RECENT PROGRESS AND FUTURE OPPORTUNITIES IN VOLCANO MONITORING USING INFRASOUND

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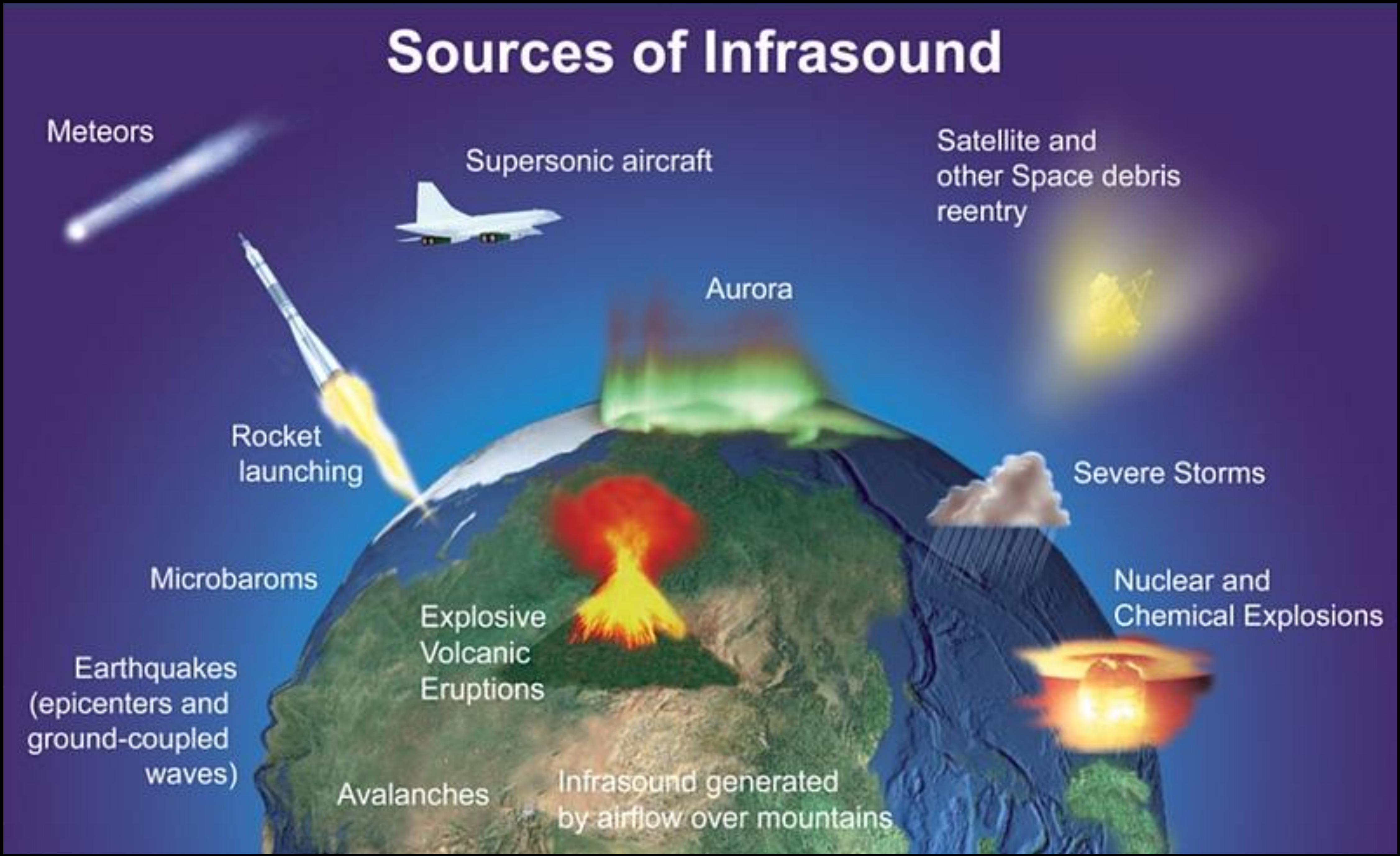
INFRASOUND – WHAT IS IT?

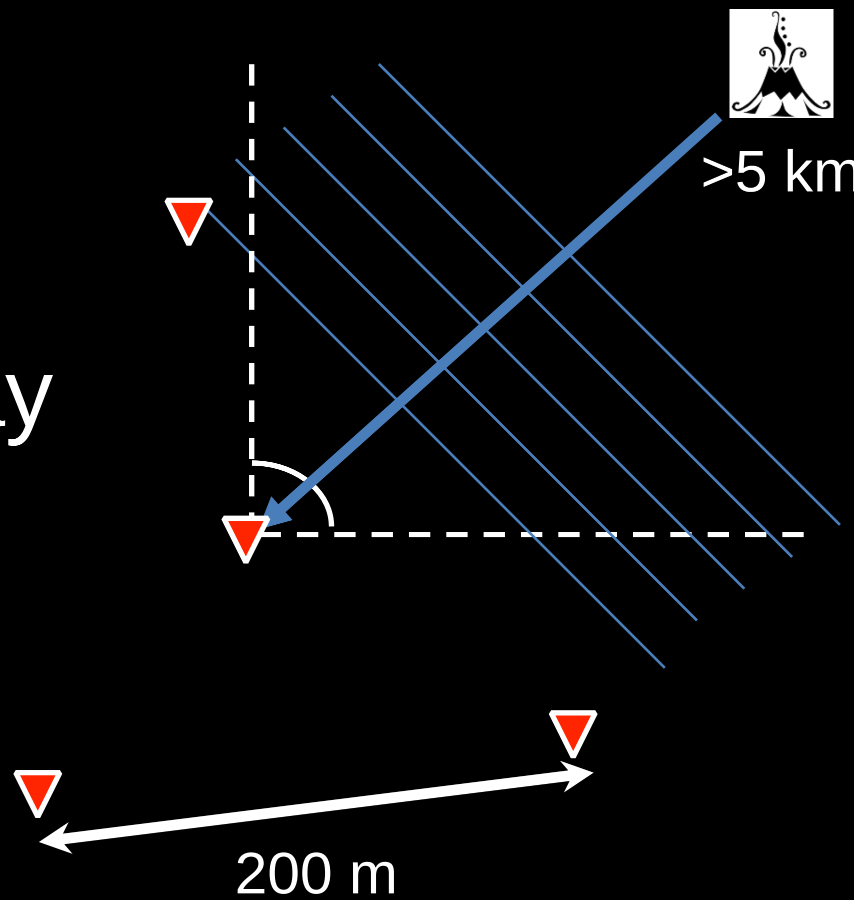
- Sound waves (pressure waves) at frequencies lower than humans can hear
- Similar to P-wave in seismology, except through the atmosphere
- Low amount of energy loss and atmospheric winds permit long-range propagation
- Not restricted by clouds, but affected by wind and temperature in the atmosphere



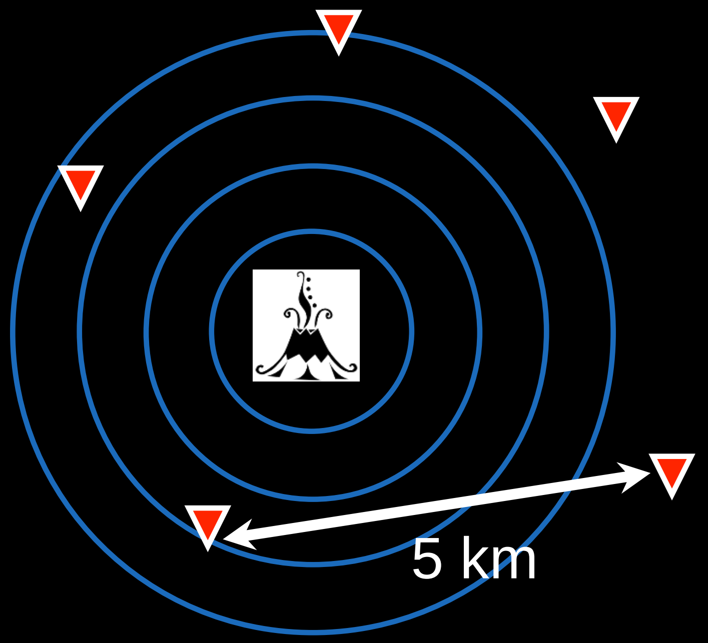
www.ctbto.org

INFRASOUND RECORDING AND PROCESSING

Array



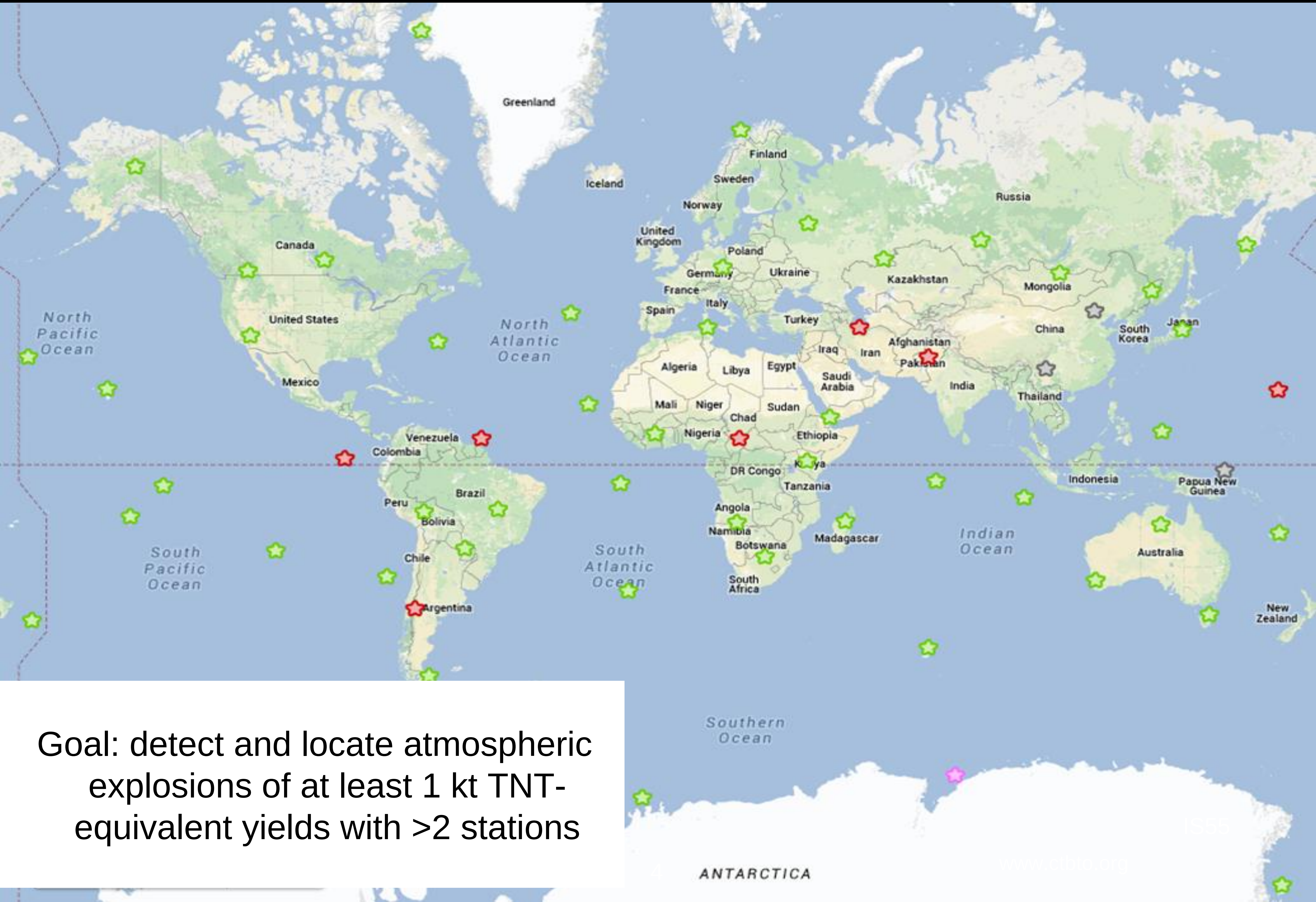
Network



- Bearing and wave velocity estimate
- Remote detection
- Often part of global network

- High-resolution detection and localization
- Typically close to source (low latency)
- Determine eruption source parameters

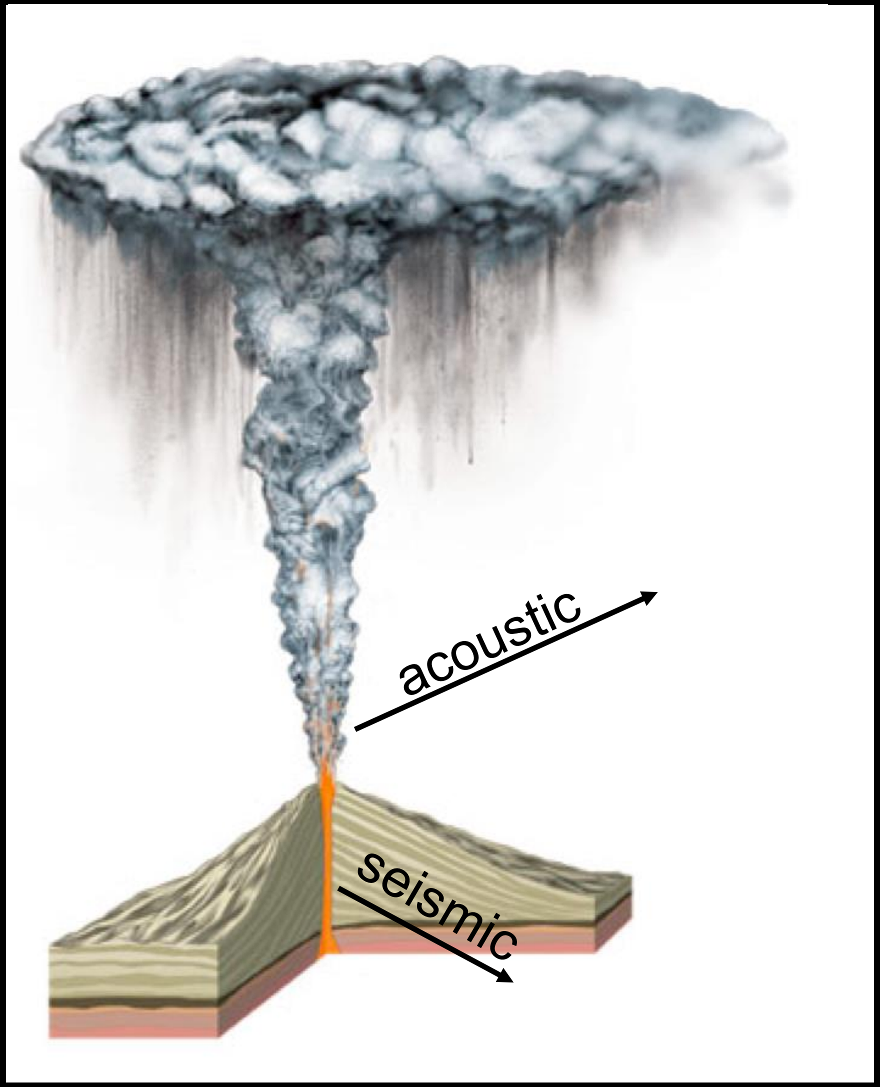
IMS INFRASOUND NETWORK



Goal: detect and locate atmospheric explosions of at least 1 kt TNT-equivalent yields with >2 stations

VOLCANO INFRASOUND

- Infrasound produced by flux of material into atmosphere
- Used to detect, locate, characterize, and quantify eruptive activity
- Infrasound signals indicative of eruption mechanisms
- Readily combined with other datasets

