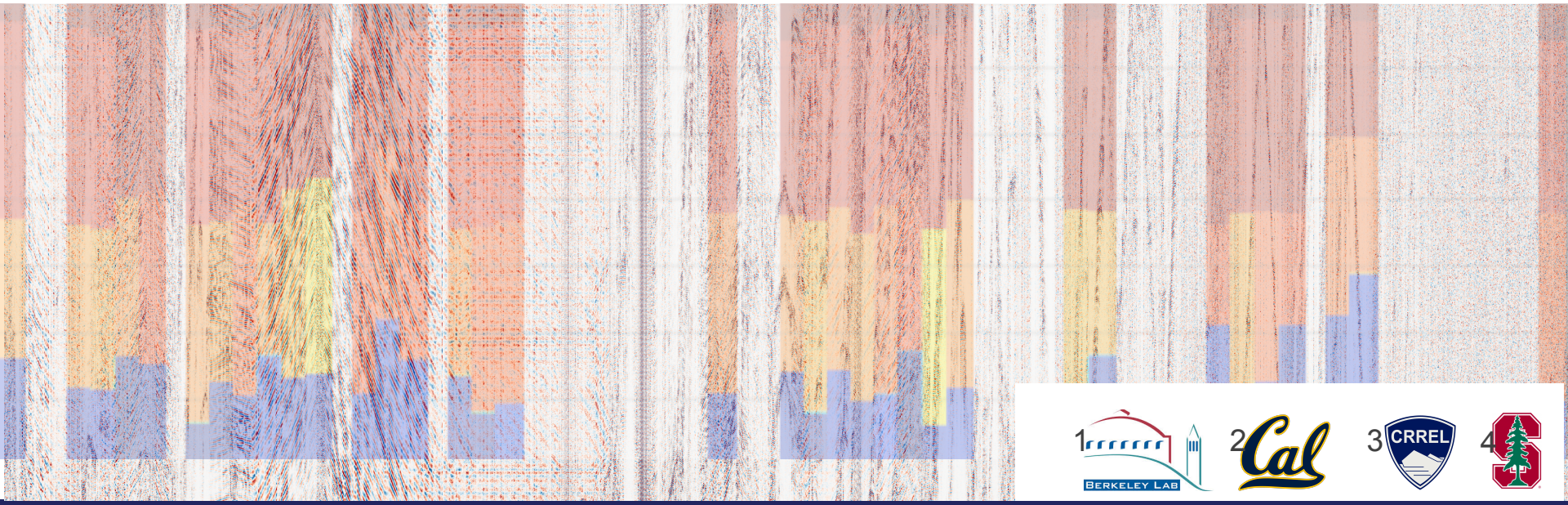
EARTH & ENVIRONMENTAL SCIENCES

BERKELEY LAB
Lawrence Berkeley National Laboratory

Dark Fiber For Soil, Water, and Earthquakes : The FOSSA Experiment

FIBER
OPTIC
SEISMIC
SUPER
ARRAY



1 BERKELEY LAB 2 Cal 3 CRREL 4

Lawrence Berkeley National Laboratory

EGD/EESA

Jonathan Ajo-Franklin

Tom Daley

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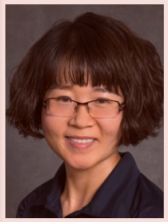
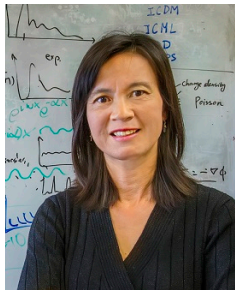
Now at FEASIBLE


Shan Dou

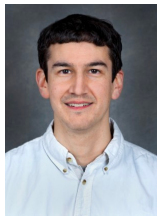

Xiaoye (Sherry) Li

Berkeley UNIVERSITY OF CALIFORNIA

(& EGD/EESA)

Nate Lindsey

ESnet ENERGY SCIENCES NETWORK


Chris Tracy

Inder Monga

On earlier SERDP project ….

Eileen Martin

Anna Wagner

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CenturyLink/Level3
Sebastiano Foti
Horst Rademacher (UCB, BSL)

A Story In Several Parts

The Need :
Gaps in Sensing Networks: Examples in Seismology and Hydrogeology

The Technology :
Distributed Acoustic Sensing

The Resource :
Dark Fiber and ESnet's Dark Fiber Testbed

The Experiment :
The FOSSA Deployment – Sacramento Basin

The Results (Preliminary):
- Ambient Noise Surface Wave Analysis for Near-Surface Structure
- Observations of Regional and Teleseismic Events

Next Steps & Challenges :

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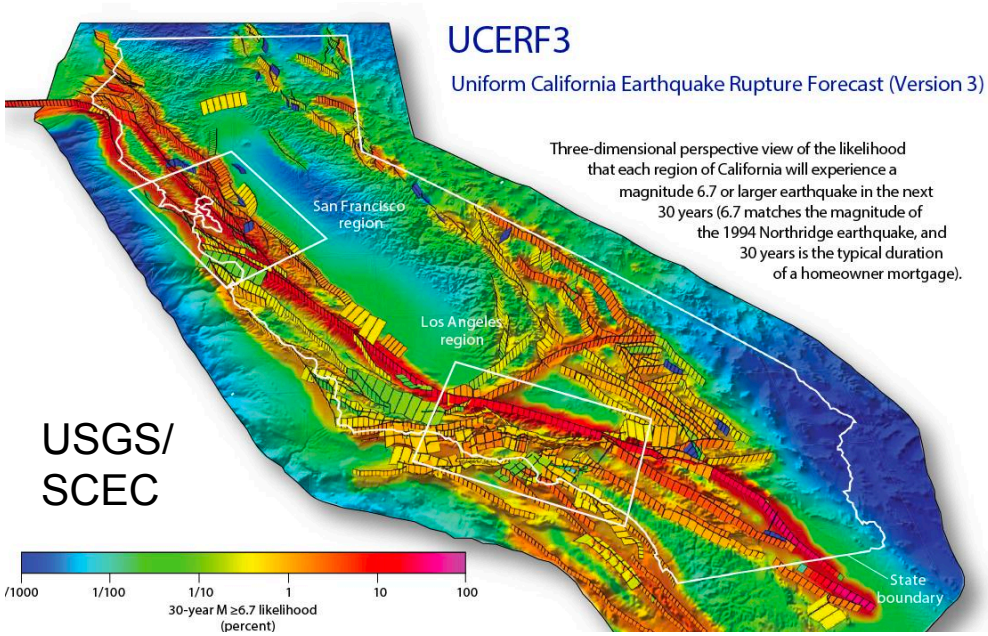
Two Challenges for California : Earthquakes & Water

Motivation : Two long-term challenges for California are

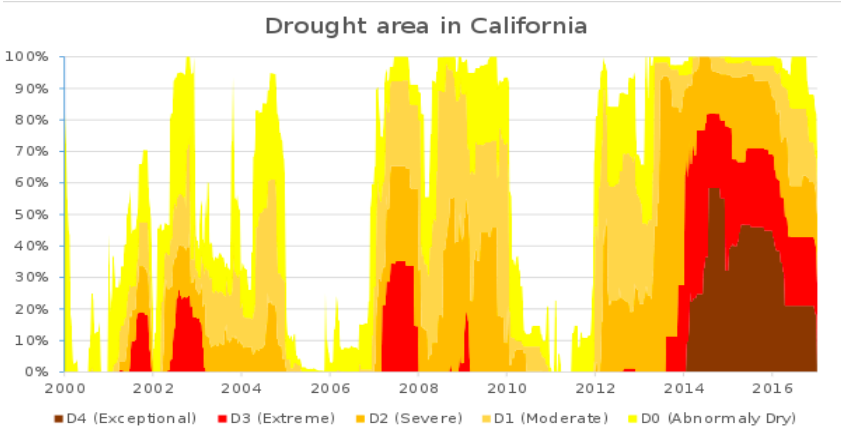
- Management of water resources in a changing climate
- Characterizing/understanding/mitigating natural seismicity.

