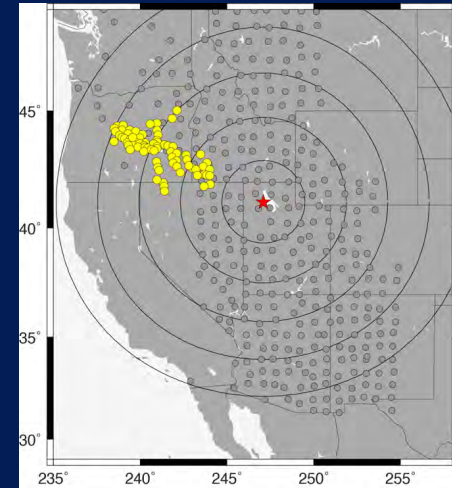
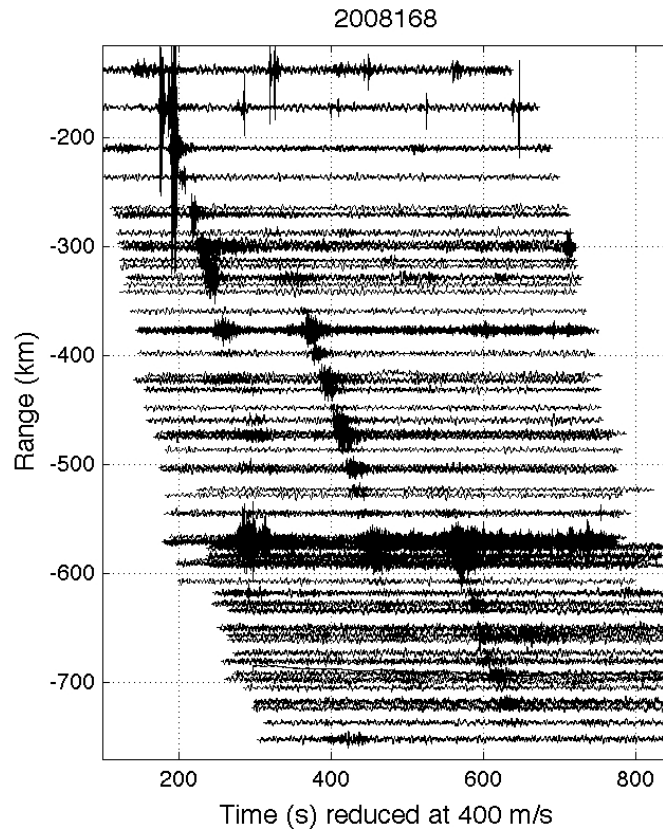


~ 17,500 kg

USArray TA and second network on day 168, 2008

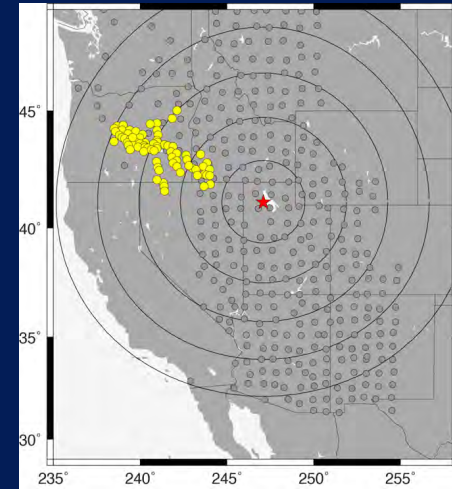
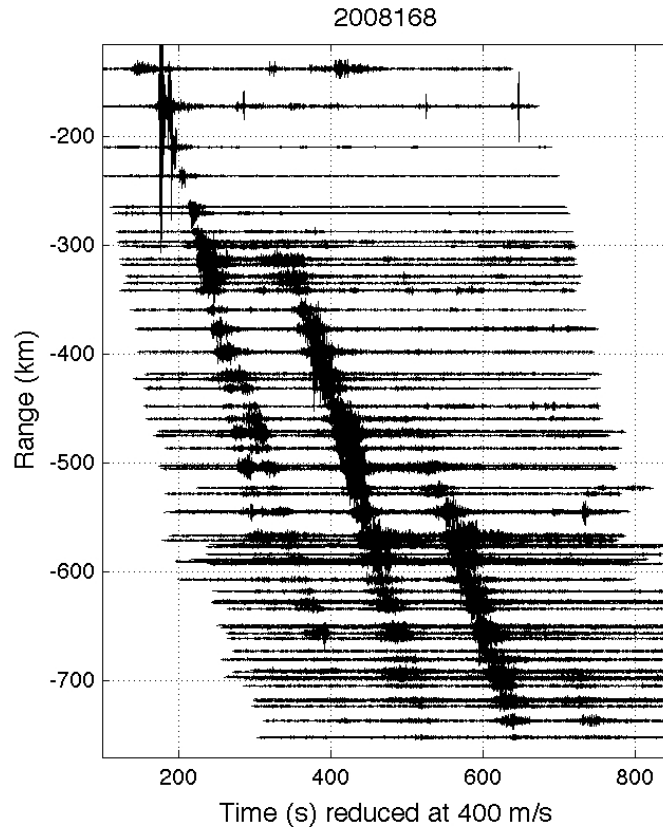


