Volcanic thunder from explosive eruptions at Bogoslof volcano, Alaska

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MOTIVATION AND OVERVIEW

- Volcano ash clouds pose hazard to aviation and can be detected by direct (e.g., satellite or webcam) or indirect (e.g., seismic or infrasound) measurements
- Volcanic lightning detection is a powerful new tool for this purpose

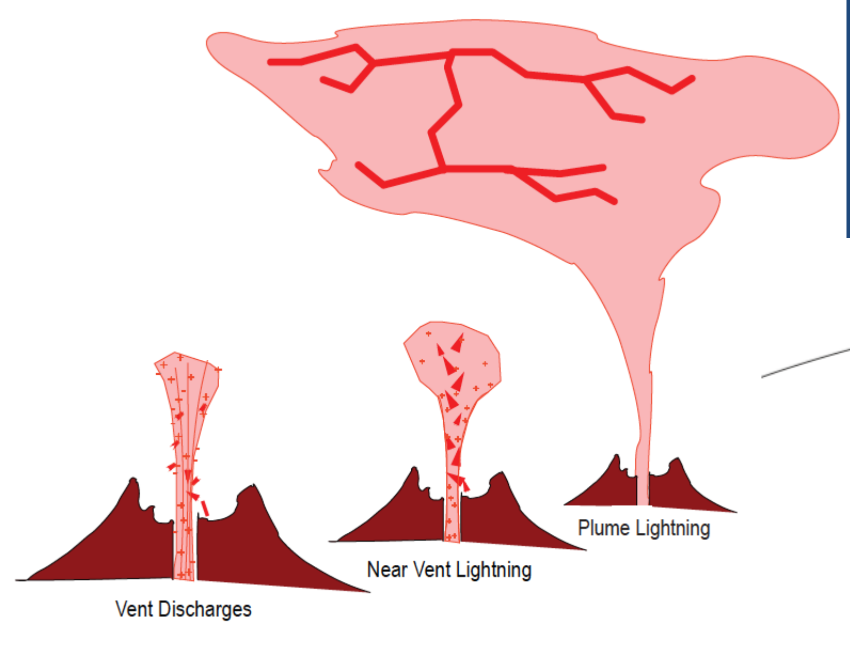
This talk:

1. Signature of lightning in ground-based geophysical data from 2016-17 eruption of Bogoslof volcano
2. Volcanic thunder
3. Cloud-to-ocean lightning strokes
4. Lightning-related glitches

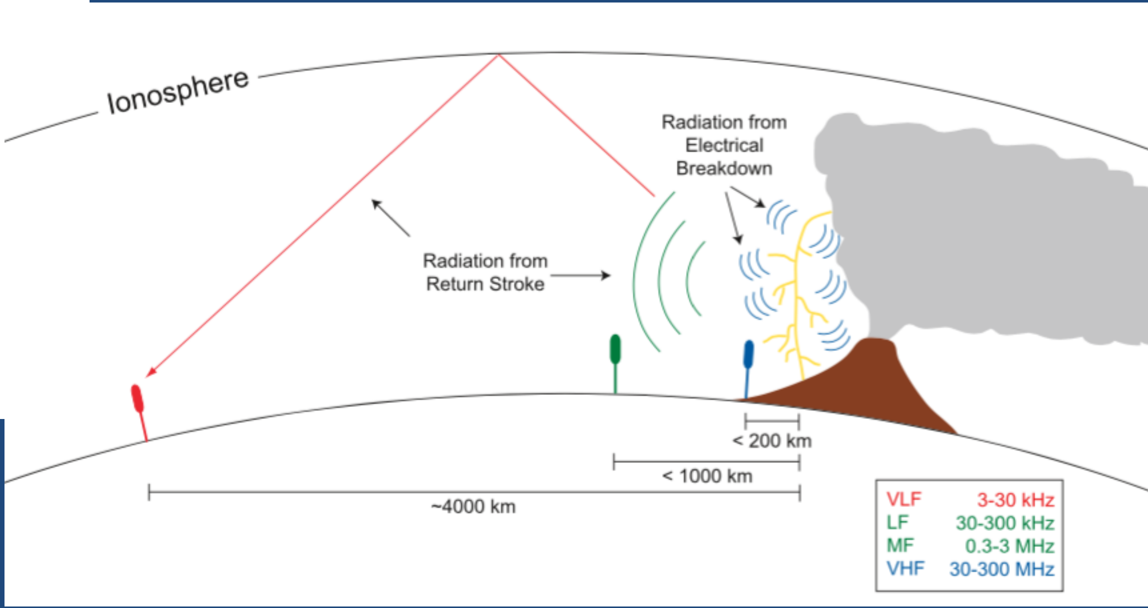
Bogoslof, June 2017
Image courtesy
Masami Sugiyama

VOLCANIC LIGHTNING AND DETECTION

- Three types of volcanic lightning
- Plume lightning most similar to normal lightning
- Global VLF networks, such as WWLLN and Vaisala, mostly sensitive to high altitude lightning



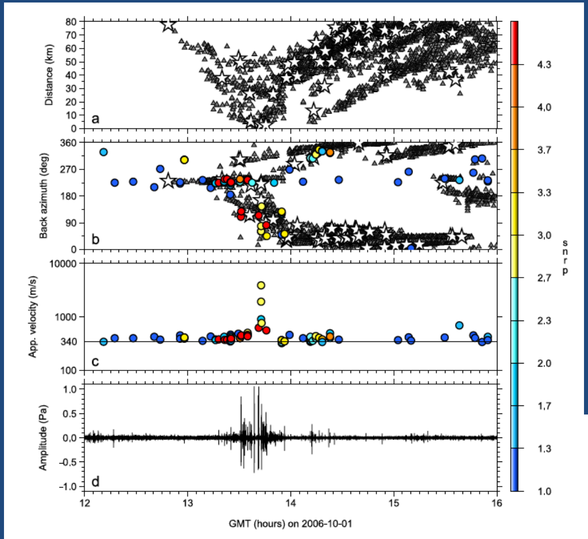
[Thomas *et al.*, 2016]



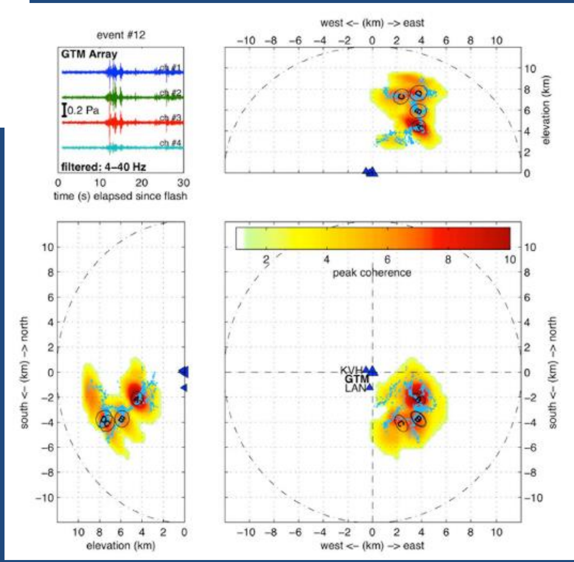
[Behnke and McNutt, 2014]

VOLCANIC THUNDER?

- Volcanic lightning has garnered considerable attention, but no documented reports of the related phenomenon of volcanic thunder
- Difficult to observe since erupting volcanoes generate of lot of sound due to ejection of mass at vent
- Thunder has been observed with sonic and infrasonic sensors during meteorological storms at ranges of up to 100 km
- Volcanic thunder, if observable, would contain additional information compared to lightning on electrification of volcanic plumes



[Assink *et al.*, 2008]