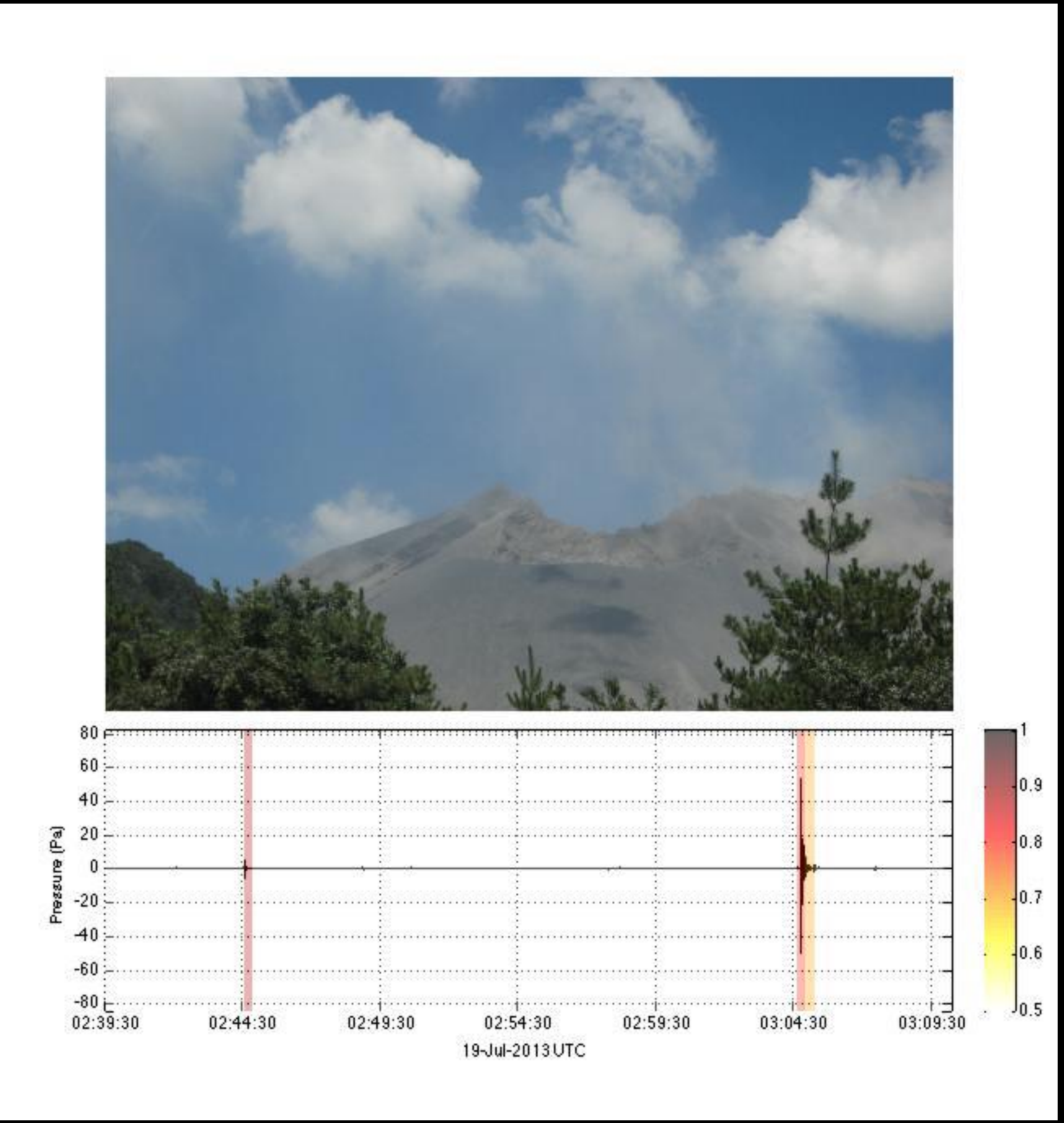


brittanica.com

Sakurajima Volcano

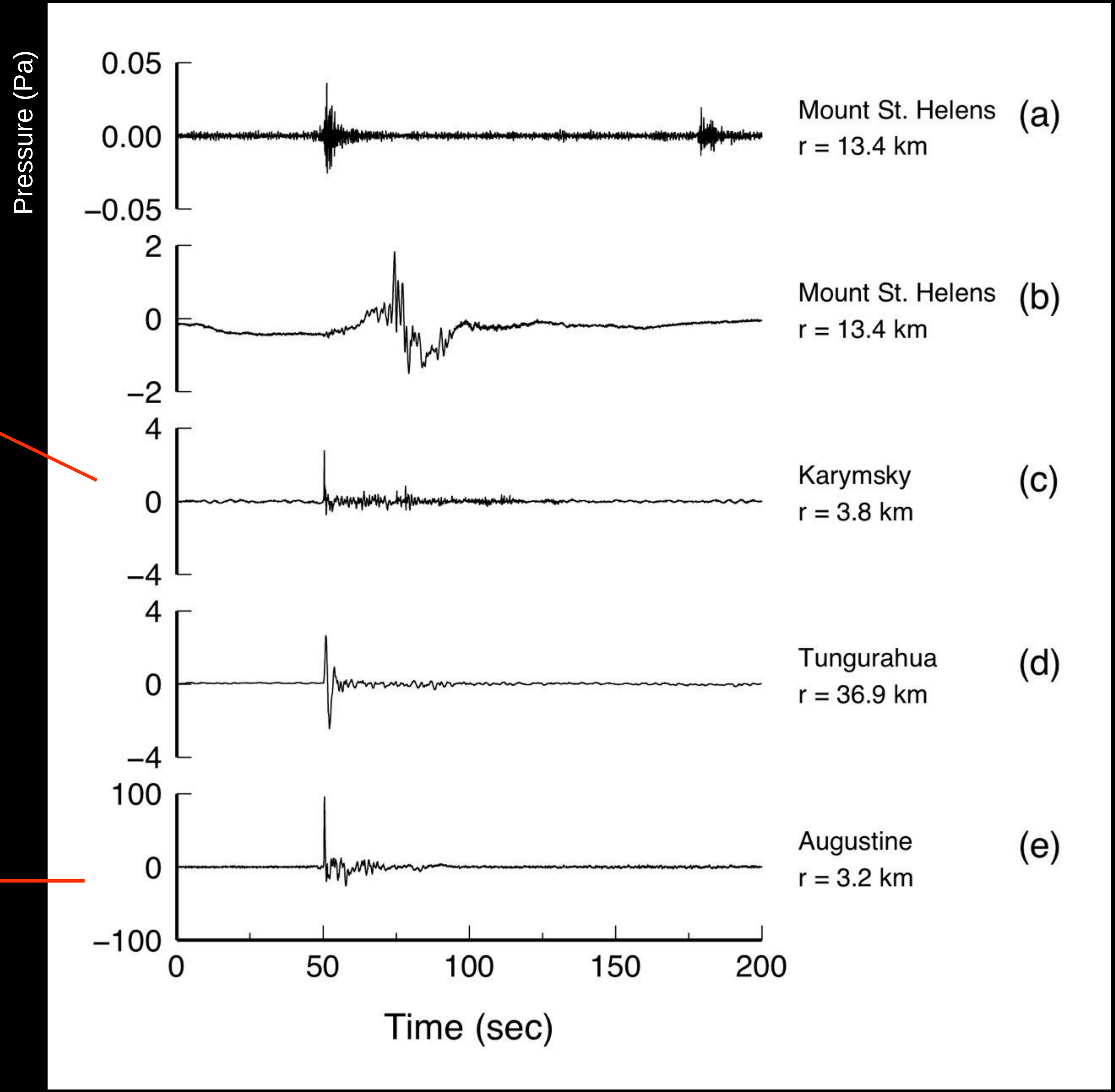
Visual 40x

Infrasound



SHORT DURATION EXPLOSIONS

Gerald Andrew Photo

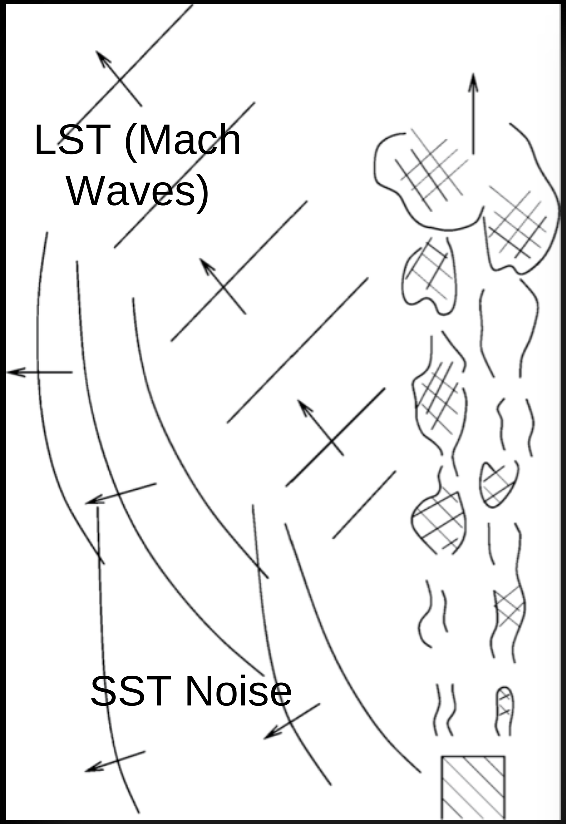


[Fee and Matoza, 2013]

SUSTAINED ERUPTIONS - VOLCANIC JET NOISE

- Similarities between sustained infrasound from large volcanic eruptions with the sound from jet engines [e.g. Matoza et al., 2009; Fee et al., 2013]
- Spectral shape and frequency can potentially be used to derive jet velocity, diameter, composition, etc.

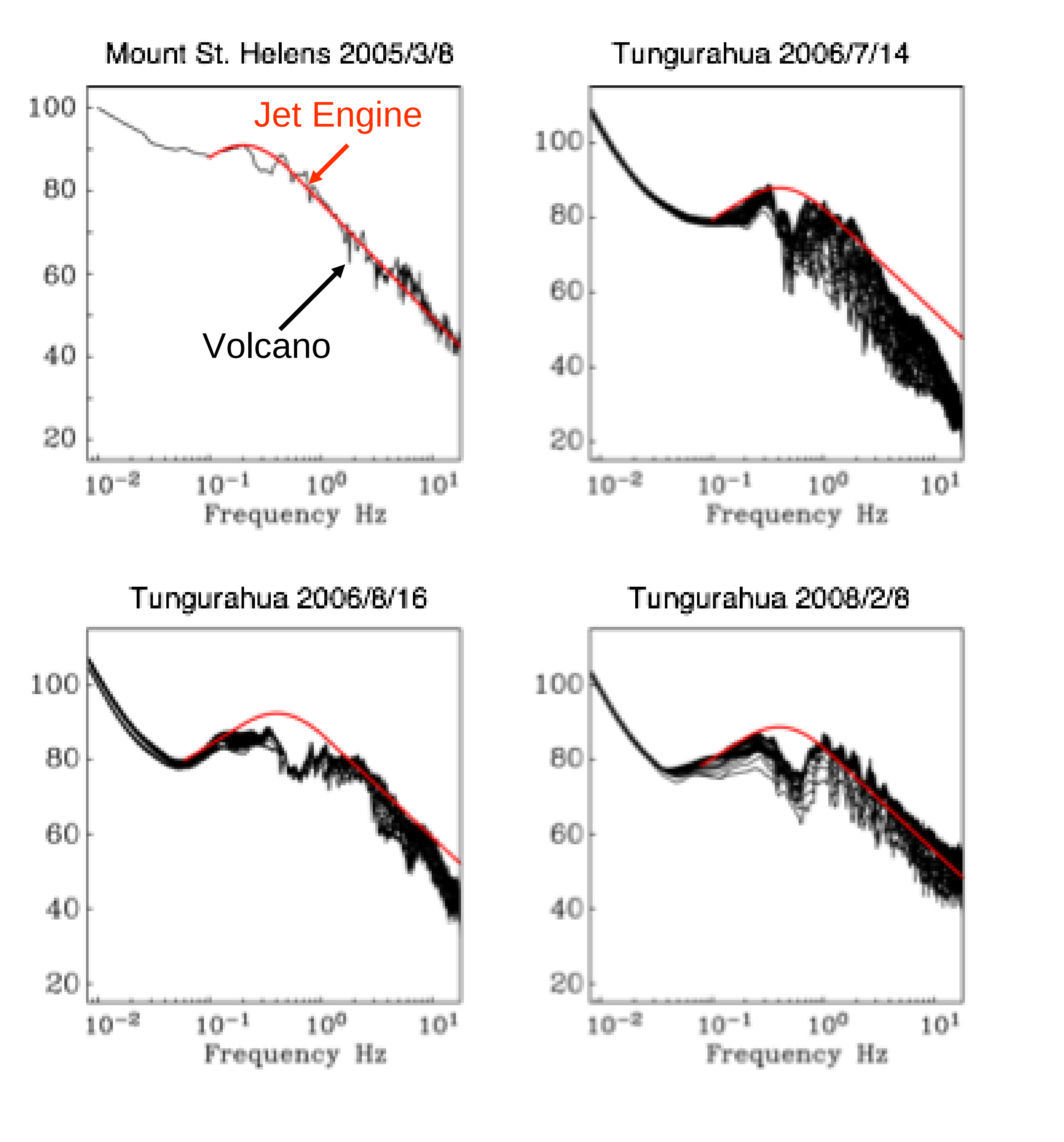
Jet Engine



[Tam et al. 2009]

Volcanic Jet

Mt. Spurr- 1992



[Matoza et al., 2009]

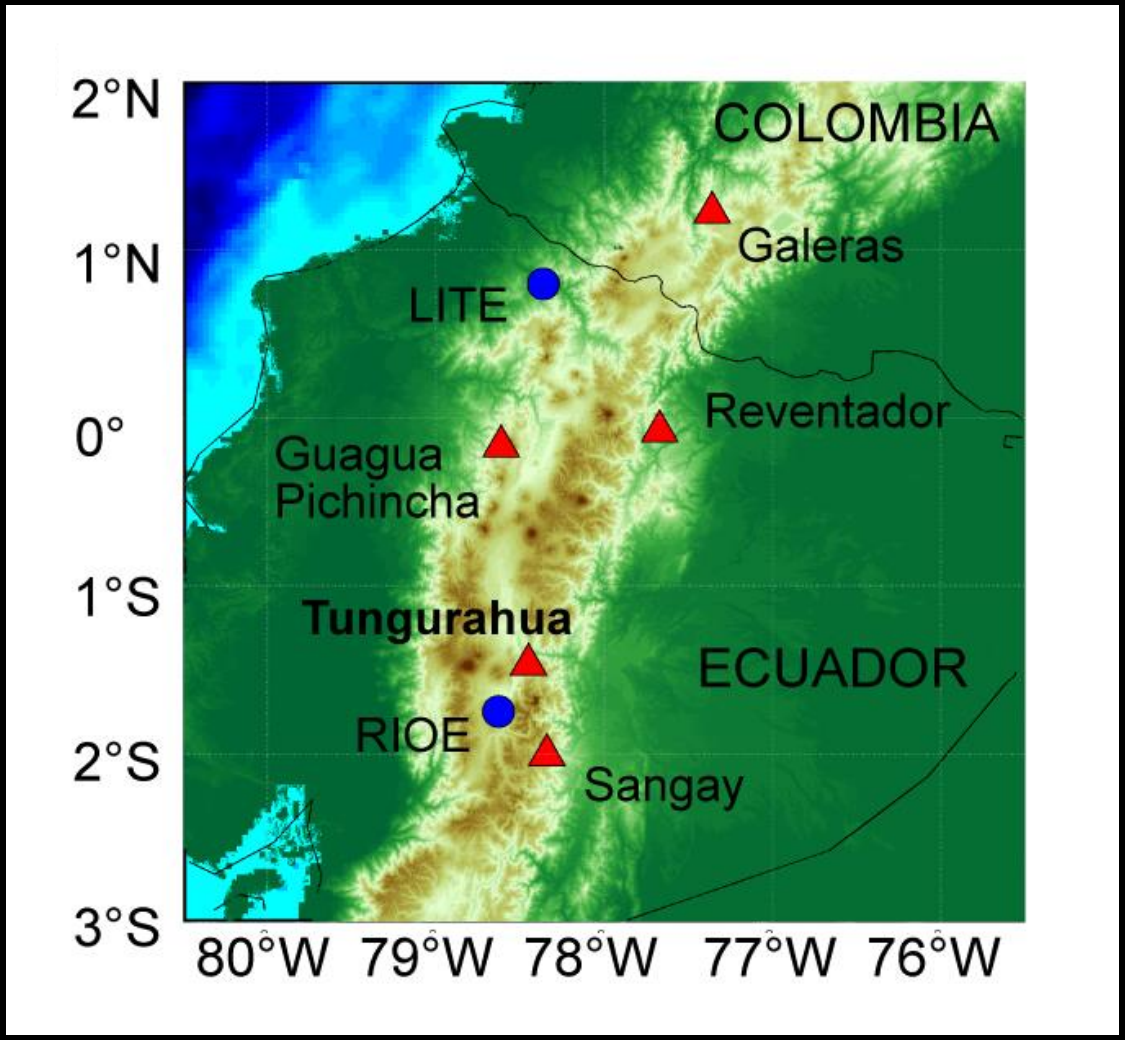
UNIQUE INFRASOUND SIGNATURES

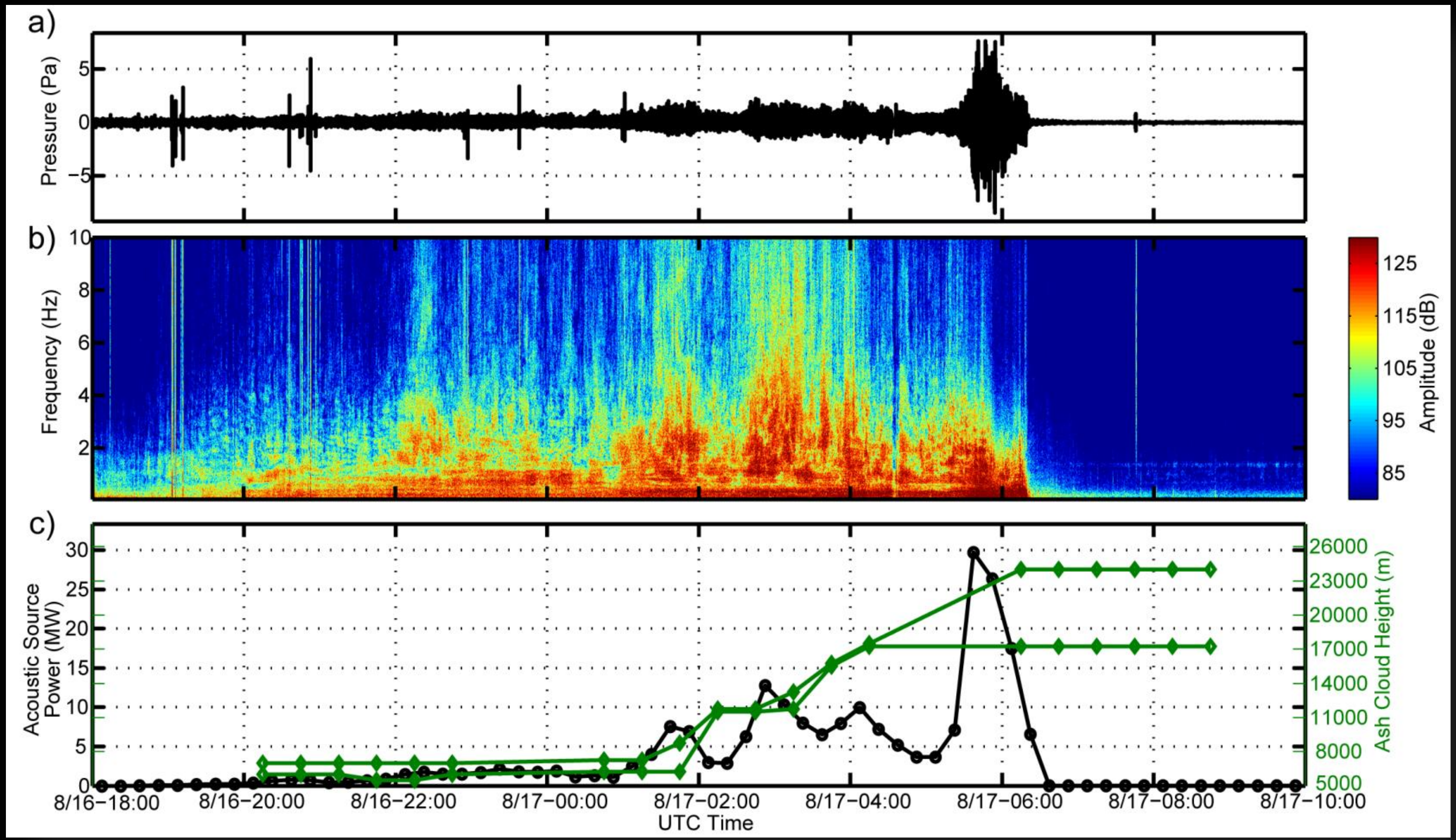
	Ash Explosions	Pulsatory Degassing	Gas Jetting	Explosive Eruption
Peak T (° C)	230	160	80	>350
IS Pressure (Pa)	±5.4	± 0.13	± 0.05	>125
IS Waveform	Impulsive Discrete	Emergent Discrete	Emergent Continuous	Impulsive Discrete
IS Frequency	0.3-10 Hz	0.5-10 Hz	~10-100 Hz	0.1-10 Hz
SO_2 ER (kg/s)	0.63±0.4	*1.40±0.1	1.0±0.3	0.71±0.6
Ash Mass (kg)	NA	0	0	>69,000

- Lopez et al. [2013] identified 4 main types of eruptive activity at Karymsky Volcano, Kamchatka
- Each type had distinguishing features
- Future work will attempt to quantitatively identify and model these sources

ERUPTION MONITORING: ACOUSTIC SURVEILLANCE FOR HAZARDOUS ERUPTIONS (ASHE)

- Test viability of monitoring remote volcanic regions using infrasound
- Multiple collaborators teamed with local institute (IG) and Washington VAAC





[Fee et al., 2010]

- Intense, low frequency, sustained infrasound coincident with high-altitude ash emissions
- Identifiable based on spectral shape and frequency content (jet noise)
- Autonomous ASHE notification system successful in detecting and notifying authorities during 6 February 2008 Tungurahua eruption

ERUPTION MONITORING: CLEVELAND VOLCANO, AK

Photo courtesy Cyrus Read, AVO

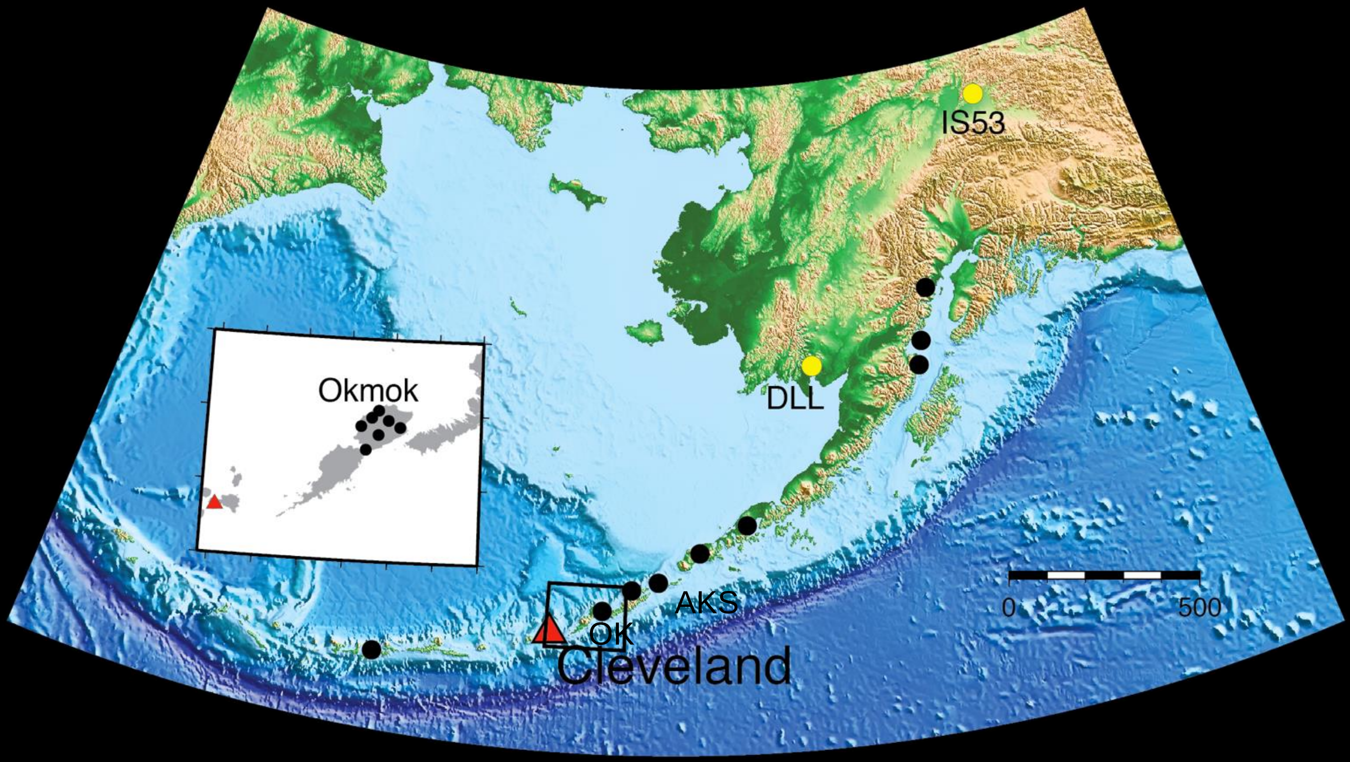
- One of the most active and remote volcanoes in the Aleutian arc
- Mostly small, ash-producing eruptions <9 km
- Before 2014:
  - no real-time, local, seismic network due to logistical challenges (closest seismic station is 75 km)
  - primarily monitored using remote sensing