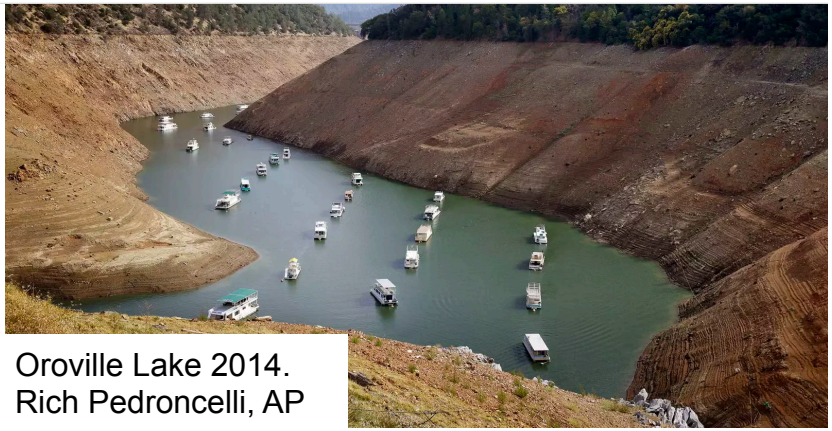
Progress on both fronts are enabled by new approaches to ***sensing*** − need to provide

- Comprehensive approaches to groundwater process monitoring
- Networks for monitoring EQ ground motion, small events, and characterize soil conditions



USGS/ SCEC





Oroville Lake 2014.
Rich Pedroncelli, AP

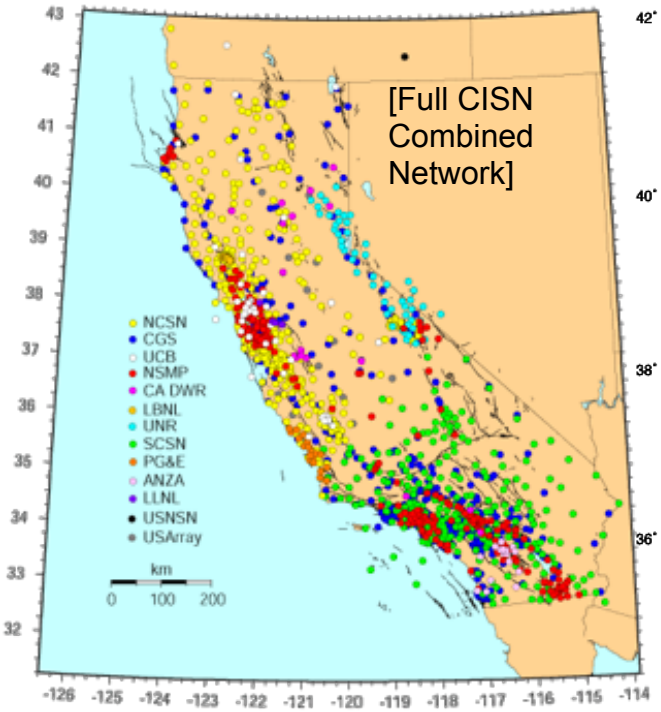
The Tyranny of **Sparse** Measurements : Part 1

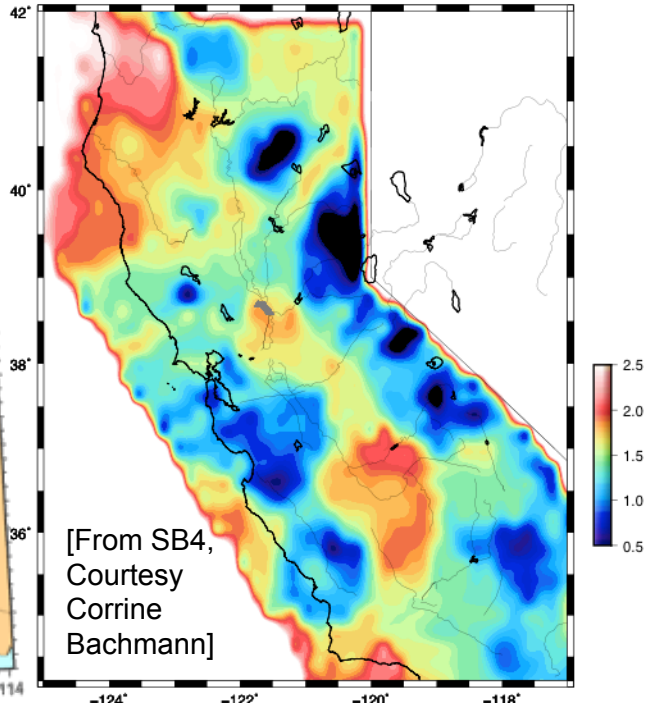
- *Despite much effort*, CA's seismic network still has significant gaps
- Stations are clustered in regions of historical tectonic activity and hard rock.
- Poor coverage in basins (Central Valley), sparsely populated regions (Modoc, west deserts), and offshore.
- **Result** : many regions with very high minimum detectable even thresholds (> M2!).

Implications :

- Difficult to detect *induced seismicity* related to O&G operations.
- Difficult to detect small (put potentially important) events on near-offshore faults.
- And CA is likely the best-instrumented state in the US

Solutions?



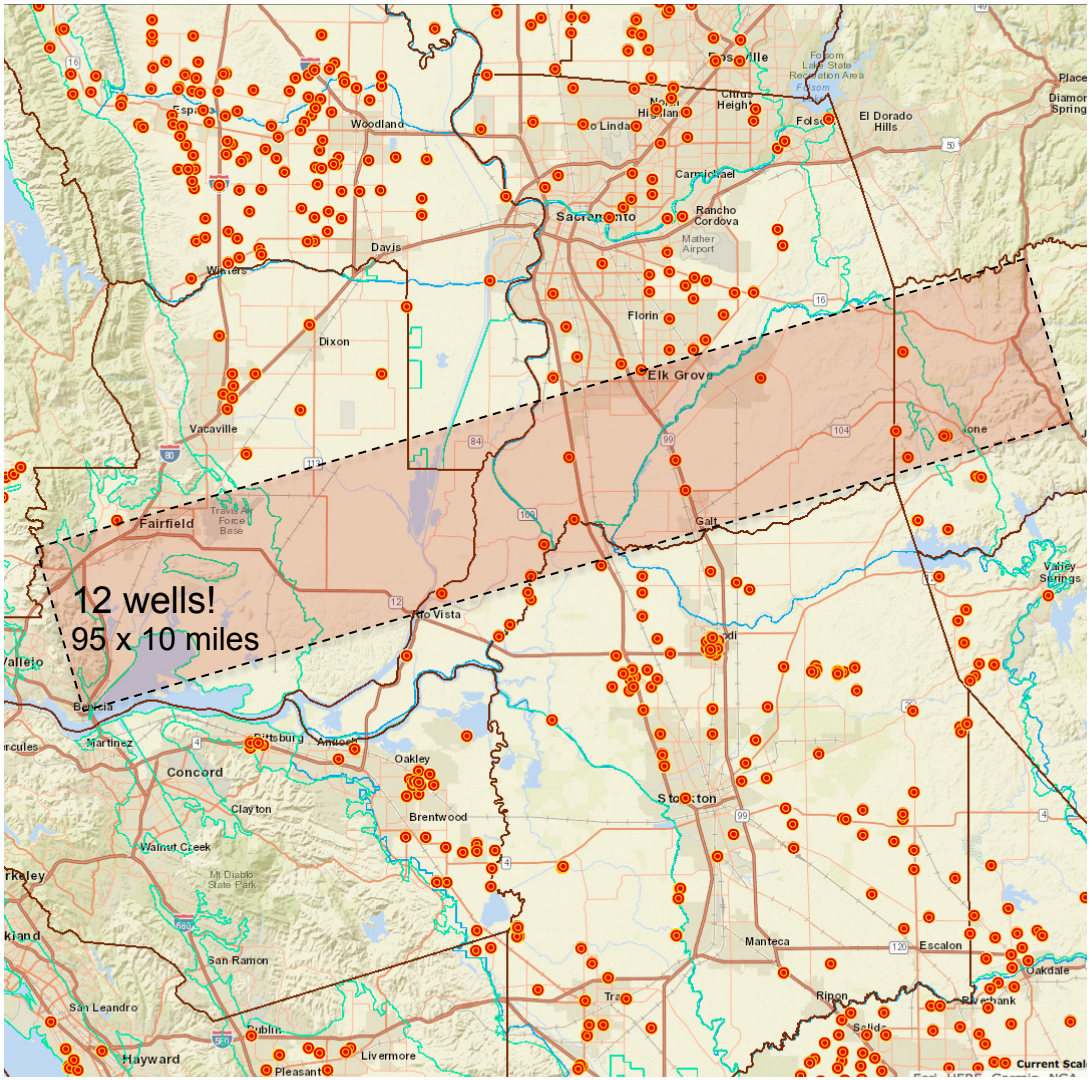


The Tyranny of **Sparse** Measurements : Part 2

- Hydrological and environmental monitoring networks have similar limitations.
- Large gaps even in regions with heavy groundwater extraction.
- Many wells are sparsely (and irregularly) sampled in time.
- Additionally, measurements have significant operator error and require extensive curation.