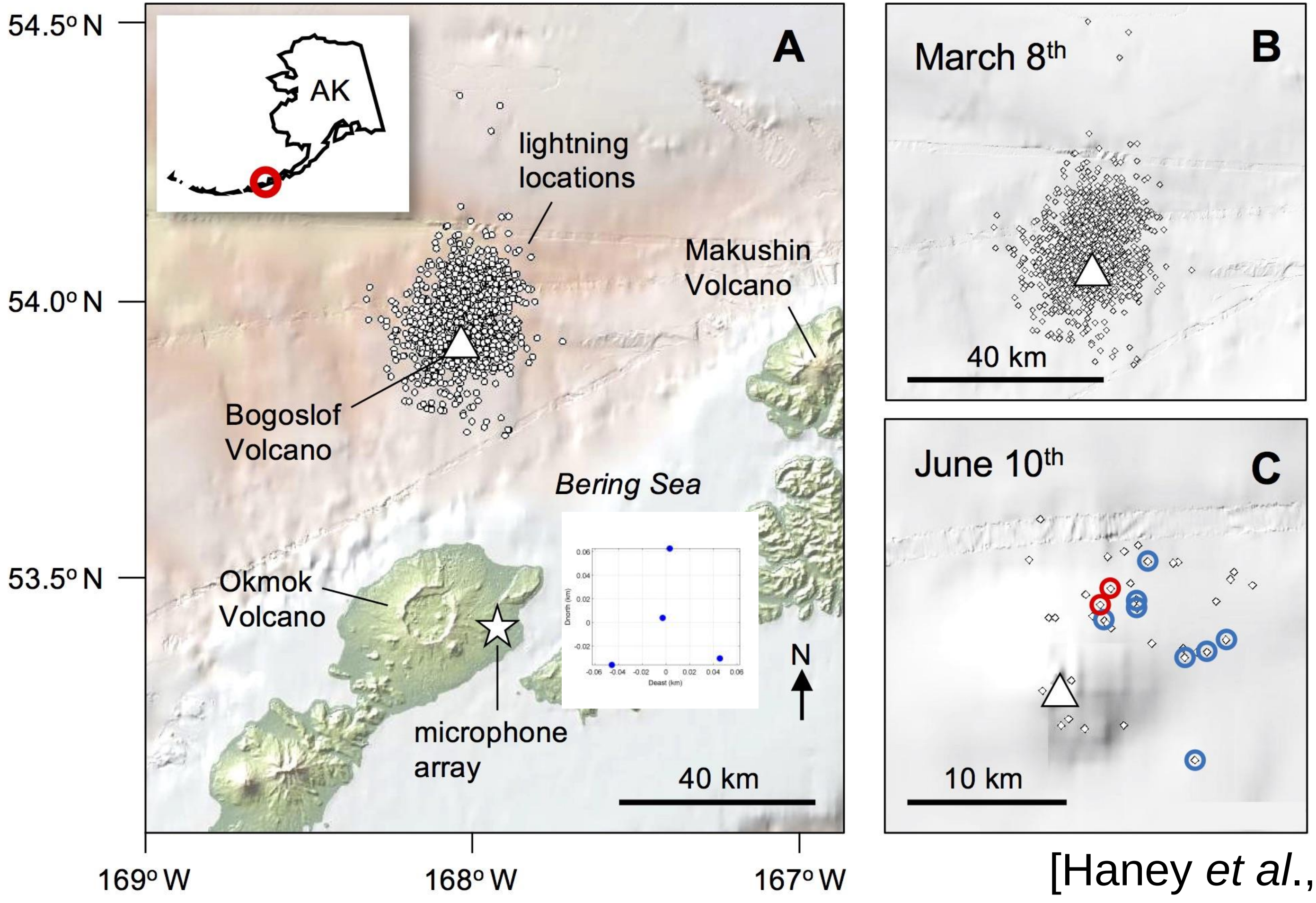


[Johnson *et al.*, 2011]

Bogoslof

- Mostly submarine volcano in Bering Sea
- Sequence of over 70 explosive eruptions from December 2016 to August 2017
- Monitored by seismic stations on nearby islands in the Makushin and Okmok networks
- Infrasound array on Okmok at 60 km range
- Lightning locations from Vaisala and World Wide Lightning Location (WWLLN) catalogs

BOGOSLOF LIGHTNING LOCATIONS



[Haney *et al*., 2018 GRL]

- Combined WWLLN and Vaisala catalog from March 8 and June 10 eruptions
- Dominated by March 8 eruption, the most prolific lightning producer of entire eruption sequence

BEAMFORMING

- 30 second windows with 50% overlap, minimum correlation of 0.5
- Frequency band from 4-8 Hz
  - Tradeoff between high SNR at high frequencies vs. coherence
- When unique pairs of interstation times exist, slowness obtained using:

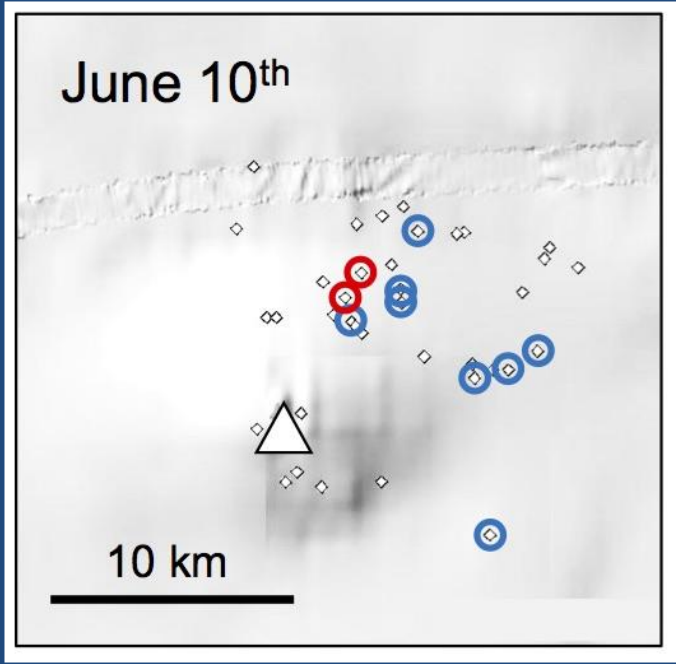
$$\vec{\Delta t} = G\vec{s} \qquad \vec{s} = (s_x, s_y)$$

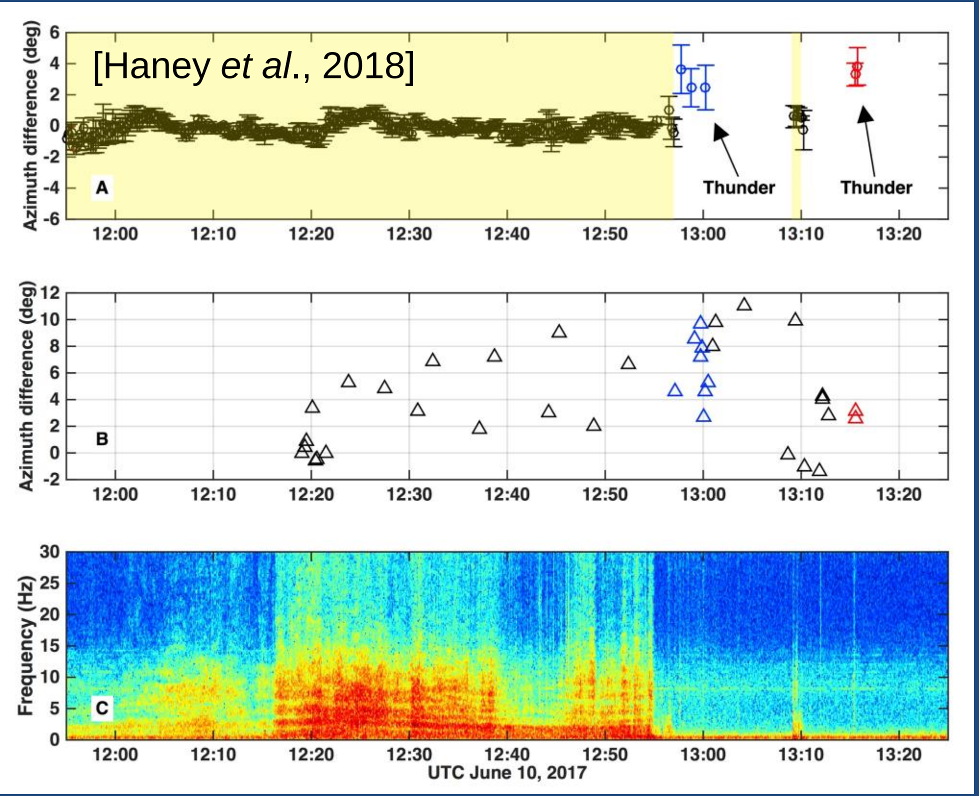
- Slowness converted into backazimuth and trace velocity

$$\theta = \tan^{-1}(s_x/s_y) \qquad v = 1/\sqrt{s_x^2 + s_y^2}$$

JUNE 10 ERUPTION

- Destroyed first confirmed lava dome
- WWLLN and Vaisala lightning locations offset to NE due to wind





- Beamforming on Okmok microphone array shows anomalous detections coming ~3 degrees east of volcano
- Shift consistent with offset in lightning locations