Okmok: 150 km, 245°

Akutan: 315 km, 245°

DLL (Dillingham): 992 km, 230°

IS53 (Fairbanks): 1827 km, 233°



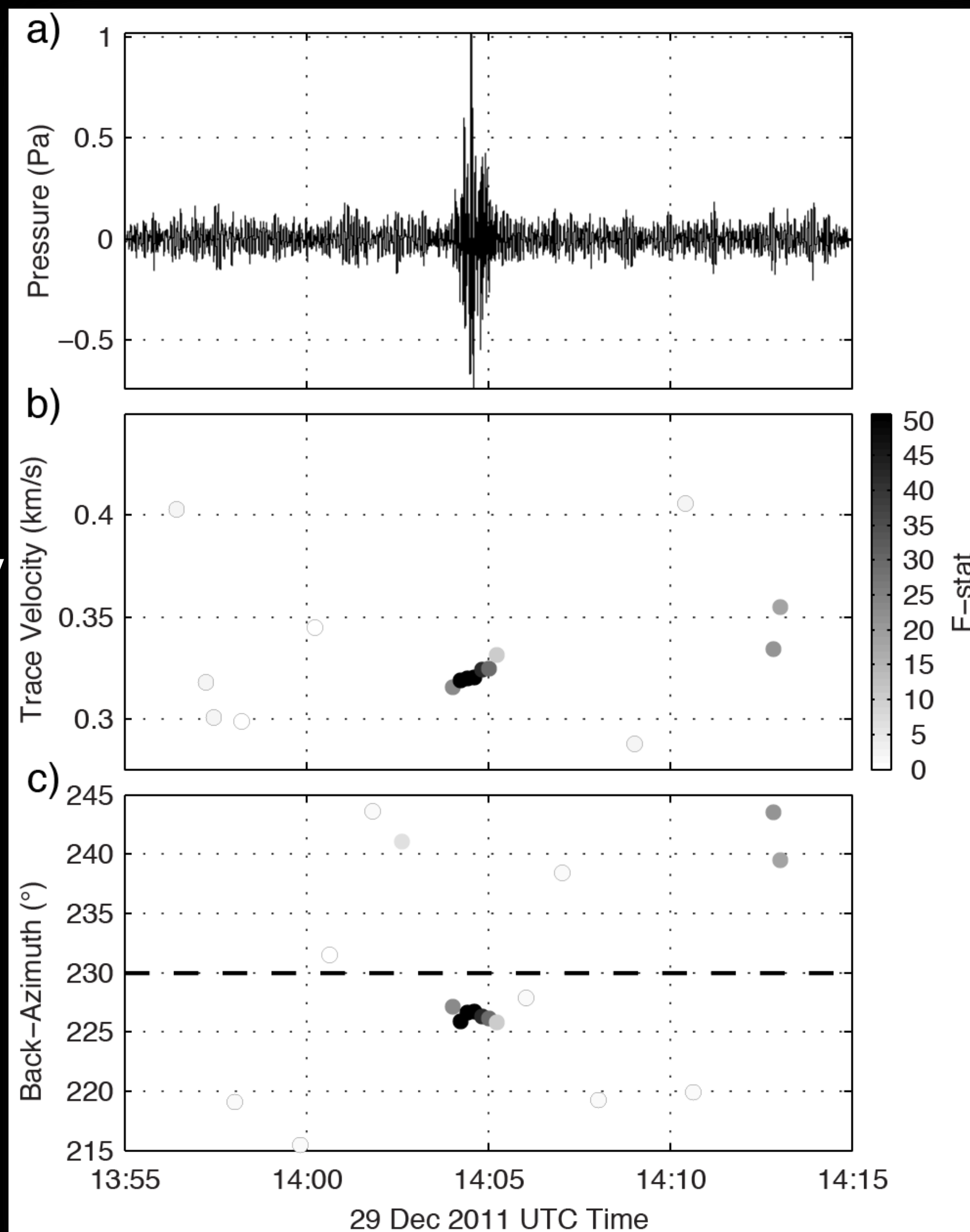
CLEVELAND VOLCANO - DETECT AND NOTIFY

Dillingham - 992 km

Infrasound

Wave Velocity

Back-Azimuth



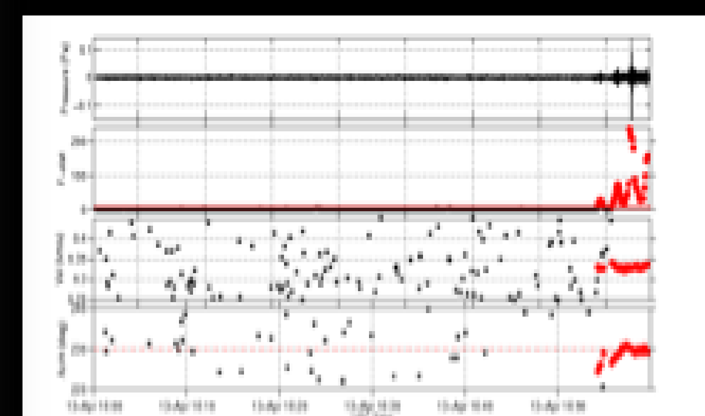
[De Angelis et al., 2012]

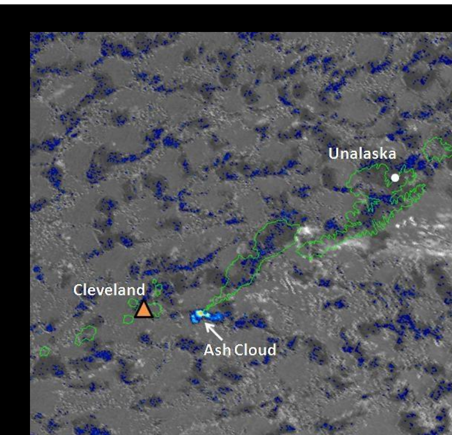
Dec 2011 – Aug 2012 Detections:
~7/20 in satellite imagery
19/20 events with infrasound

From: David Fee dfee@gi.alaska.edu
Subject: Cleveland Volcano Dillingham Infrasound Detection Alert: 13-Apr-2012 1600 - 13-Apr-2012 1700 UTC
Date: April 13, 2012 10:08:14 AM PDT
To: David Fee <dfee@gi.alaska.edu>, volcanodoctor@gmail.com, Silvio De Angelis <silvio.deange@gmail.com>, 9073478599@txt.att.net, 9079782561@txt.att.net, 9073220676@txt.att.net, Colin Rowell <rowell.colinr@gmail.com>

Cleveland Infrasound Detection Alert
Dillingham Infrasound Array, 992 km from source

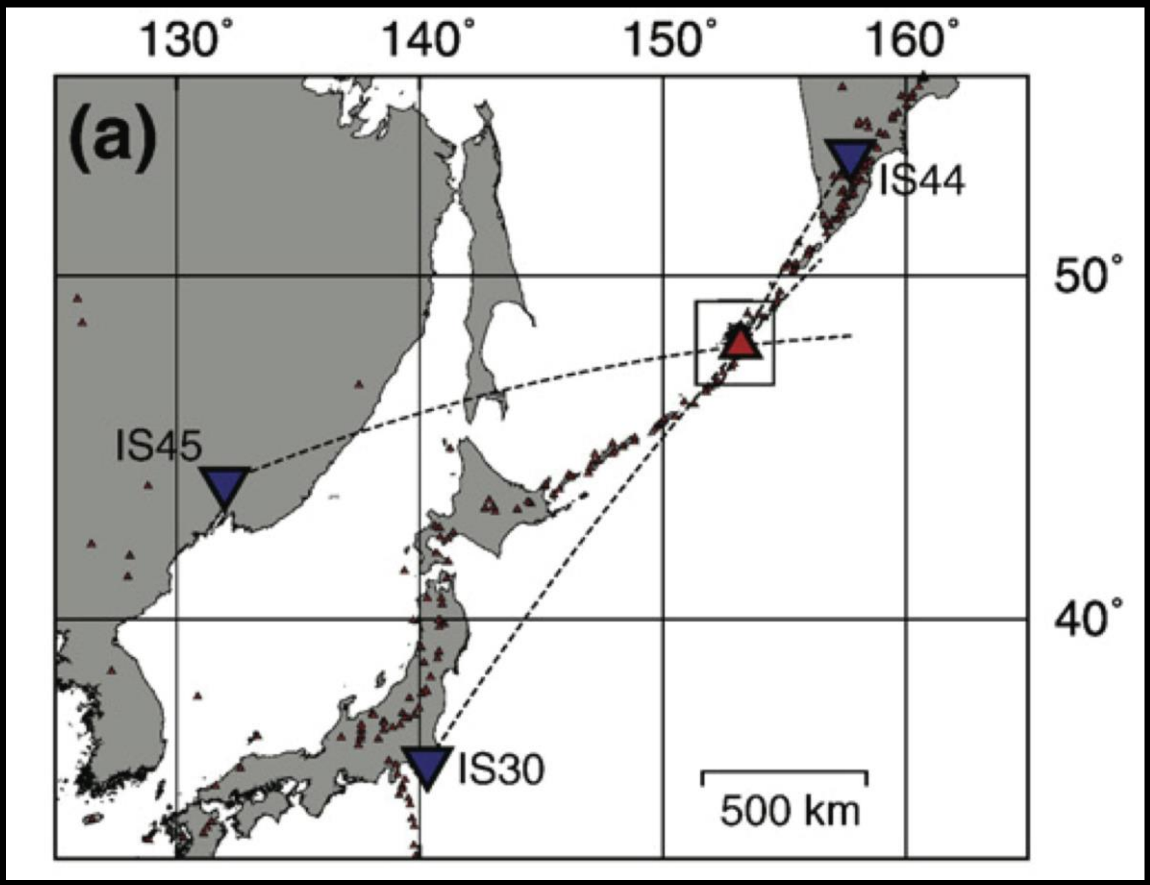
Dillingham Detection Time: 13-Apr-2012 16:54:27 UTC
Approx. Origin Time: 13-Apr-2012 16:02:47 UTC
Max Pressure Amplitude: 0.143 Pa
Max Fisher Ratio: 237

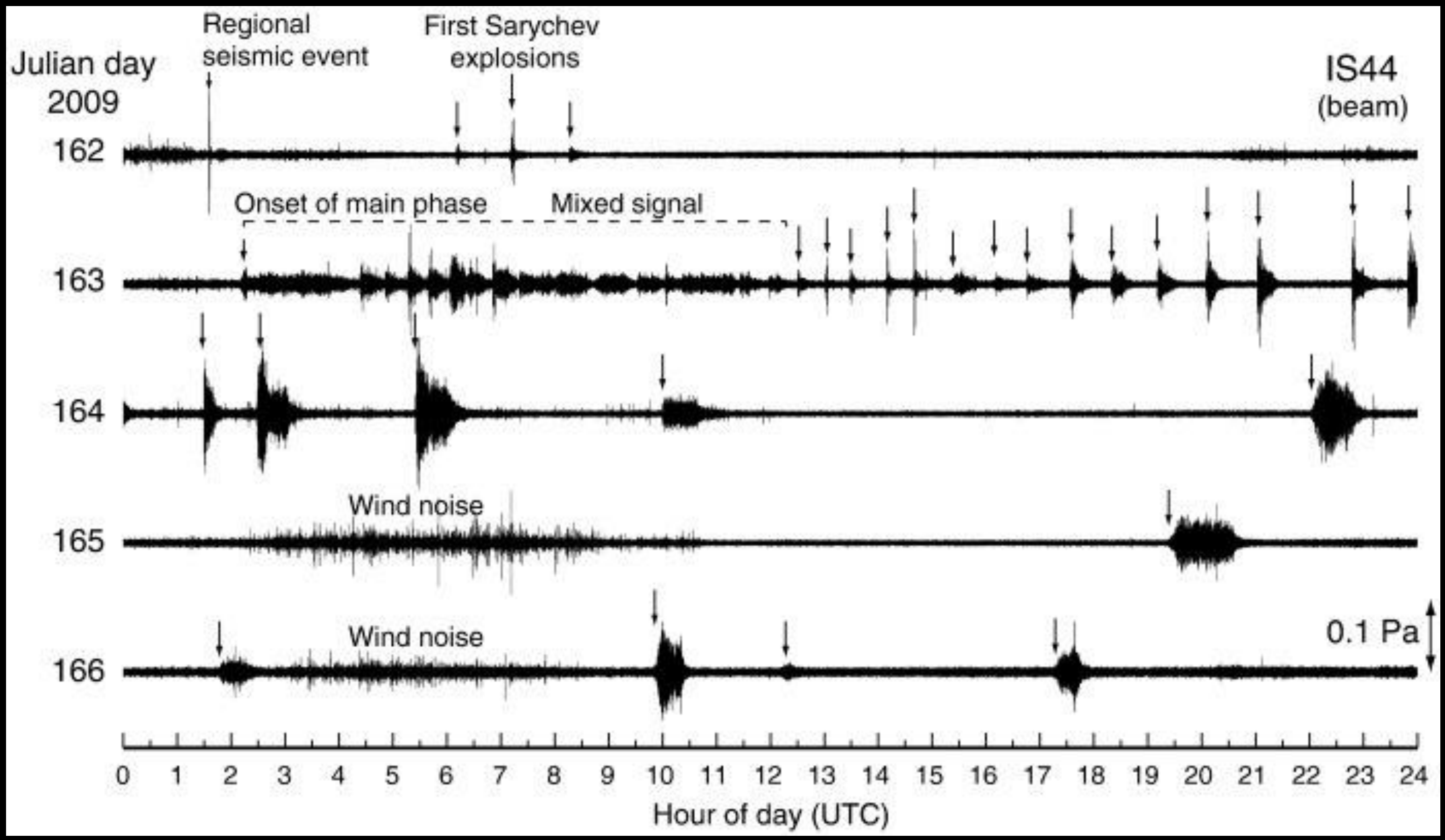




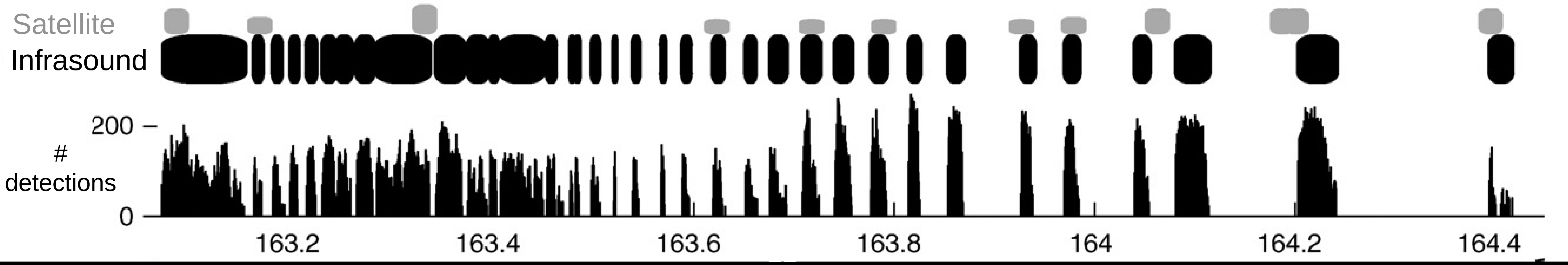
Automated detections trigger alerts to AVO personnel

2009 SARYCHEV PEAK, KURILE ISLANDS





- Matoza et al. [2011] found remote infrasound arrays (640-6400 km) provide most detailed eruption chronology
- Correlates well with eruption chronology from satellite data
- High signal-noise at IS44, Kamchatka (640 km northeast)



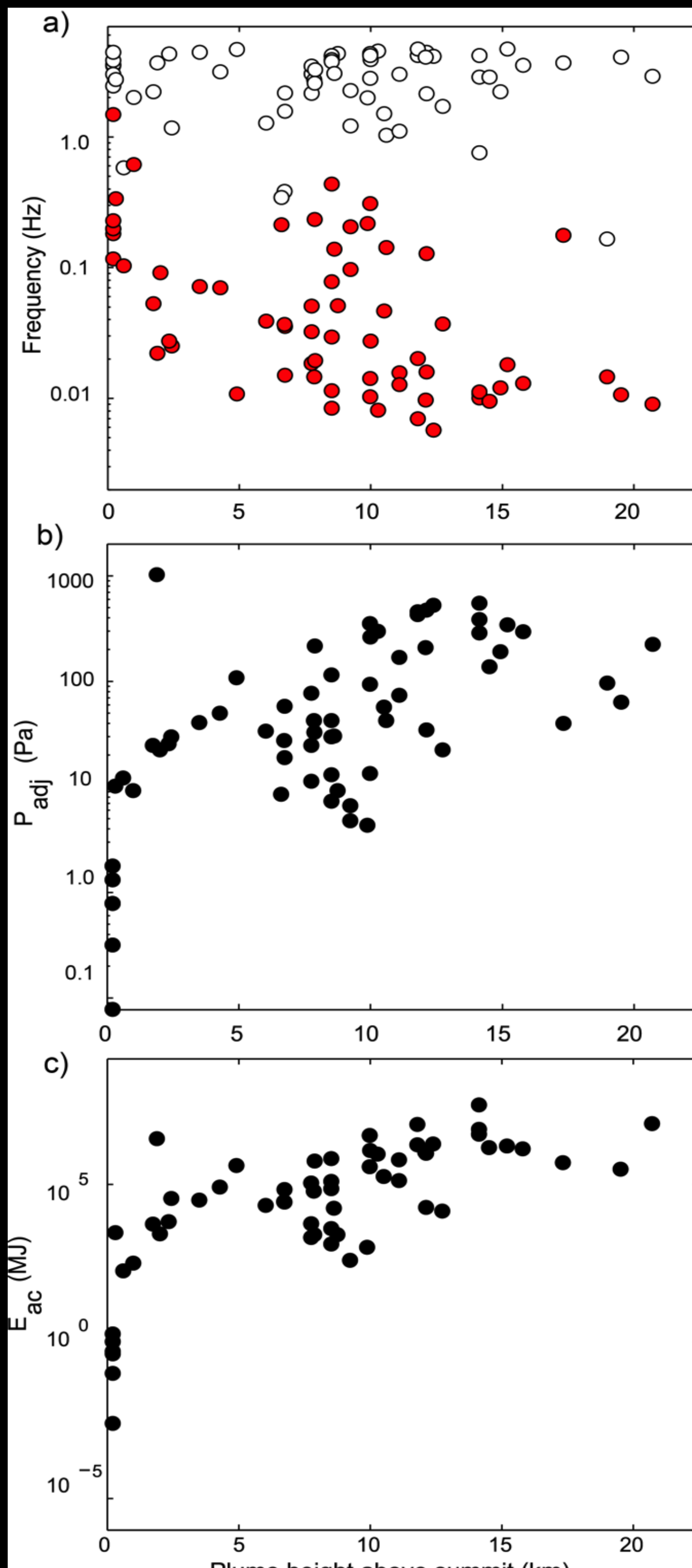
GLOBAL IMS VOLCANO DETECTIONS

Plume Height->

Frequency [Hz]

Peak Pressure

Acoustic Energy



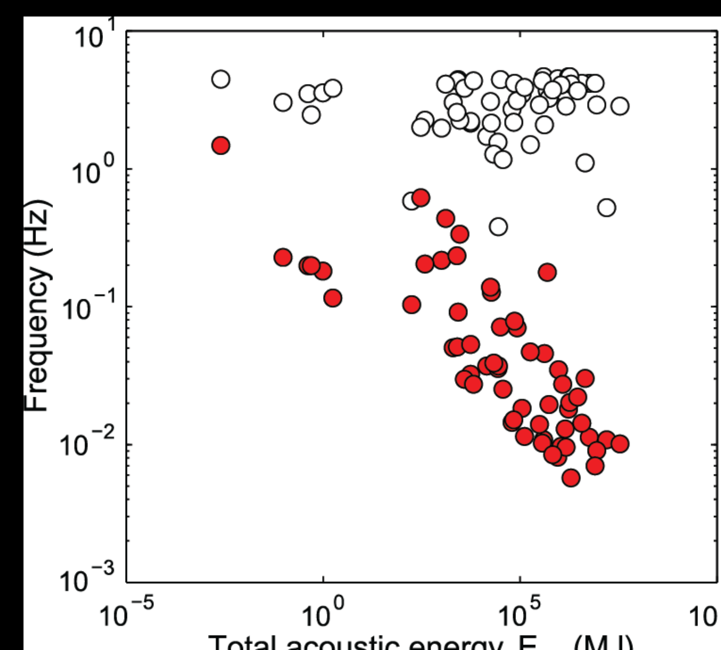
Dabrowa et al. [2011]: comprehensive study on IMS volcano infrasound observations

