Fiber Optics foR Environmental SEnsE-ing (FORESEE) at Pennsylvania State University

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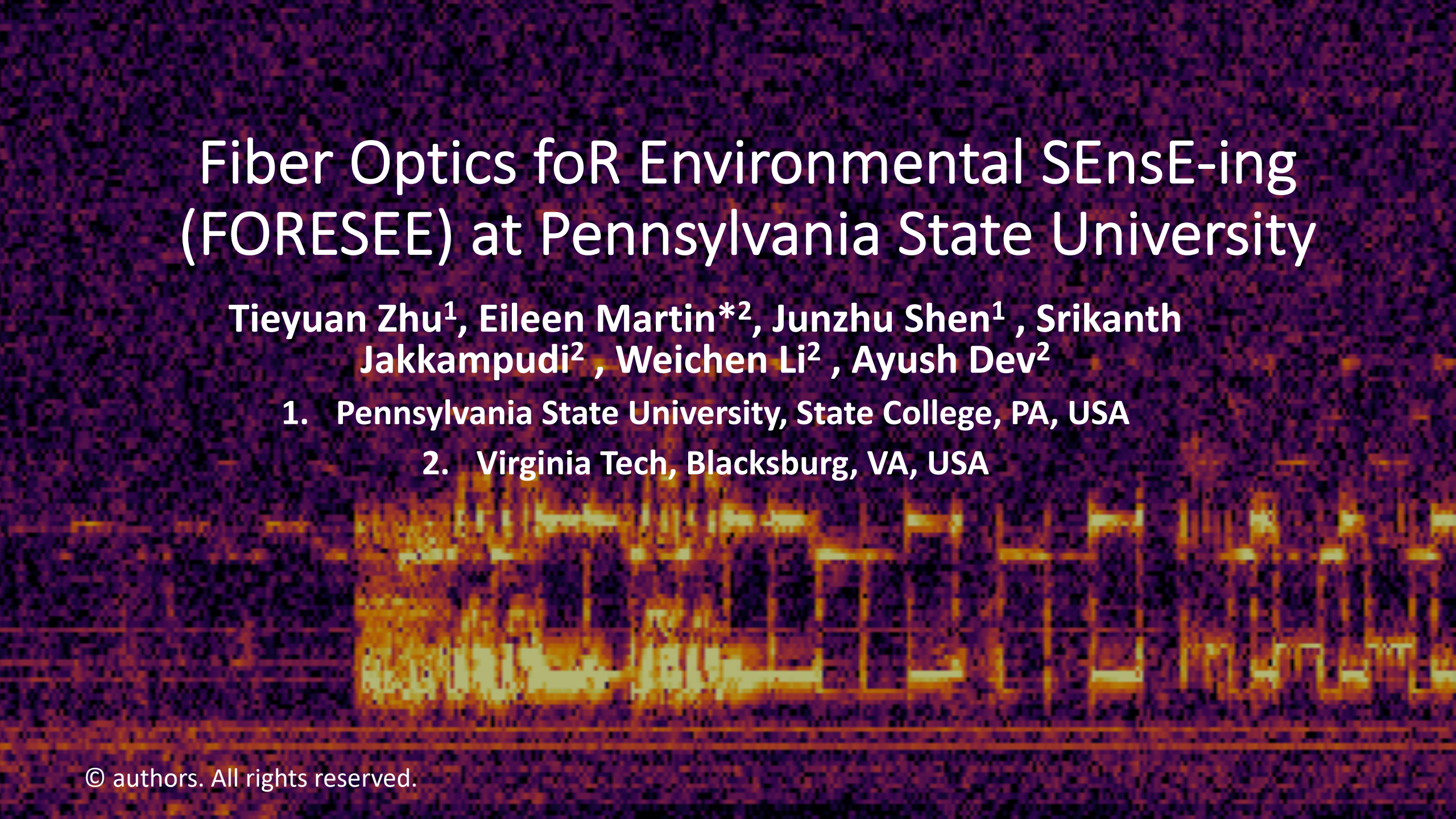
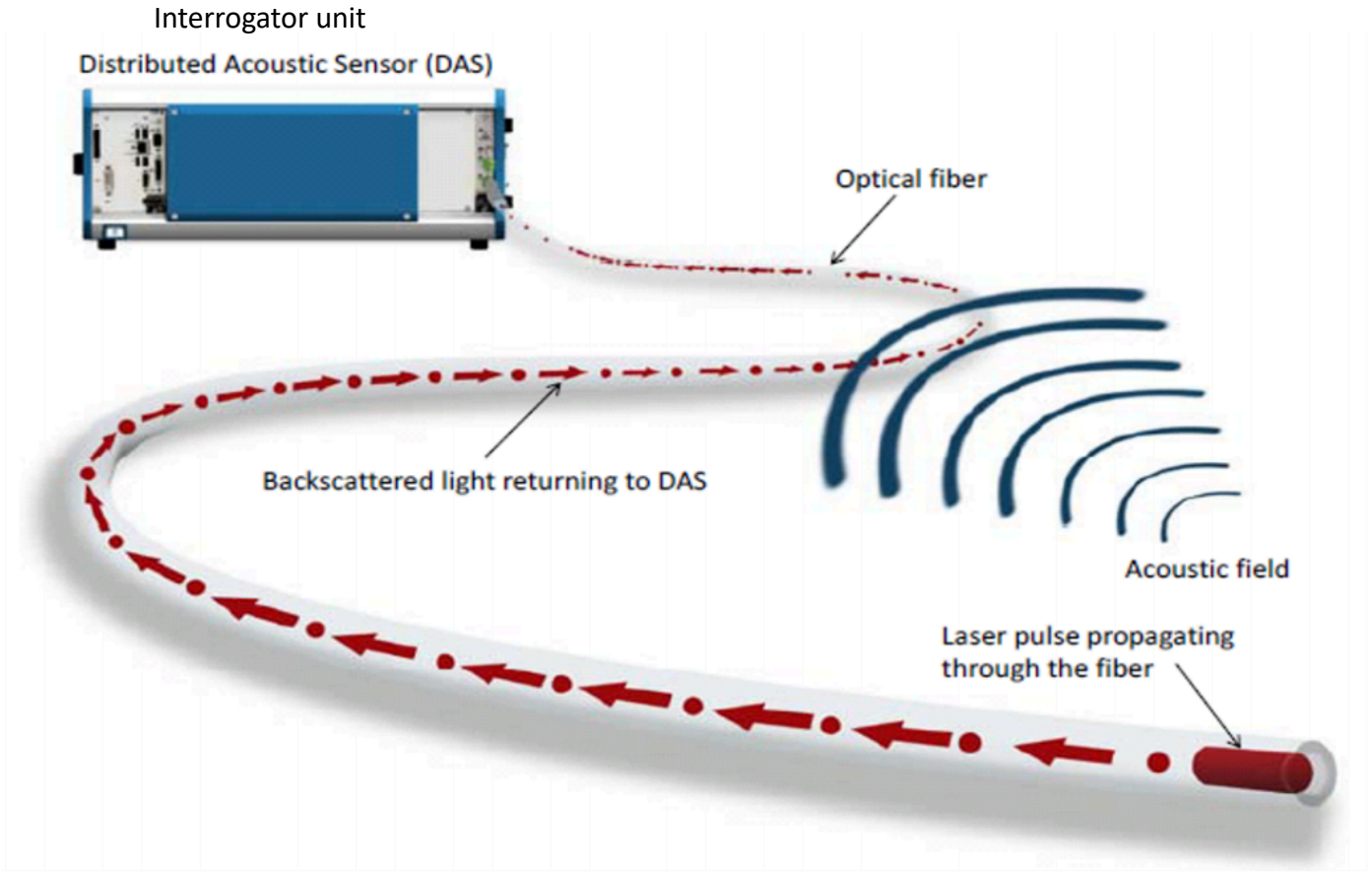
1. Pennsylvania State University, State College, PA, USA
2. Virginia Tech, Blacksburg, VA, USA