COMPARISON OF LIGHTNING AND ACOUSTIC DATA

- Unlike June 10, lightning distributed more or less uniformly around Bogoslof during March 8 eruption
    - Arrivals likely from multiple backazimuths within time window

- Instead of beamforming, direct comparison of lightning and acoustic data

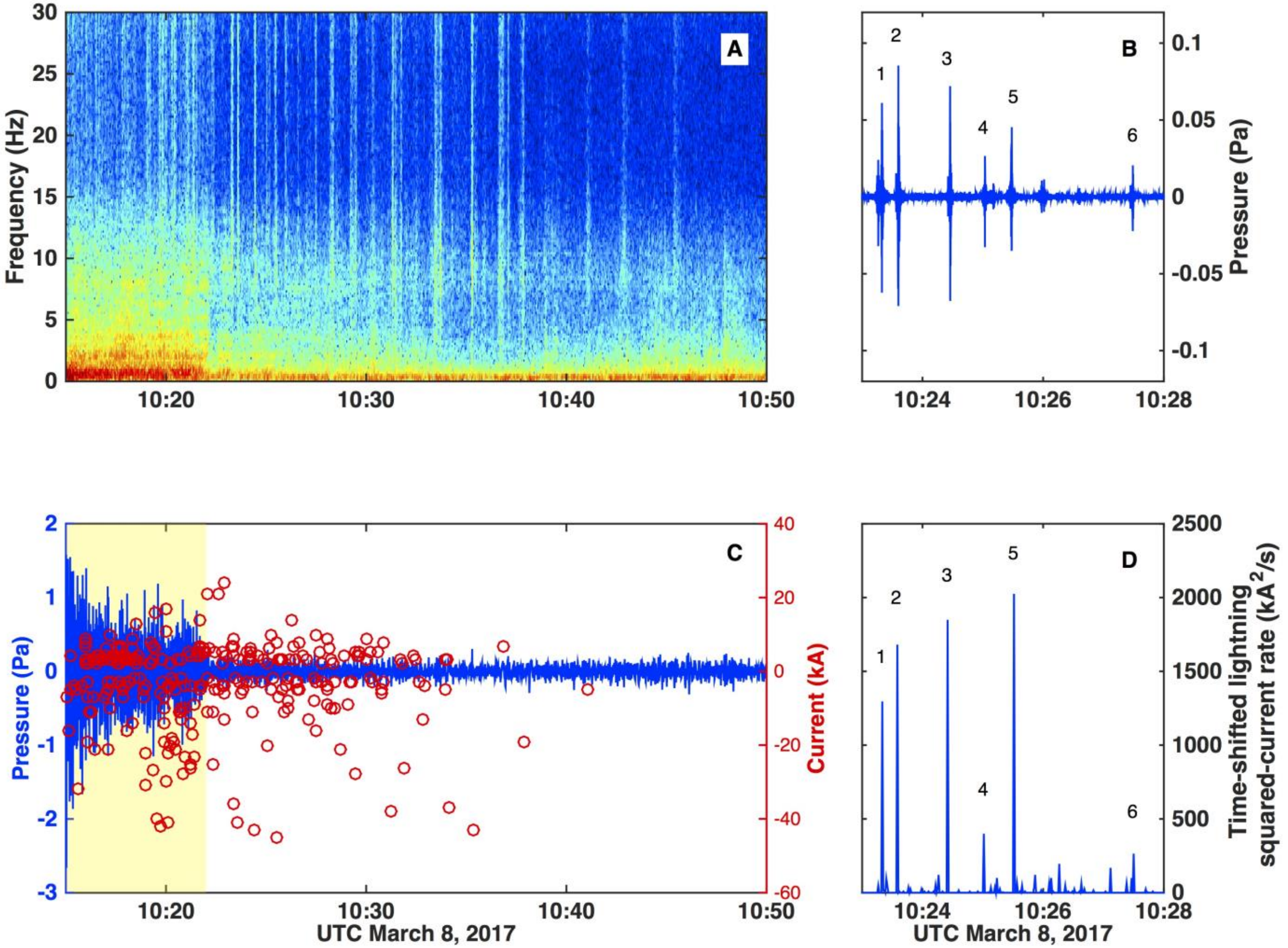
- Vaisala lightning catalog converted into time-shifted squared-current rate:
    - Timing of each stroke adjusted according to its Vaisala location and an assumed acoustic speed of 335 m/s to array
    - Total squared-current summed within 1 second bins

- Acoustic data bandpassed above 20 Hz

MARCH 8 ERUPTION

- WWLLN and Vaisala lightning continued for ~15 minutes afterward
- Comparison of time-shifted squared-current rate from Vaisala (Panel D) has close correlation with high frequency (>20 Hz) acoustic data (Panel B)
- Lightning continues in plume after eruption has ended

[Haney *et al*., 2018]

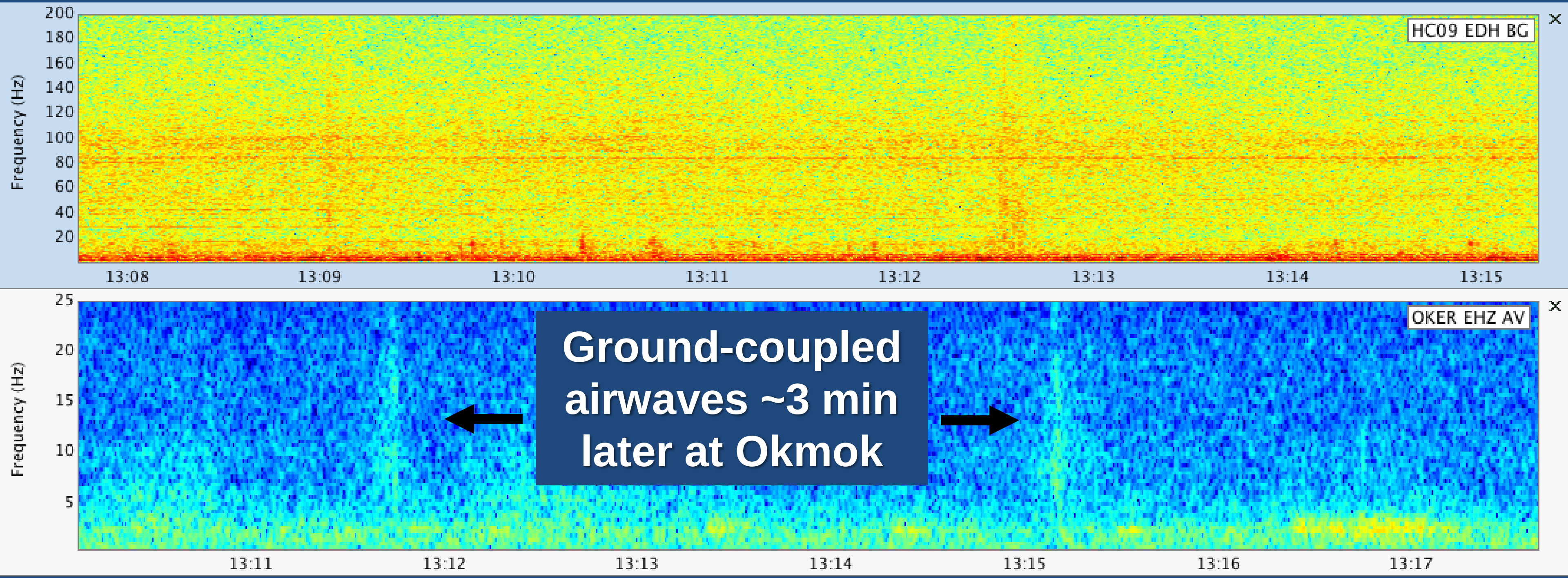


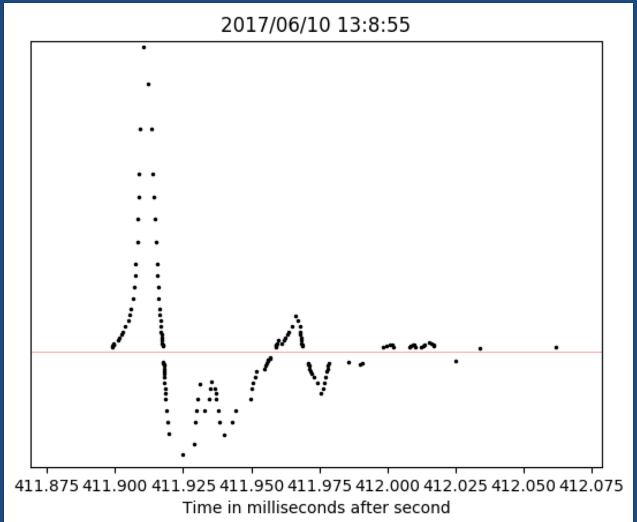
VOLCANIC LIGHTNING ON HYDROPHONE?