1) recorded distance increases with ash plume height

2) lowest detected infrasonic frequency decreases with increasing plume height

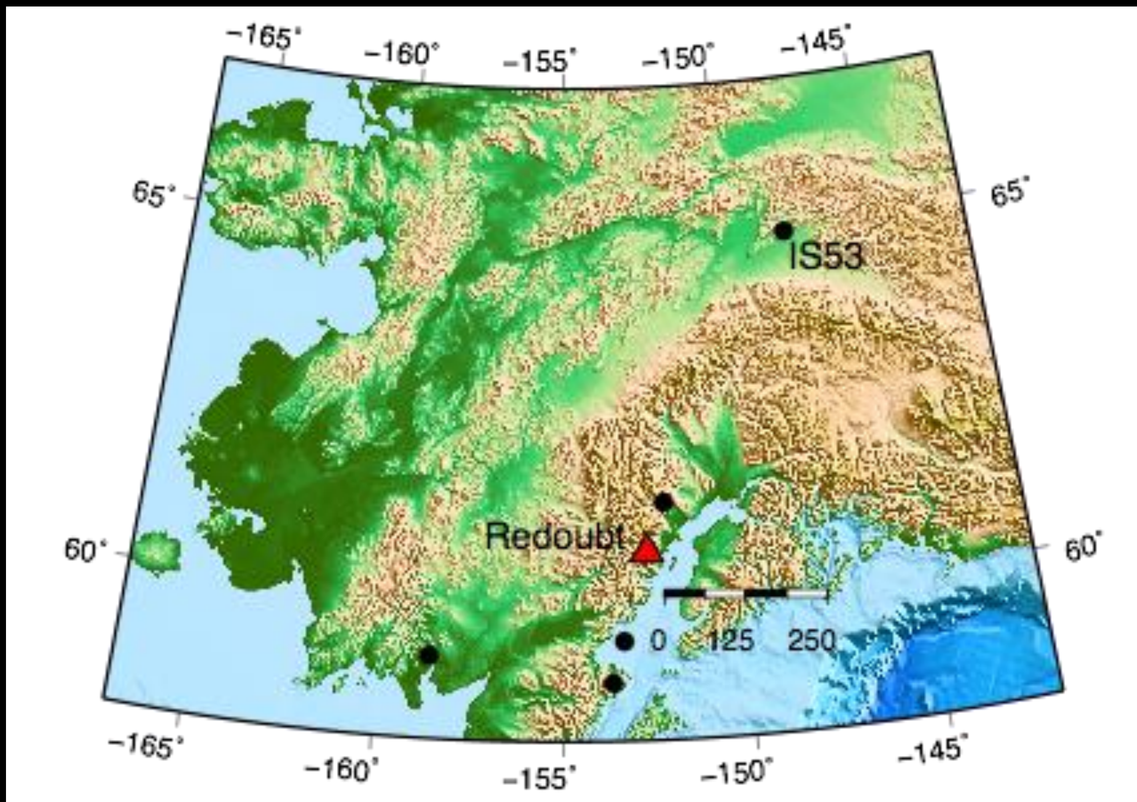
3) total acoustic energy and distance-corrected amplitude increase as a function of plume height

Frequency [Hz]



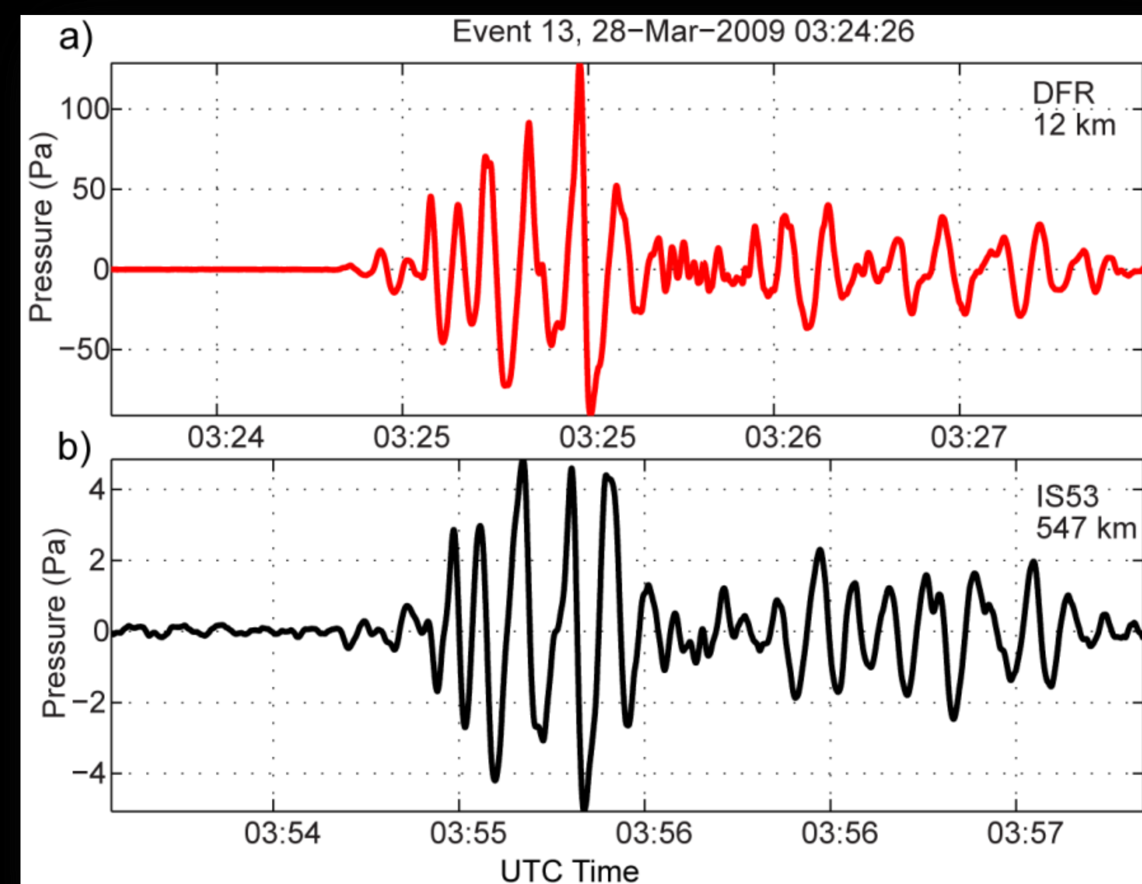
Acoustic Energy

2009 REDOUBT VOLCANO ERUPTION



- Erupted 23 March - 4 April 2009
- >19 explosive eruptions (events)
- Ash plumes to 19 km
- Significant pyroclastic flows, lightning, and seismicity
- Relative proximity to Anchorage and North Pacific air routes

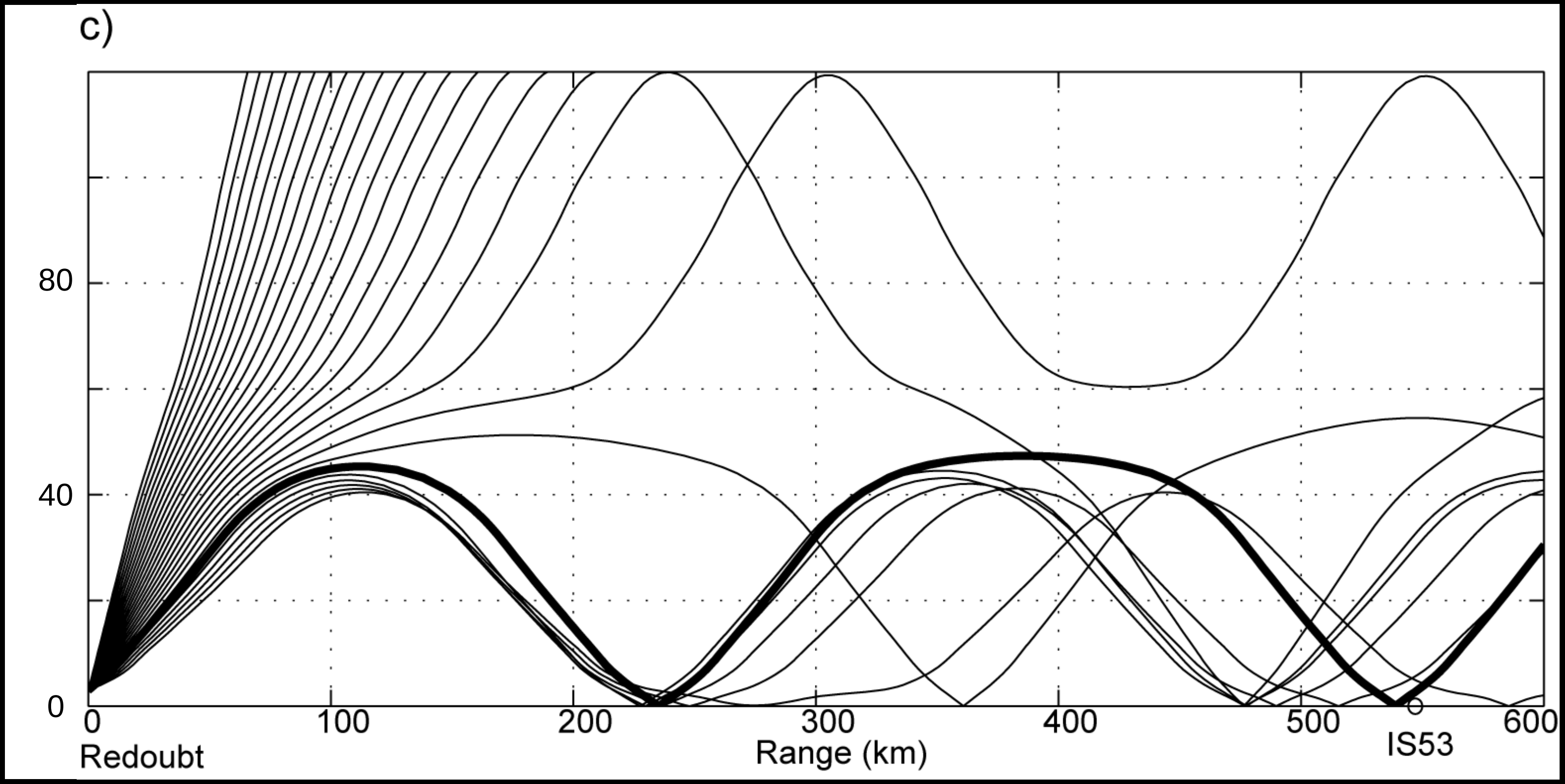
- DFR: Single infrasound sensor @ 12 km
- IS53 : 8-element infrasound array @ 547 km
- All significant explosive events clearly detected IS53
- Unique opportunity to compare local and remote data and examine long-range propagation

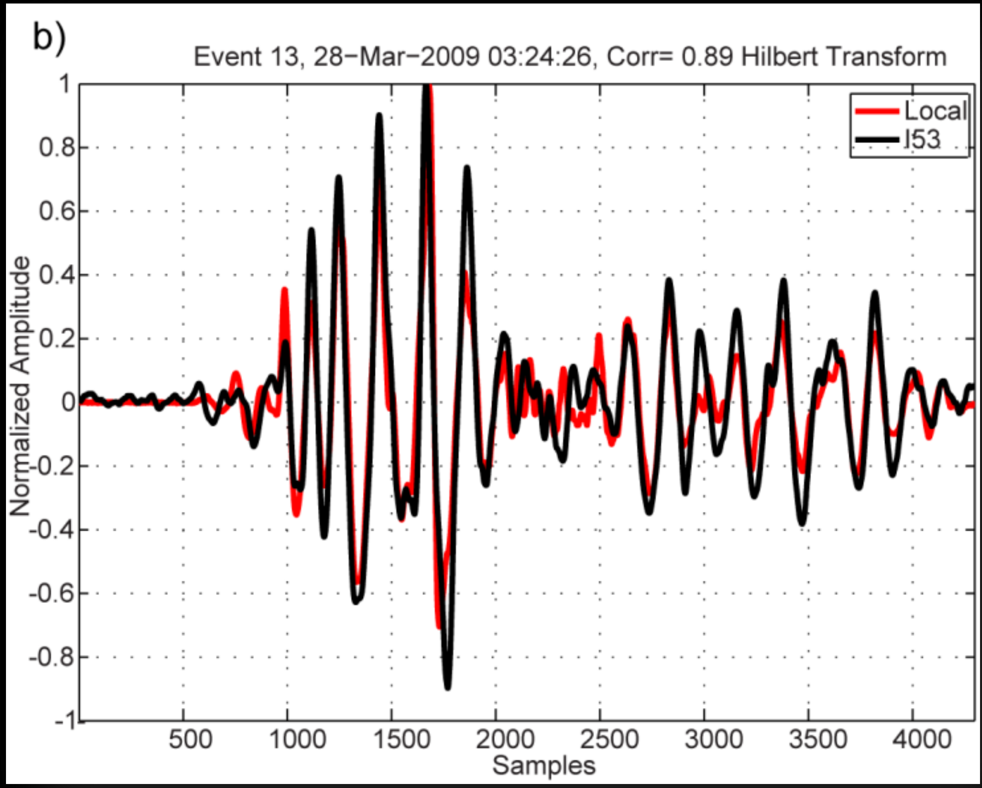


[Fee et al., 2013]

REDOUBT: LOCAL AND REMOTE INFRASOUND COMPARISON

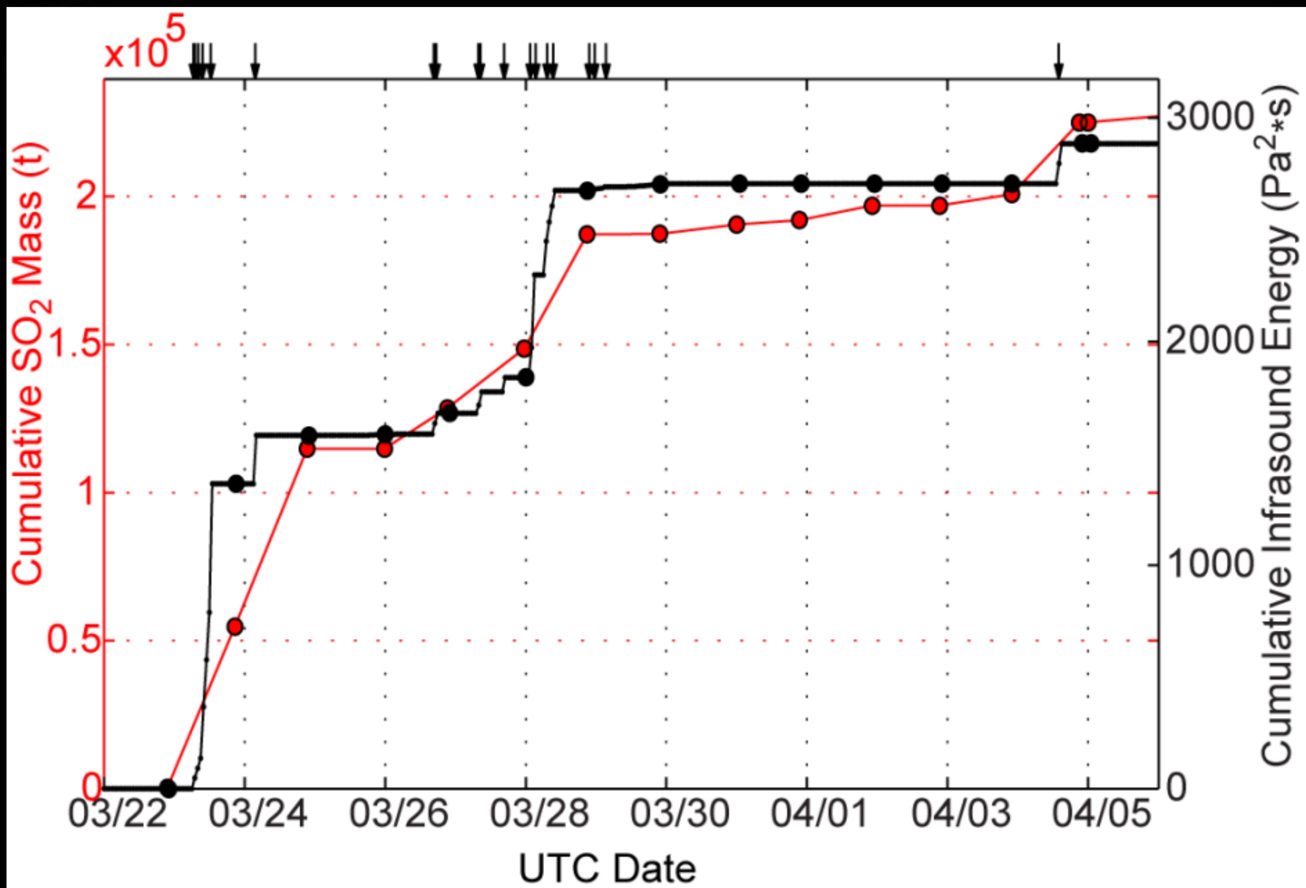
- Compute cross-correlation between local and remote data
- Propagation modeling predicts 90° phase shift, improves cross-correlation to 0.89
- Remote infrasound can provide good representation of local infrasound





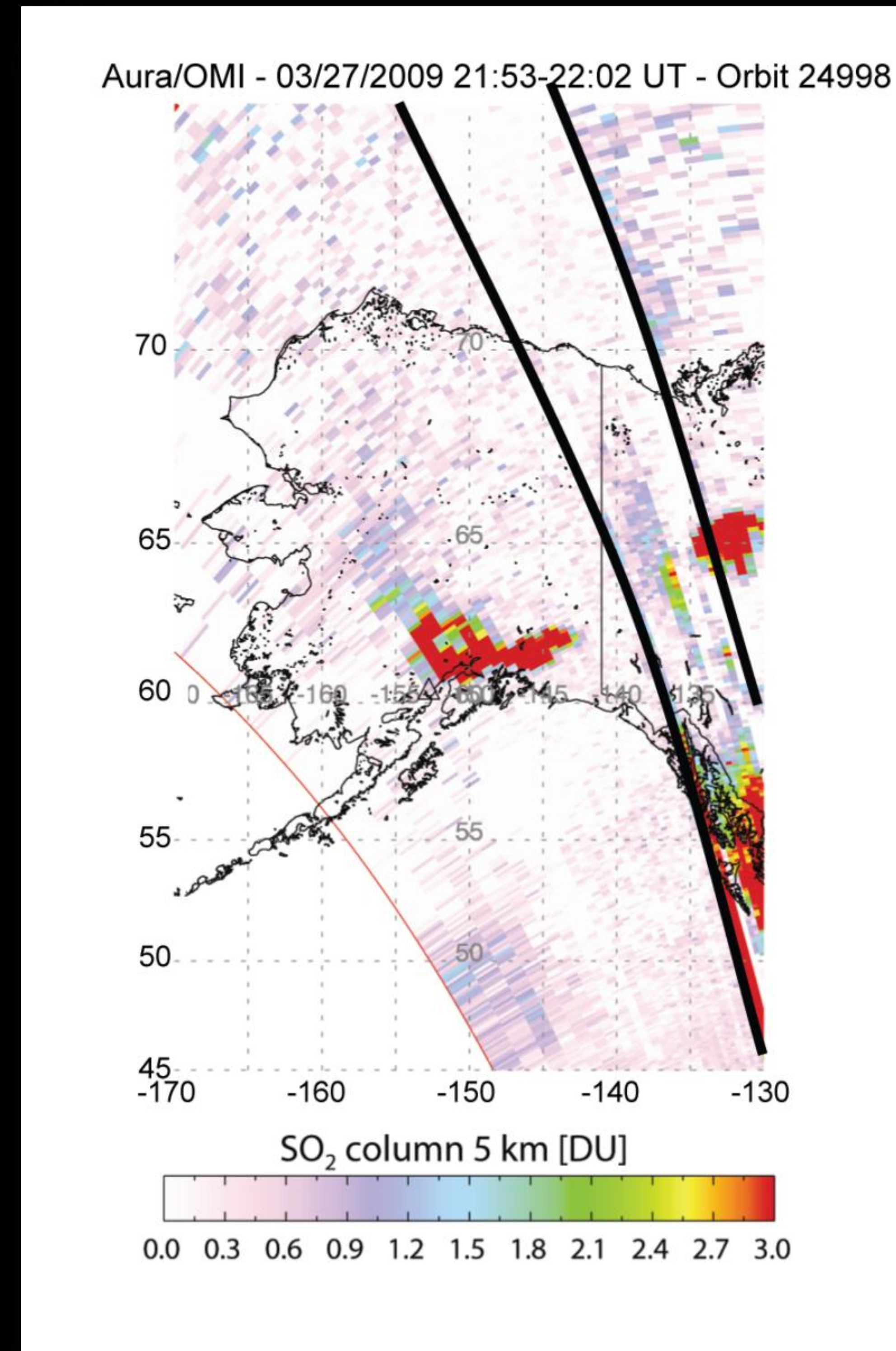
[Fee et al., 2013]