# 150-km wide corridor at 300°



Unfiltered vertical components

# 150-km wide corridor at 300°

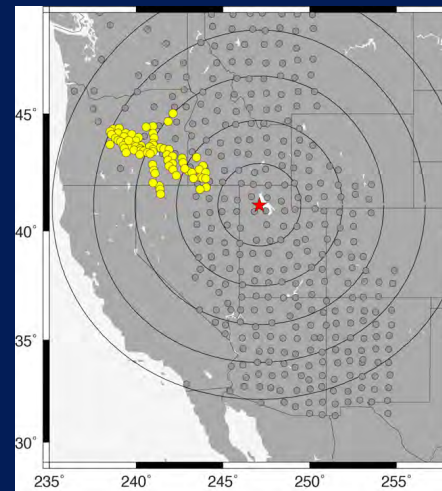
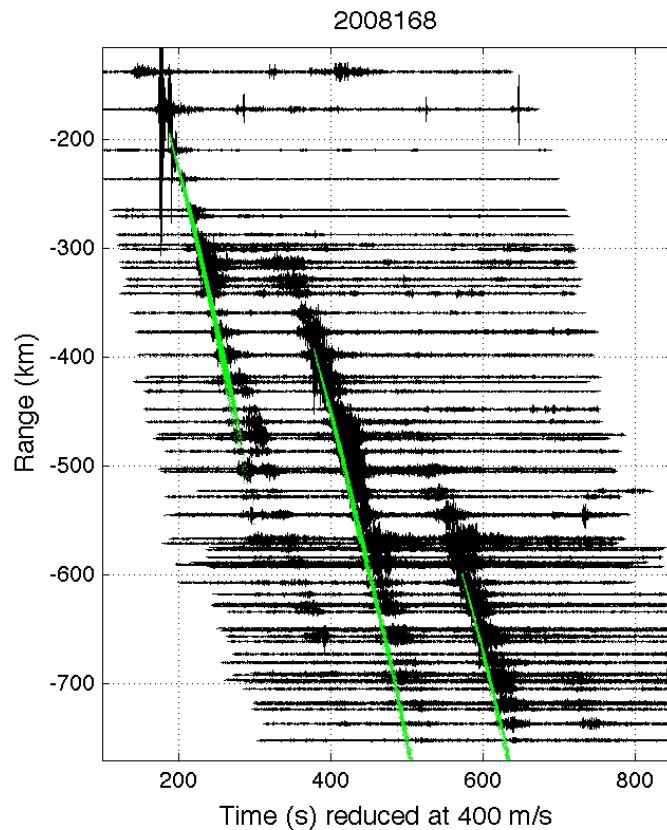


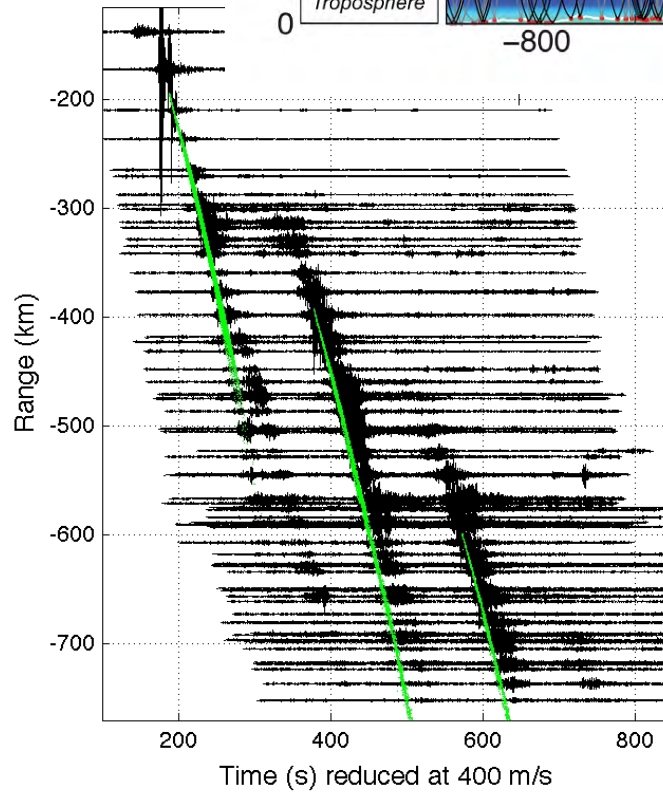
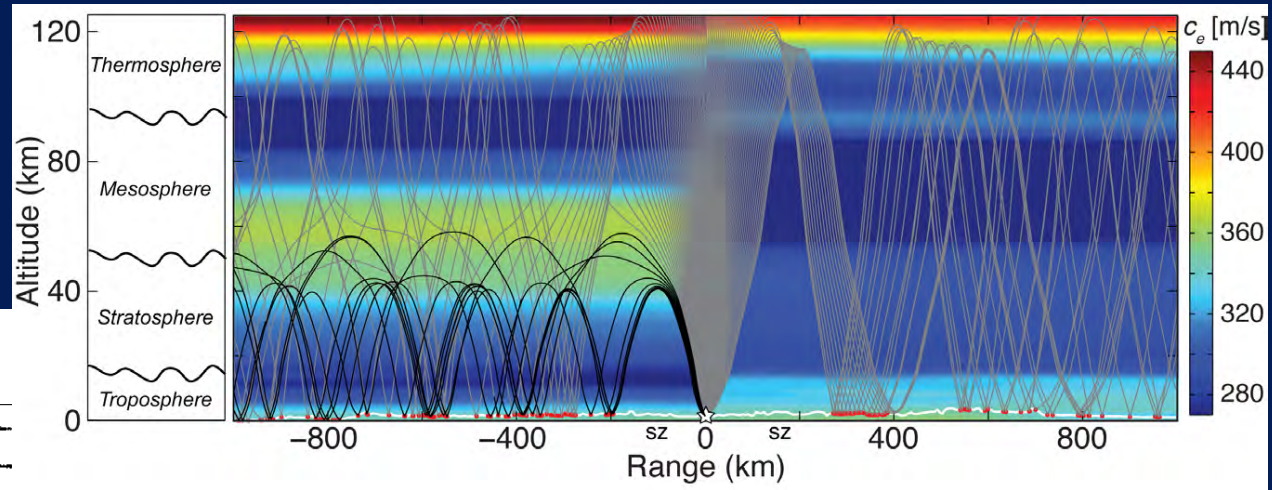
Vertical components 0.8 - 3.0 Hz BP



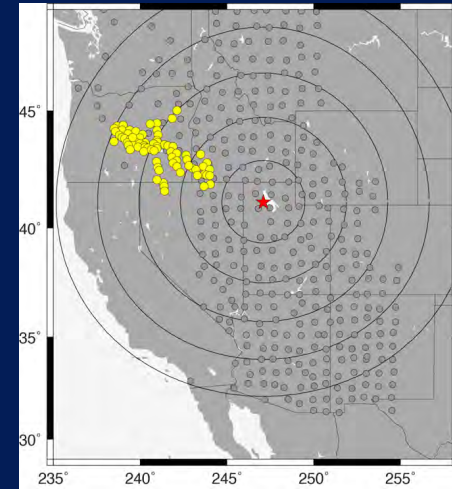
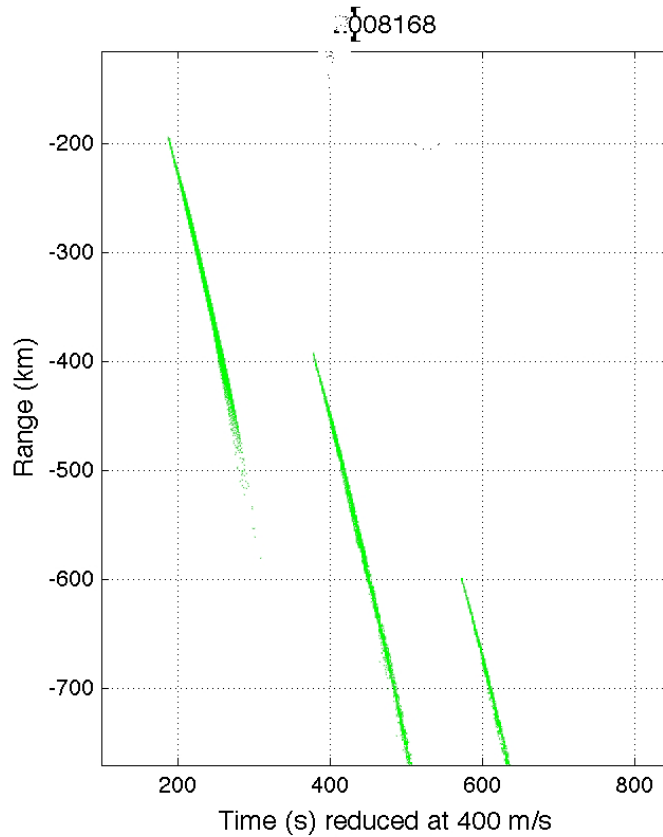