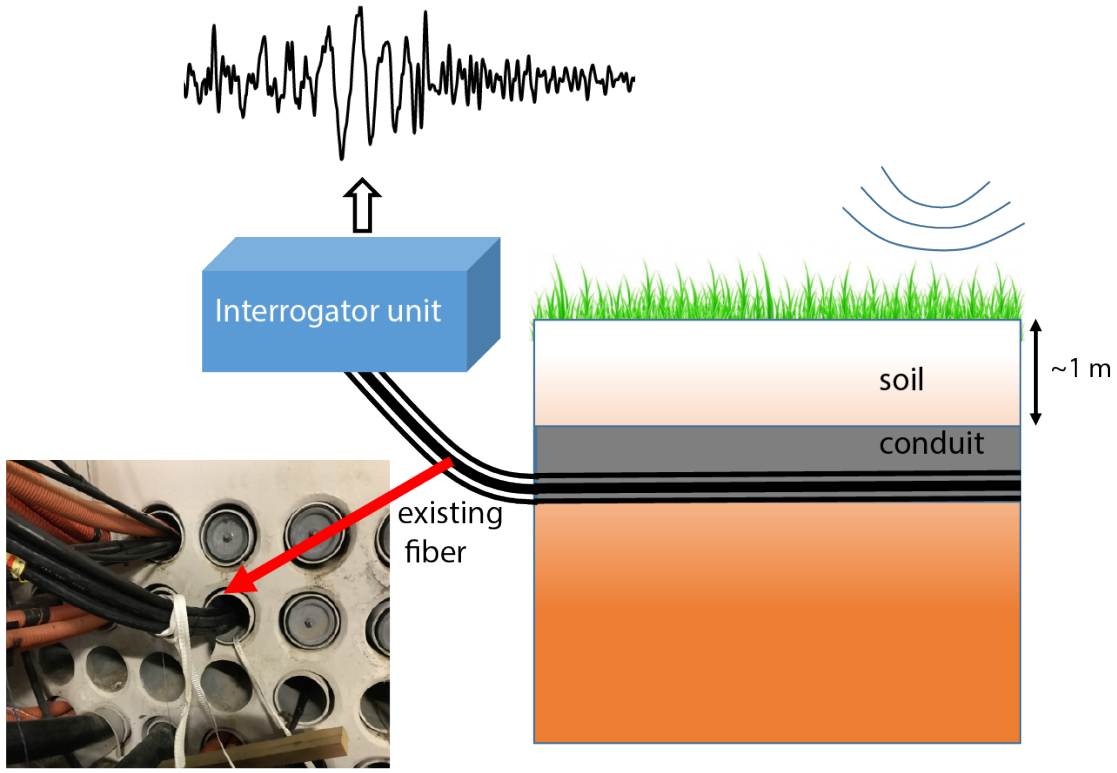
Outline

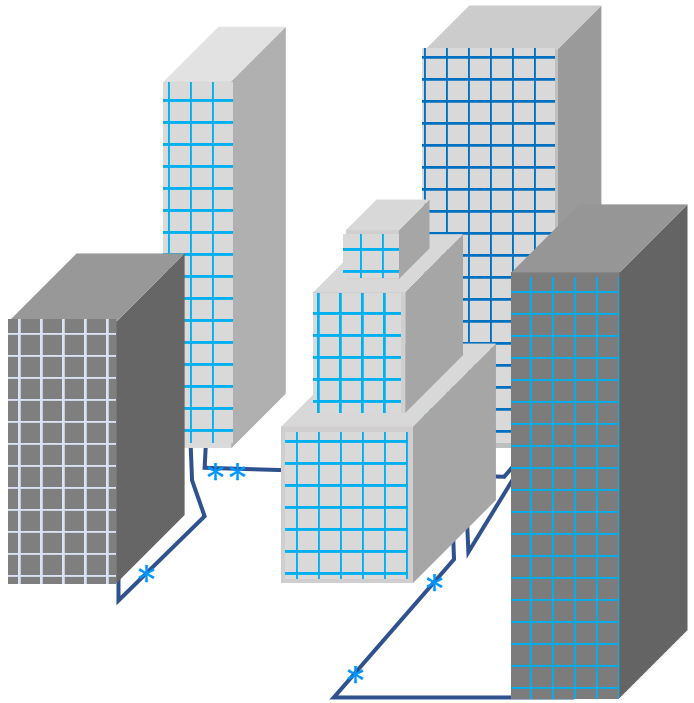
- Motivation
- Experiment and data overview
- Some new signals:
  - Concert – buried sensors detecting sounds
  - Thunder – potential new source for imaging
  - Footsteps – more sensitive than we expected
- Summary

Distributed Acoustic Sensing (DAS) repurposes fiber optics as dense seismic arrays.



Urban fiber optic systems make dense seismic monitoring much easier, and the cost for long-term maintenance per additional sensor is low.





Dark fiber:
fiber that is already installed for future telecommunications purposes, but is not being used yet

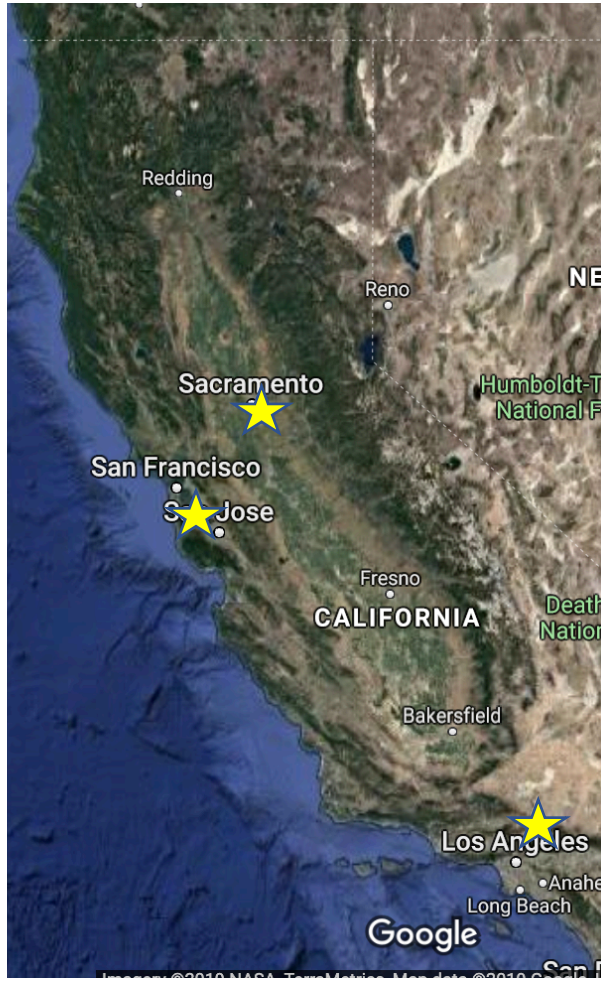
Prior DAS + dark fiber experiments showed us some successes.

Previous experiments:

1. Stanford Fiber Optic Seismic Observatory
2. Sacramento FOSSA
3. Goldstone Array at Jet Propulsion Lab

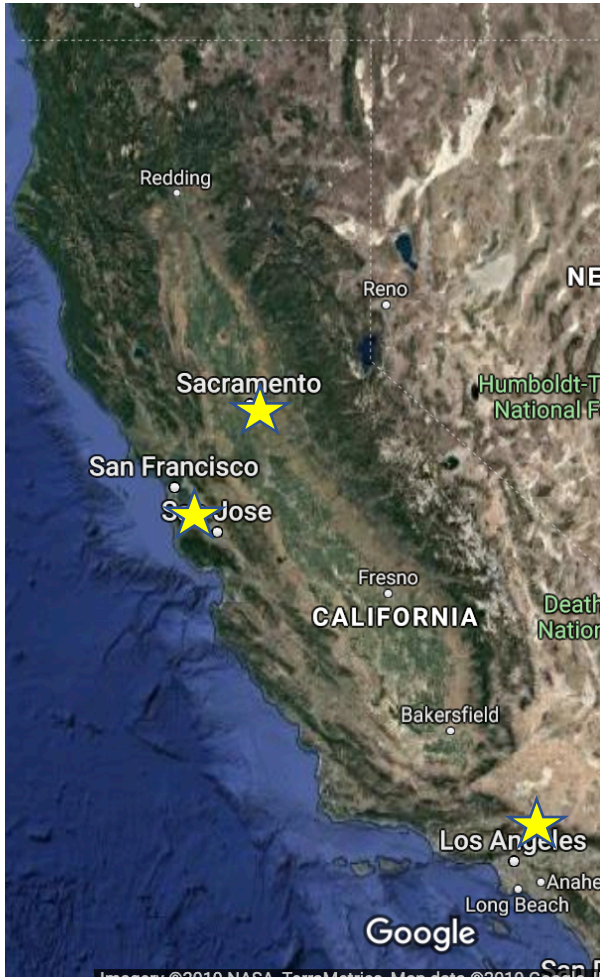
Applications:

- Earthquake detection (1+2+3)
- Surface wave analysis with passive data (1+2)
- Water table changes (2)
- Isolation of anthropogenic sources (1)



What is the value in doing yet another DAS + dark fiber experiment?

- Differences in fiber installations not well characterized
- Variability in noise environment of cities not well characterized
- Previous DAS + dark fiber experiments were all in California
  - Small seasonal variability in temperature and precipitation
  - Geoscience questions focused primarily on earthquake hazards
  - Abundance of mid-sized earthquakes to study



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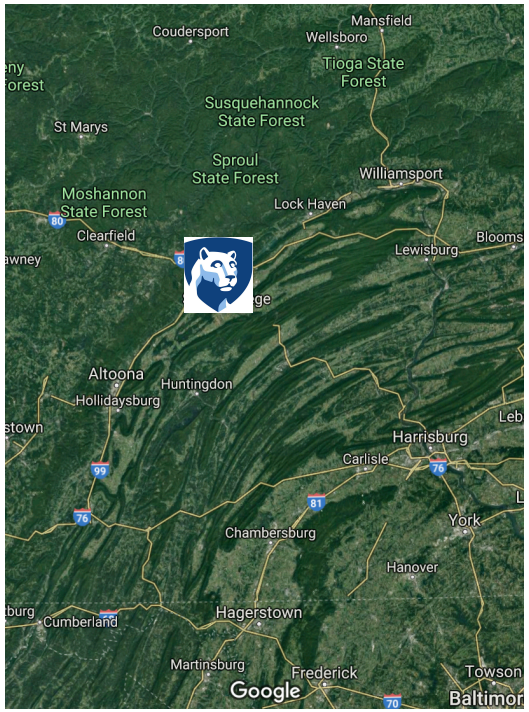
  - Abundance of mid-sized earthquakes to study
- Installation on East Coast could study urban groundwater flow, flooding, and potential geohazards (sinkholes)
- Only small teams have access to data from previous experiments -> public data needed!