REDOUBT INFRASOUND AND SO2



[Fee et al., 2013]

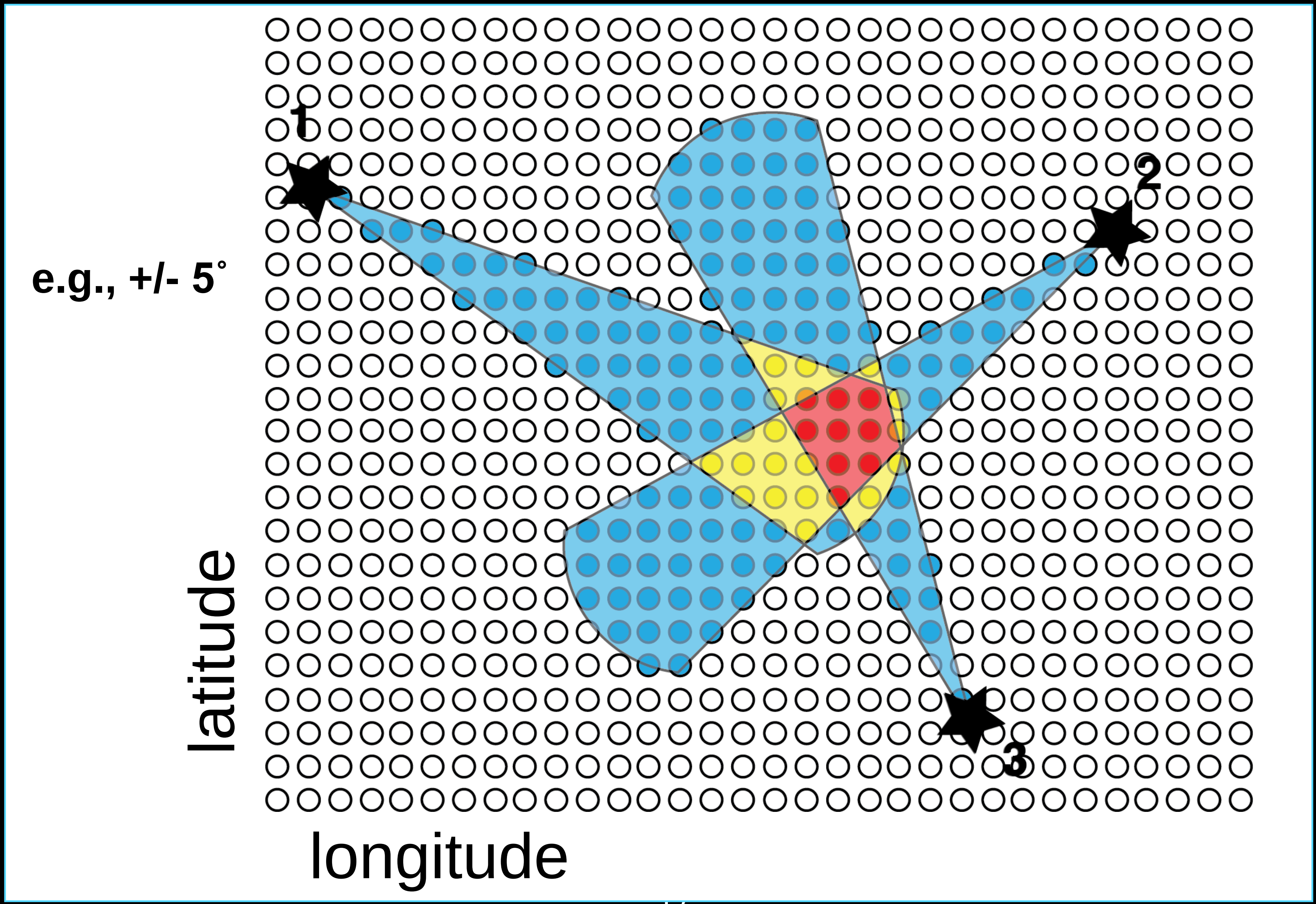
- Very good correlation between cumulative infrasound energy (black) and daily SO_2 estimates (red)
- Relationship between SO_2 production and infrasound energy still being explore
- Potential to use remote infrasound arrays as real-time detector of elevated SO_2 (and ash?)



[Lopez et al., 2013]

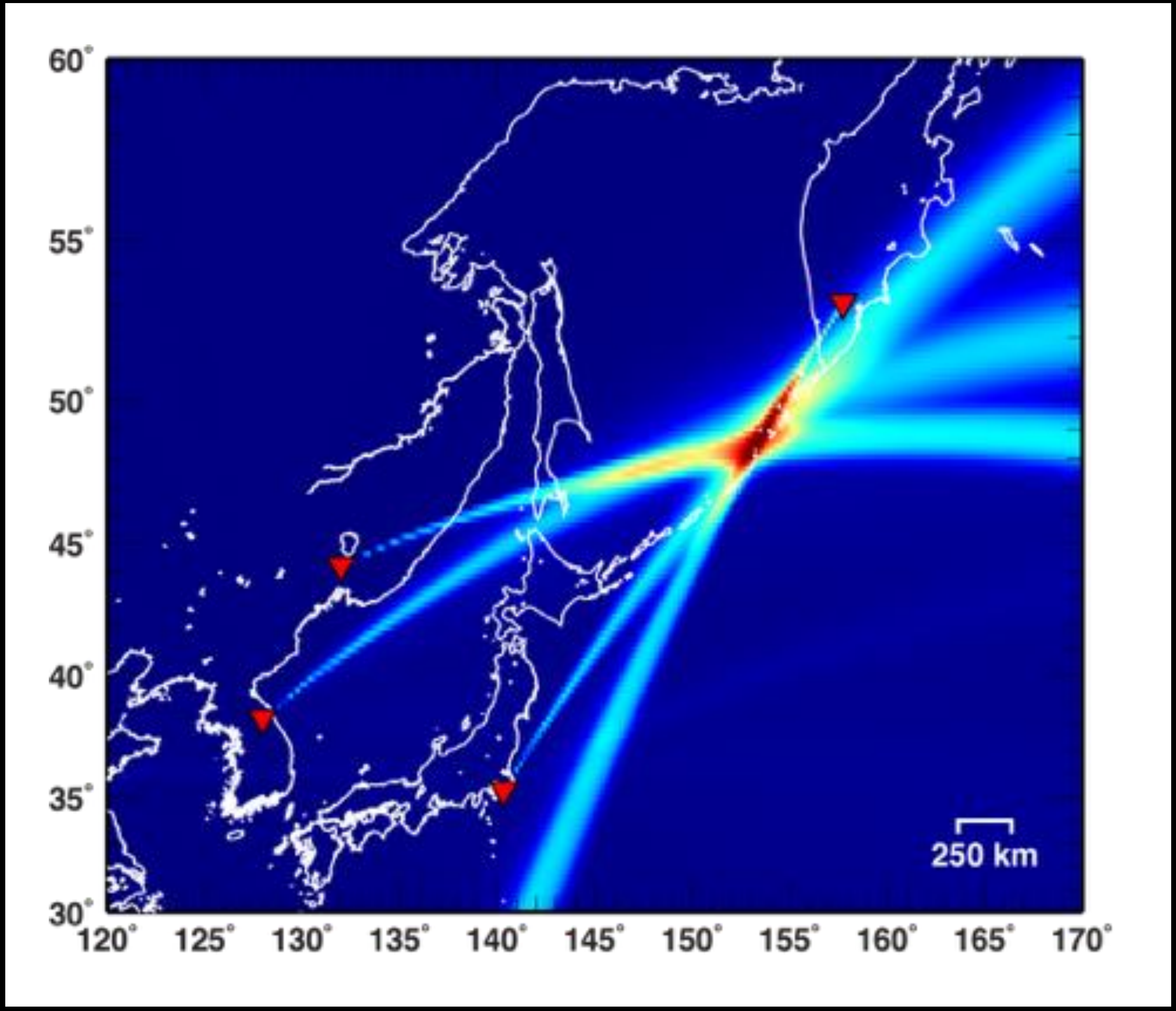
CURRENT PROGRESS: GLOBAL CATALOGING OF EXPLOSIVE VOLCANISM

- Goal: Search infrasound data from multiple infrasound arrays to identify volcanic signals recorded consistently (associated) across multiple stations
- Method: Association and location via brute force grid-search cross-bearings approach
- Project led by Robin Matoza (UCSB)

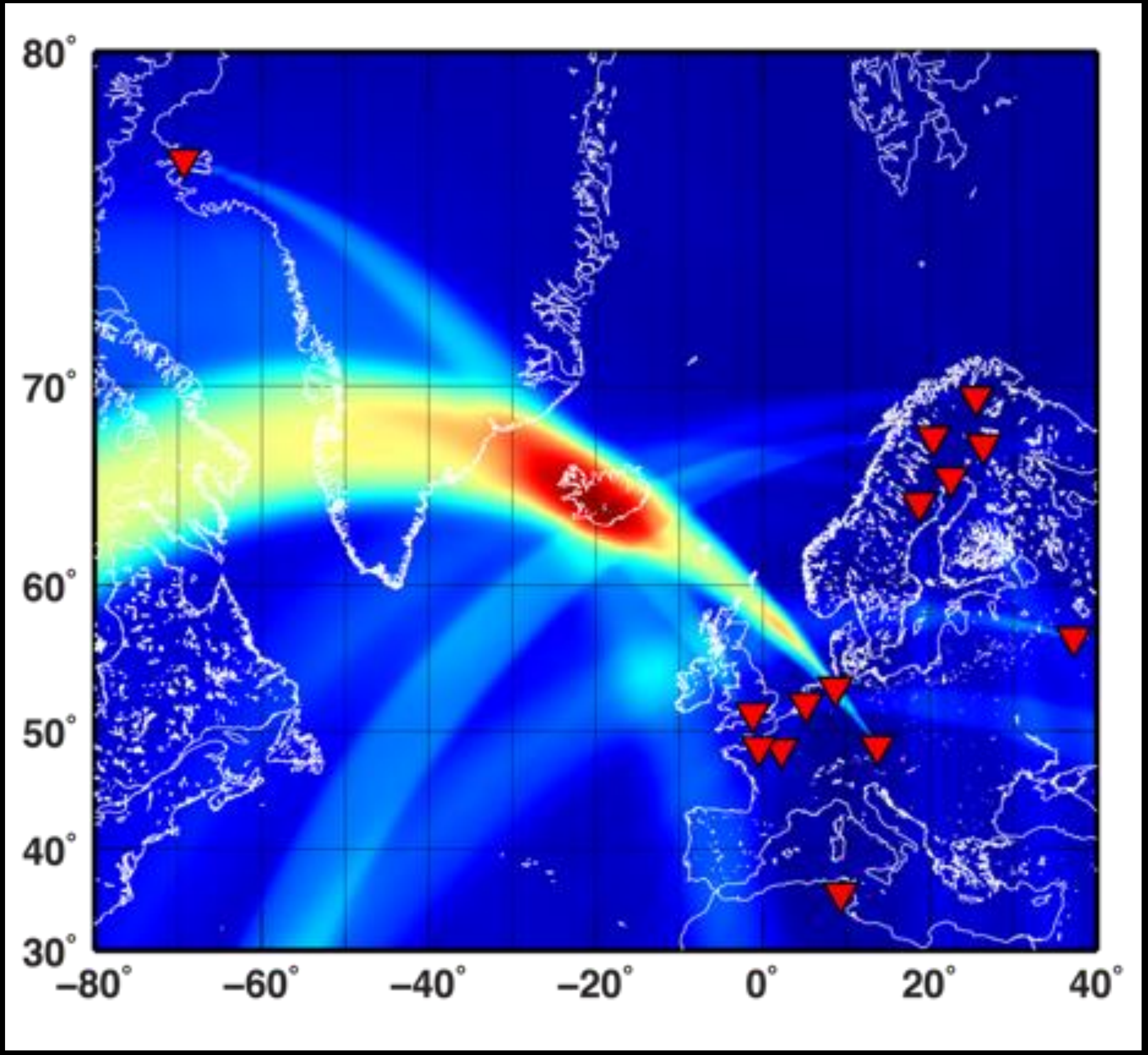


CURRENT PROGRESS: GLOBAL CATALOGING OF EXPLOSIVE VOLCANISM

- Example: Sarychev Peak
- 4 stations
- 11-16 June 2009



- Example: Eyjafjallajökull
- 14 stations
- 14 April - 1 June 2010



CURRENT PROGRESS: ERUPTION SOURCE TERM

Simplified view of an infrasonic signal:

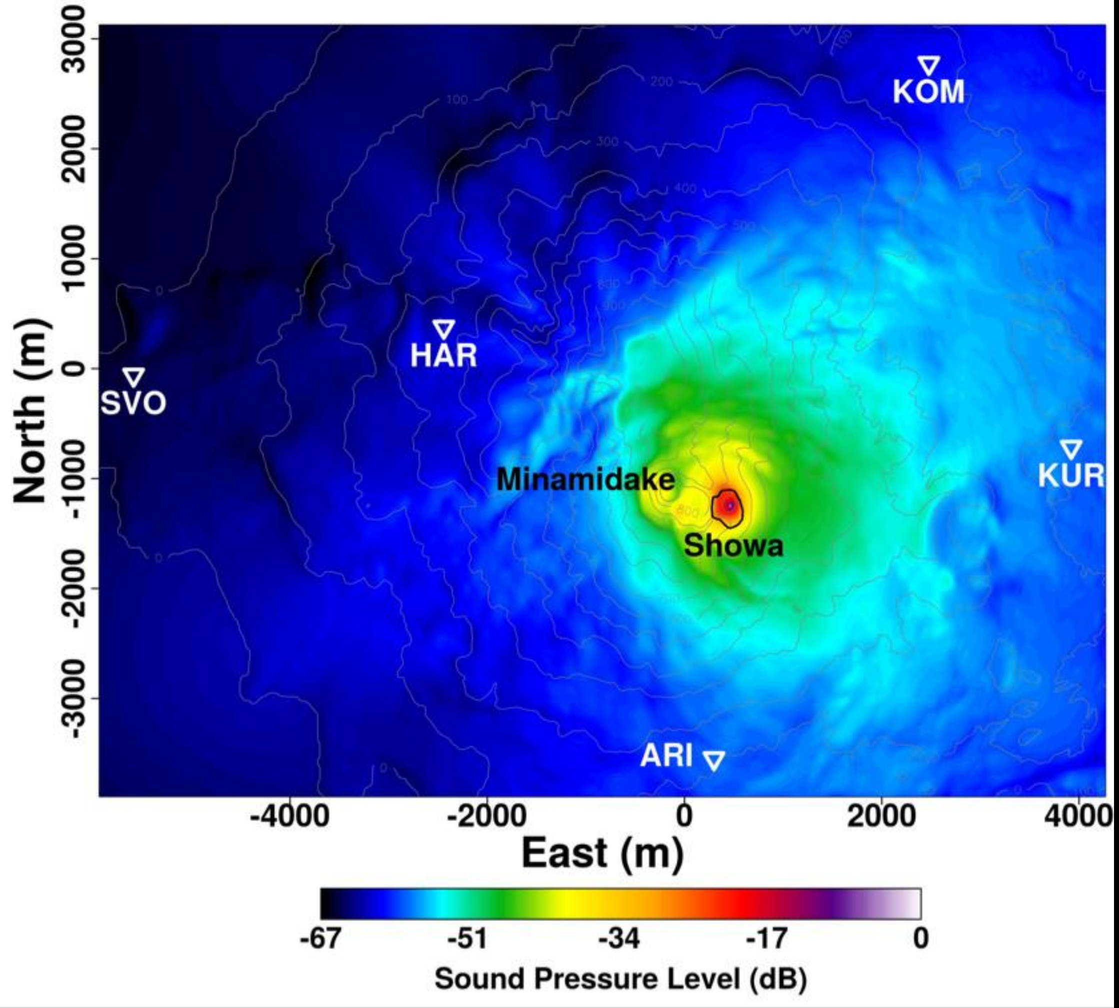
$$p(x,t) = G_0(x,t;x_0,t_0) * Q(t)$$

acoustic pressure — Green's Function (propagation) — Volume flux (monopole source strength)

$$M = Qr$$

Mass flux (kg/s) — Volume Flux (m^3/s) — Flow Density (kg/m^3)