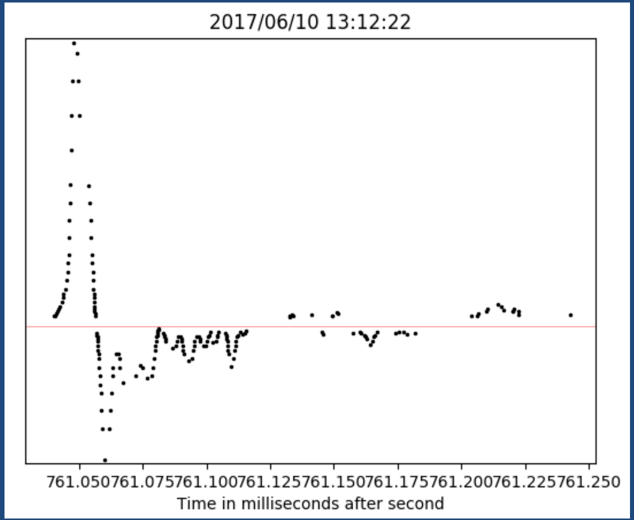
13:08:55 stroke

13:12:22 stroke

June 10 eruption







DUTCH HARBOR LIGHTNING DATA

- EM recordings of 13:08:55 and 13:12:22 strokes from Dutch Harbor station, courtesy of Jeff Lapierre (Earth Networks)
- Largest pulse typical of positive current cloud-to-ground (or cloud-to-ocean) lightning
- Hydroacoustic signals generated in the ocean from volcanic lightning strikes

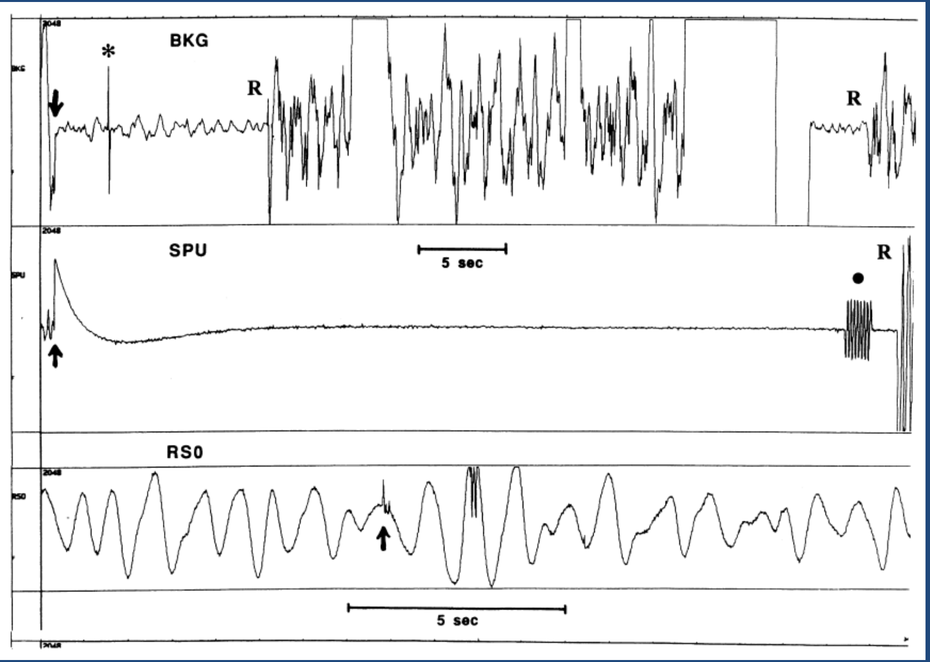
Underwater sound from lightning strikes to water in the Gulf of Mexico

Roy T. Arnold, Henry E. Bass, and Anthony A. Atchley
Physical Acoustics Research Laboratory, Department of Physics and Astronomy, The University of Mississippi, University, Mississippi 38677

(Received 12 October 1983; accepted for publication 20 March 1984)

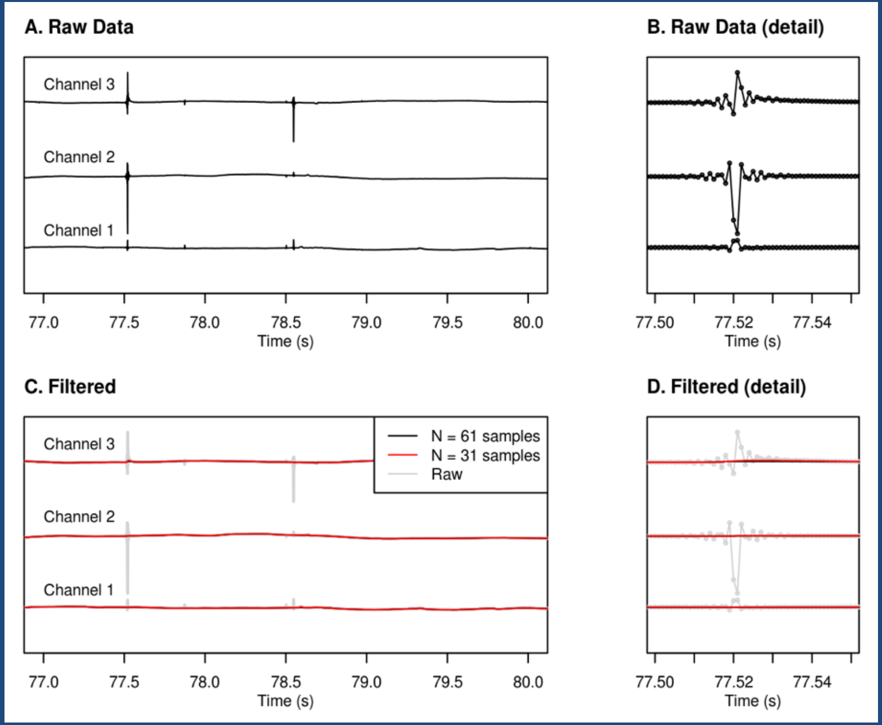
[Arnold *et al*., 1984]

LIGHTNING-RELATED GLITCHES



[McNutt and Davis, 2000]

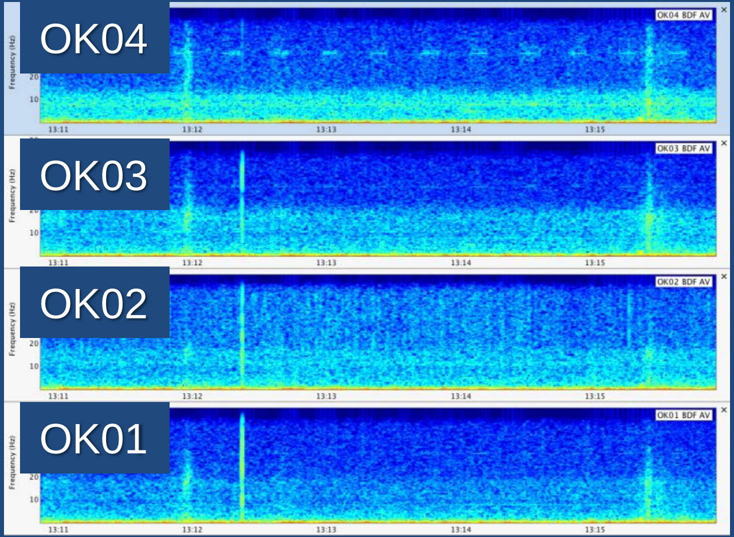
Mt. Spurr 1992 eruption

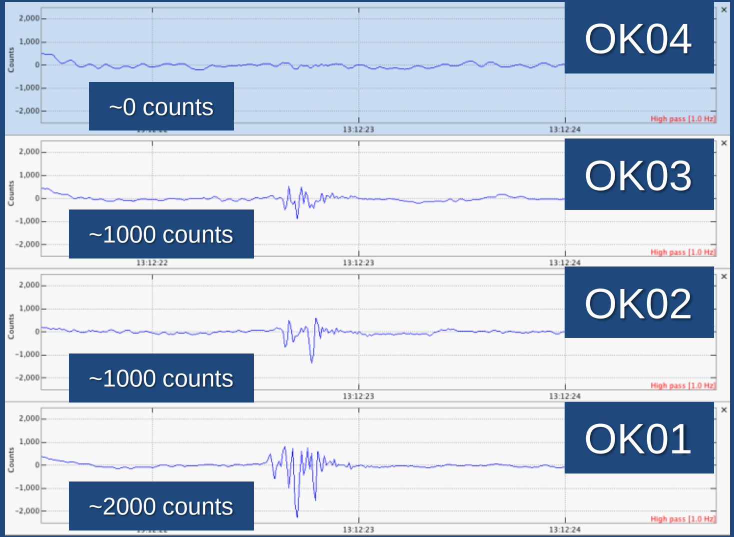


[Anderson *et al.*, 2018]