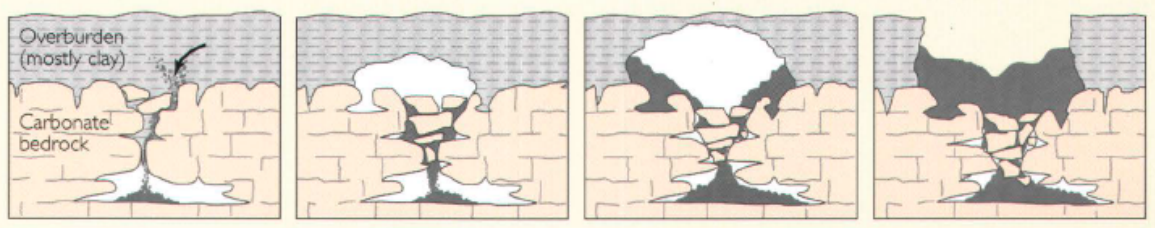


Figure from Tihansky, 1999, USGS Circular

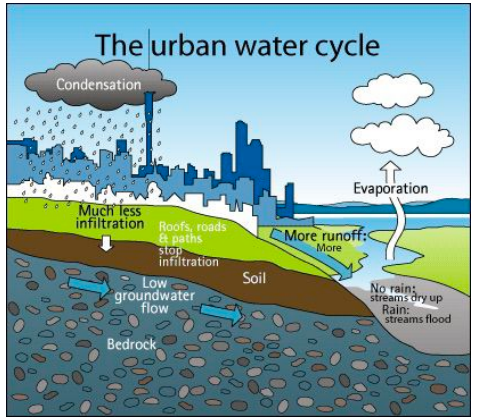
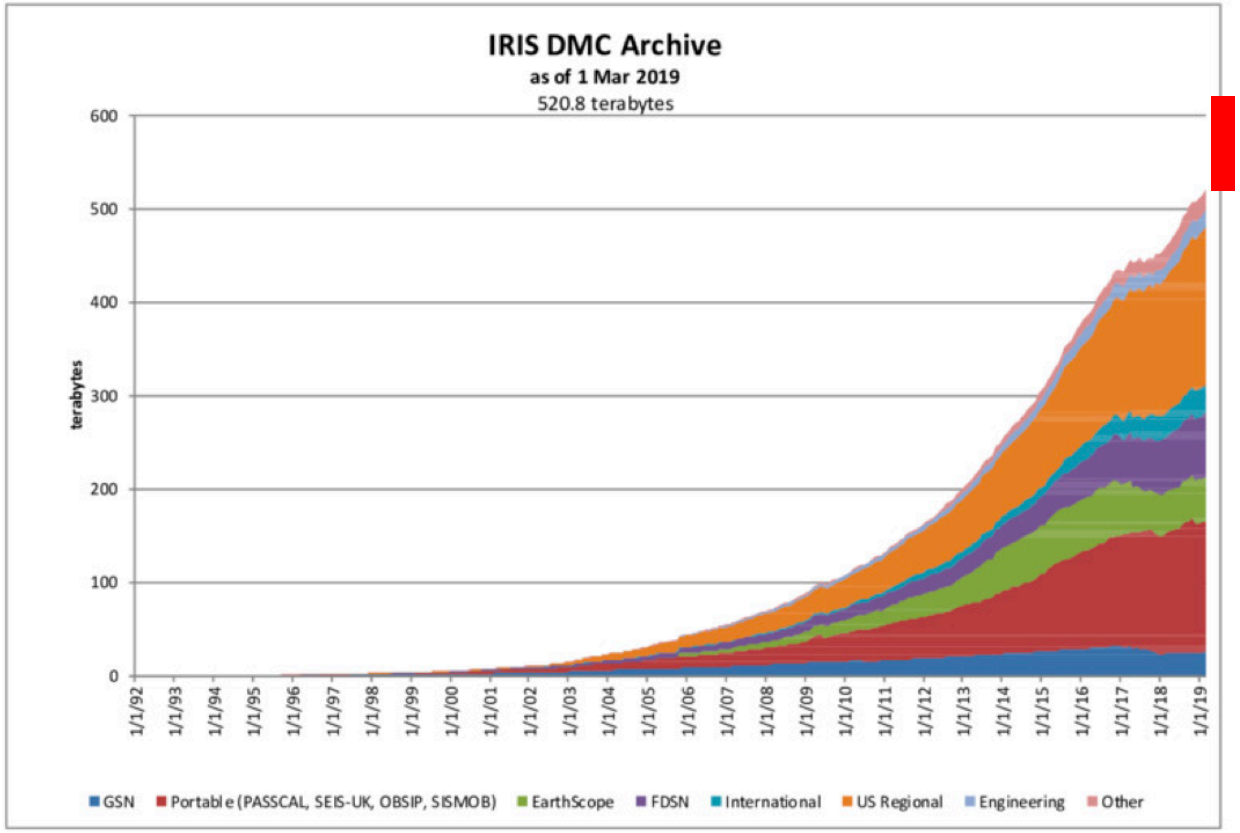


Image from National Geographic Society

We need public DAS data, but it is hard to host.

Reference point:
Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC) Archive in USA



Amount that would be added by FORESEE if it were included.

Penn State Data Commons has agreed to host our entire +100 TB data set publicly upon release (2-3 years from now).

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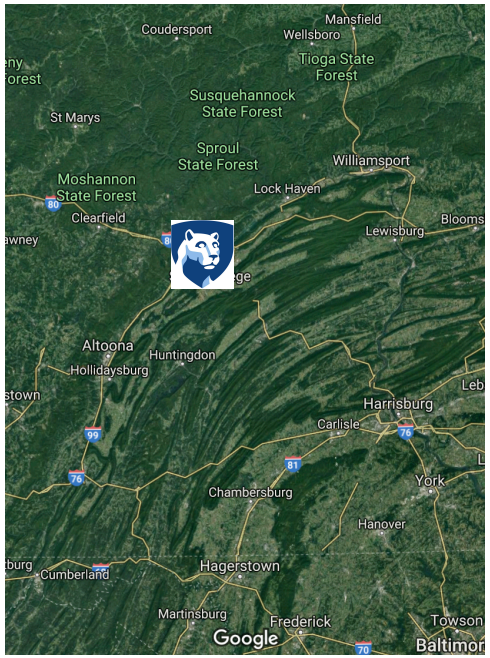
FORESEE Array Location: State College, Pennsylvania

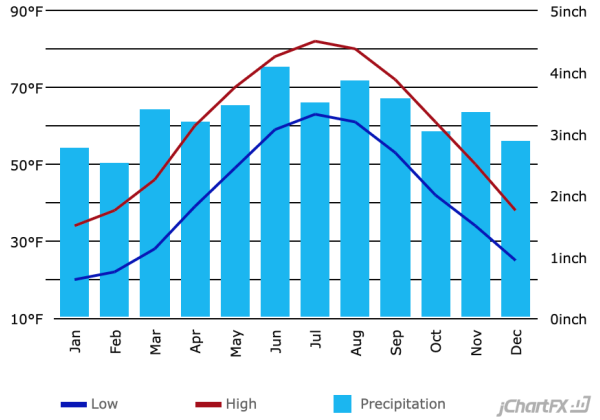
(**F**iber **O**ptics fo**R** **E**nvironmental **SE**ns**E**-ing)

On the East Coast of USA

In the Alleghany Mountains



Much more temperature variability and more precipitation than California



Limestone in region leads to many caves, and potential for sinkholes

Maps from Google Maps, climate chart from usclimatedata.com, and cave photo from visitpennstate.org

Array Design and Data Quantities

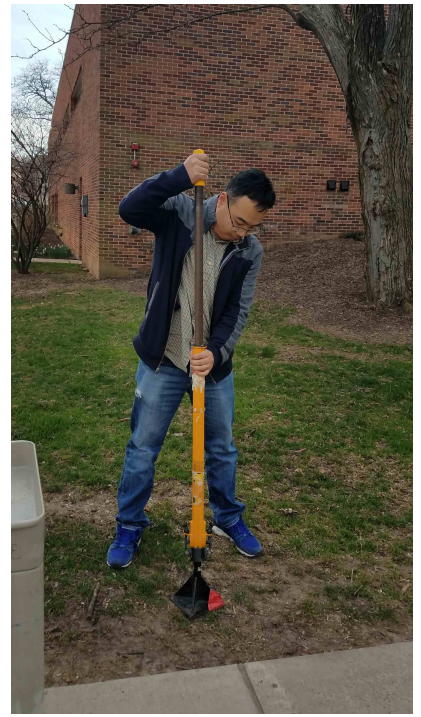
Resolution:

- 2 meter spacing
- 500 samples/second

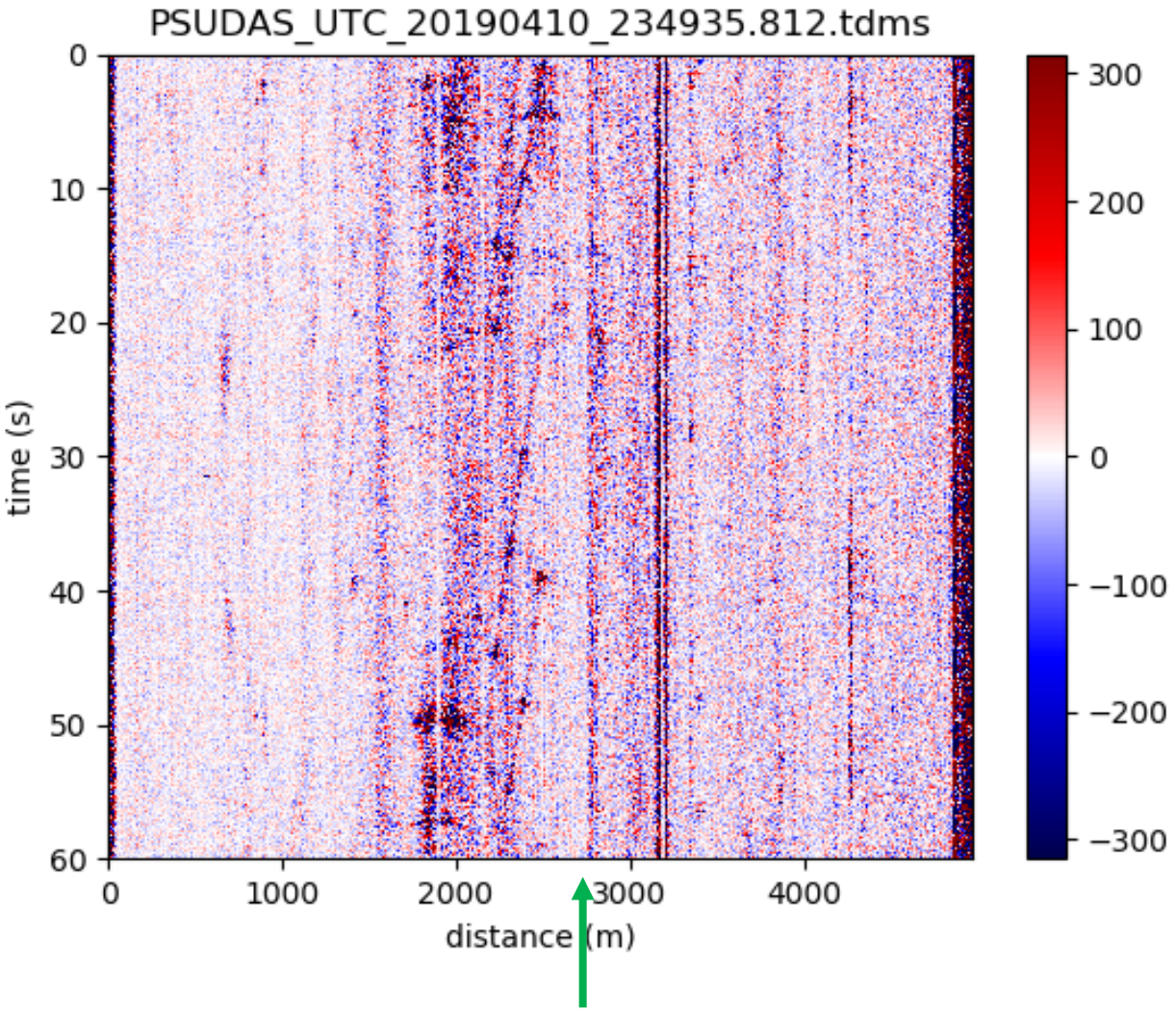
5x tap tests at 121 locations

Data quantities:

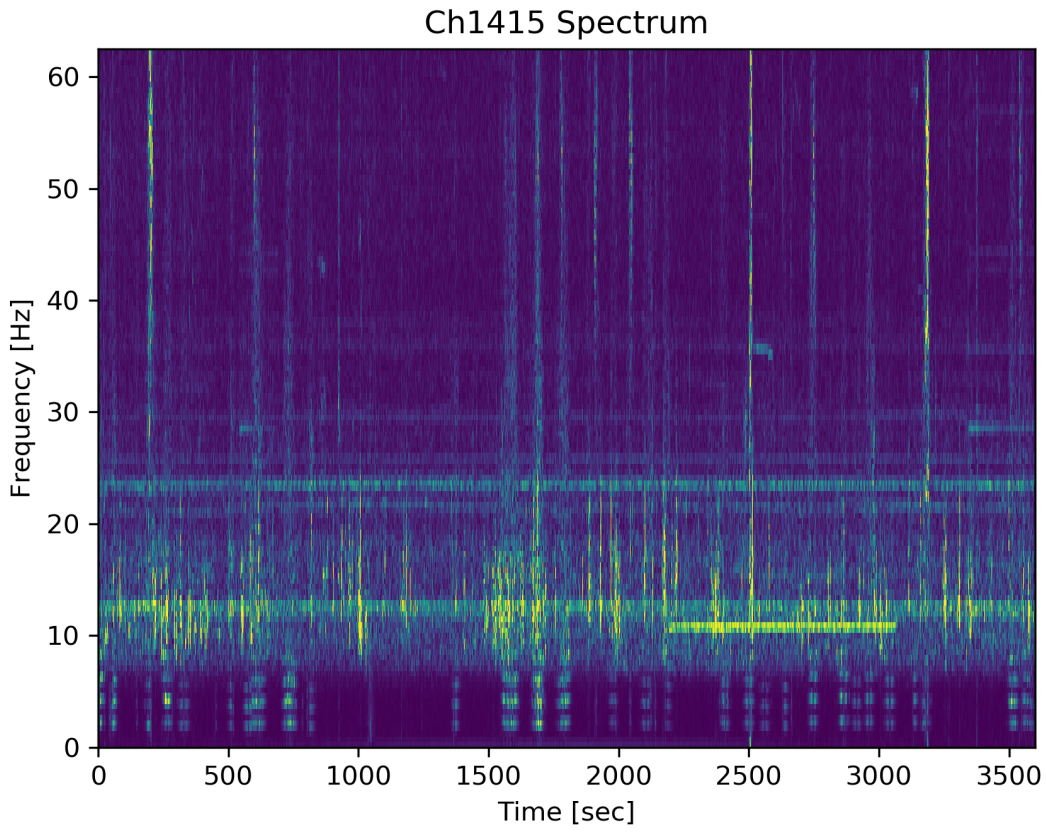
- 0.4 Terabytes of data/day
- Recording started April 2019