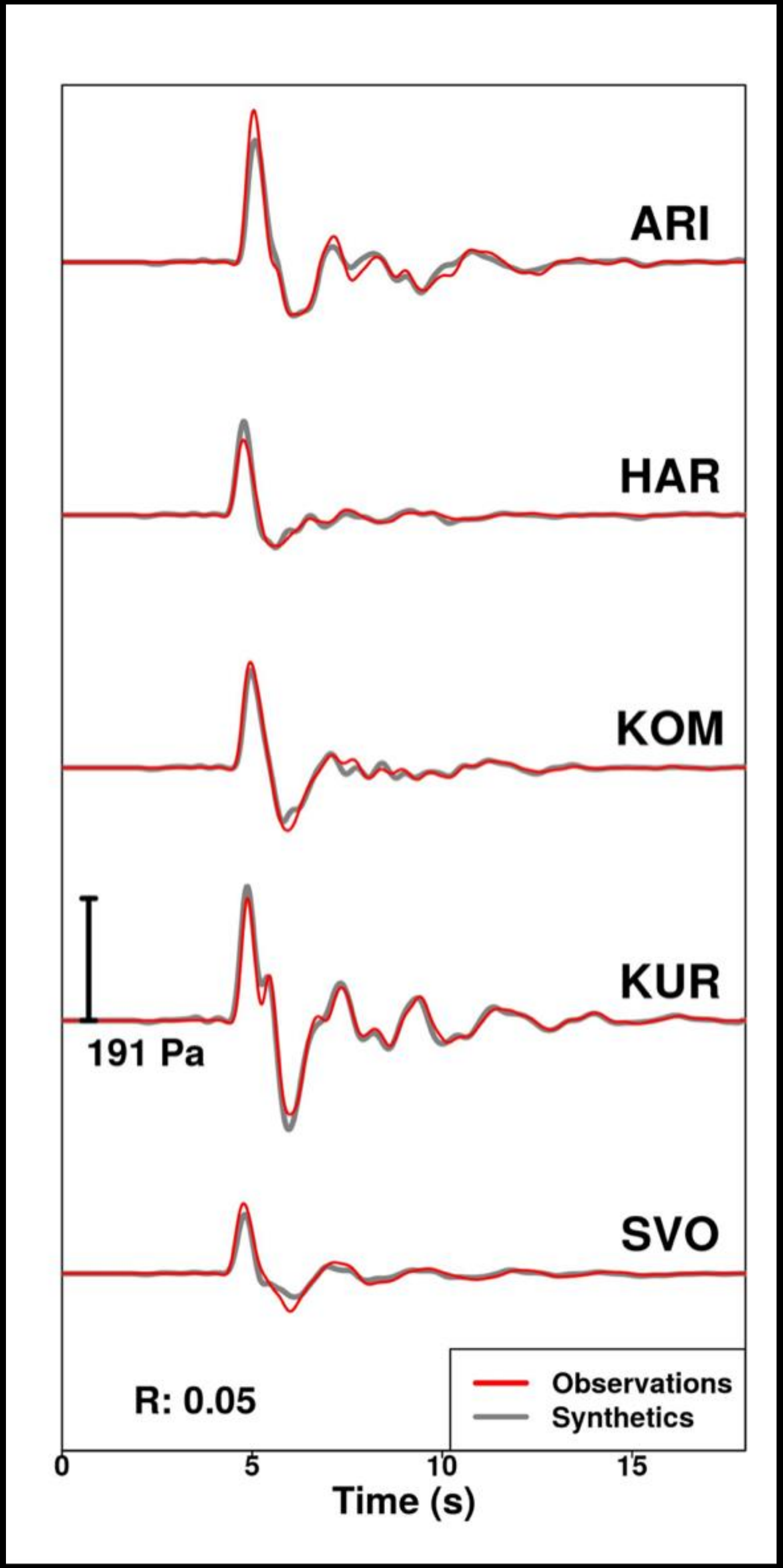
Sakurajima Volcano, Japan



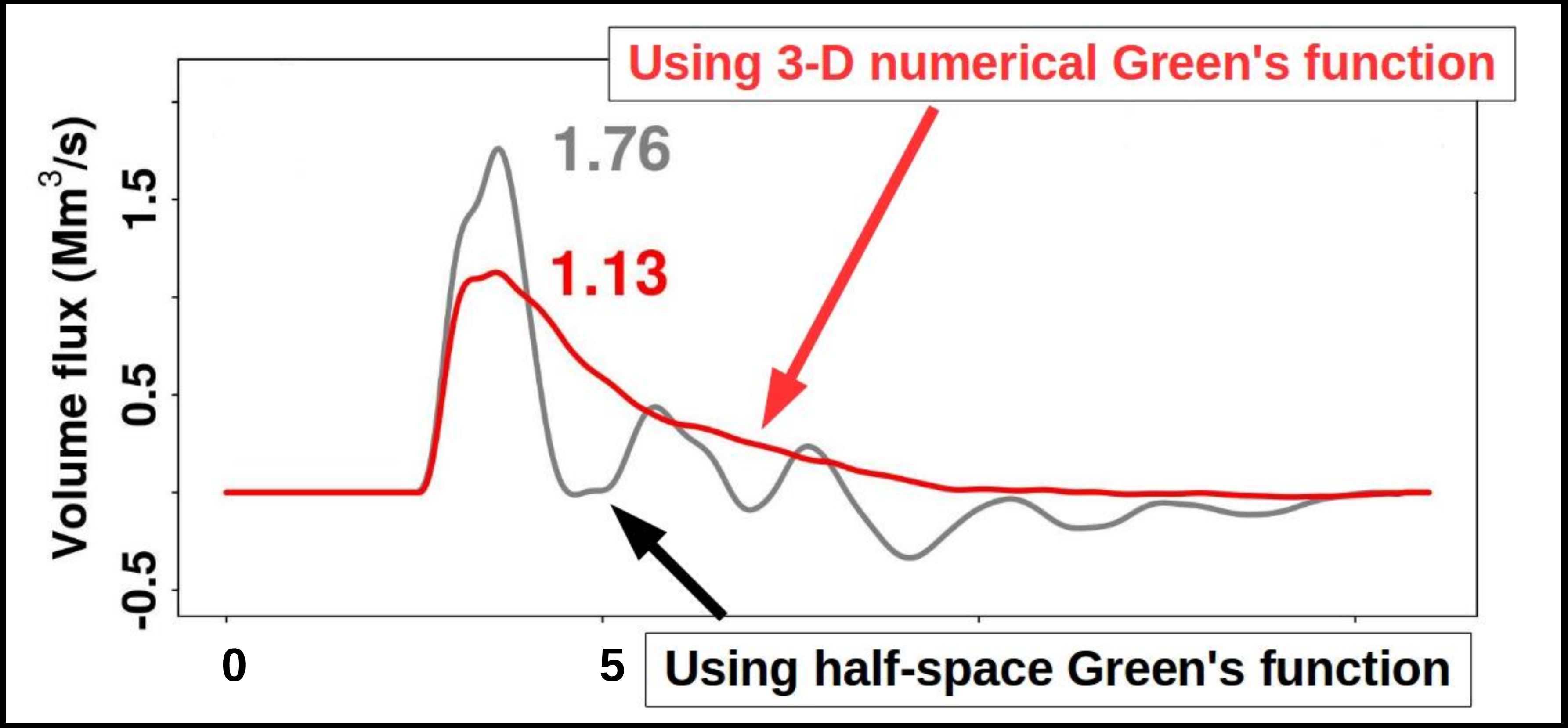
[Kim and Lees, 2014]

- Time-dependent flow density needed to convert volume flux to mass flux
- Waveform inversion to solve for volume flux [e.g. Ohminato et al., 1998]
- 3-D Finite Difference Time Domain modeling needed to solve Green's function

CURRENT PROGRESS: ERUPTION SOURCE TERM



- Excellent waveform fit to observations
- Source time history (volume flux)
  - 3-D Green's function: smoothly decreasing
  - Half-space Green's function: oscillatory curve
- First acoustic inversion with computed, 3-D Green’s functions
- Volume/mass flux critical parameter for hazard mitigation



[Kim et al., 2015]

CONCLUSIONS

- Explosive volcanoes produce prodigious, varied infrasound signals indicative of the style of eruption
- Infrasound is produced by flux of material out of the vent

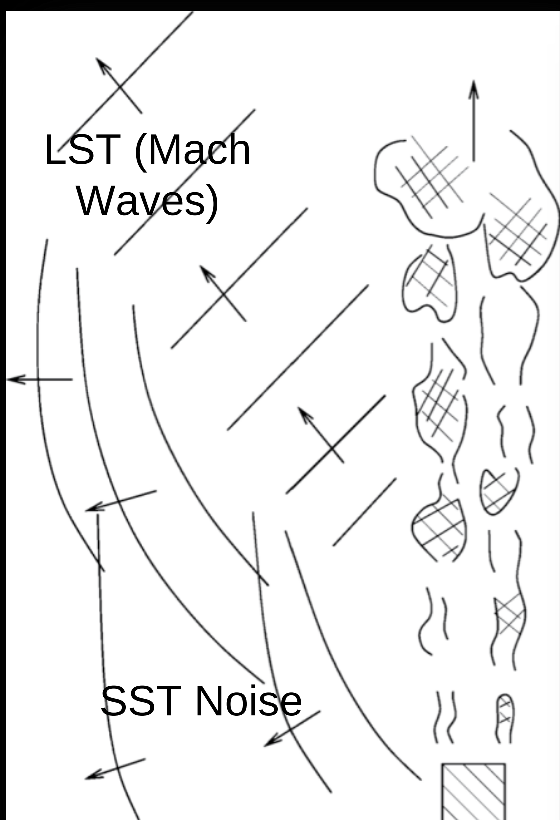
  ➡Permits real-time estimate of volume flux
- Infrasound correlates qualitatively (and quantitively) with plume height
- Proper understanding of acoustic propagation and the atmosphere is necessary to model the acoustic source
- Readily combinable with other datasets

NEXT STEPS?

- More and better understood quantitative models: source and propagation
- Real-time volume (and mass?) flux
- Better integration of regional infrasound with IMS infrasound. Data fusion.
- Local networks required for low-latency, high-resolution source studies and monitoring
- Integrate with remote sensing and hazard monitoring community

NABRO VOLCANO, ERITREA - EVIDENCE FOR SUPERSONIC JET NOISE

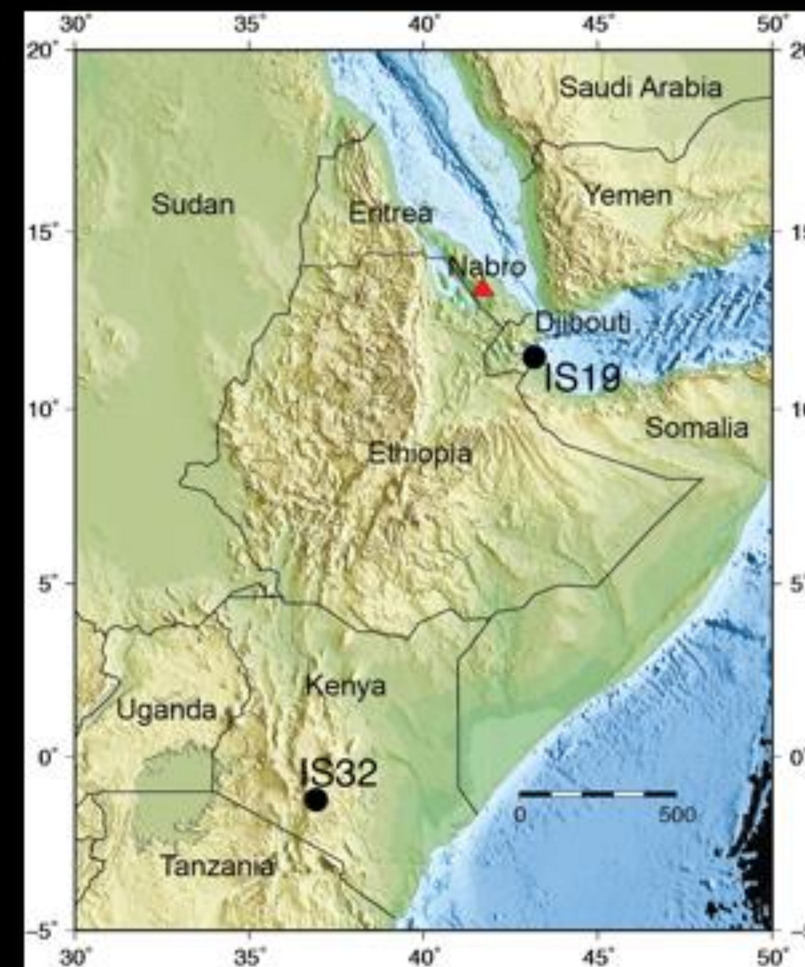
Jet Engine



[Tam et al. 2009]

Volcanic Jet

Mt. Spurr- 1992



Previous work has shown similarities between sustained infrasound from large volcanic eruptions with the sound from jet engines [e.g. Matoza et al., 2009]

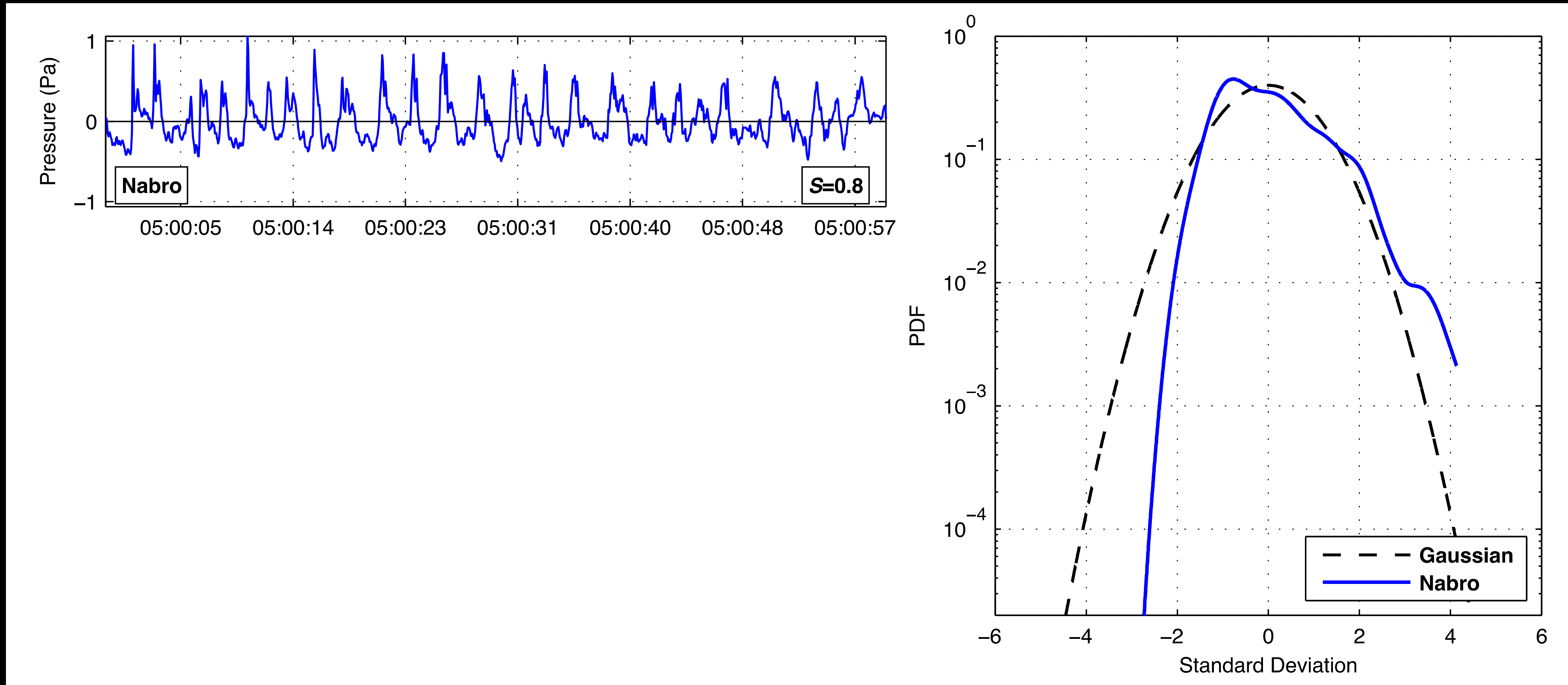
Detected by 2 CTBTO IMS infrasound arrays:

- IS19 (Djibouti): 264 km, 323°
- IS32 (Kenya): 1708 km, 18°

NABRO VOLCANO VS. SUPERSONIC AIRCRAFT AND ROCKET NOISE

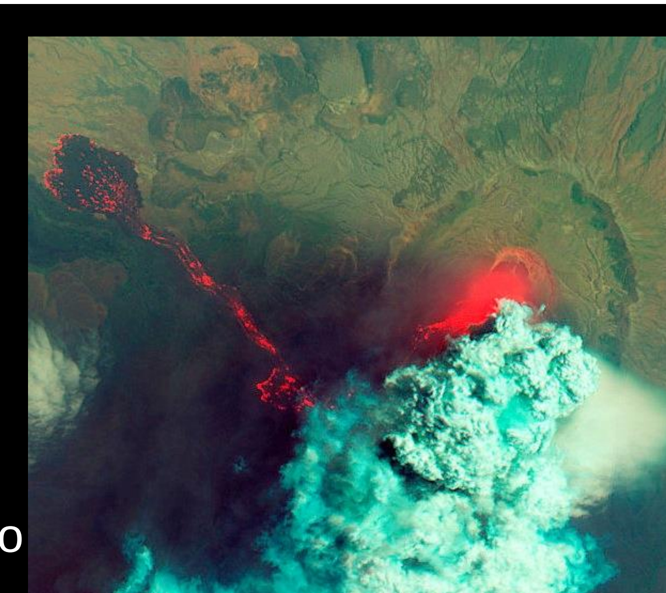
Nabro
(high-amplitude)

PDF of Pressure



[Fee, Matoza, Gee, Nielsen, and Ogden, 2013]

- Asymmetric waveform with shock-like compression
- Nabro (blue) PDF differs substantially from Gaussian (black)
- PDF has positive tail



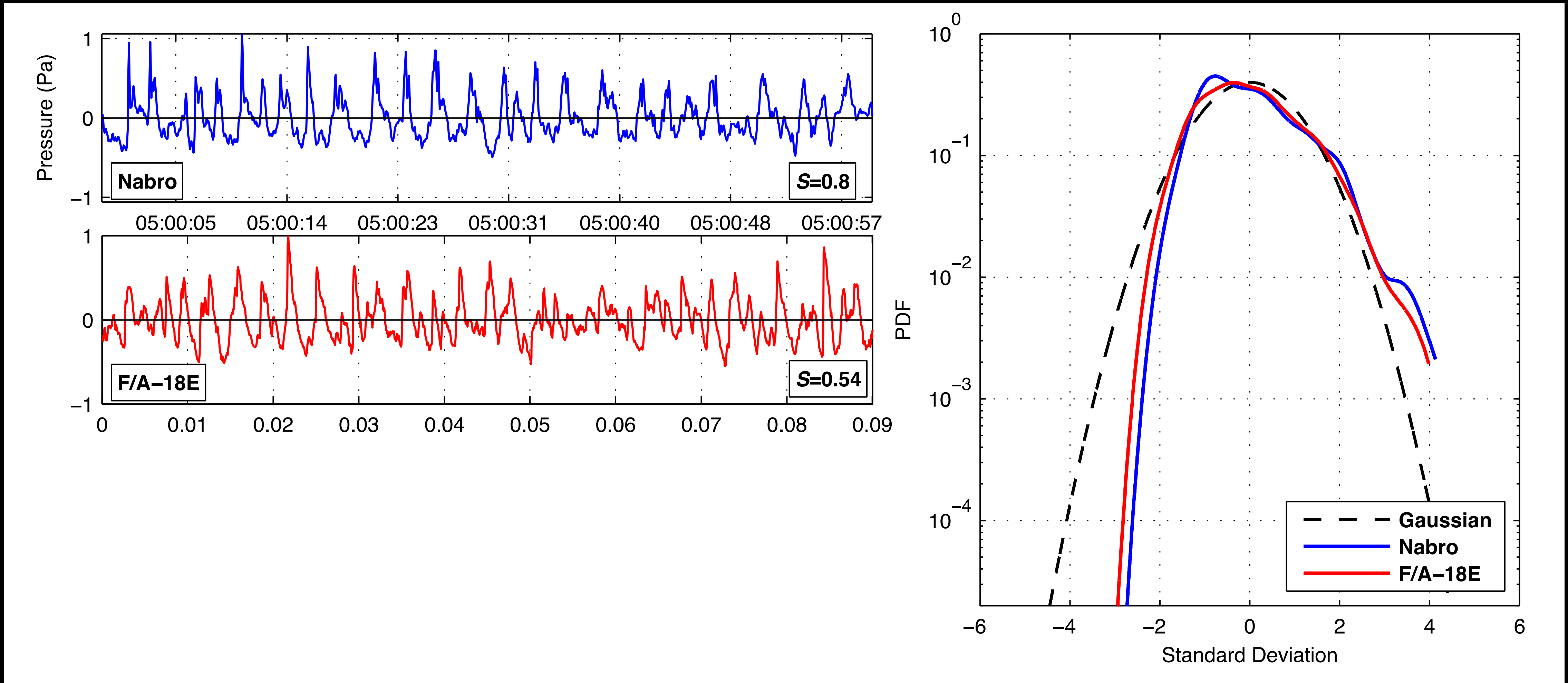
Satellite image of Nabro Volcano, Eritrea

NABRO VOLCANO VS. SUPERSONIC AIRCRAFT AND ROCKET NOISE

PDF of Pressure

Nabro
(high-amplitude)

F/A-18E
at afterburner



[Fee, Matoza, Gee, Nielsen, and Ogden, 2013]

- Nabro and F/A-18E have similar waveforms and PDF
- High positive skewness
- F/A-18E data from [Gee et al., 2007]

F/A-18 Engine (US Navy)

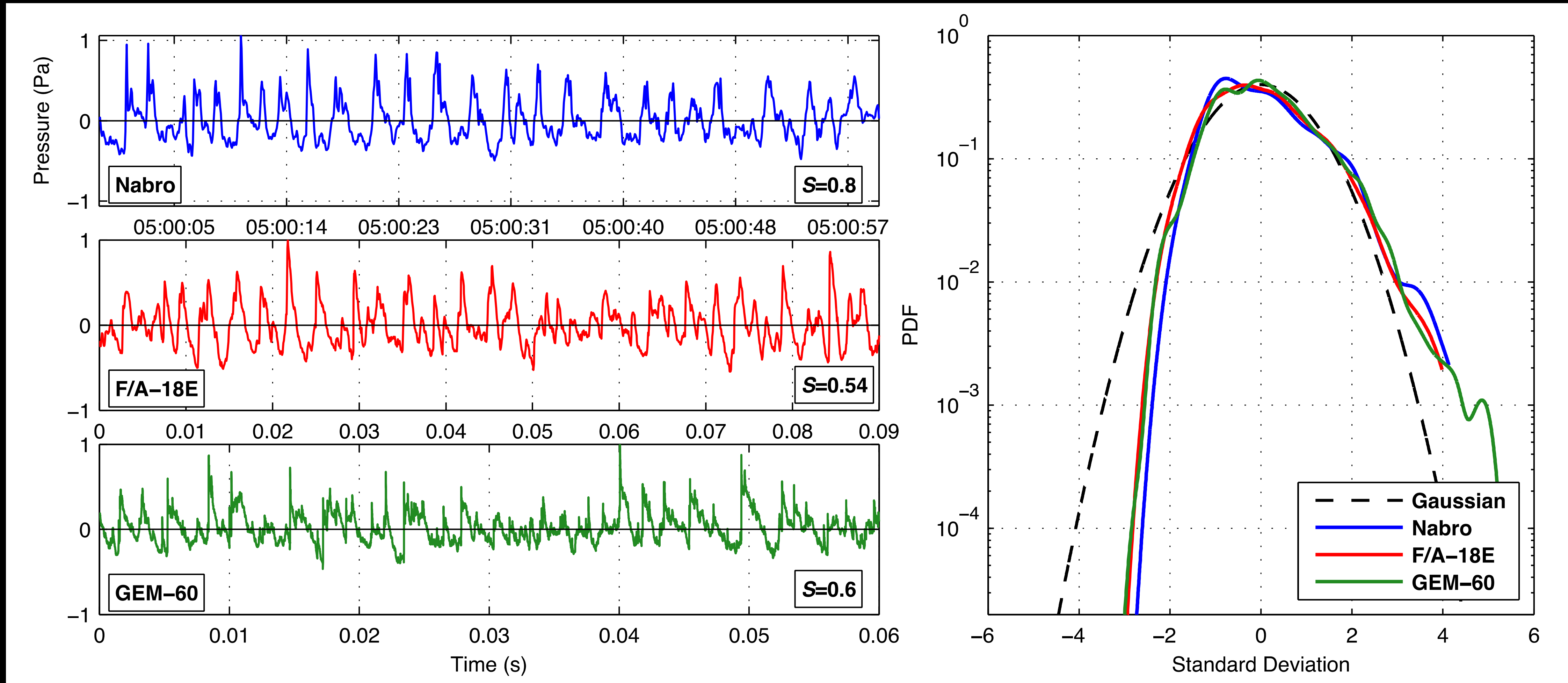
NABRO VOLCANO VS. SUPERSONIC AIRCRAFT AND ROCKET NOISE