# Data and rays through basic model



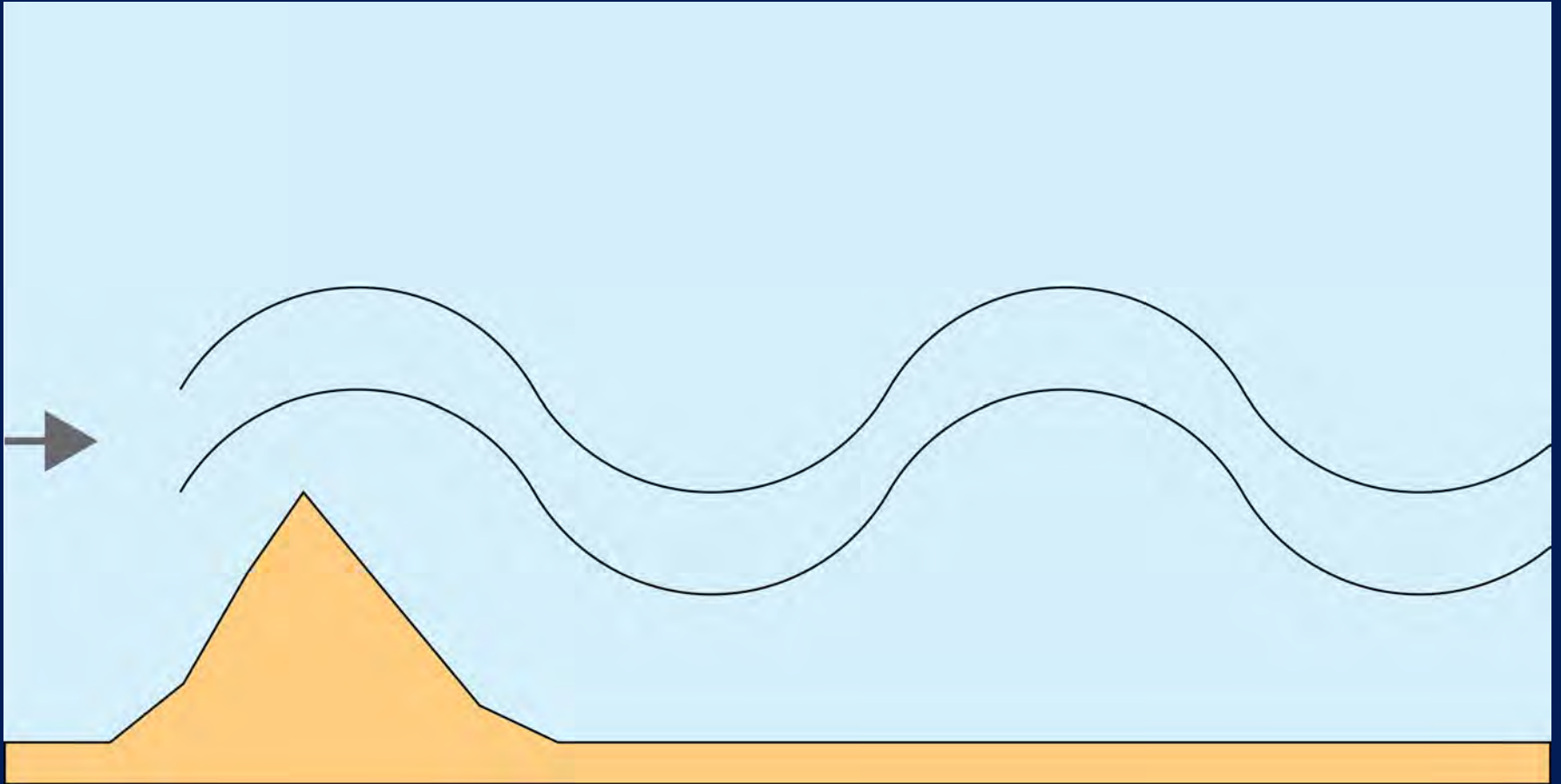


# Rays through basic model

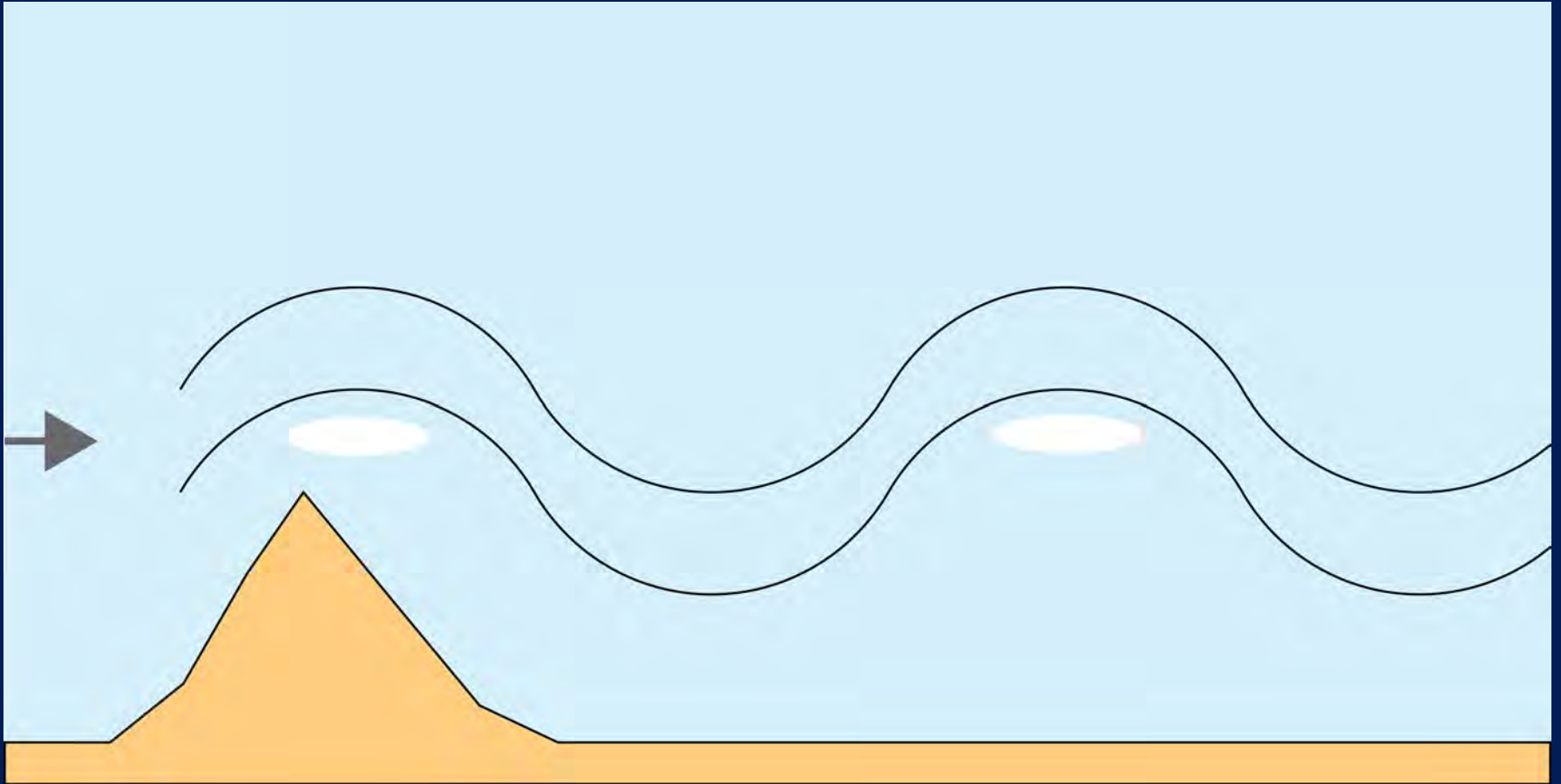