Result :

- Even in heavily monitored basin, water table depths and aquifer state are poorly resolved in space and time.
- NOTE : similar limits for many geotechnical parameters (Vs30) and soil properties.



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Distributed Fiber-Optic Sensing : A Tool For Continuous Monitoring of Infrastructure

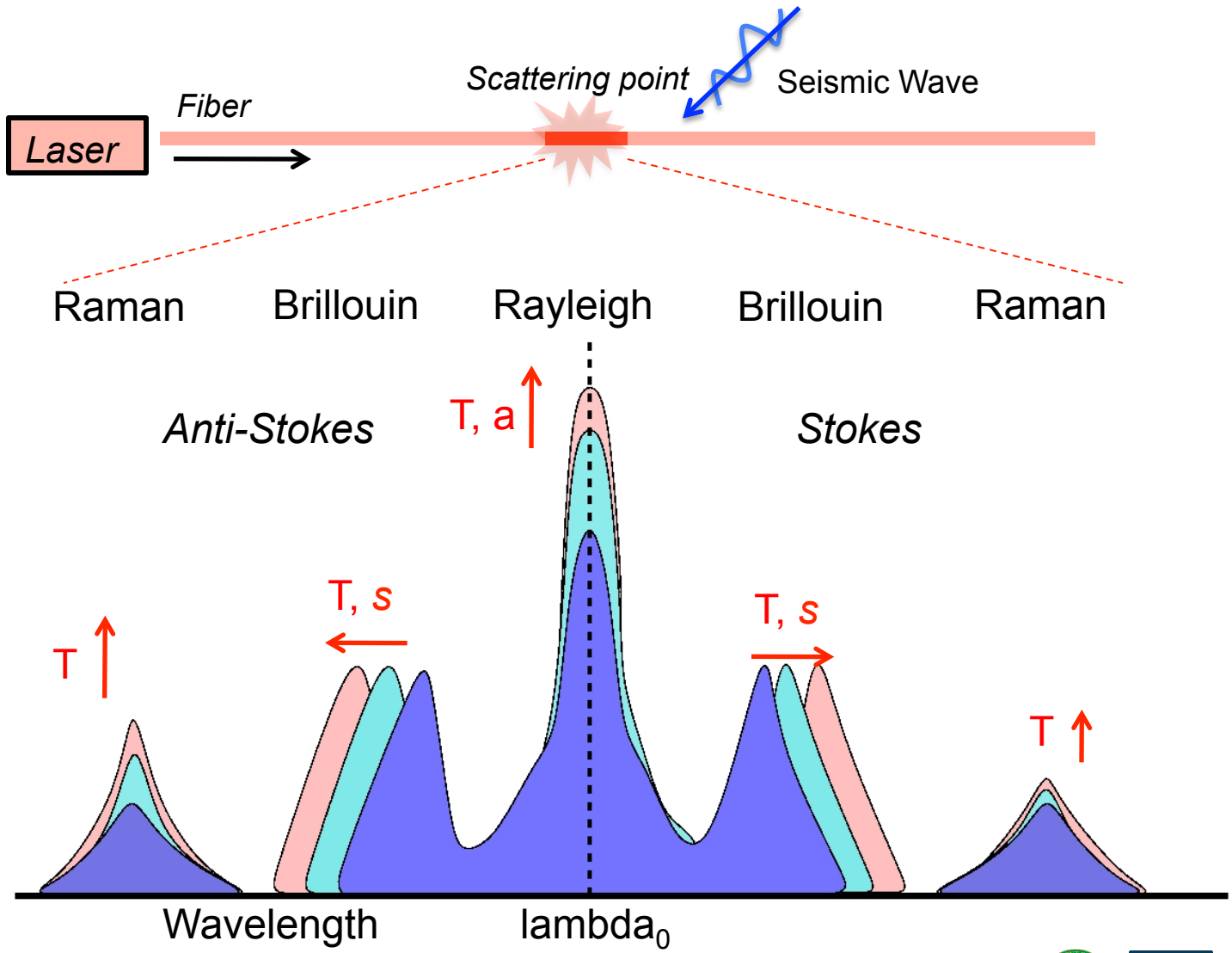
Concept :
Measure scattering from every point along a continuous fiber

Changes in fiber environment (T, strain, vibration) alter scattering.

Raman : (DTS)
Strong T dependence

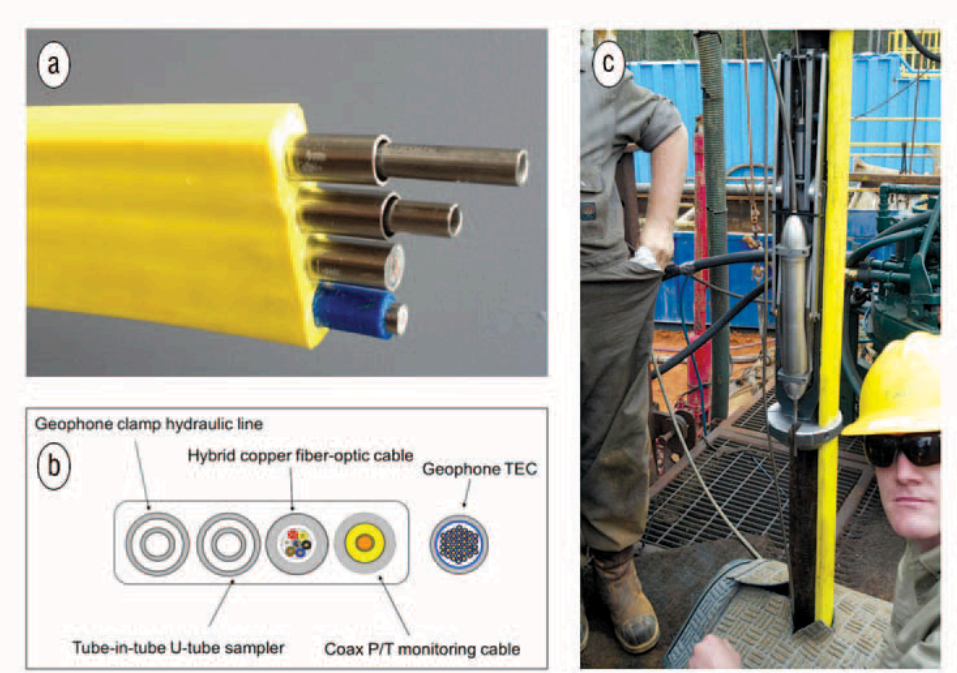
Brillouin : (DTS,DSS)
Wavelength shift during strain and T variation

Rayleigh : (DAS)
Amplitude variation induced by vibration, also T.