Nabro
(high-amplitude)

F/A-18E
at afterburner

GEM-60
Solid fuel rocket

PDF of Pressure

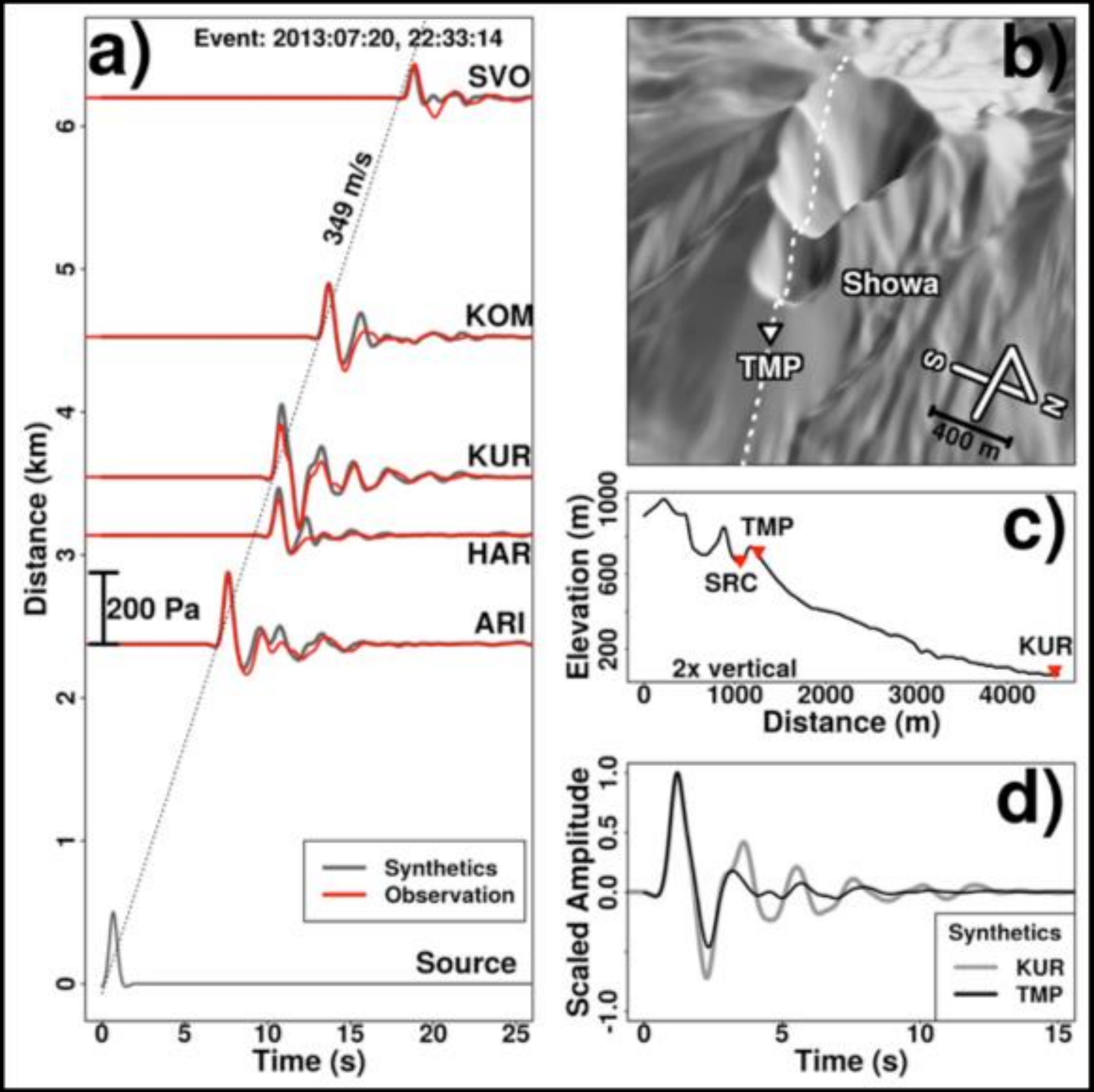


[Fee, Matoza, Gee, Nielsen, and Ogden, 2013]

- All three waveforms have high positive skewness values
- PDFs all have long positive tails
- Rocket and Nabro show strongest similarity
- Rocket data from [Gee et al., 2009]

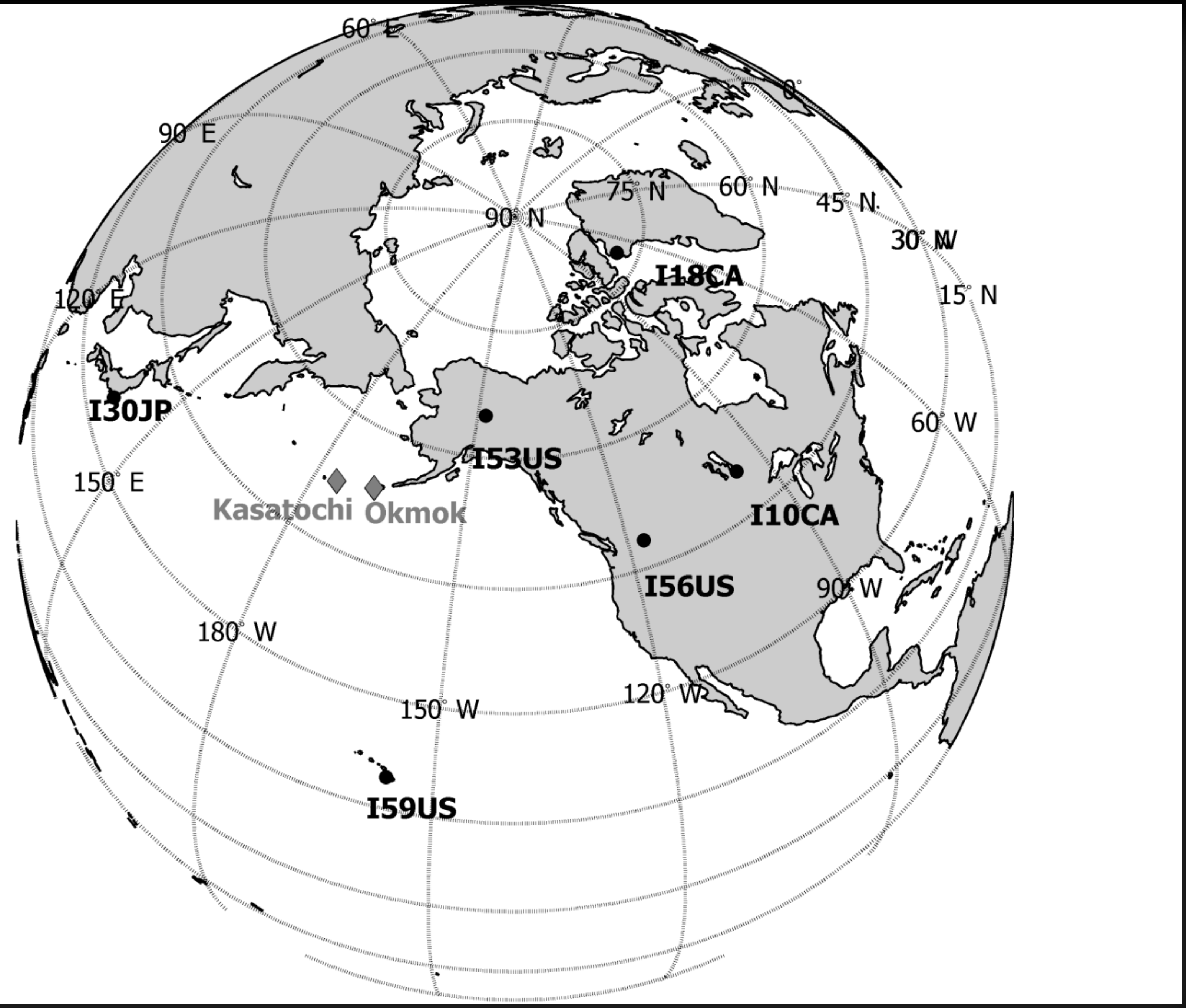
GEM-60

TOPOGRAPHIC EFFECTS



[Kim et al., 2015]

KASATOCHI VOLCANO

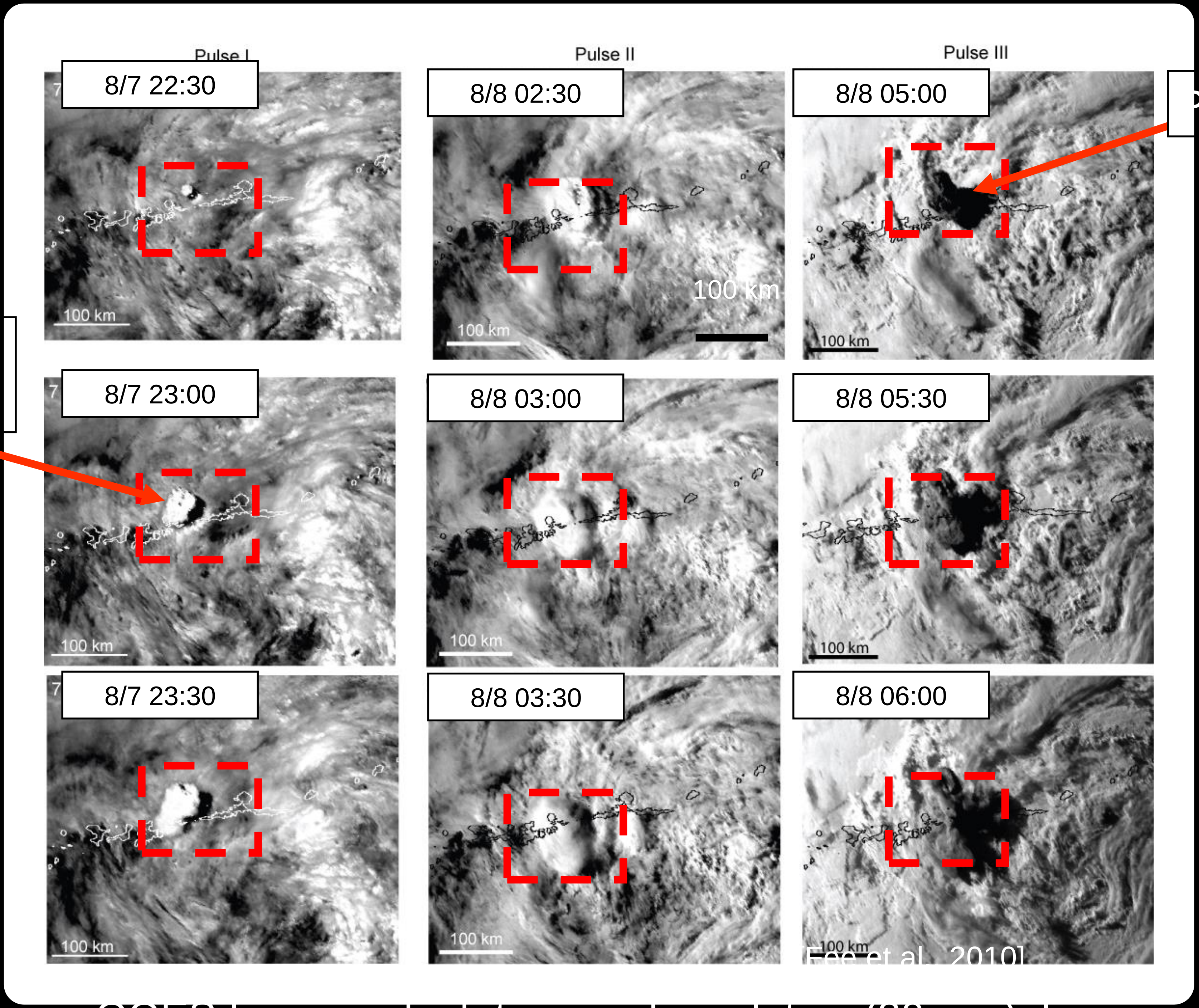


Kasatochi Volcano

- Erupted August 7th-9th, 2008
- Previously unmonitored
- Ash to ~55,000’ (17 km)
- Extensive SO2 and ash
- Disrupted N Pacific air travel

KASATOCHI: SATELLITE IMAGERY

Pulse 1 Pulse 2 Pulse 3



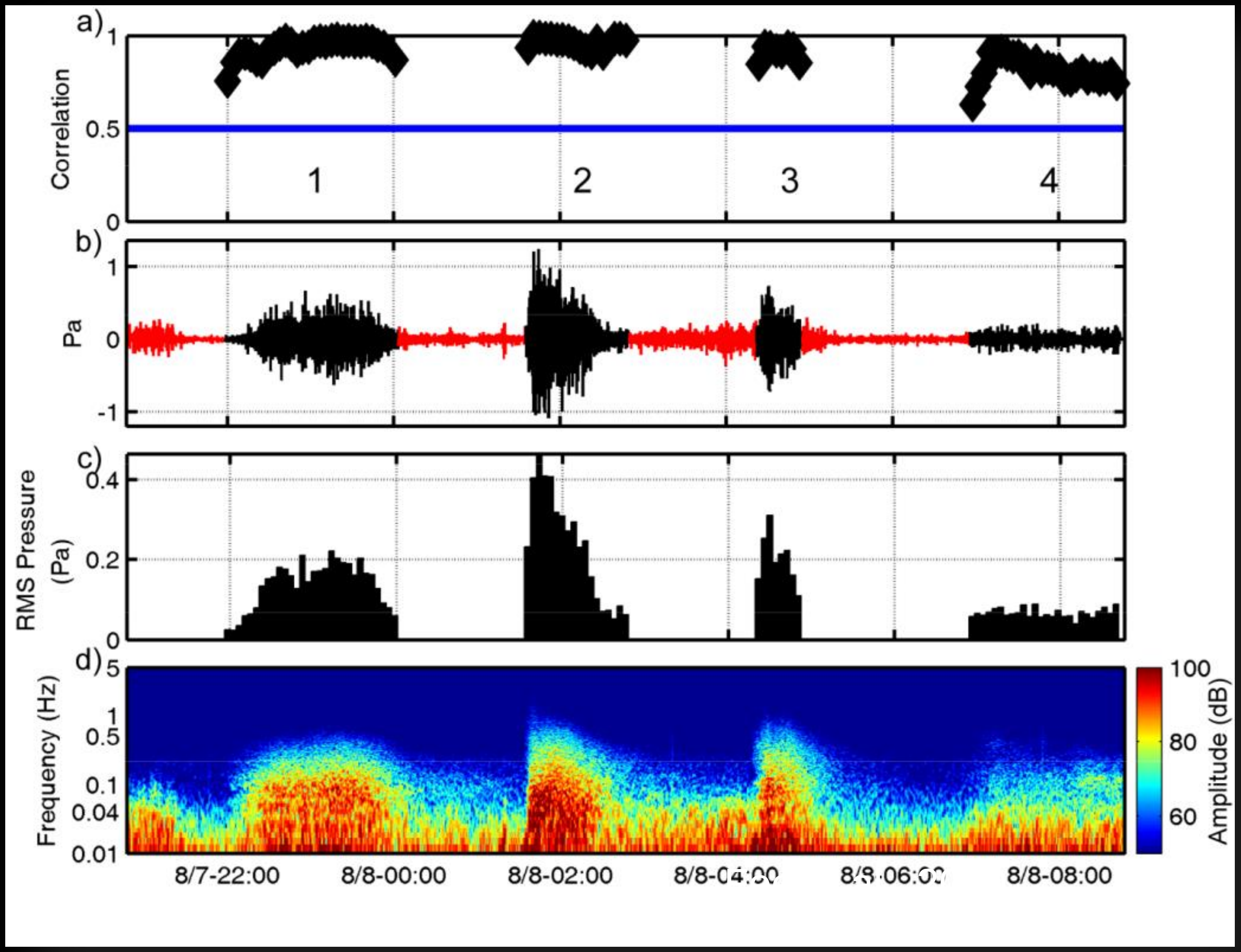
Pulse 3 ash-rich

Pulse 1-2 steam-rich

- Compare plume top temperatures with atmospheric model temperatures
- Plume heights roughly the same for all three pulses: ~16-17 km
- Stratospheric emissions

GOES Imagery: high temporal resolution (30 min), low spatial resolution

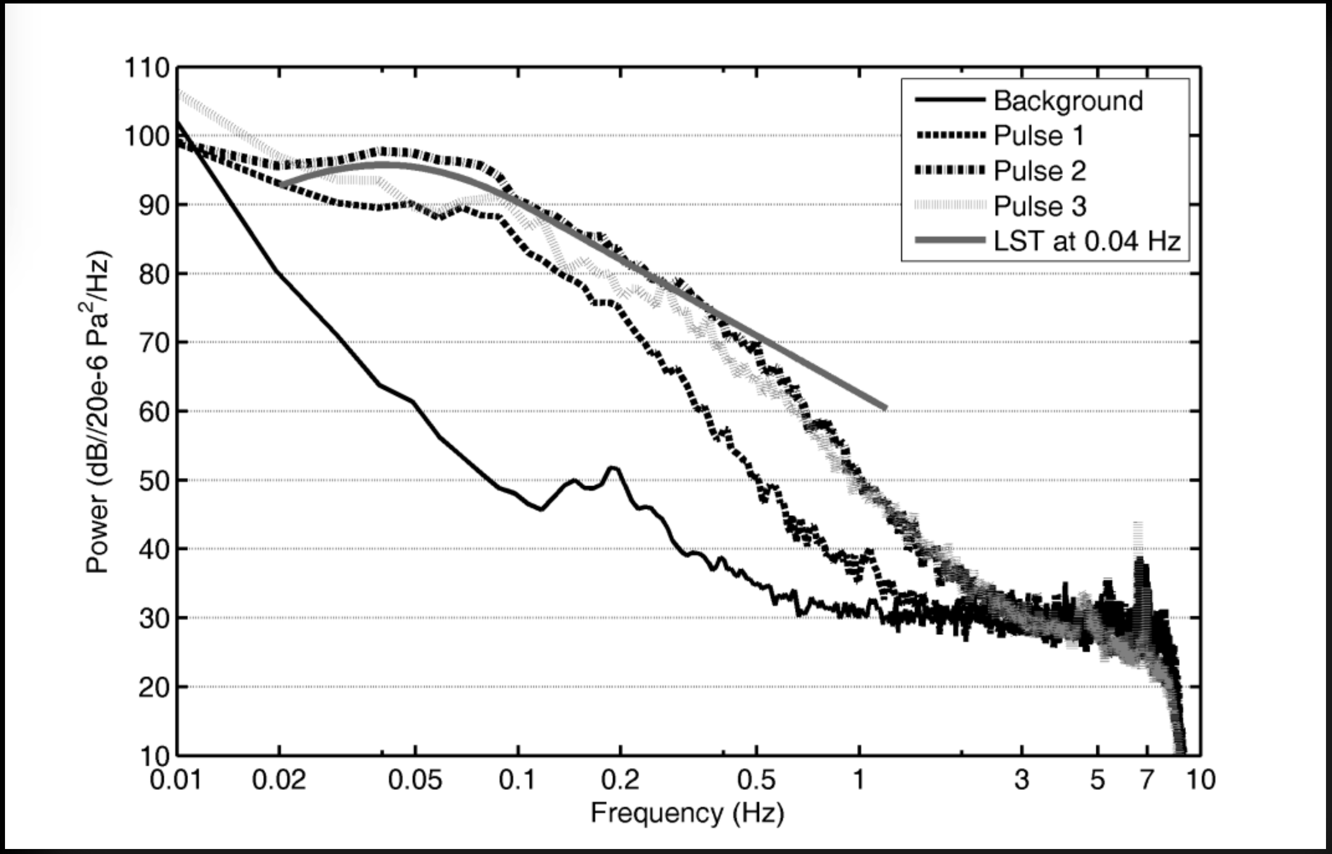
KASATOCHI: INFRASOUND



Spectra of three main pulses resemble that of man made jets (solid gray)