Example of Passive Noise

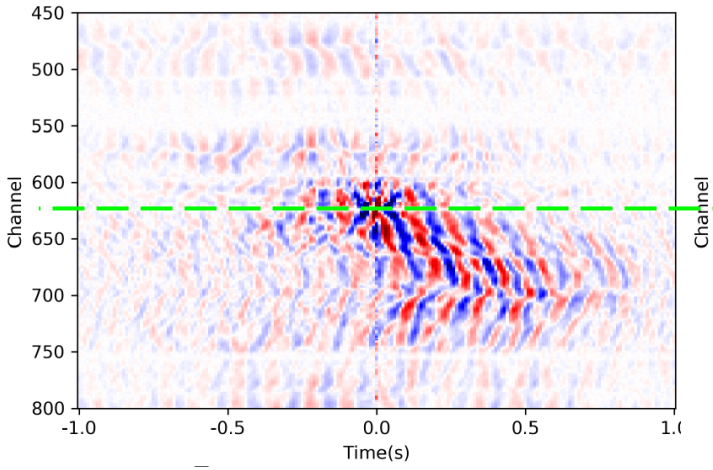


Channel 1415

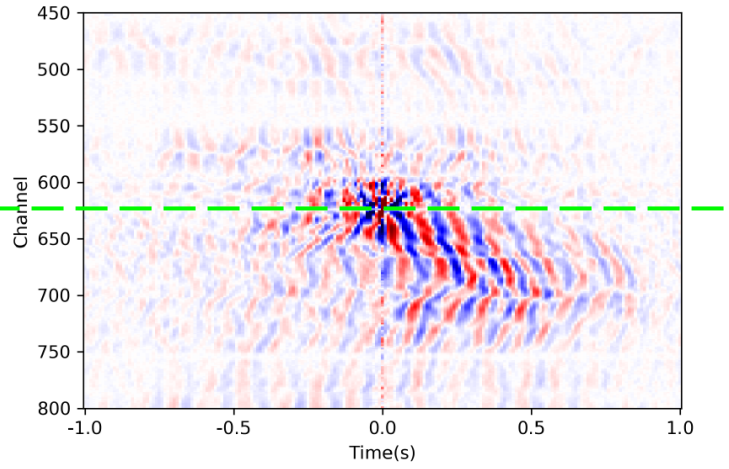


Examples of 1 Day of Noise Correlation Functions

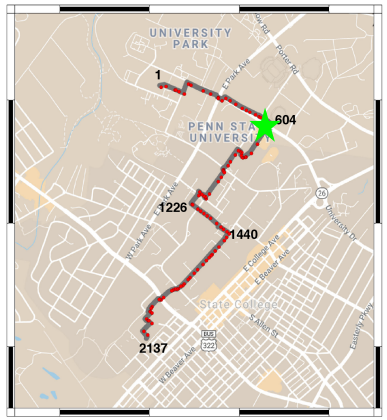
May 12



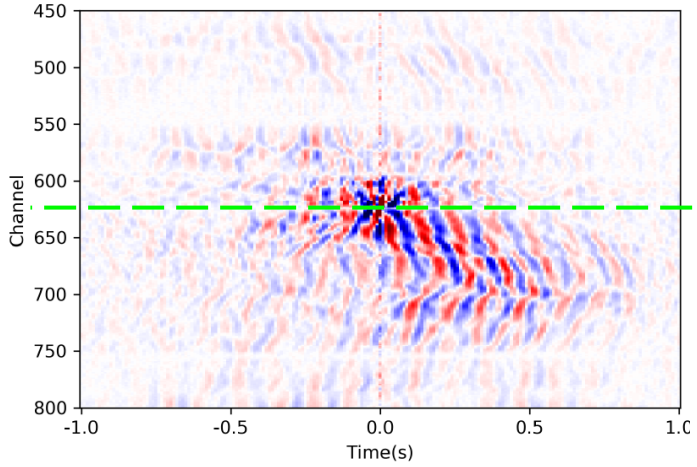
May 13



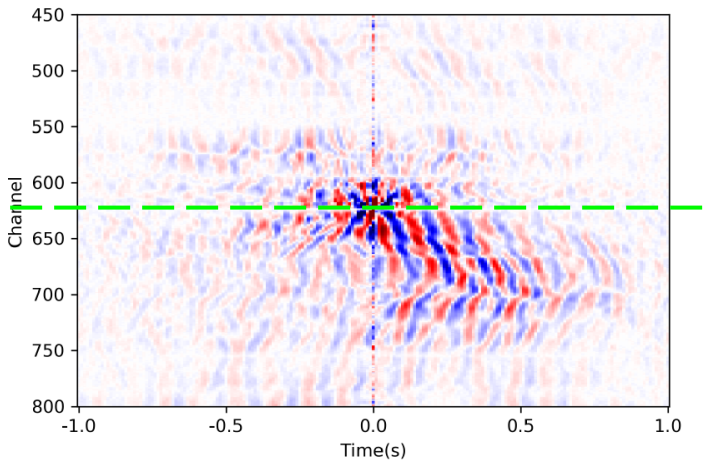
360 m oriented in same direction as virtual source



May 14



May 15



Processing details:
- 1 day of data
- Cross-coherence with 5% of frequencies at water-level
- For a given channel reject any windows that are either L1 or L2 outliers in raw noise amplitudes
- Ongoing work to ensure reliability in many parts of campus with variety of noise profiles

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Movin’ On Concert: Expectations

image from Penn State News

Prior result:

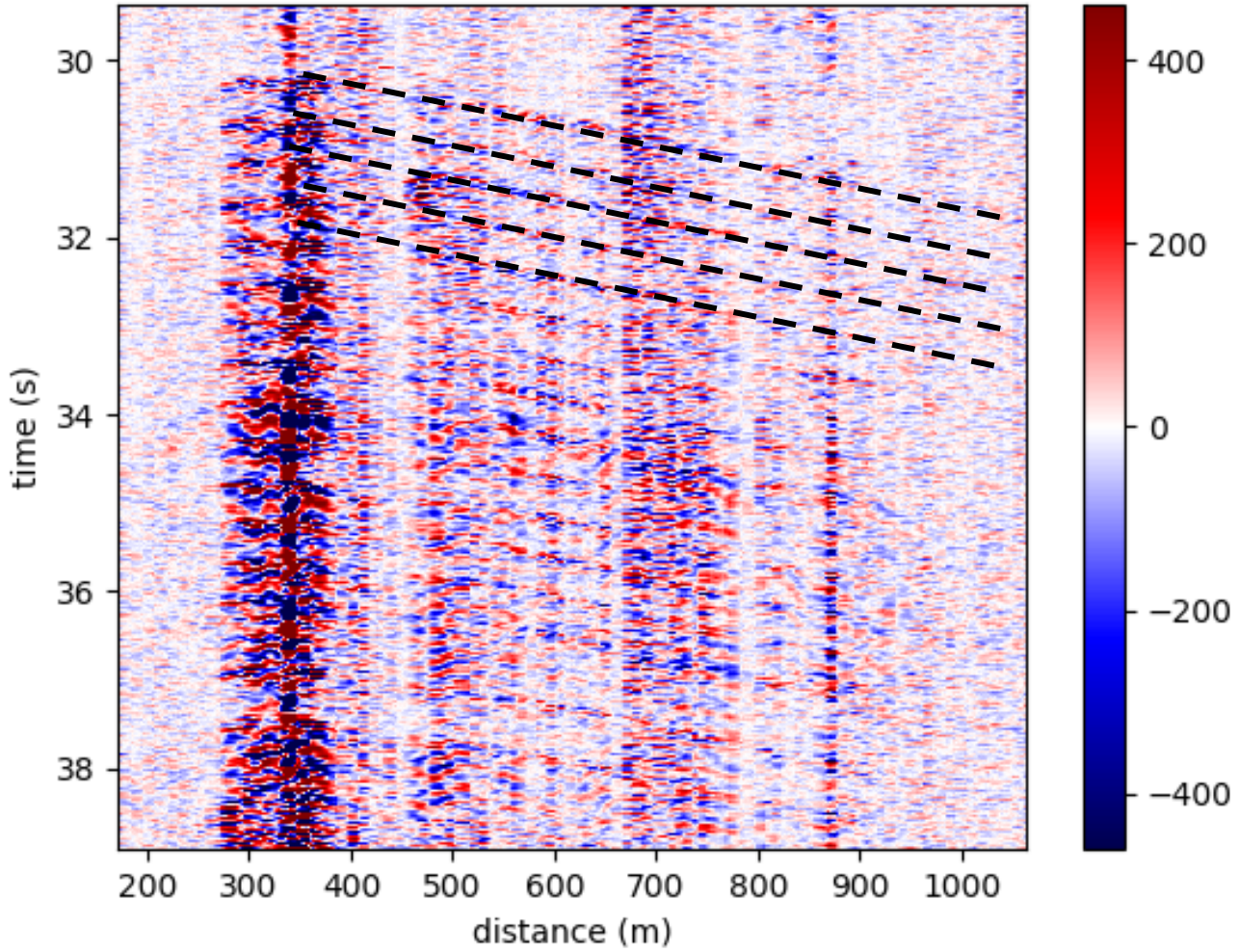
No air wave during seismic survey with dark fiber DAS installation at Stanford

(Martin, et al., 2017, The Leading Edge)

What we expected:

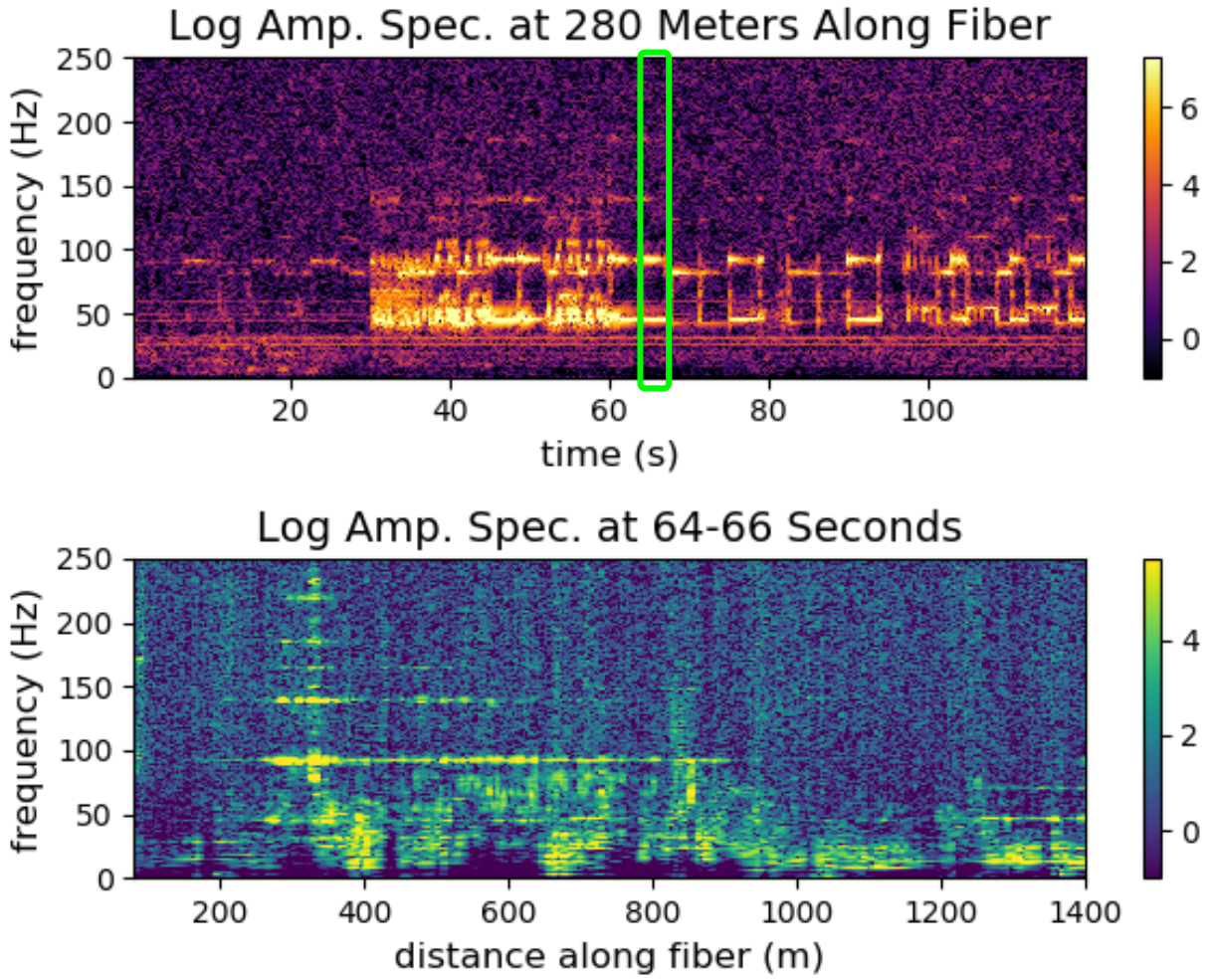
No music signals, but maybe extra human and vehicle activity around the concert

Movin’ On Concert: Reality



What we observed:
Clear rhythmic signals on channels up to 0.6 km away.