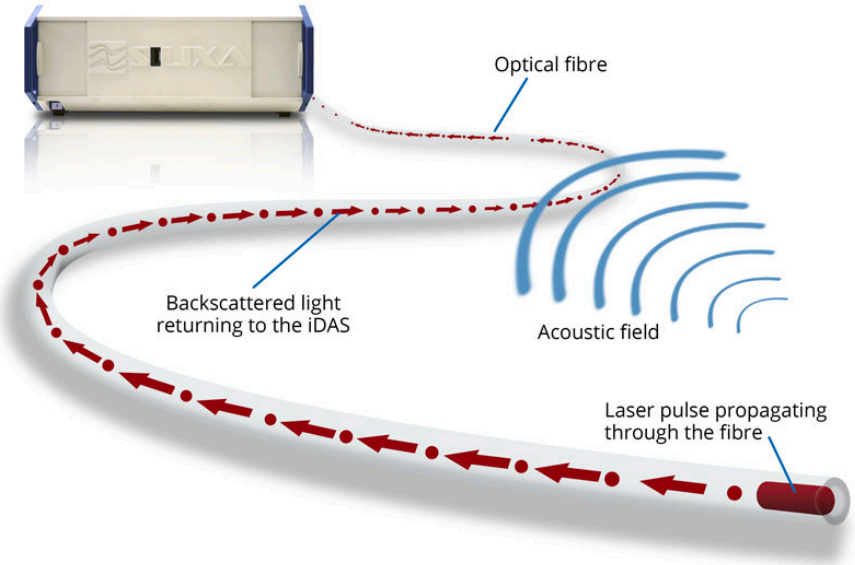


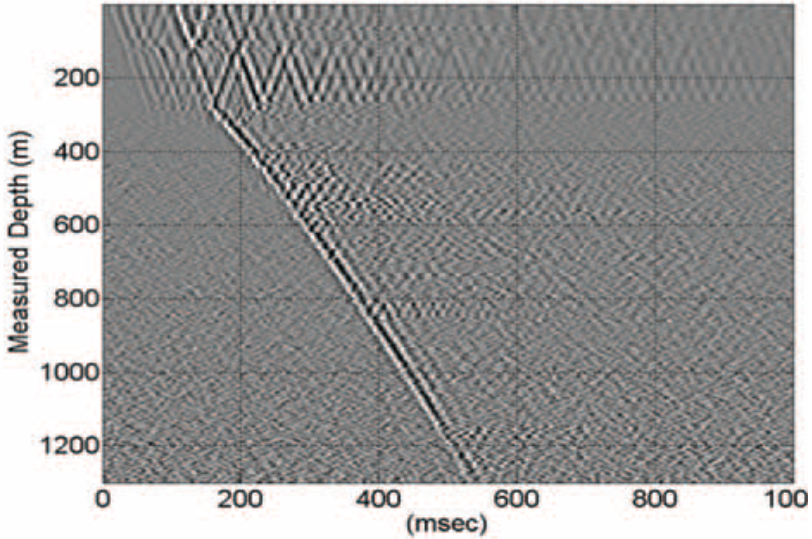
Distributed Acoustic Sensing : A Platform For Seismic Monitoring

- **Distributed Acoustic Sensing [DAS]** is a rapidly advancing approach for measuring the seismic wavefield using commercial fibers (SM, telecom)
- **Recent** : S/N became sufficient for seismology around 2011. Our work started ~2012/13 out of CO_2 GCS program (borehole applications)
- **Large N** : Easy to deploy in wells, behind casing, 1000s to 100,000s of channels available (big data) over 10+ km (biggest current use is VSP)
- *Very low cost per "sensor"* : $/ft for cable
- *Rugged* : handles high/low T, high pressures.



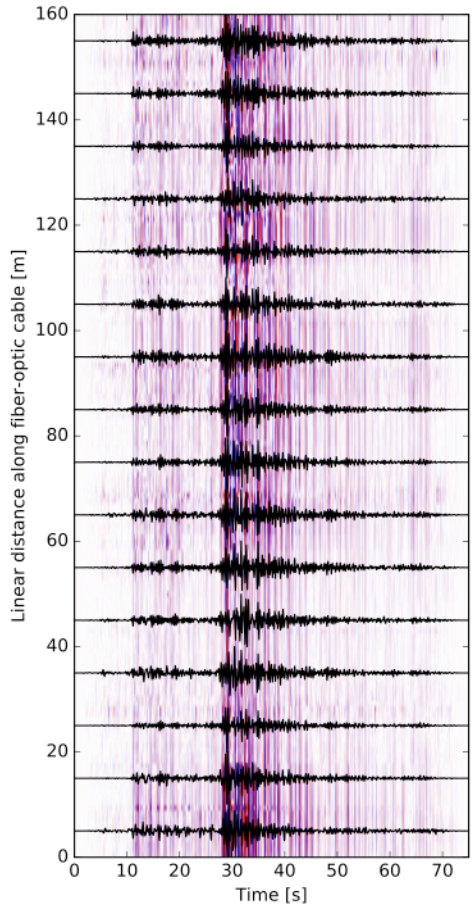
Daley et. al. 2016 (Geop Prosp.), Daley et.al. 2013, (TLE)

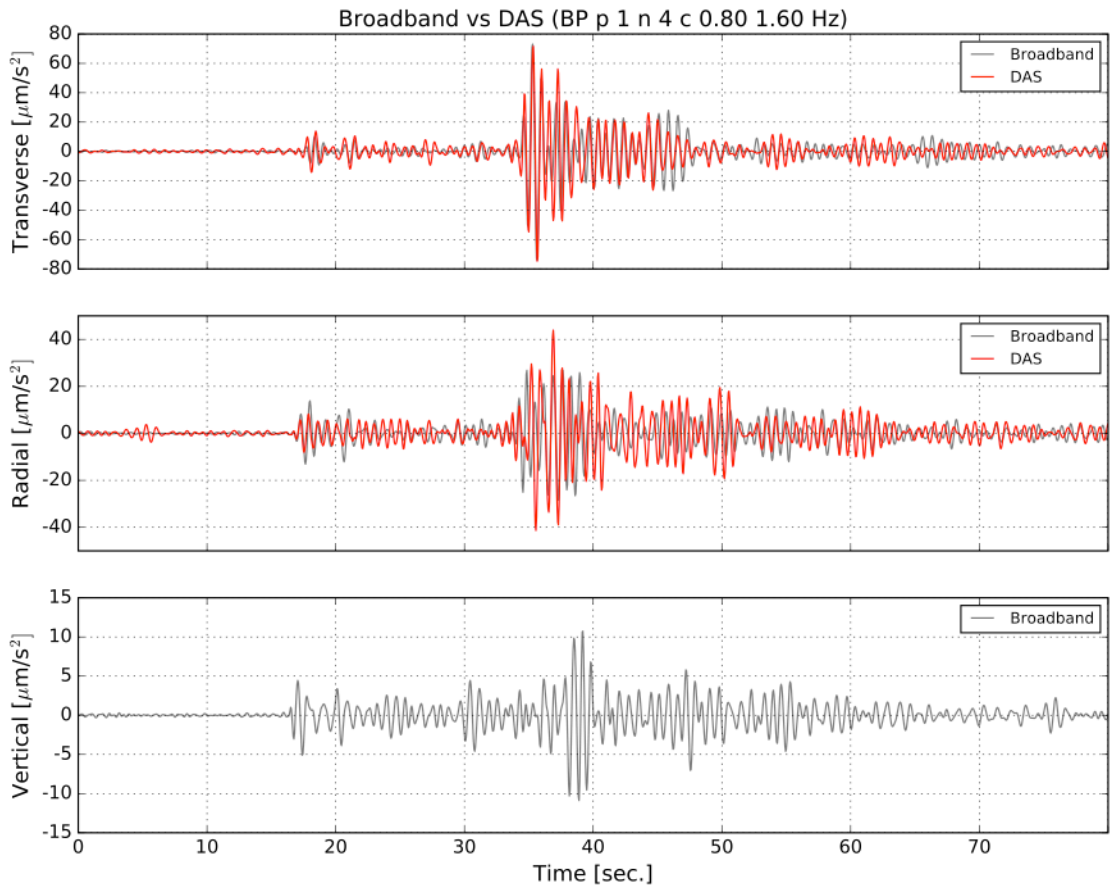




Comparable to Seismographs? Getting Closer

- Comparison between trenched (30 cm) fiber and Trillium PC120s (Lindsey et al. 2017)
- Regional M3.8 recorded in Fairbanks AK.
- After rotation and conversion to particle velocity, reasonable comparison
- Much lower band (0.8-1.6 Hz) – some signal even lower.





Lindsey et al. 2017

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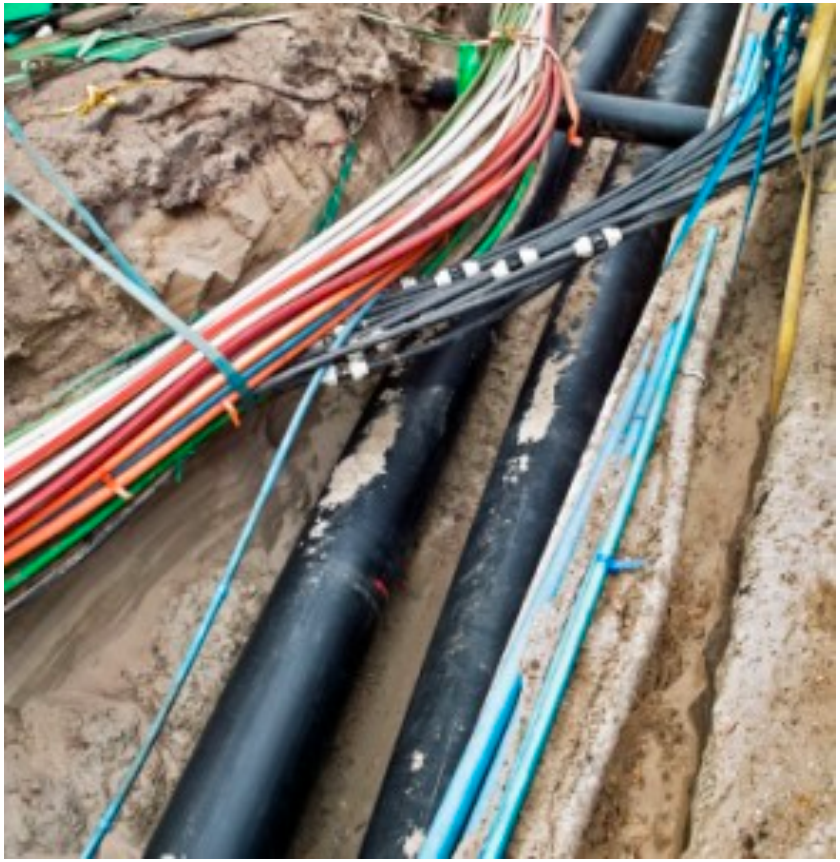
What is Dark Fiber?