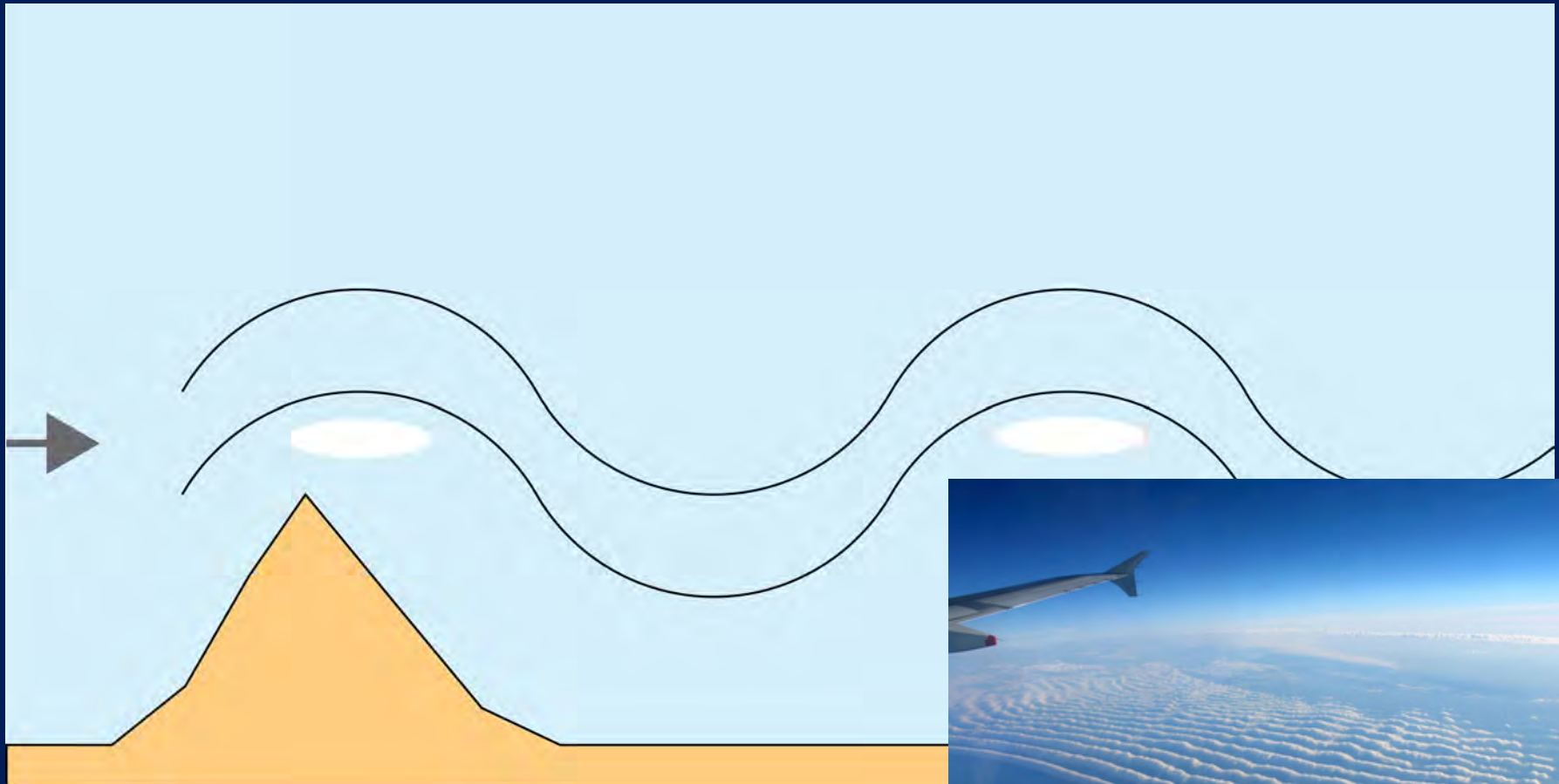
# Gravity Waves



# Gravity Waves

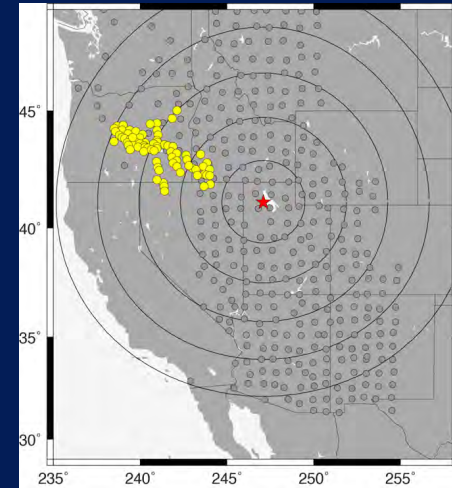
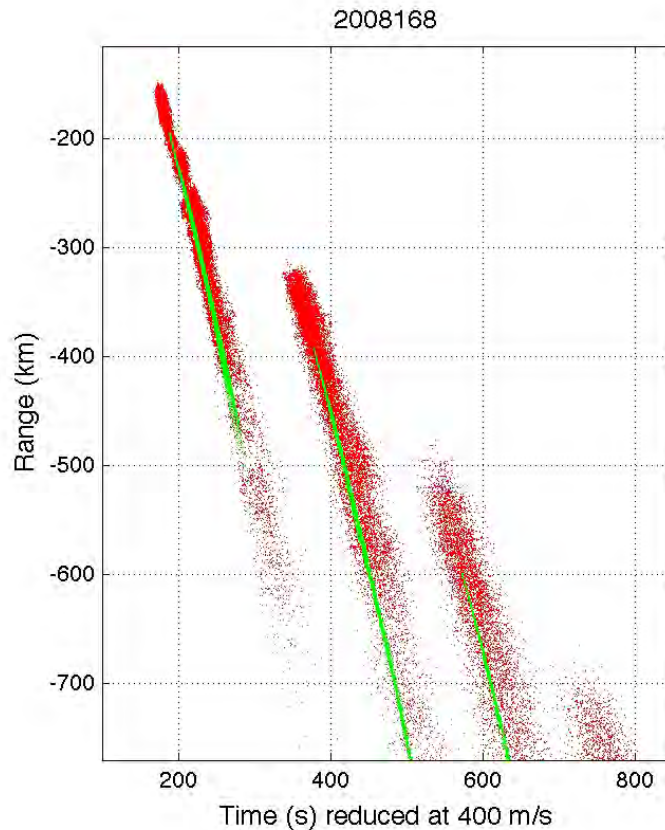