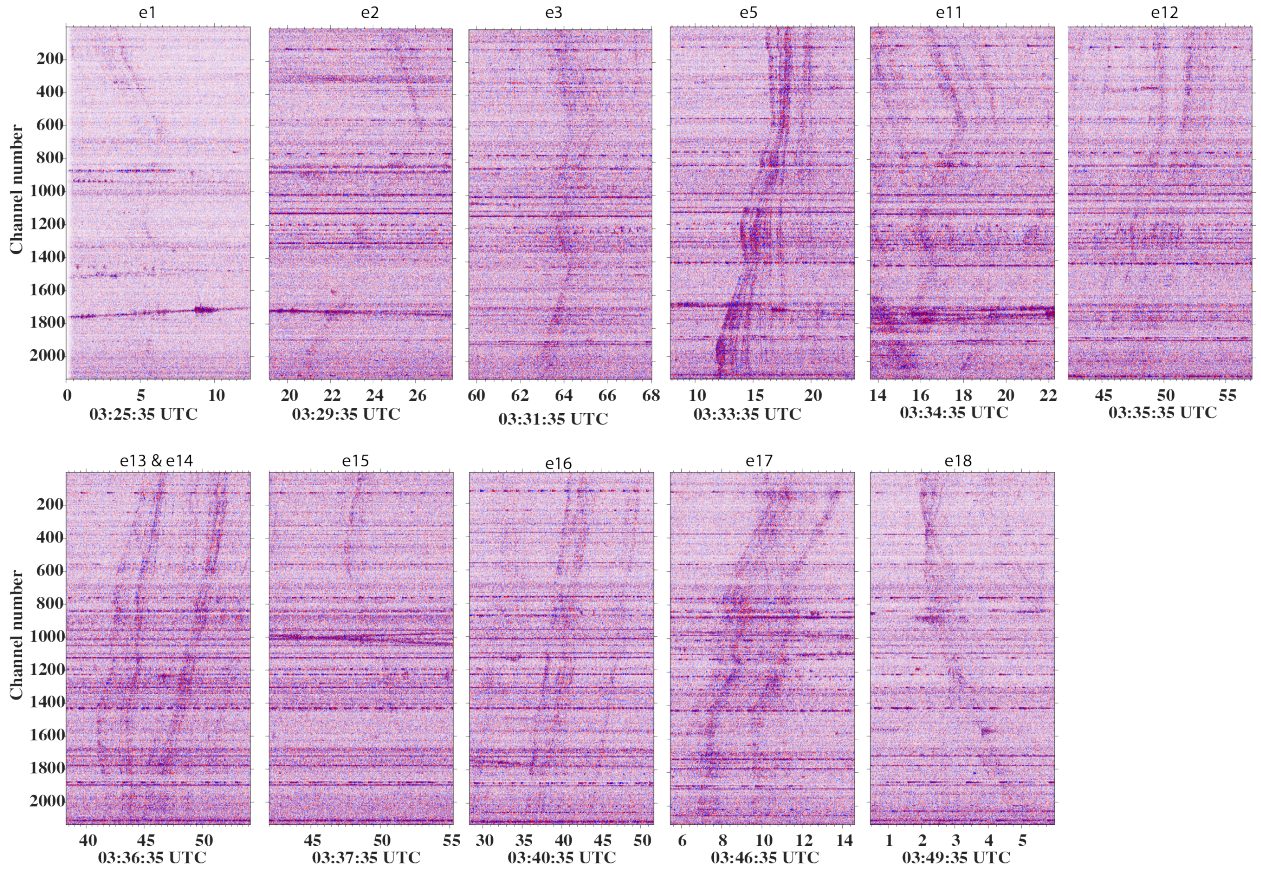
Movin’ On Concert: Reality



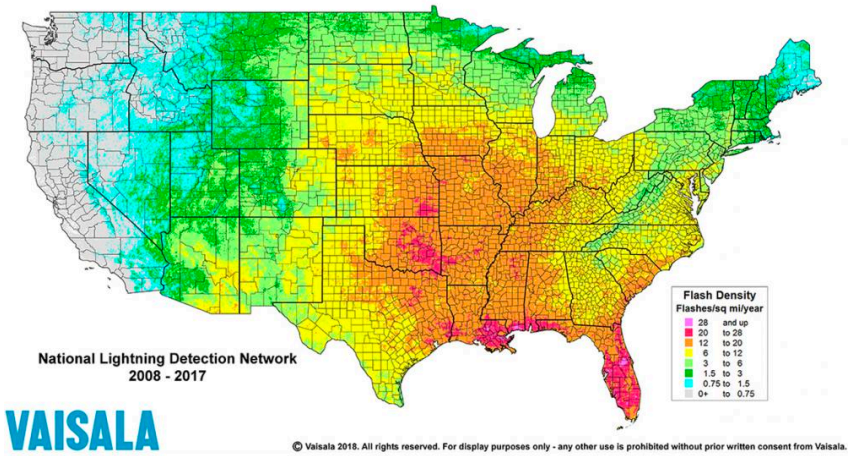
What we observed:
Clear musical bass-lines
on channels up to 0.6 km away.

What this means:
We can detect loud sound signals (possibility for other smart-city applications)

During a thunderstorm, signals are clearly detected throughout the array.

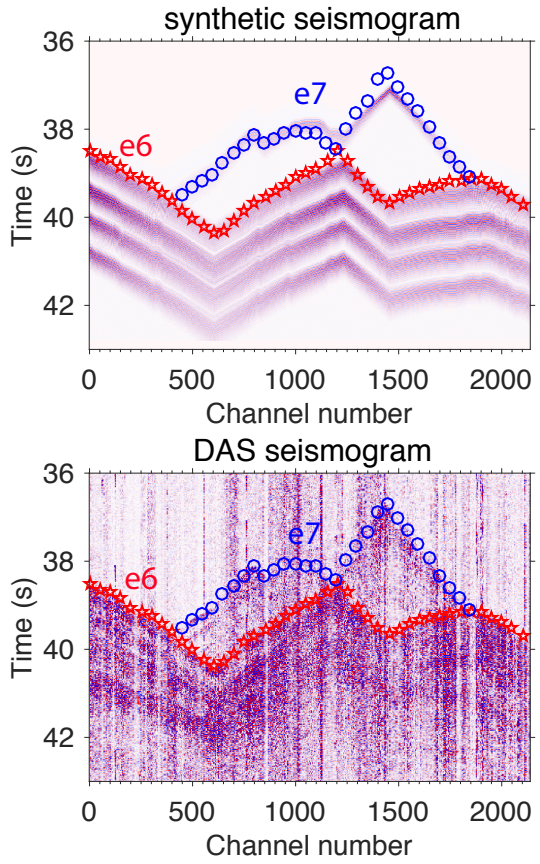


Lightning could not be studied by previous dark fiber DAS arrays because lightning is extremely rare in the Western US.

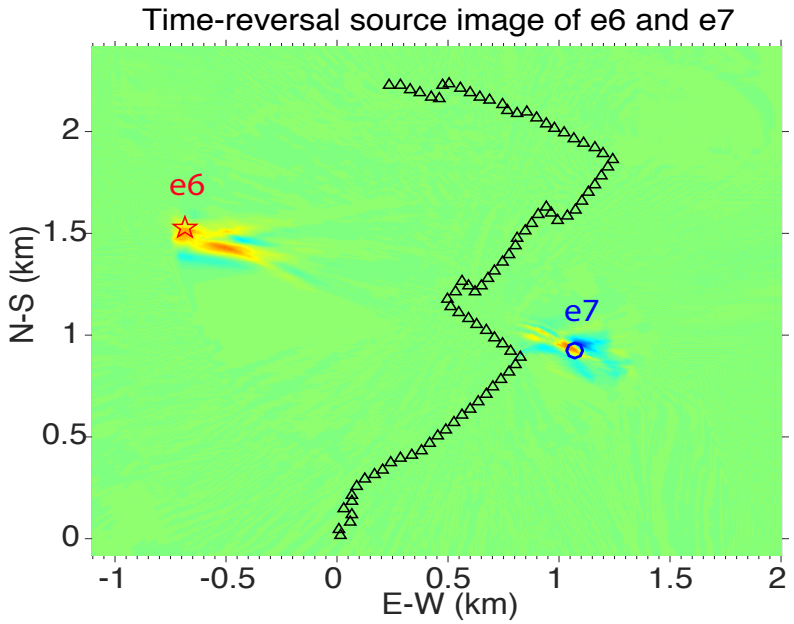


T. Zhu, D. Stensrud, “Tracking thunderstorms by fiber-optic distributed acoustic sensing array,” accepted JGR: Atmospheres.

Thunder sources can be located with time-reversal.



Bigger question: Could thunder be an alternative source for high-resolution imaging in the Eastern US where there is little seismicity?