- **Dark Fiber** = fiber installed for telecommunication purposes but not currently used (e.g. “lit”) and lacking required hardware. ***Can we use it for sensing applications?***

- During the 1st dot-com boom, cheap capital led to over-supply of installed fiber, subsequent improvements in bandwidth resulted in an even larger set of unused fiber strands.

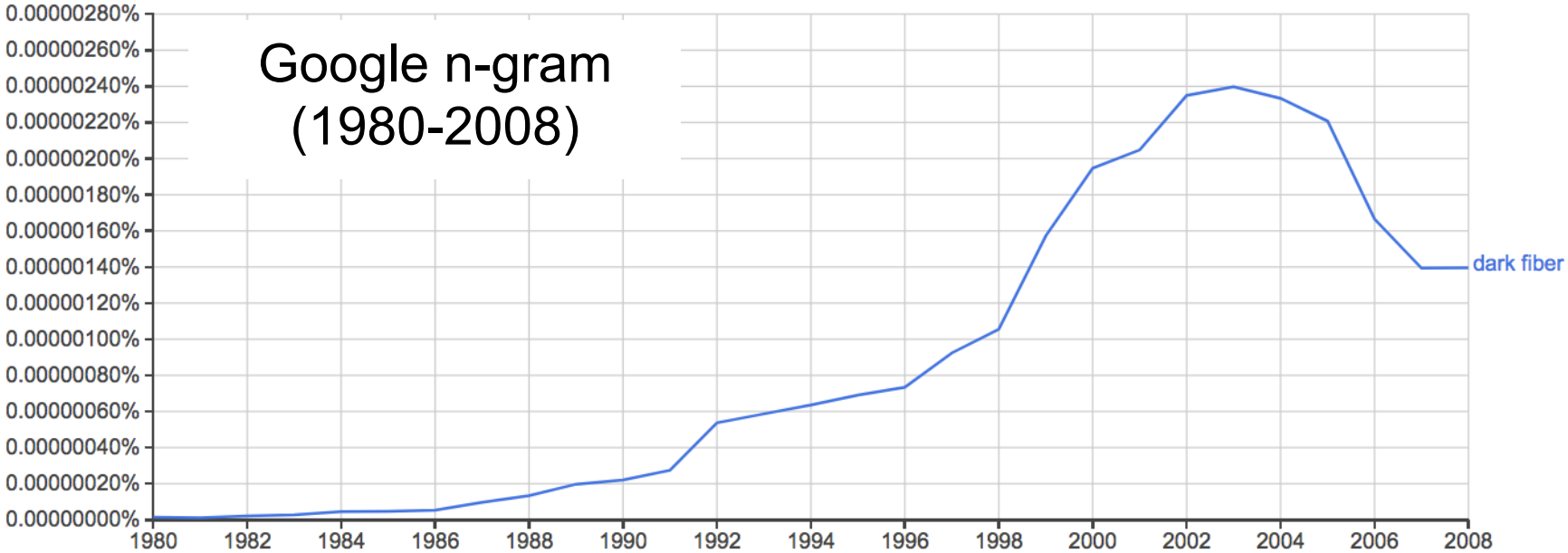
- Only ~10% of fiber install cost is the physical cost of the fiber/packaging. The rest is trenching, permitting etc.

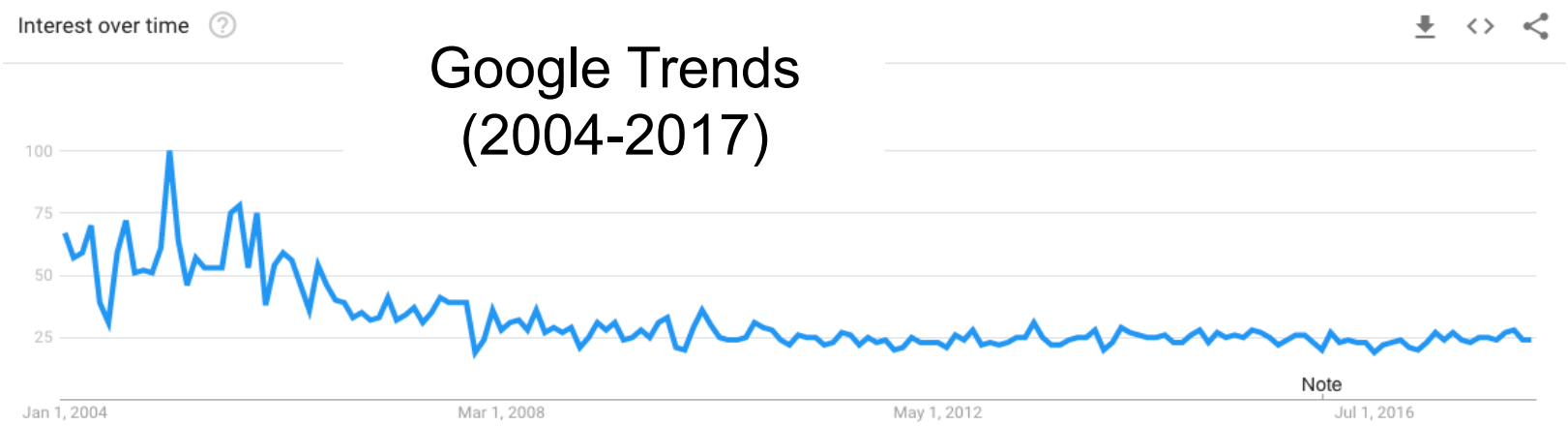
- Dark fiber can now be leased, bought, from providers − if not used, a stranded asset of decreasing value. Low cost links (down to $200/linear mile) in some corridors.



“Popularity” of Dark Fiber over time ….

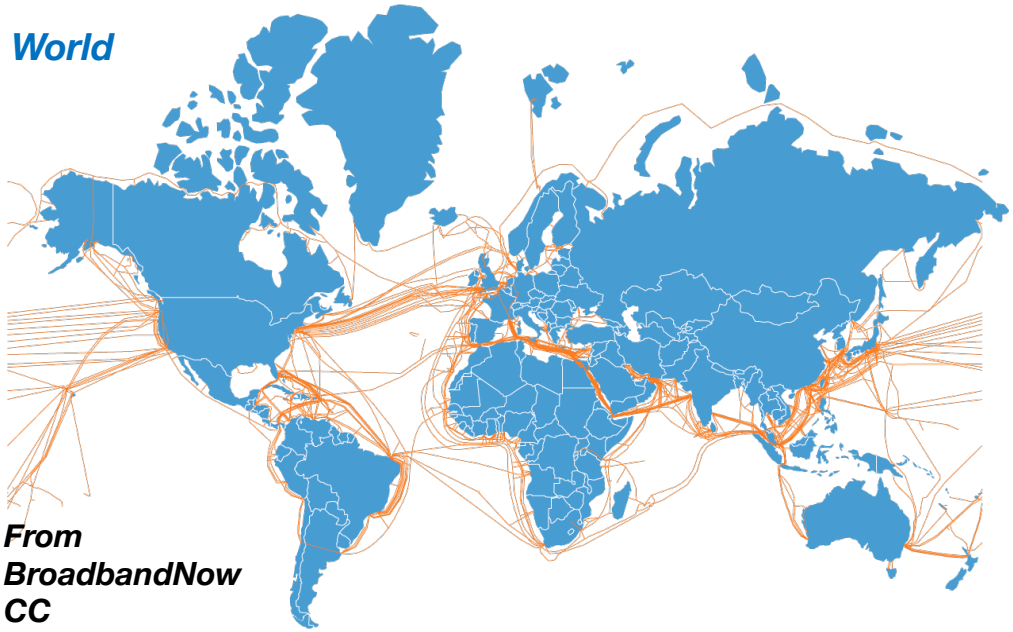
Peak in the post dot-com 1 period, going down since…..