Tungurahua 2013 eruption

GLITCHES ON OKMOK INFRASOUND ARRAY

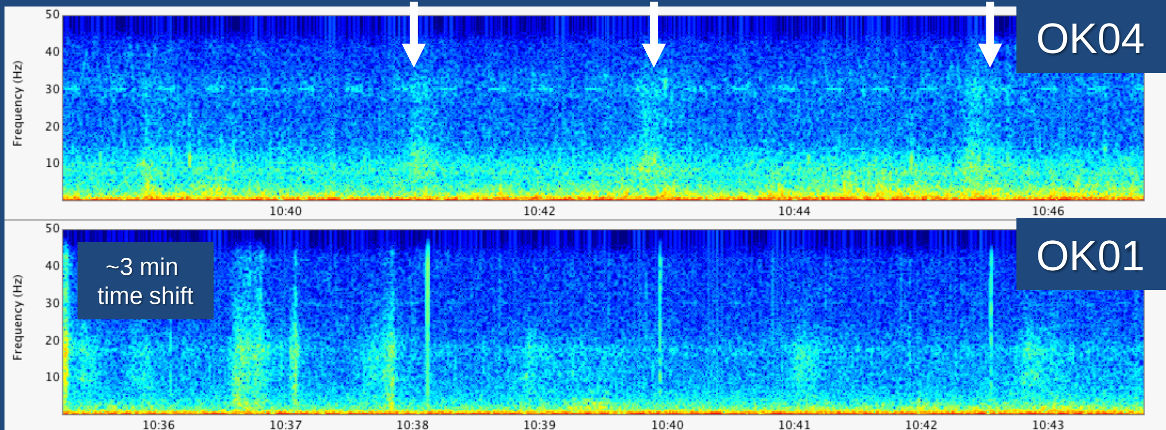




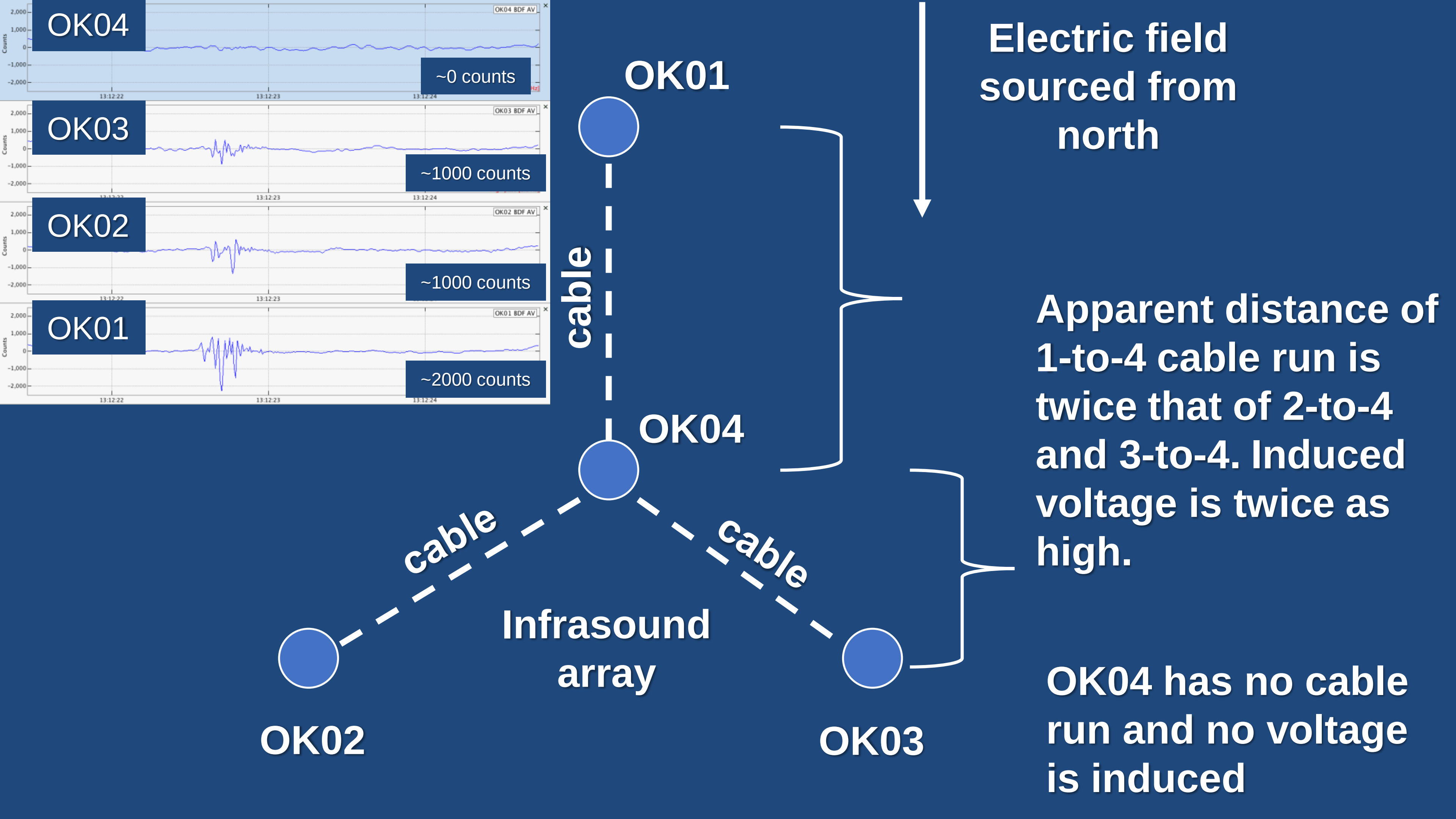
June 10
eruption

Glitch

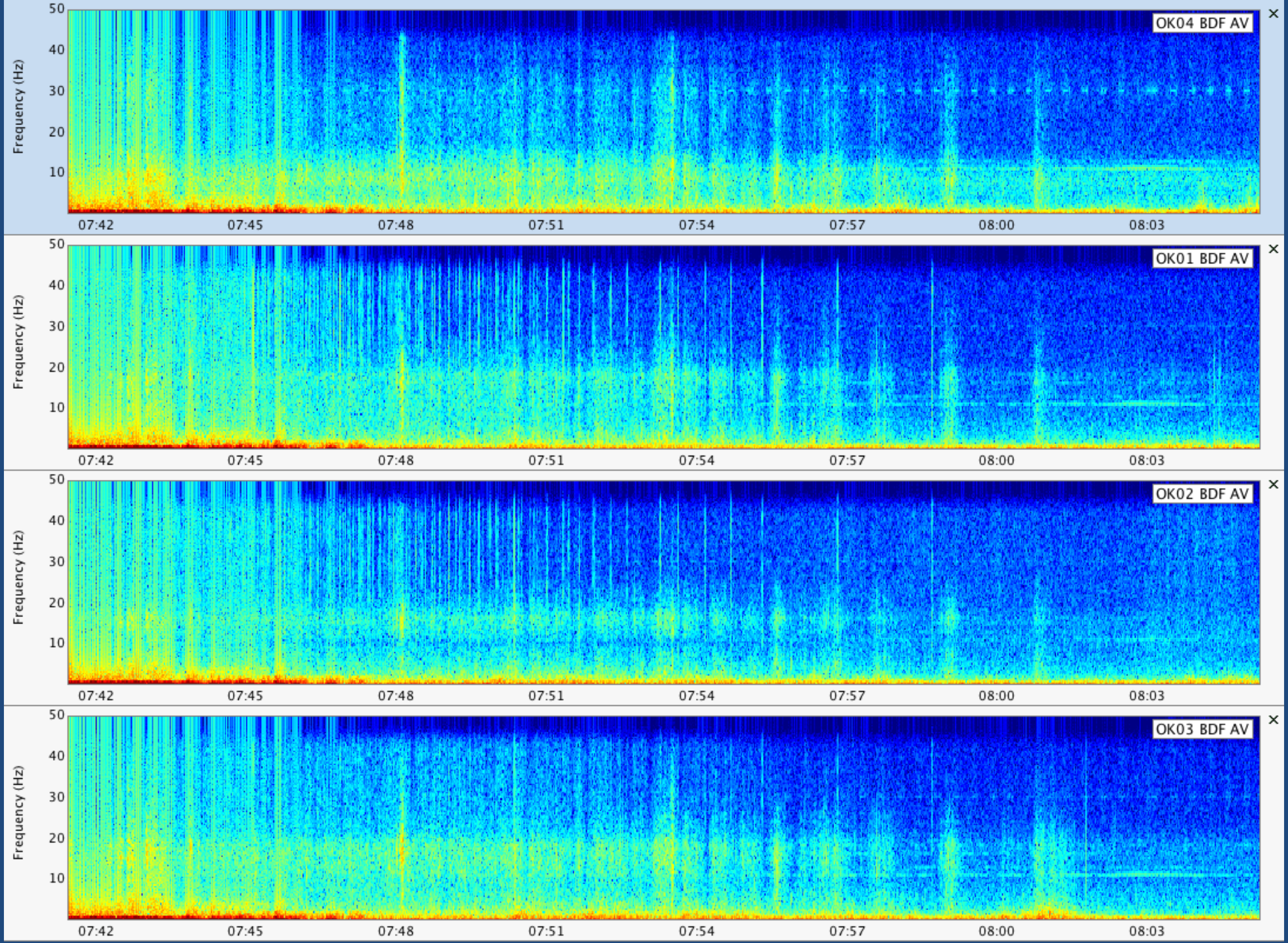
Thunder



March 8
eruption

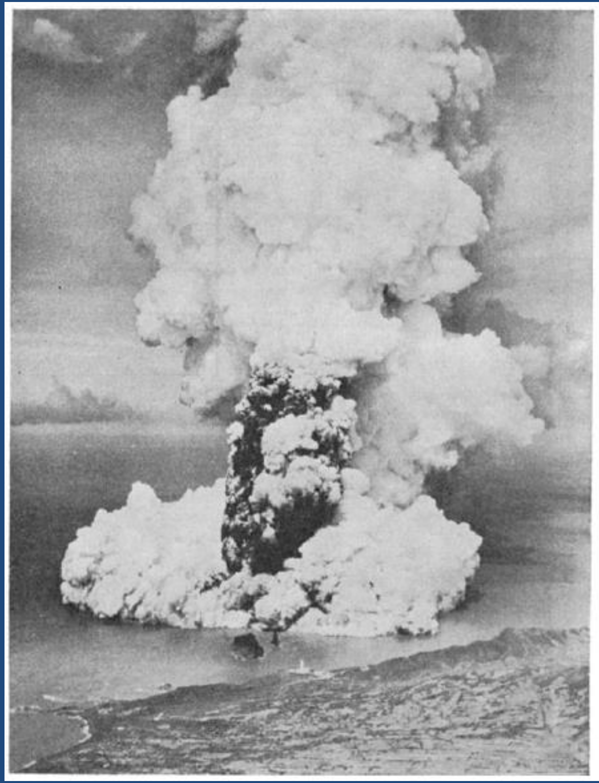

OK04
~0 counts
OK03
~1000 counts
OK02
~1000 counts
OK01
~2000 counts
OK01
cable
OK04
cable
cable
Infrasound array
OK02
OK03
Electric field sourced from north
Apparent distance of 1-to-4 cable run is twice that of 2-to-4 and 3-to-4. Induced voltage is twice as high.
OK04 has no cable run and no voltage is induced

MAY 17 BOGOSLOF ERUPTION