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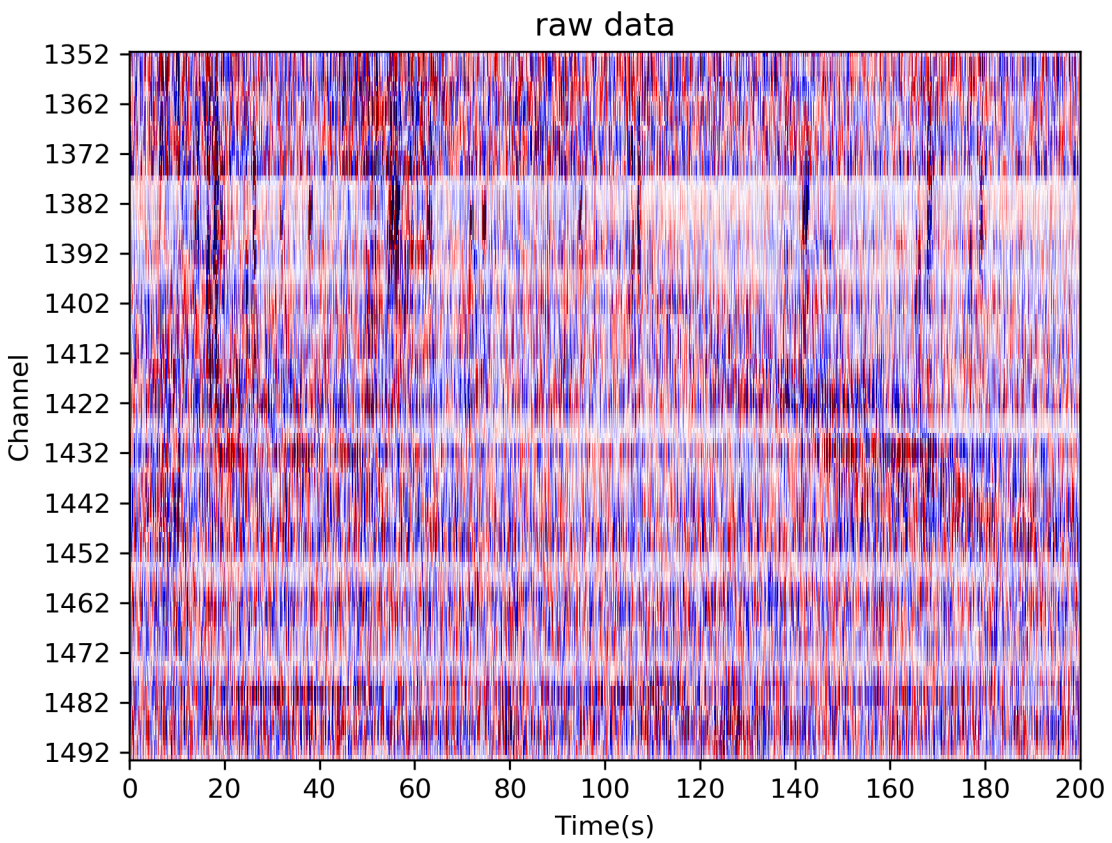
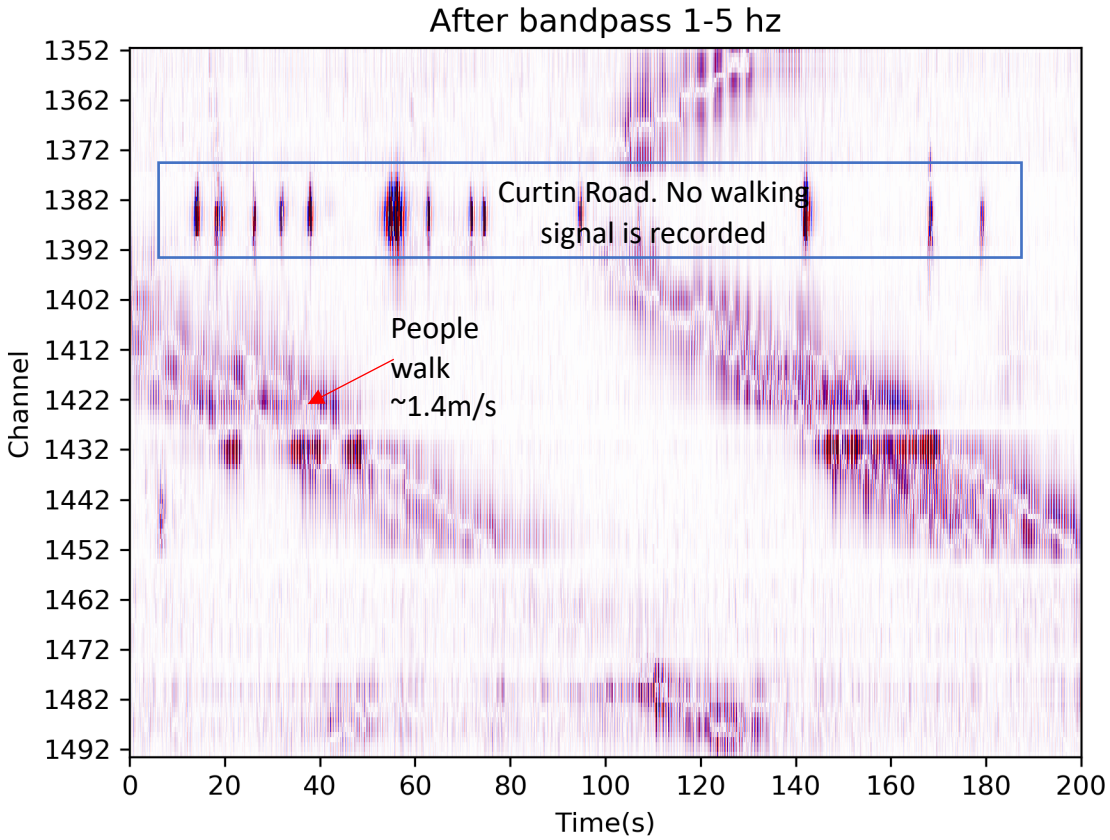
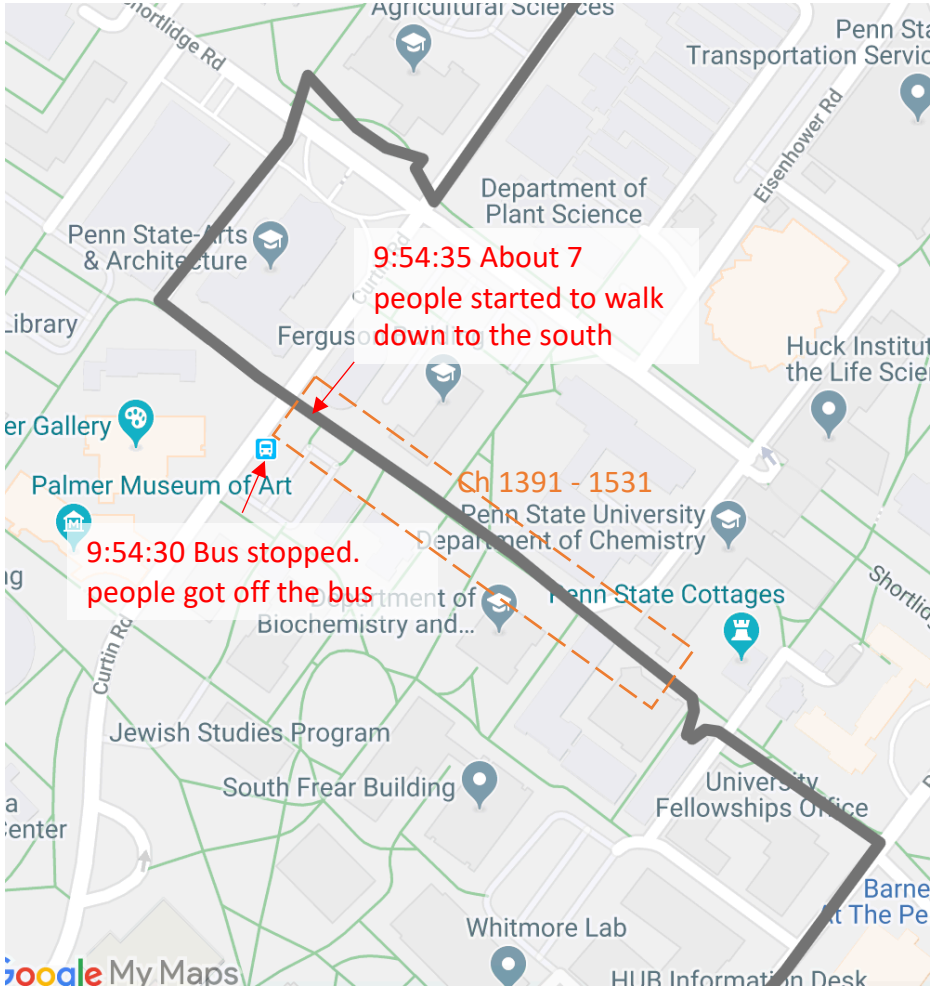
We see footsteps along a pedestrian area