Where is Dark Fiber? Everywhere

- Dark Fiber is everywhere! But also poorly mapped.
- No reliable global estimates but well over 10M km of linear fibers.
- Transoceanic : a zone without traditional sensors globally [note: not many “dark” links in operative oceanic cables].
- Urban, rural, and all the spaces in between
- Biggest strength : global reach + density
- Challenges : heterogeneous installation methodologies, access



From BroadbandNow CC

Zayo’s SF Bay Metro Dark Fiber Resources.

From Site Selection magazine, March 2015

ESnet & the Dark Fiber Testbed

- **Challenge :** While Dark Fiber is ubiquitous, not always easy to get access and information required for sensing tests!

- ESnet, an LBNL user facility which manages high performance fiber communication links between major DOE user facilities (e.g. synchrotrons, neutron sources) and super-computing centers (e.g. NERSC).

- **Solution :** ESnet's Dark Fiber Testbed − developed to allow testing of long-distance fiber links. National extent but not fully connected. We are exploiting CA network within the testbed.

LBNL Long Haul Dark Fiber Routes
12,924 miles

BayExpres Metro Fibers: 432 miles
ChiExpress Metro Fibers: 167 miles
NYExpress Metro Fibers: 6 miles

Western US ESnet Dark Fiber Routes

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FOSSA : Fiber Optic Seismic Super Array

What?

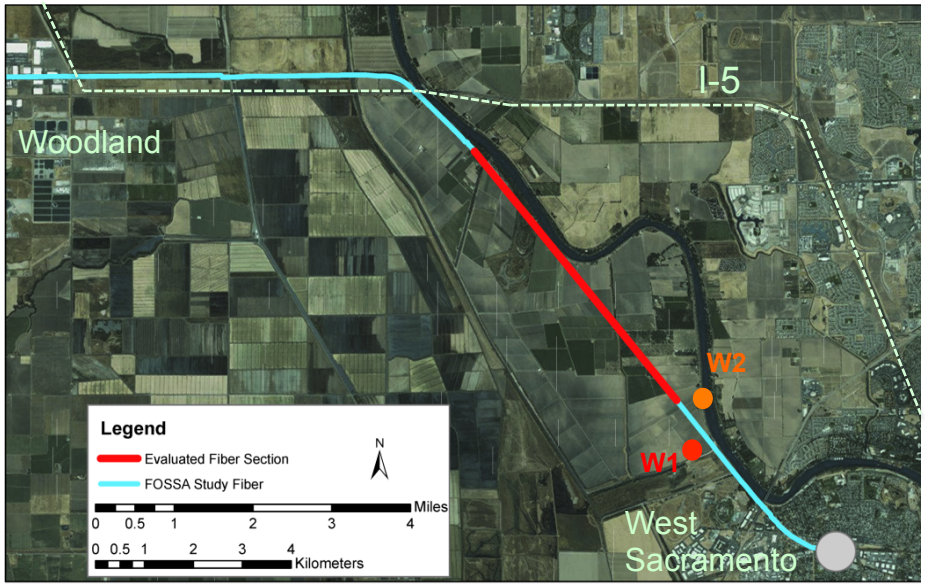
- First test of Dark Fiber imaging concept on true vintage
- Large N (12500 channels, 25 km) and growing T (7 months continuous record)

Why?

- Unknown coupling – what can we retrieve? Effect of old fiber, telecom install etc
- Can ambient noise field (infrastructure) be used to monitor near-surface properties?
- Can EQs (regional/teleseismic) be recovered in the noisy environment using DAS?

End Question : How can Dark Fiber be utilized for observational seismology?

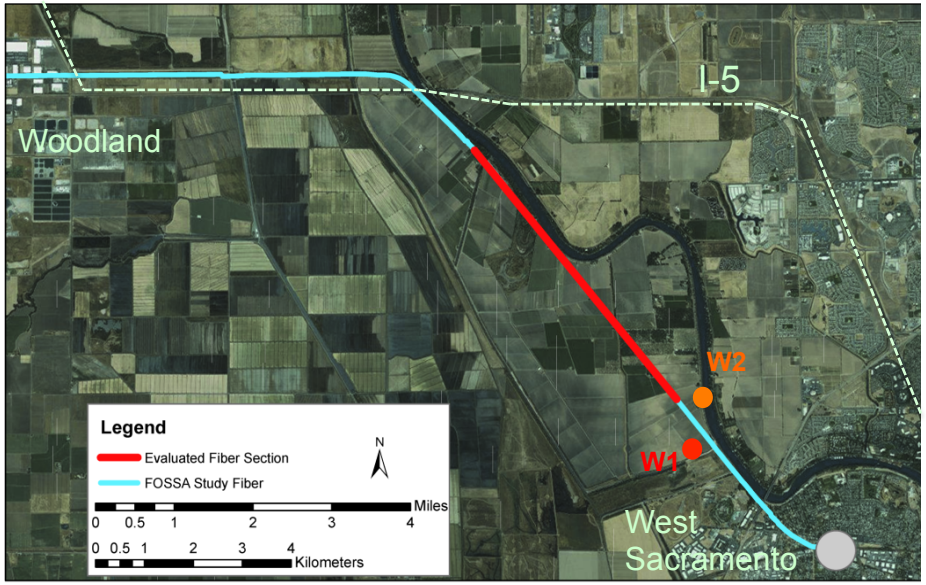
FIBER
OPTIC
SEISMIC
SUPER
ARRAY

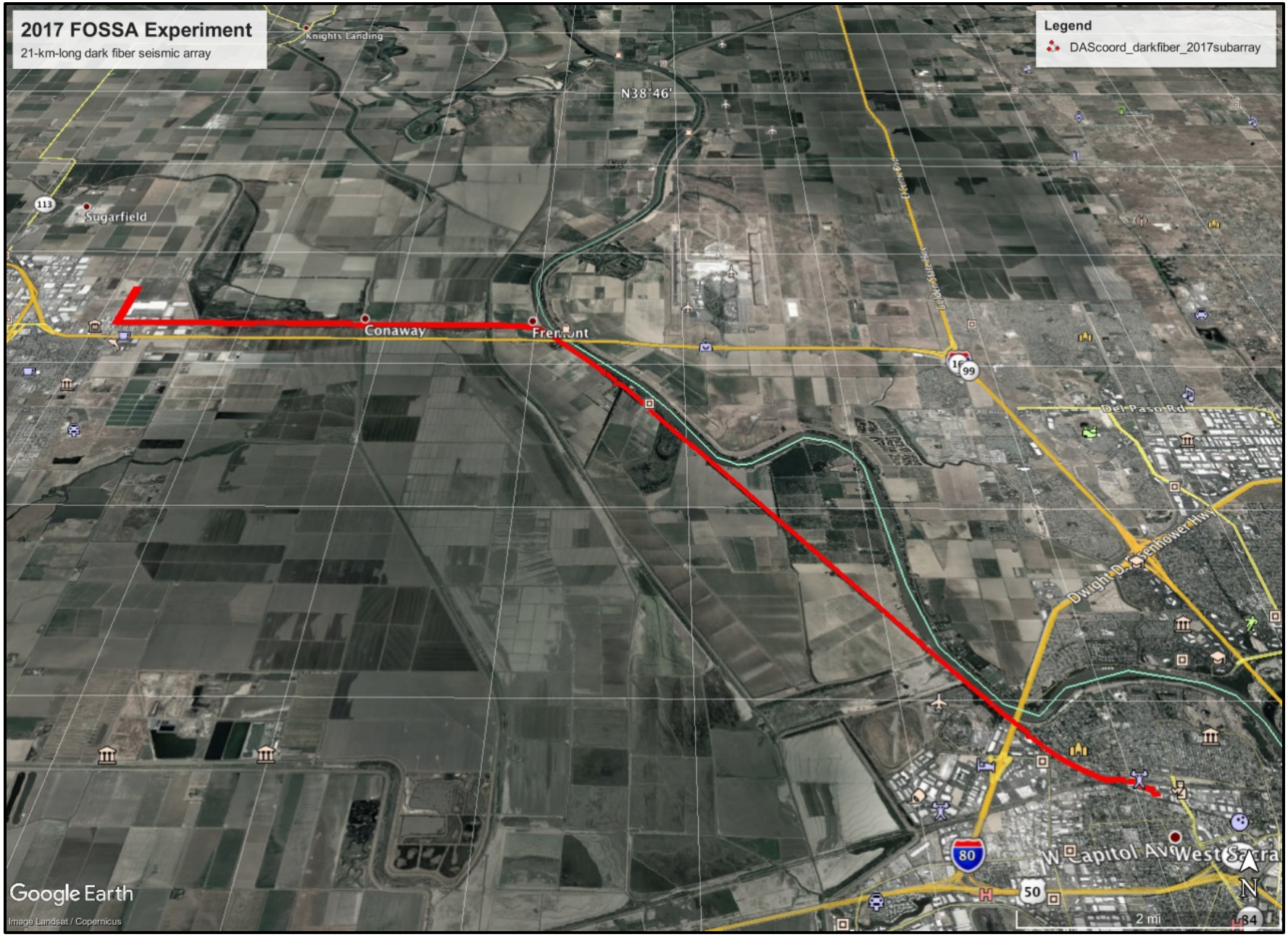


FOSSA : Why West Sacramento?