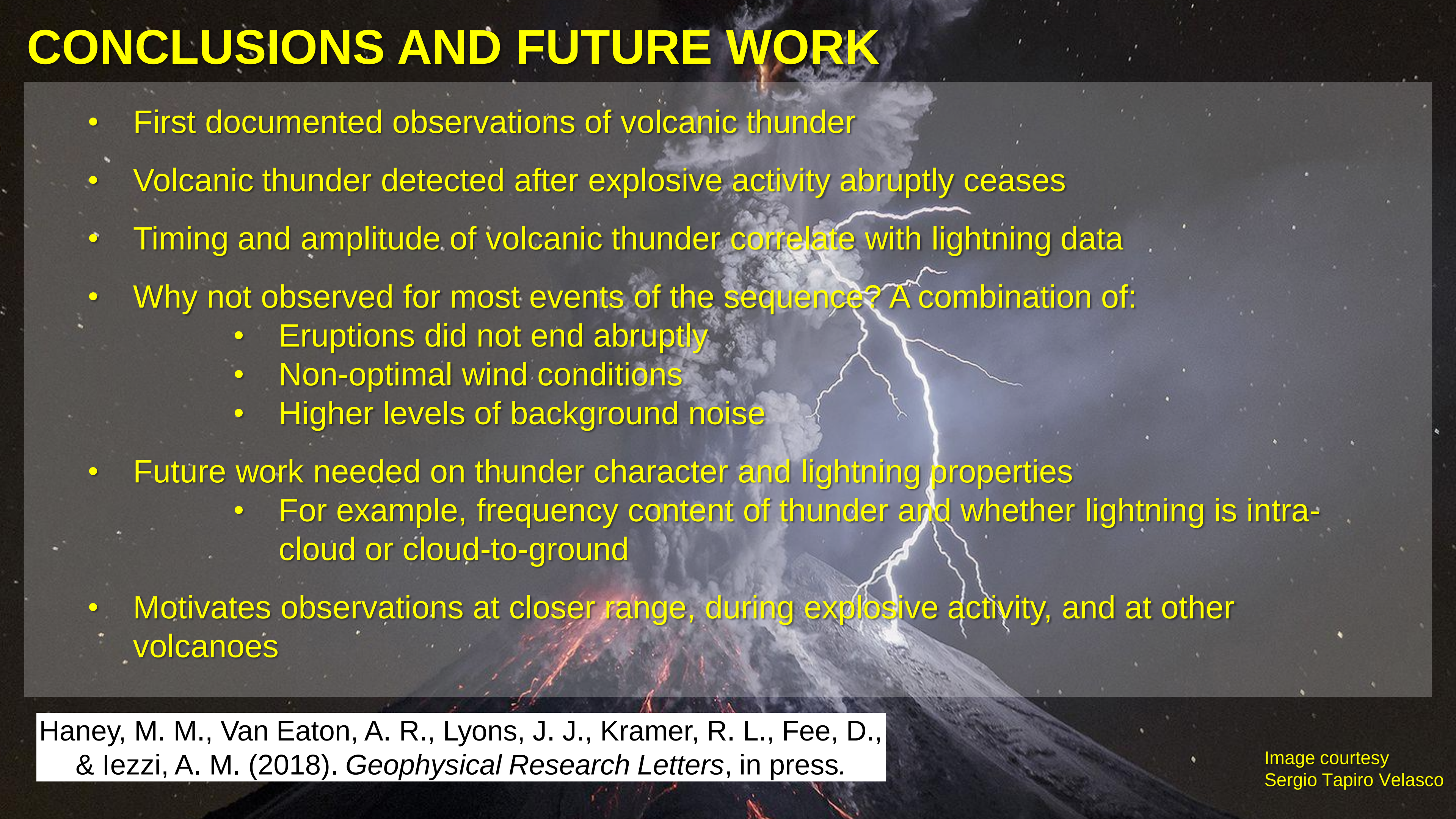
- Glitches stand out for elements 1-3, implicating lightning
- Thunder signals continue and are visible as eruption wanes
- Thunder exists for at least March 8, May 17, and June 10 eruptions
- Late spring timeframe a tradeoff between extensive lightning in winter versus better acoustic propagation conditions in summer

OTHER ERUPTIONS?



Fayal Volcano, Azores
Machado *et al*. (1962) JGR

Explosions were nearly noiseless and were accompanied by ground vibration (volcanic tremor) and electrical phenomena [see photographs in *Scofield*, 1958, p. 755] producing small thunderlike sounds.