# Gravity Waves

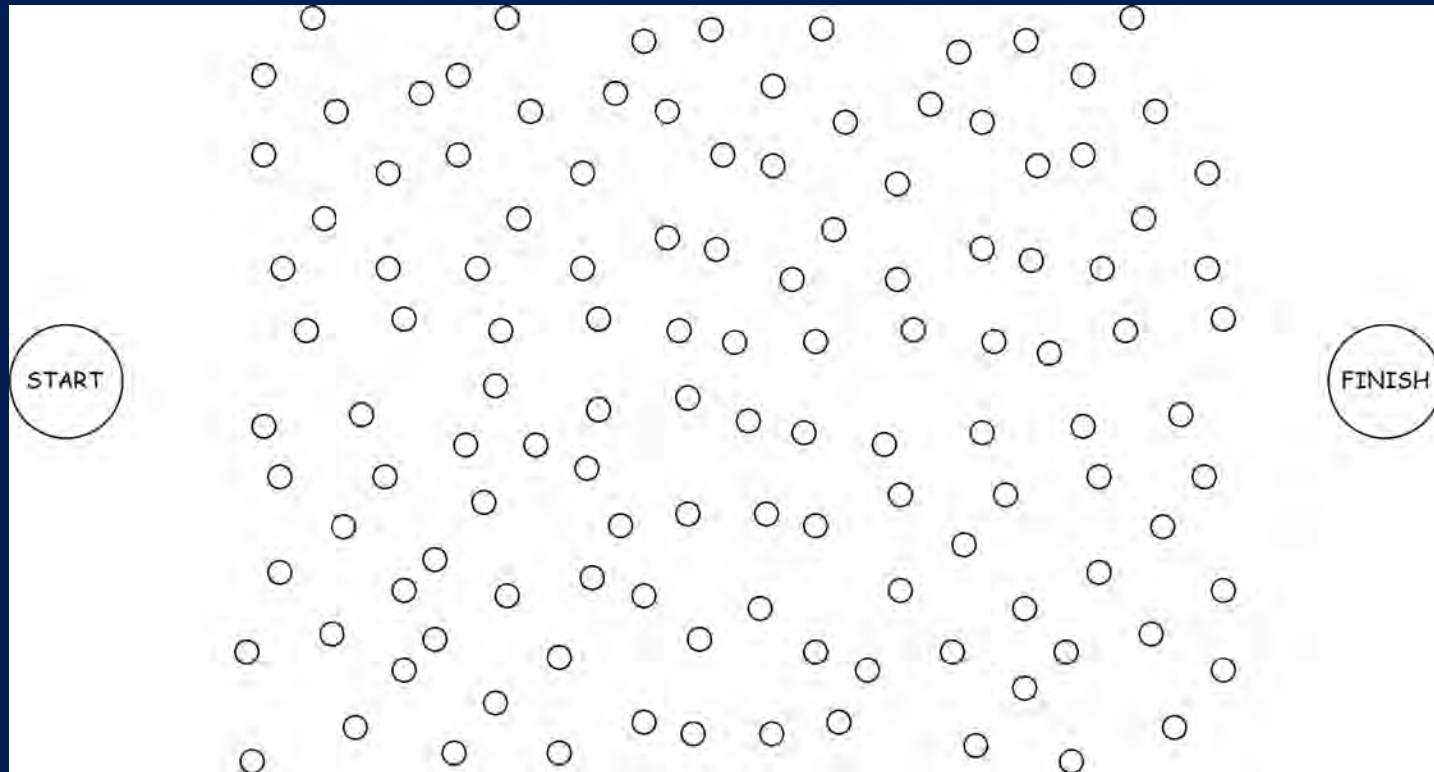




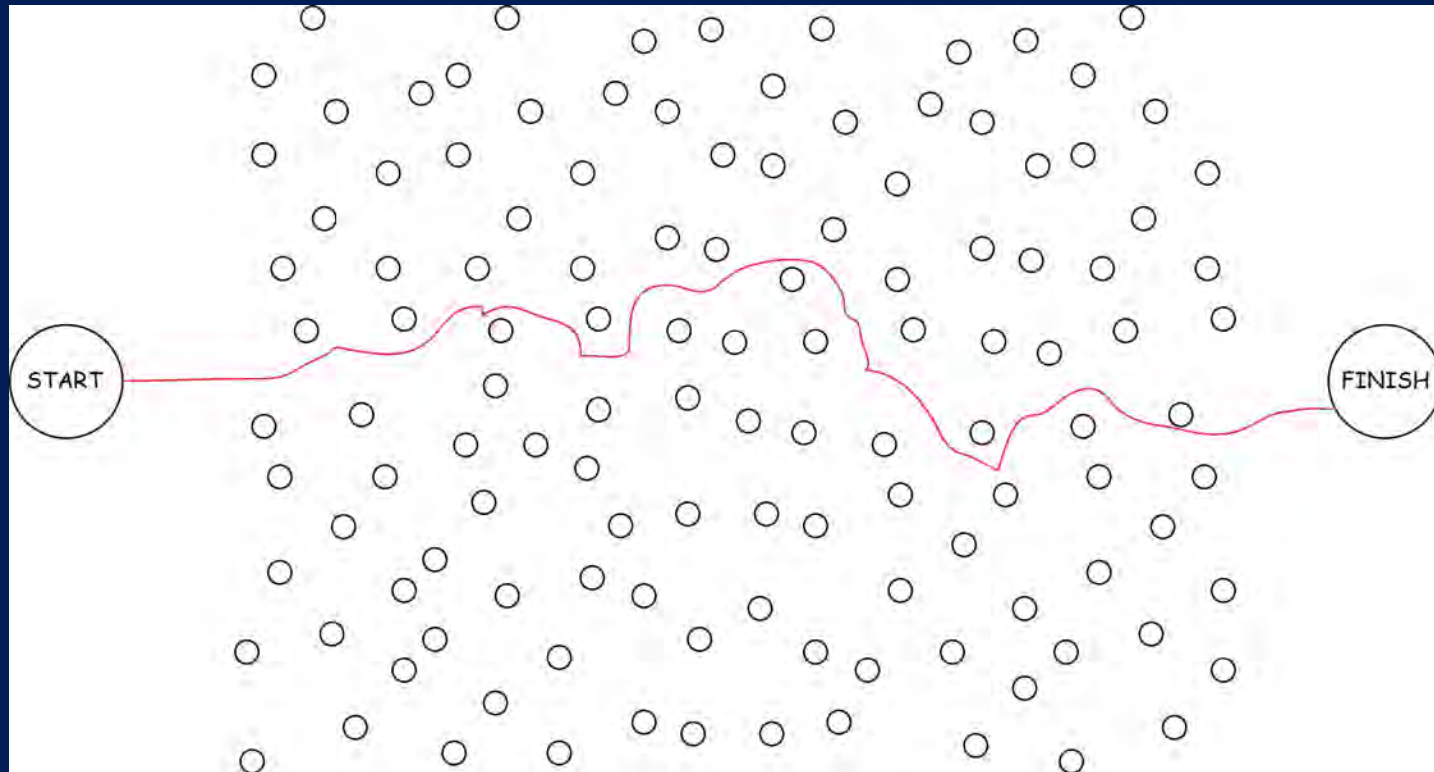
# Rays through perturbed model in red



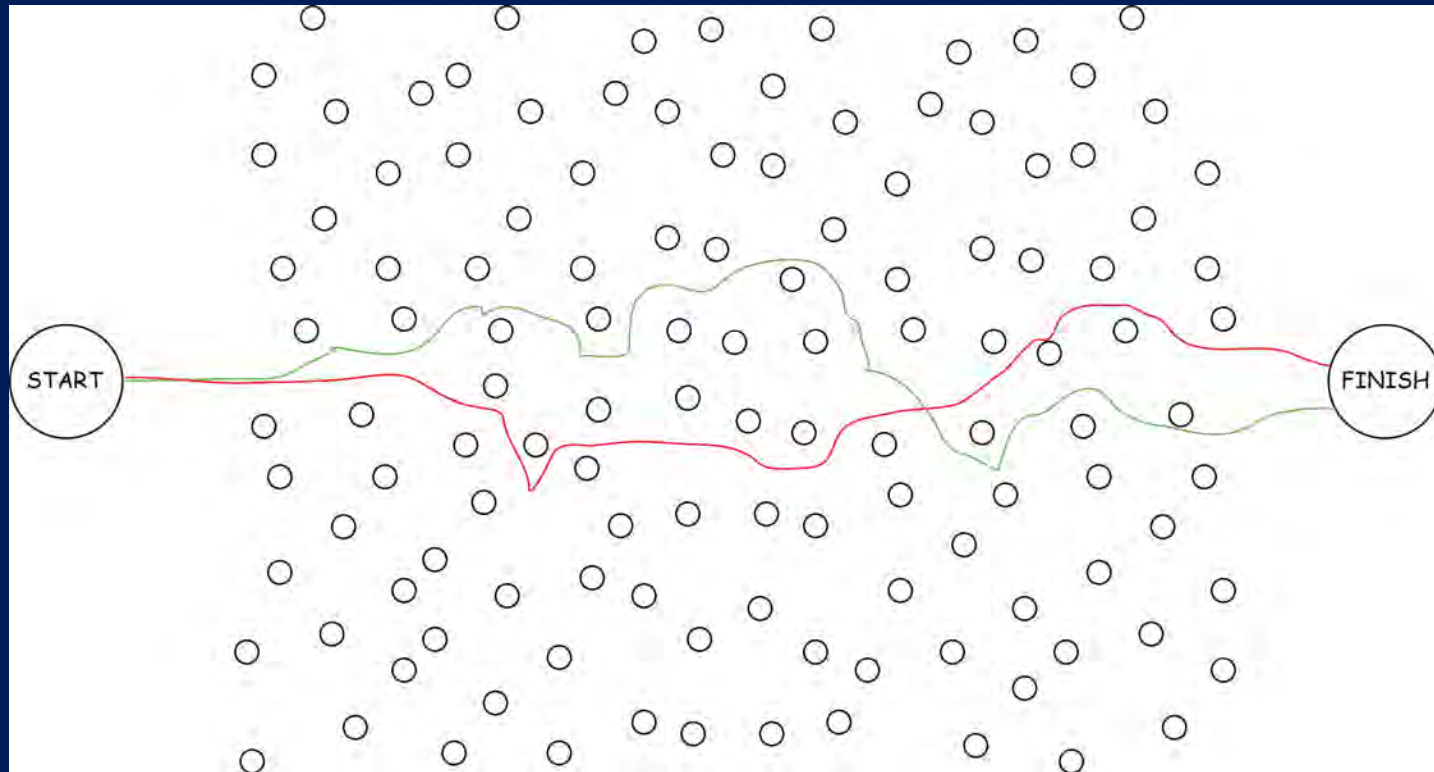
# Forest walk analogy



# Forest walk analogy

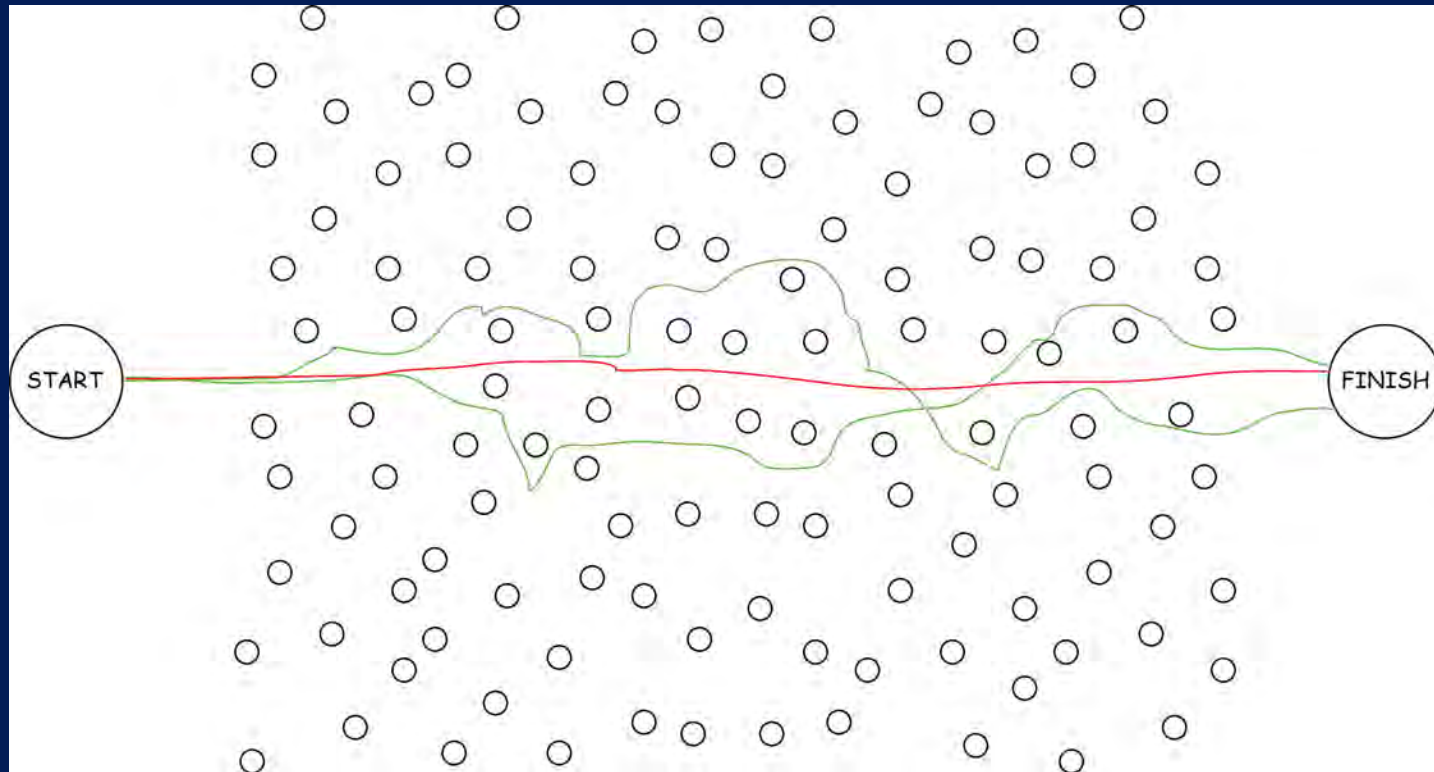