- Access to ESnet Dark Fiber Testbed (not connected everywhere)
- Physically close enough for HD exchange (dealing with the data “fire hose”)
- PoP large enough and sufficiently secure to house iDAS (not all are….)
- In an area with active hydrologic variations zones with pumping and recharge.
- In a “gap” in the network – high minimum “M”.
- Near zones of significant dry gas production and waste water re-injection
- Good subsurface constraints from shallow/deep wells.

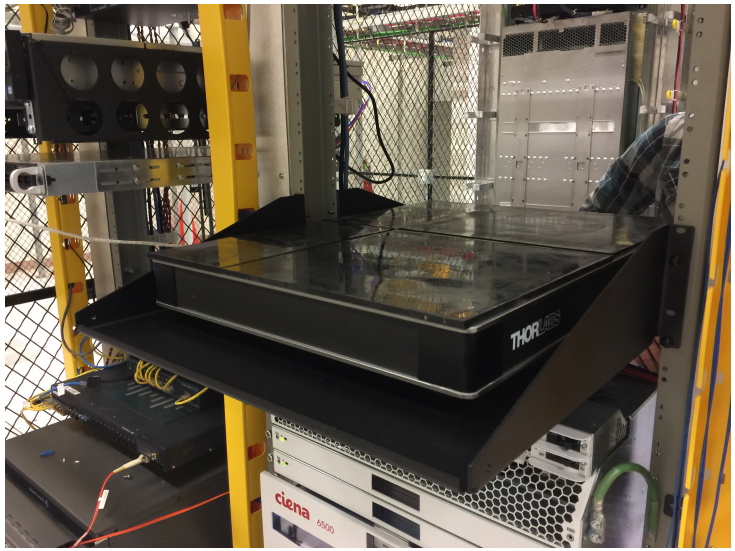
FIBER
OPTIC
SEISMIC
SUPER
ARRAY

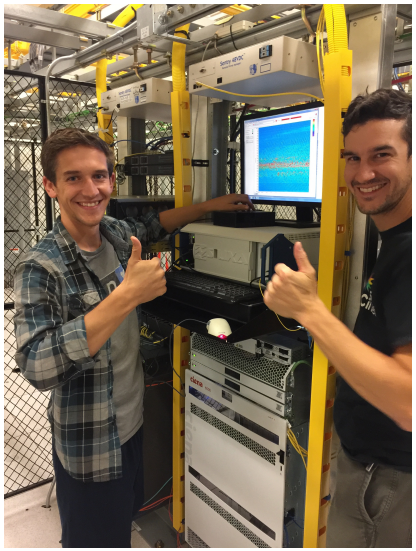



2017 FOSSA Experiment
21-km-long dark fiber seismic array
Legend
DAScoord_darkfiber_2017subarray
Knights Landing
N38°46'
Sugarfield
Conaway
Fremont
Del Paso Rd
Dwight D. Eisenhower Hwy
W Capitol Av
West Sacra
Google Earth
Image Landsat / Copernicus
2 mi

PoP (Point-of-Presence) DAS Installation

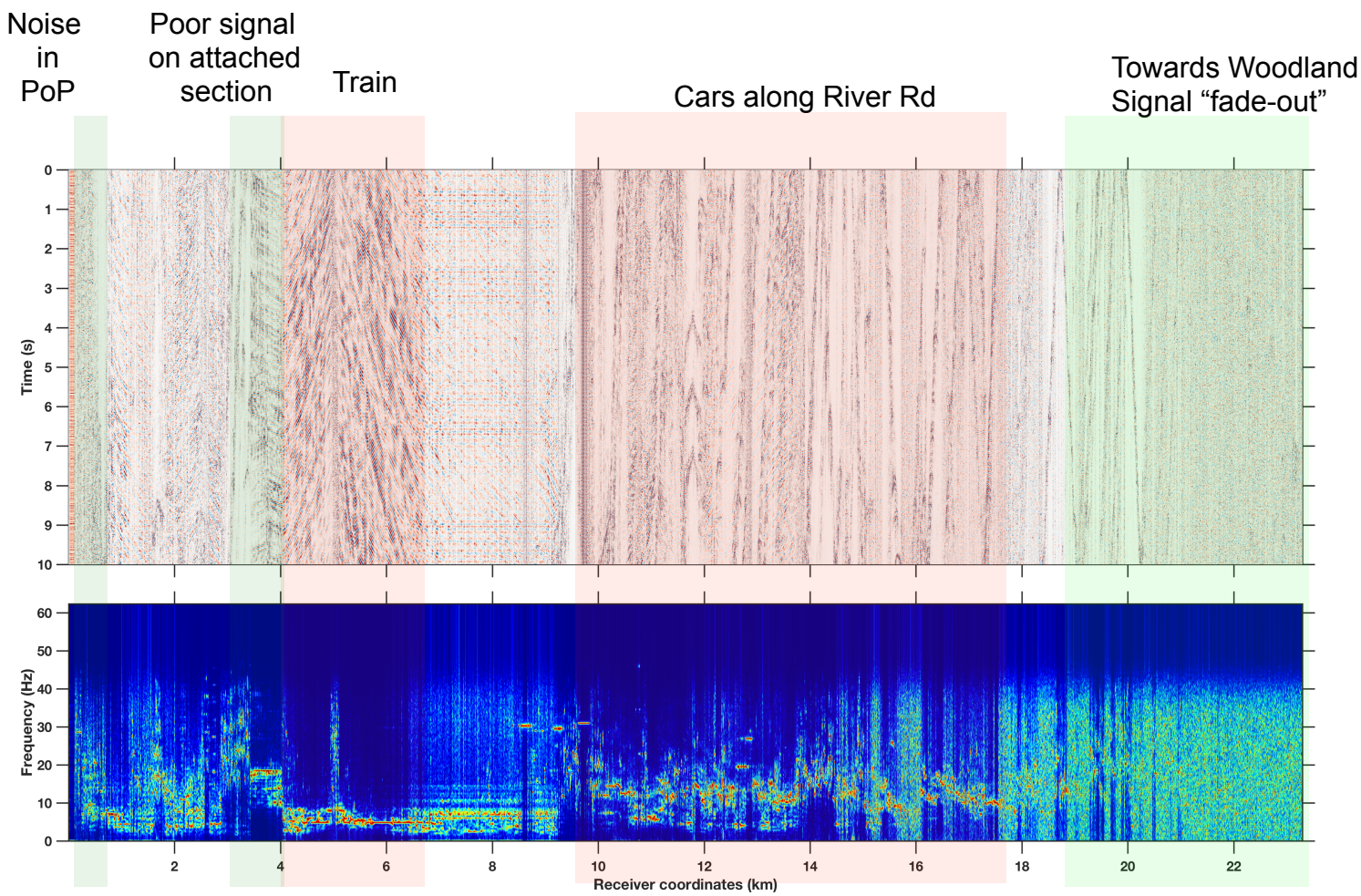
- Where are fibers connected to? PoPs : cages for individual system access control
- Interrogator installed at West Sacramento PoP, vendor terminated fiber to cage
- **Acquisition details** :
  - Silixa iDAS v.2 interrogator, installed July 2017-Mar. 2018
  - Dedicated dark fiber strand (ESnet/CenturyLink) terminated in PoP cage
  - Installed on vibration isolated (ThorLabs)
  - Recording continuously at 500 hz, 2 m spatial sampling, 10 m gauge length
  - 25 km of fiber sampled (12500 channels)
  - Data recorded on 8 TB external drives, swapped weekly and copied at LBNL





“Noise” in Space & Time

- Example to the left shows 10 s unfiltered record on 12000 channels.
- Majority of noise is infrastructure use related (cars/trains) in the 2-30 Hz band.
- Freight train parallel to fiber near river is strongest noise source, visible 1 km out.
- Some sections with “reverberation” correspond to suspended pipe crossing a bridge
- Fade-out visible as scattered light drops below optical budget.