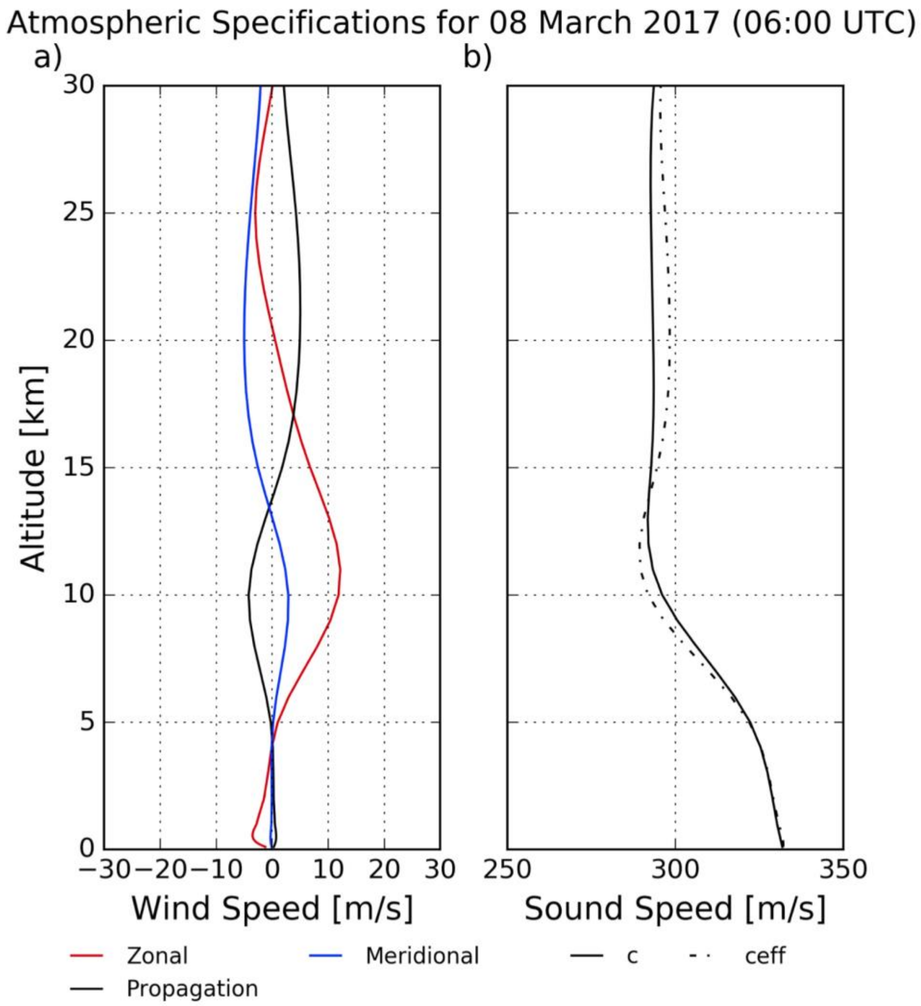


CONCLUSIONS AND FUTURE WORK

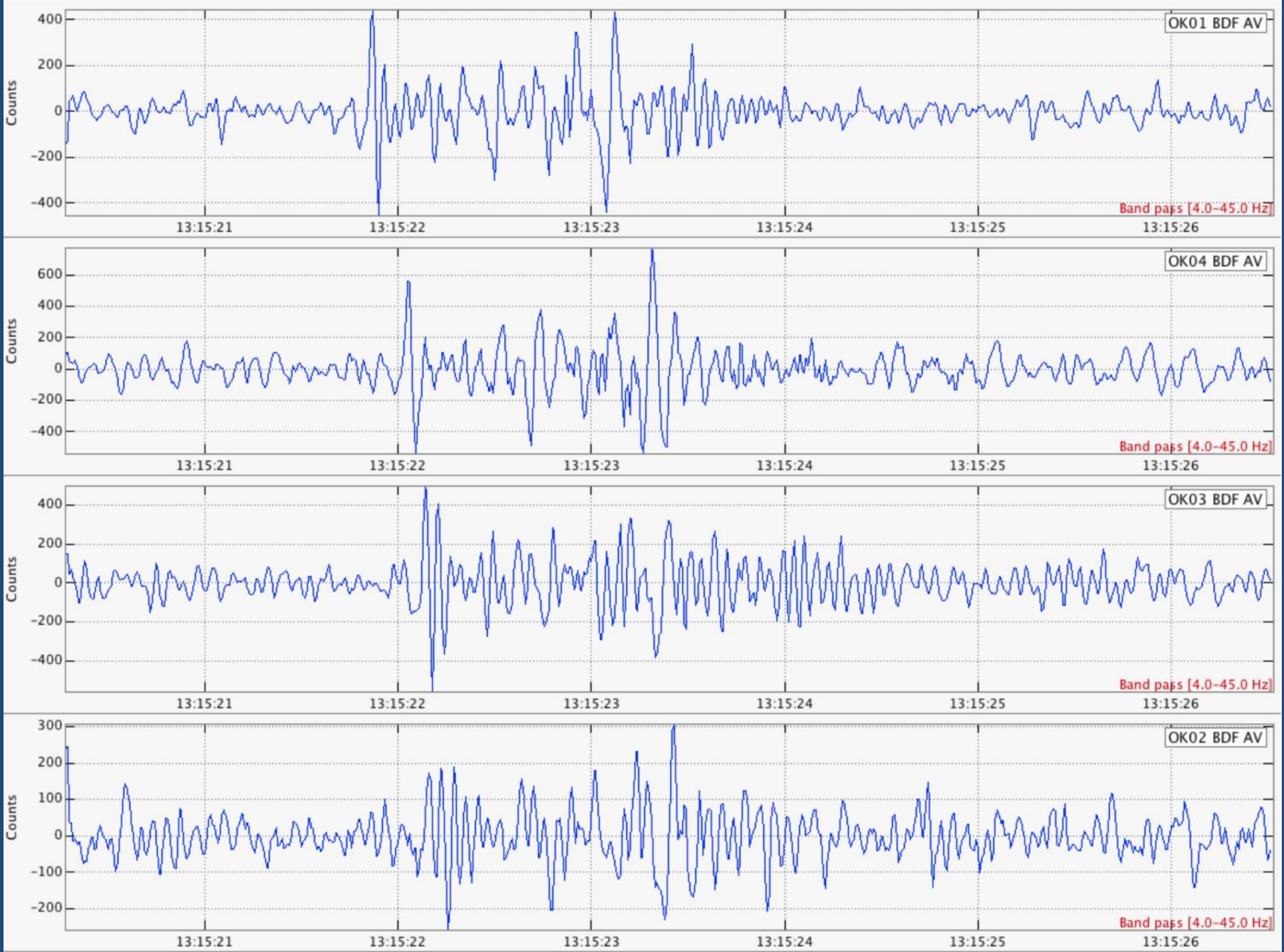
- First documented observations of volcanic thunder
- Volcanic thunder detected after explosive activity abruptly ceases
- Timing and amplitude of volcanic thunder correlate with lightning data
- Why not observed for most events of the sequence? A combination of:
    - Eruptions did not end abruptly
    - Non-optimal wind conditions
    - Higher levels of background noise
- Future work needed on thunder character and lightning properties
    - For example, frequency content of thunder and whether lightning is intra-cloud or cloud-to-ground
- Motivates observations at closer range, during explosive activity, and at other volcanoes

Haney, M. M., Van Eaton, A. R., Lyons, J. J., Kramer, R. L., Fee, D., & Iezzi, A. M. (2018). *Geophysical Research Letters*, in press.