Minor variations in spectra between eruption pulses
-Negligible effect of ash particles in jet

Highly correlated at three stations with similar spectral shape
-Frequency-dependent propagation effects similar between stations



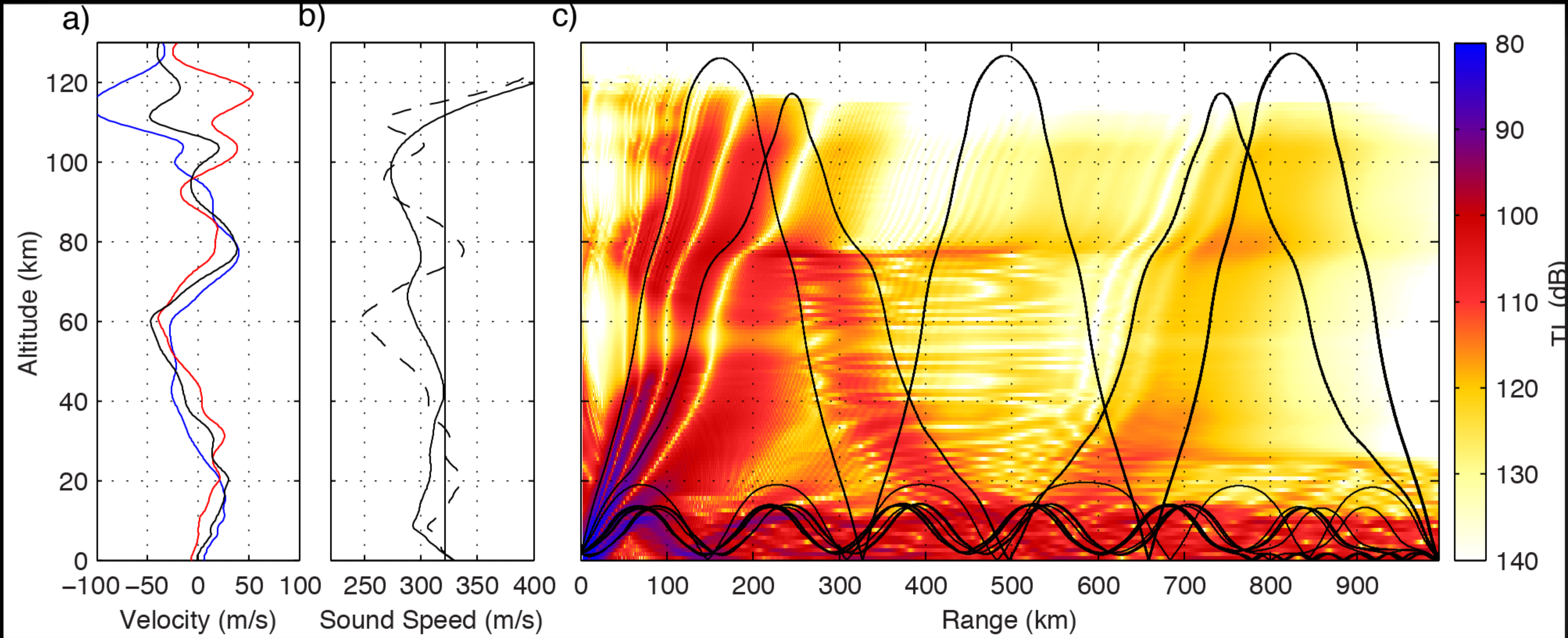
Signal focused in VLP (0.01-0.1 Hz) band

Four pulses detected: 1: 2159 UTC, 123 min
2: 0135 UTC, 59 min
3: 0420 UTC, 33 min
4: 0654 UTC, 112 min

Significant low frequency infrasound coincident with high altitude ash emissions

DLL PROPAGATION MODELING– 29 DECEMBER 2012

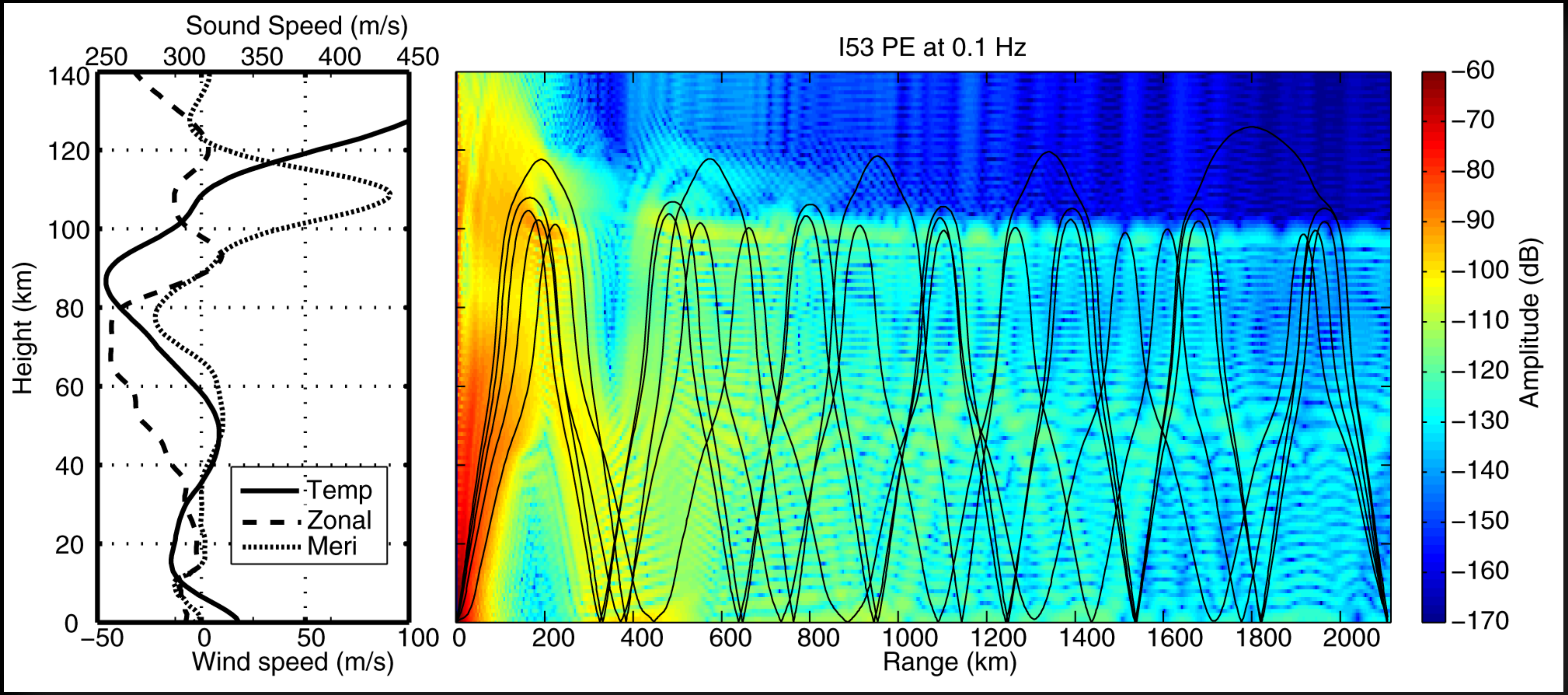
- Winds characterized by easterly wind jet at ~20 km and westerly wind jet at ~60 km.
- 0.5 Hz PE modeling and ray tracing show rays and sound are primarily guided in the troposphere at 15-20 km and the thermosphere at ~120 km.
- Transmission loss (TL) is the accumulated loss in amplitude predicted by the PE, where warmer colors indicate lower transmission loss or higher amplitudes.



KASATOCHI - IS53: THEORETICAL PROPAGATION

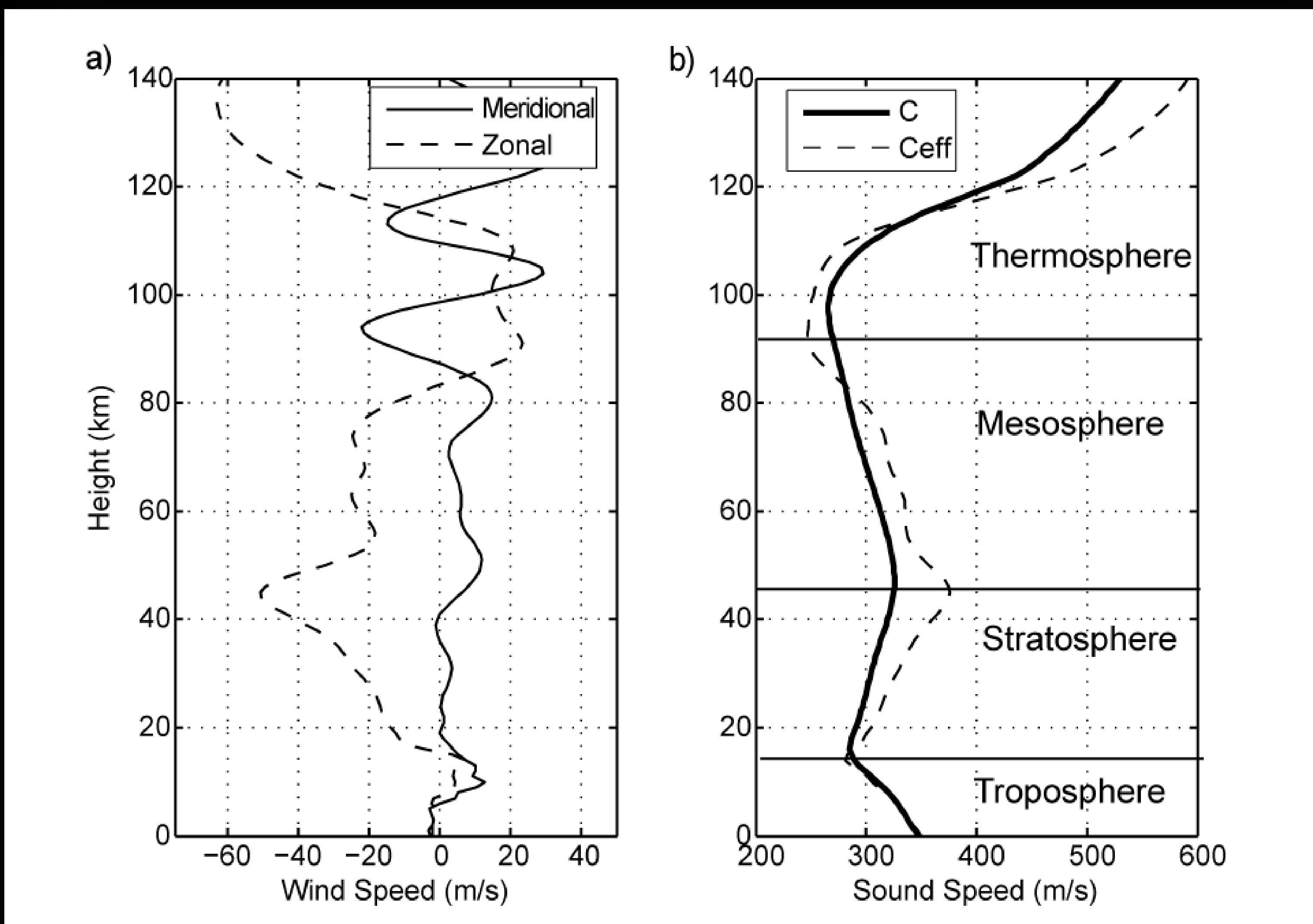
Increased attenuation due to thermospheric propagation path energy refracted down around

Acoustic Travel Time: ~7968 s (2 h 12 min) 90-110 km (thermospheric)
No stratospheric arrivals predicted



Kasatochi IS53

INFRASOUND PROPAGATION



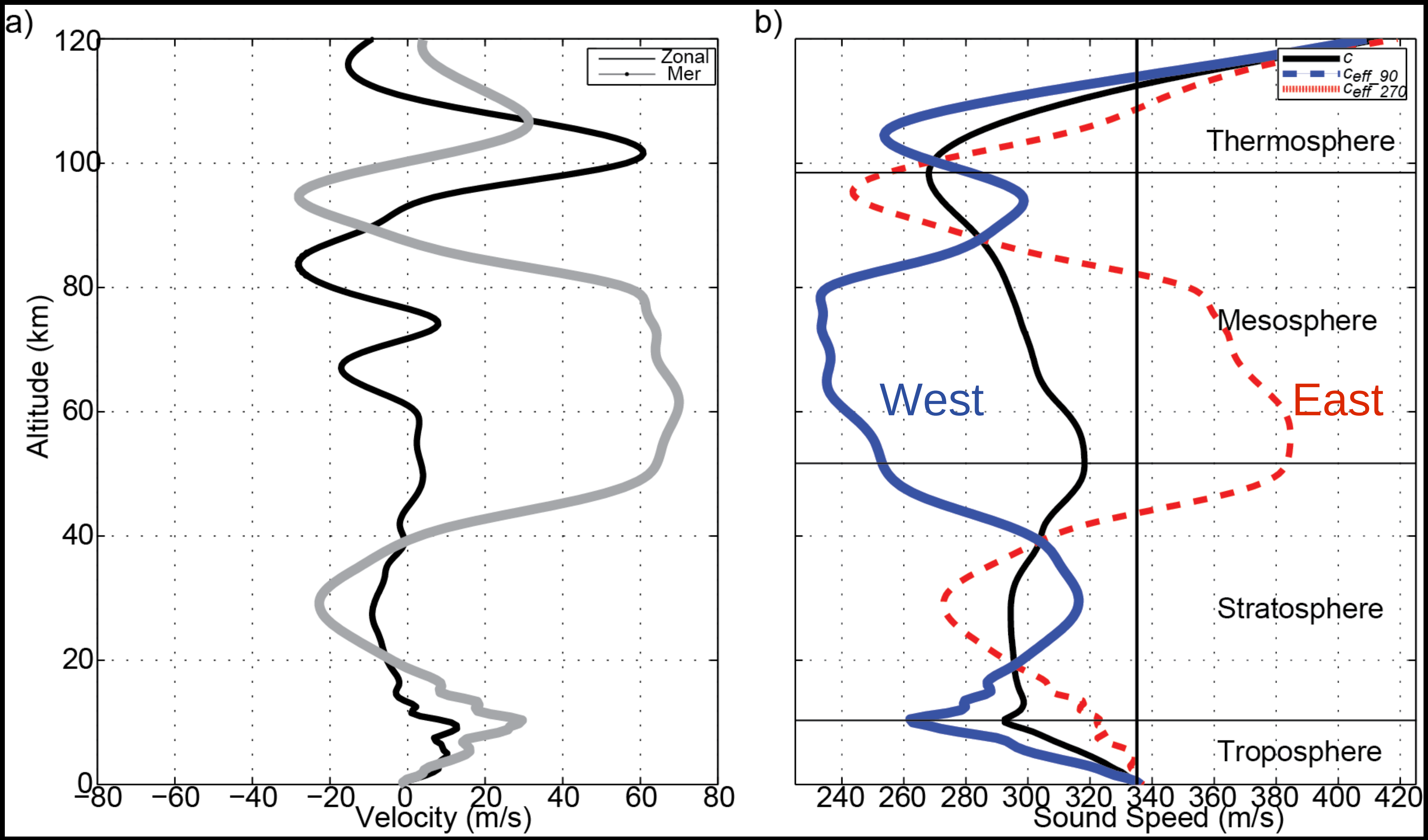
- Sound energy can be represented as rays refracting according to Snell's Law
- Rays often refract up, until c_{eff} exceeds that at the source
- Need detailed and accurate atmospheric specifications

$$c = \sqrt{\gamma R T} \qquad c_{eff} = c + \vec{v} \bullet \vec{n}$$

The atmosphere varies spatially and temporally!

PROPAGATION EXAMPLE

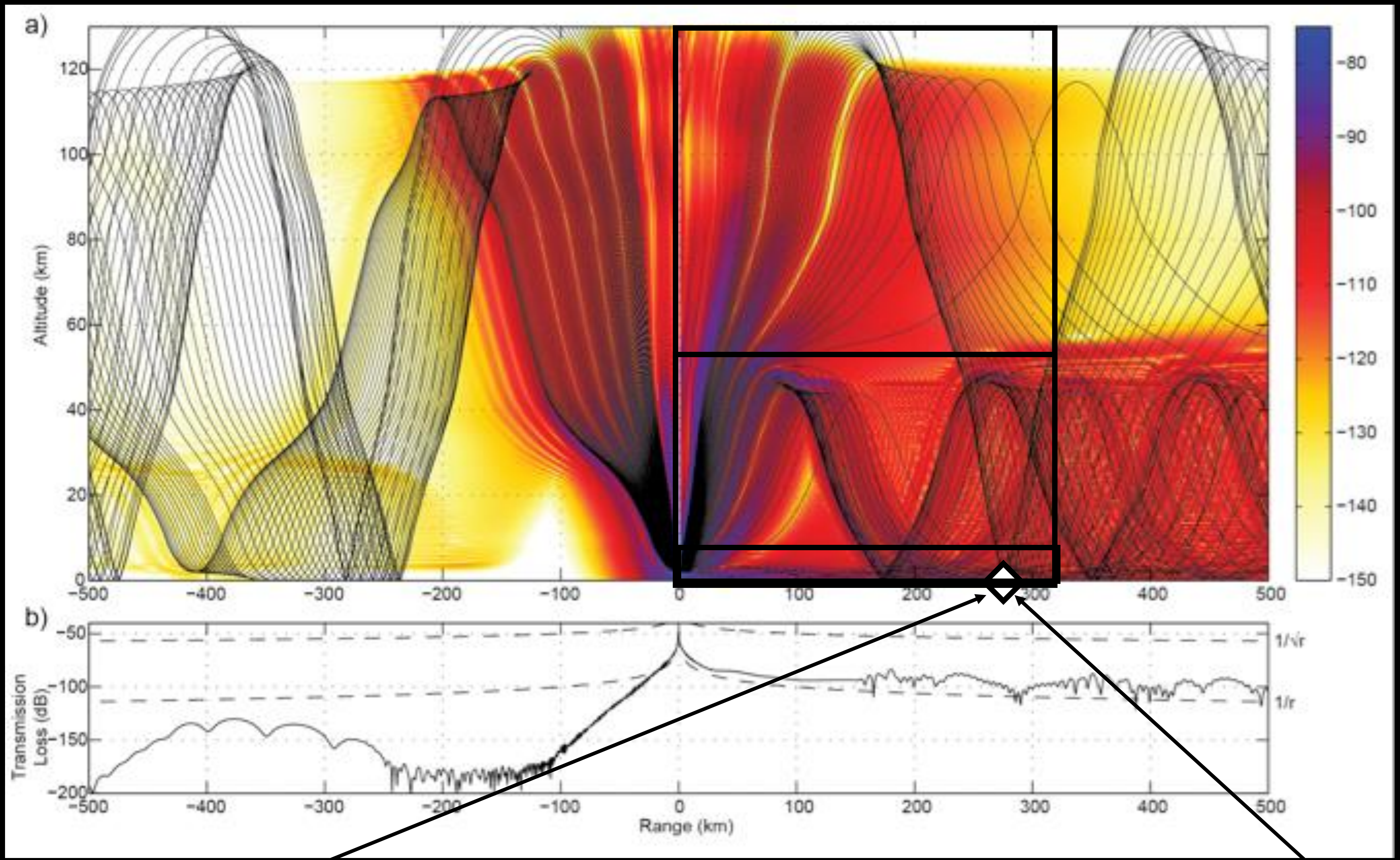
Mount St. Helens, 1 July 2012



[Fee and Matoza, 2013]

Zonal Winds: east-west
Meridional Winds: north-south

PROPAGATION EXAMPLE



[Fee and Matoza, 2013]