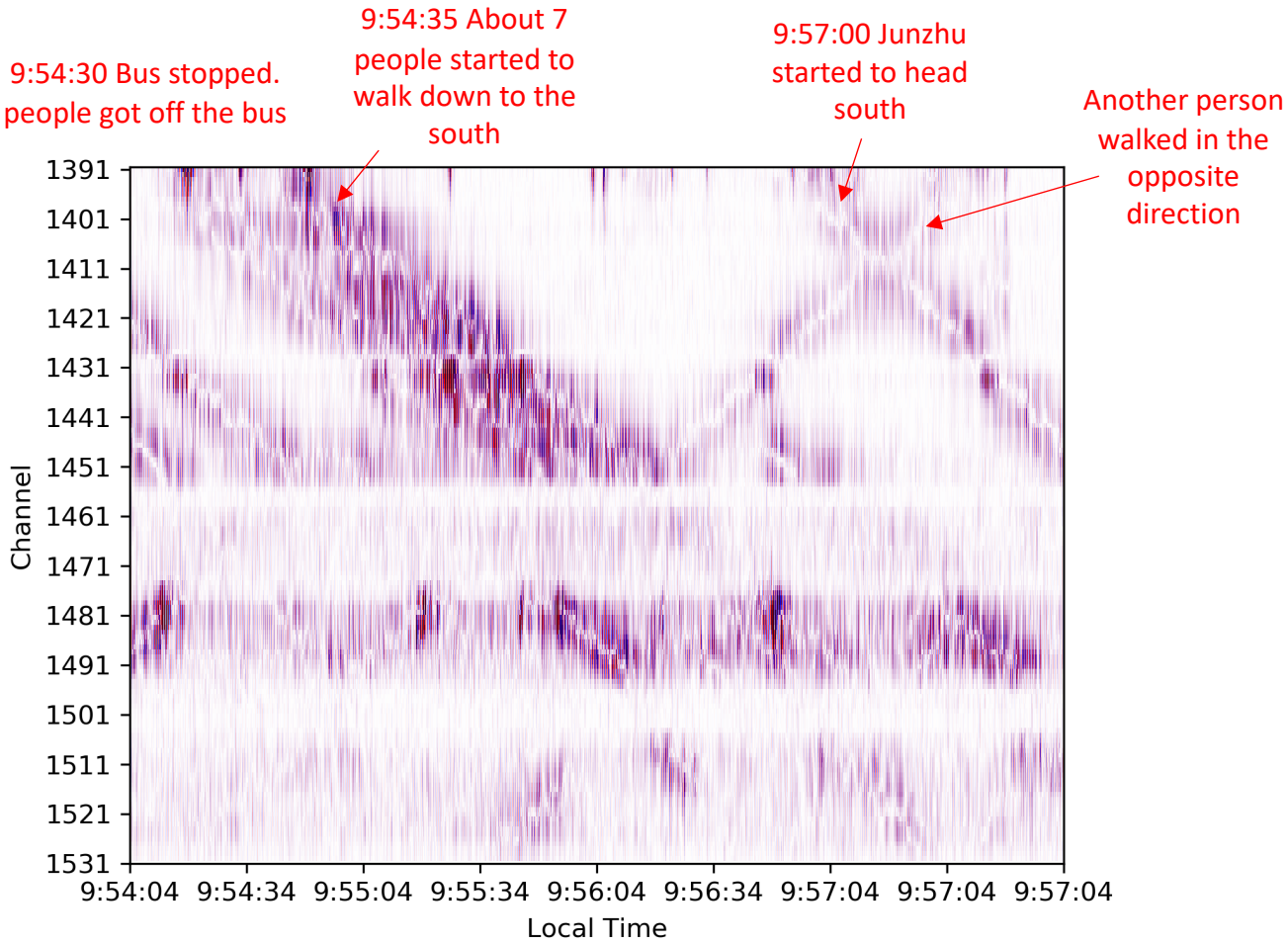




“Footstep Detection in Urban Seismic Data with a Convolutional Neural Network,” Jakkampudi et al., recently submitted.

We see footsteps along a pedestrian area





data bandpassed to 1-5 Hz

"Footstep Detection in Urban Seismic Data with a Convolutional Neural Network," Jakkampudi et al., recently submitted.

We **don't want to** see footsteps along a pedestrian area

in particular, as we expand these systems into urban areas with a mix residential and commercial.

image by Gene.arboit via Wikipedia

image from strongtowns.org

image by Andrew Jameson via Wikipedia

Possible solution building on prior work:

F. Huot led effort to remove car noises from Stanford data via clustering followed by wavelet-domain filtering, and later improved with neural network.

Huot et al., 2017, SEG Expanded Abstracts
Martin et al., 2018, IEEE Signal Processing Magazine

Huot et al., 2018, SEG Expanded Abstracts
Huot et al., 2019, SEG Expanded Abstracts

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so a team of CMDA undergraduates has automated detection, then we will use this to remove them.

Final workflow

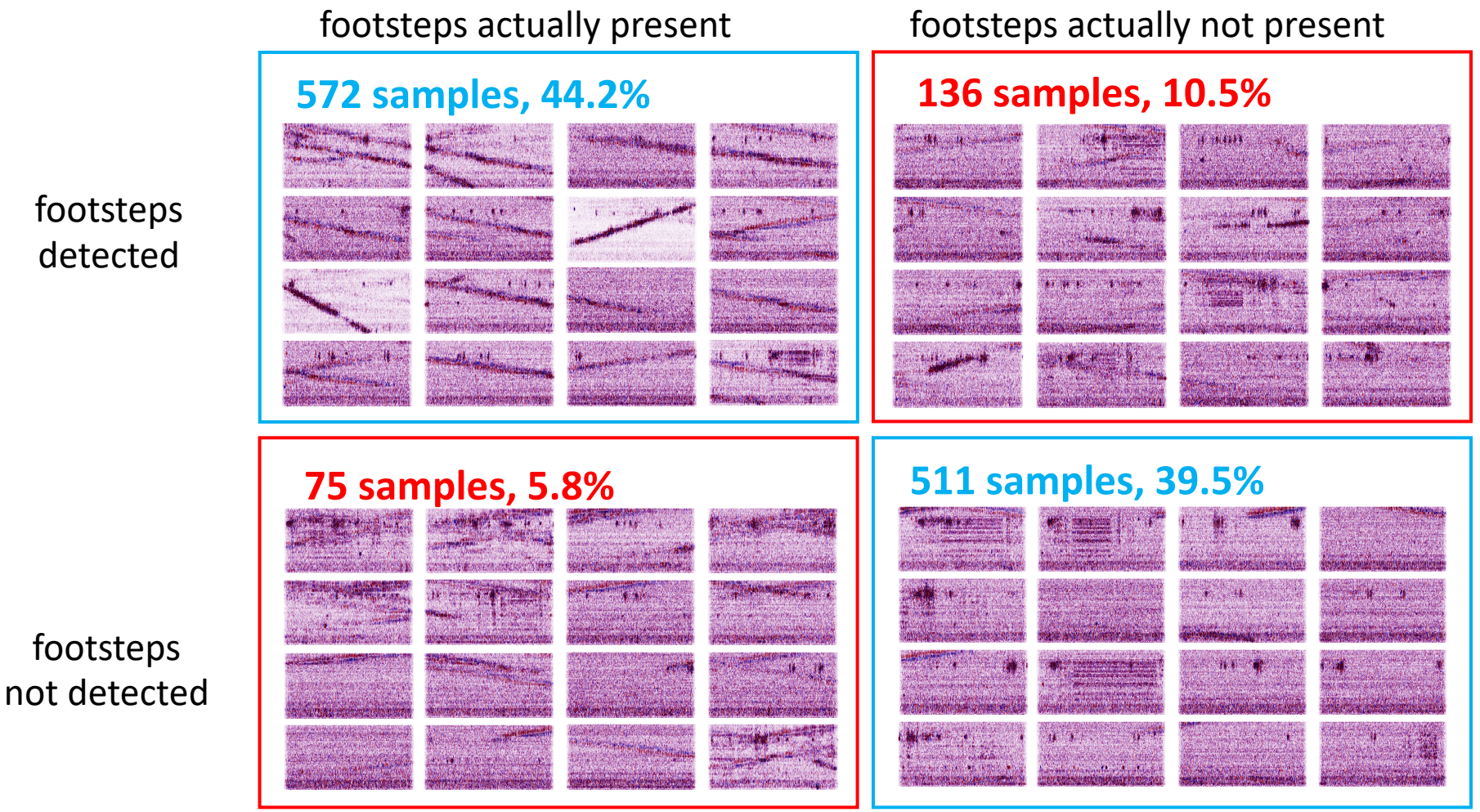
project started through senior CMDA capstone course

lots of details on ruling out simpler models, training data, and optimizing this in paper

"Footstep Detection in Urban Seismic Data with a Convolutional Neural Network," Jakkampudi et al., recently submitted.

Footstep removal requires detection (done), followed by removal (next step).

Detection phase accuracy on test data is 83.7%.



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Summary

New questions:
The FORESEE data has acquired a year of data to study urban hydrology and geohazard challenges.

New signals:
Not all DAS + dark fiber installations are the same.

- new signals
- different coupling

New privacy challenges:
As we move towards geophysical monitoring in mixed residential-commercial areas, it is our responsibility to ensure residents' privacy is respected.

Acknowledgements

The FORESEE data acquisition and initial analysis was funded by a seed grant from the Penn State Institutes of Energy and the Environment.

We would like to thank collaborators on the FORESEE array including Patrick Fox, David Stensrud, and Andy Nyblade.

The DAS interrogator used was a Silixa iDAS system, supported by Thomas Coleman.

We would like to thank Penn State IT for providing dark fiber access, computing and data archiving resources; as well as Virginia Tech Advanced Research Computing for computing resources.

E. Martin was supported in part by a Hamlett Junior Faculty Fellowsh in the Virginia Tech Academy of Integrated Science.

S. Jakkampudi was supported in part by the Hamlett Undergraduate Research Program in the Virginia Tech Academy of Integrated Science.

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Thank you for your time.
Looking forward to discussing more with you!