# Forest walk analogy

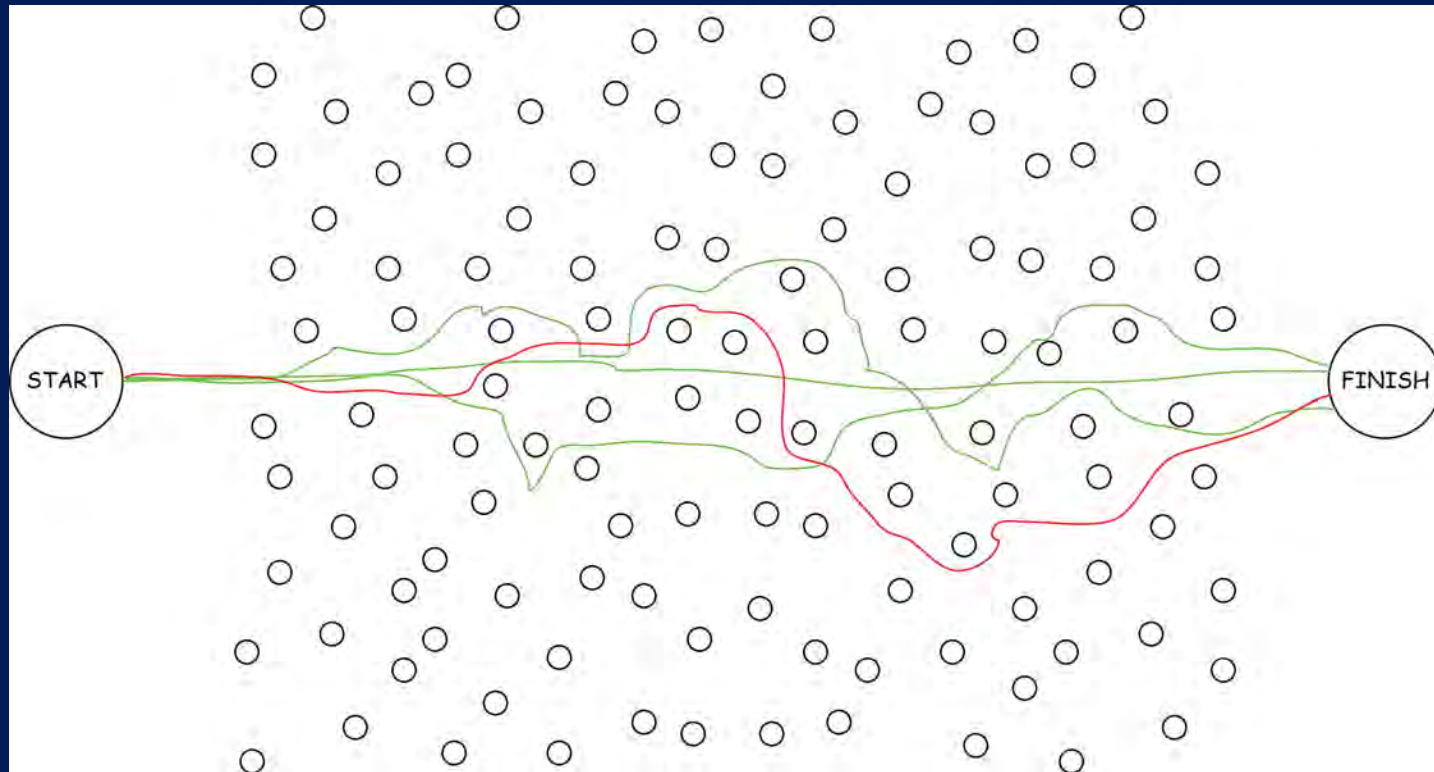




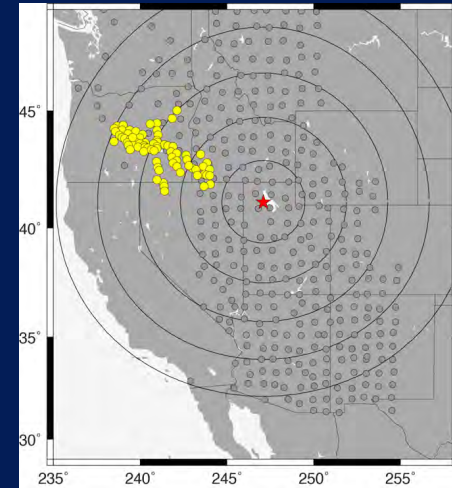
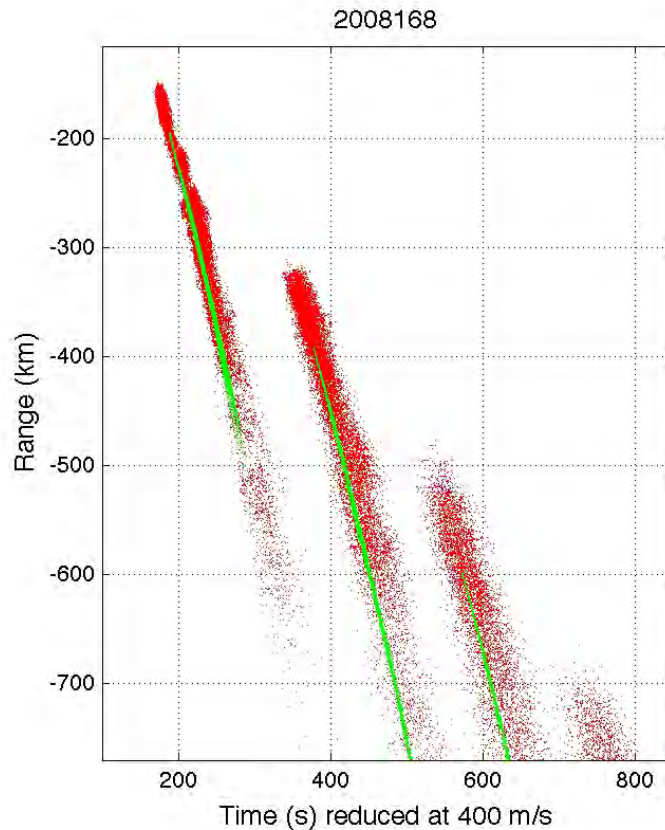
# Forest walk analogy



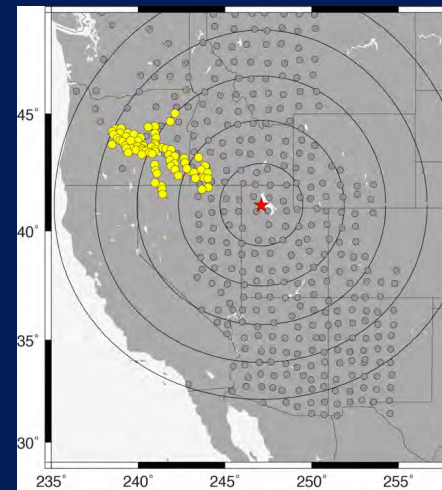
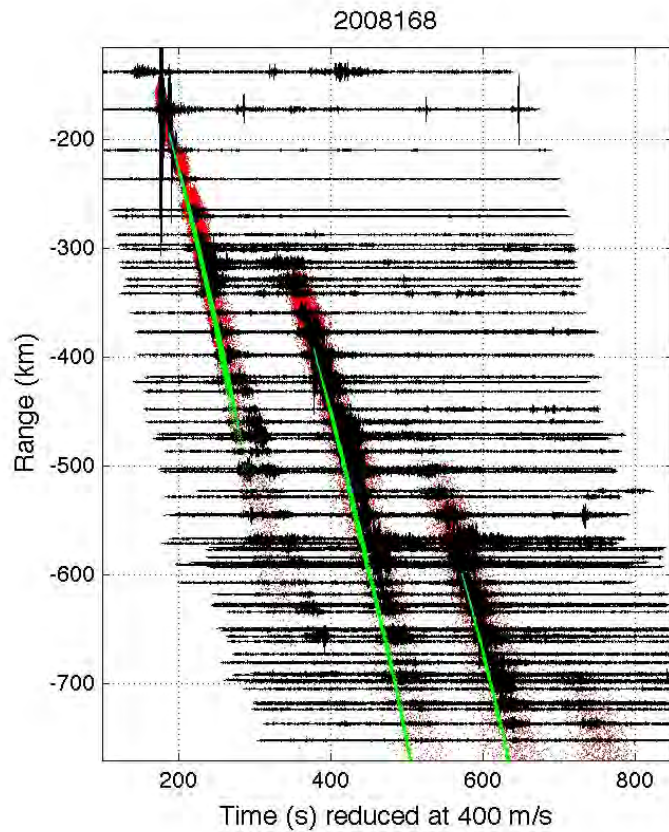
# Forest walk analogy



# Rays through perturbed model in red



# Rays and data





# Concluding remarks

- We used rather elementary processing methods to uncover a distinctly different, atmospheric, type of source in seismic data
- Our large catalog of atmospheric events provides the foundation for statistical studies of infrasound propagation
- Close-up studies of cataloged events reveal details of how low-frequency sound travels through the atmosphere
- Infrasound is an independent means to probe the atmosphere