Image courtesy
Sergio Tapiro Velasco



Atmospheric Specifications for 08 March 2017 (06:00 UTC)
a)
b)
Altitude [km]
30
25
20
15
10
5
0
−30 −20 −10 0 10 20 30
Wind Speed [m/s]
250 300 350
Sound Speed [m/s]
Zonal
Meridional
Propagation
c
ceff


OK01 BDF AV
OK04 BDF AV
OK03 BDF AV
OK02 BDF AV
Counts
Band pass [4.0-45.0 Hz]
13:15:21
13:15:22
13:15:23
13:15:24
13:15:25
13:15:26

JUNE 10 ERUPTION

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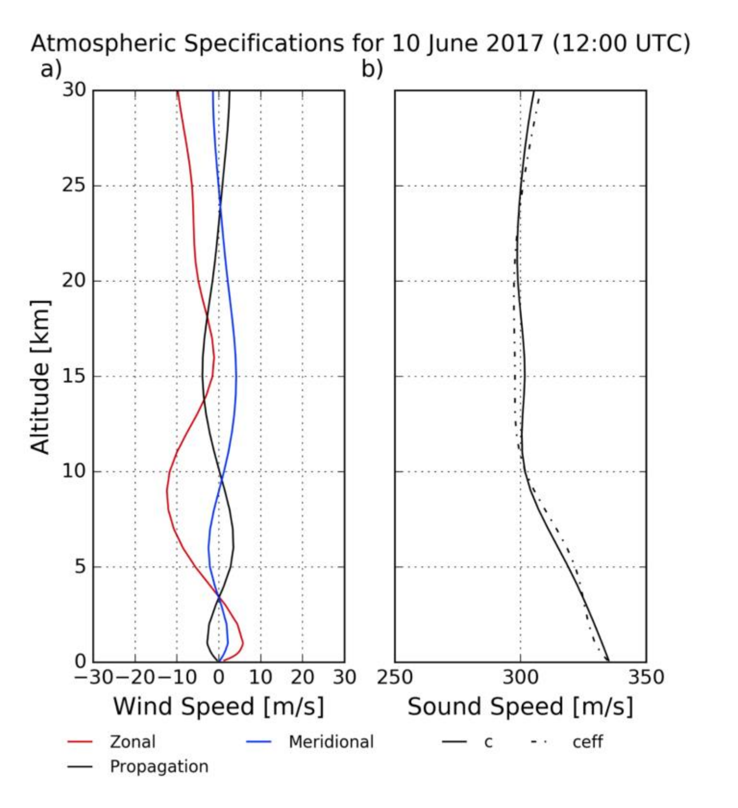

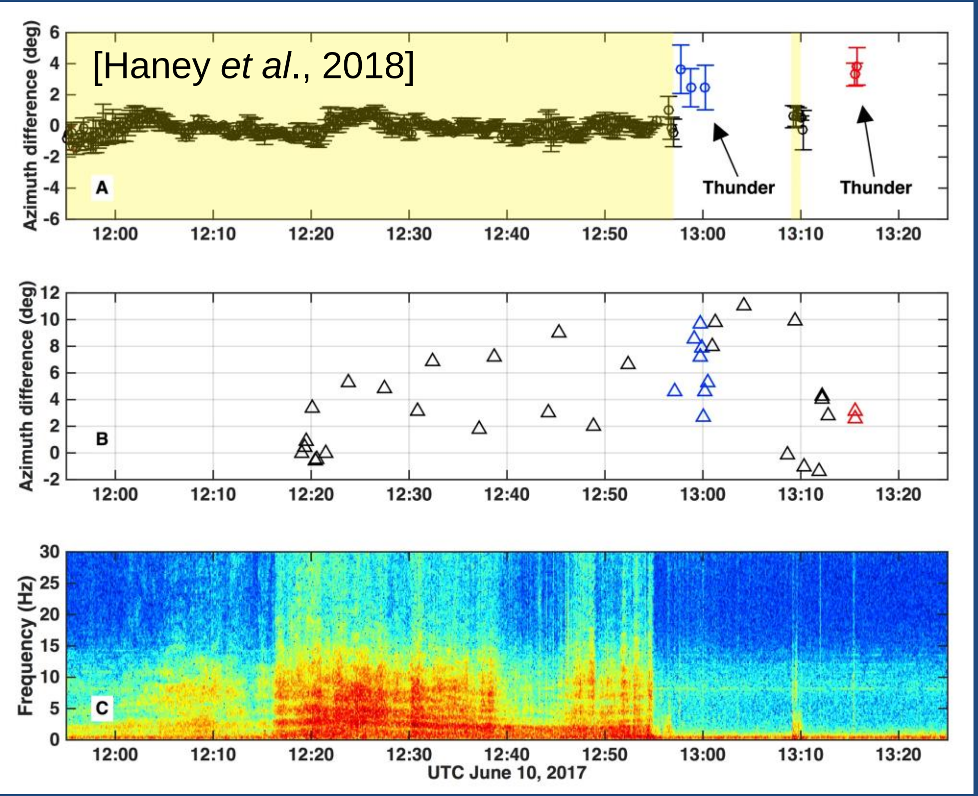

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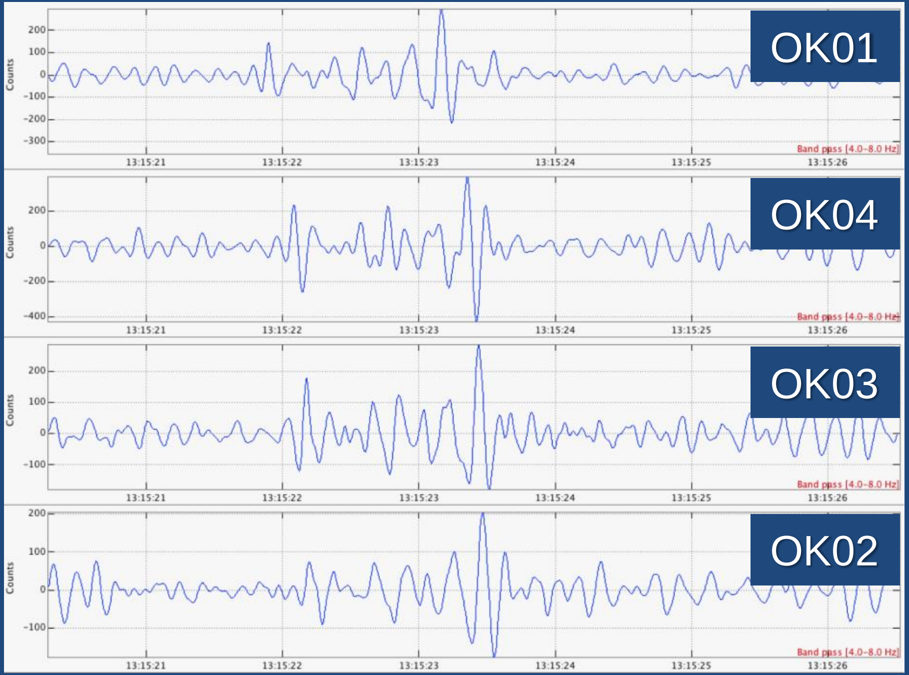
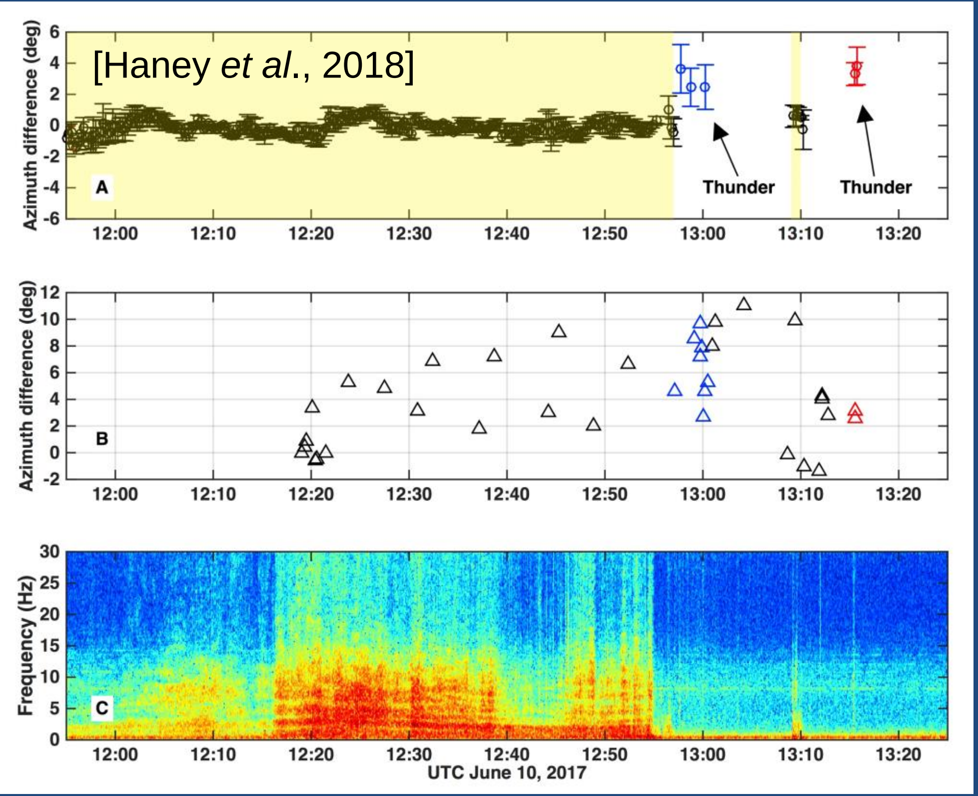


13:12:22 stroke ~ 13:15:22 arrival



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