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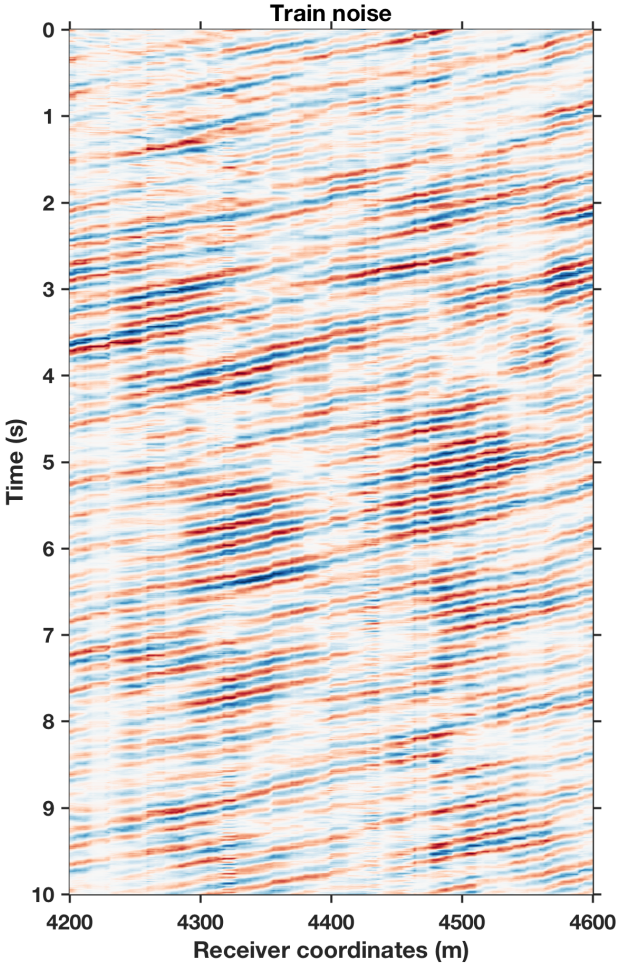
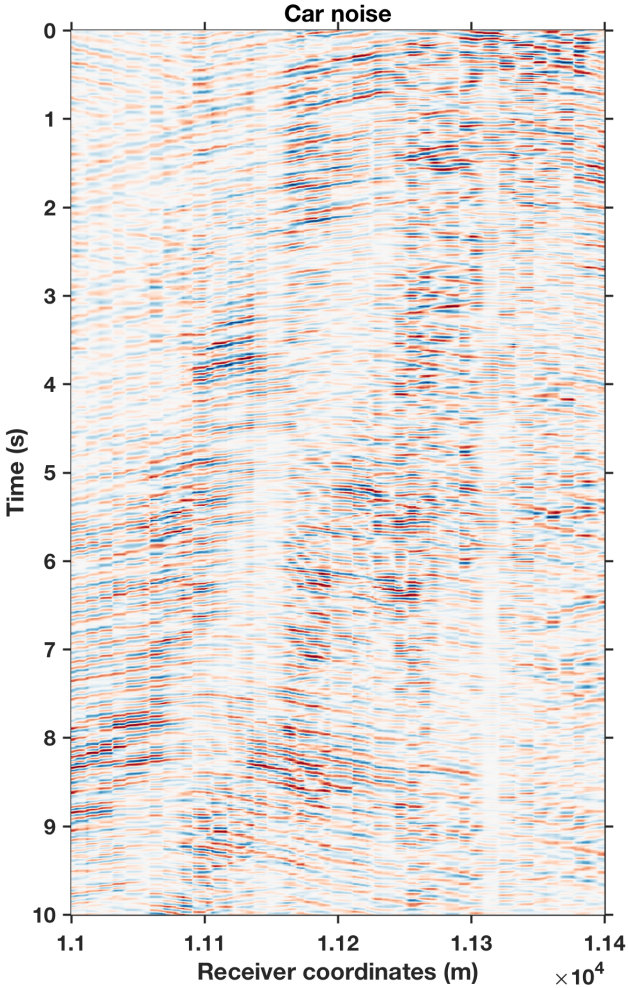


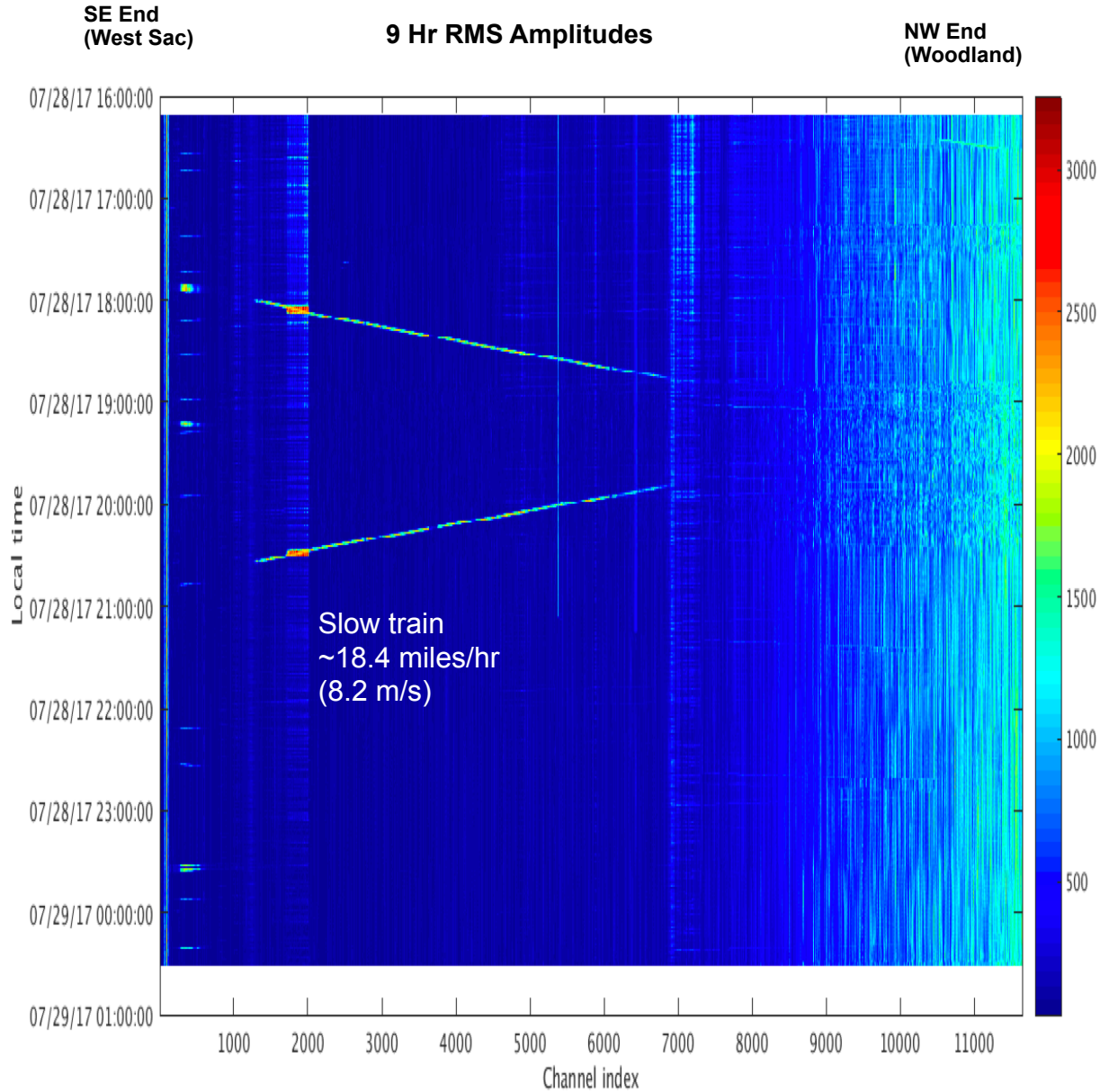


Examples :

Surface waves generated by vehicles …

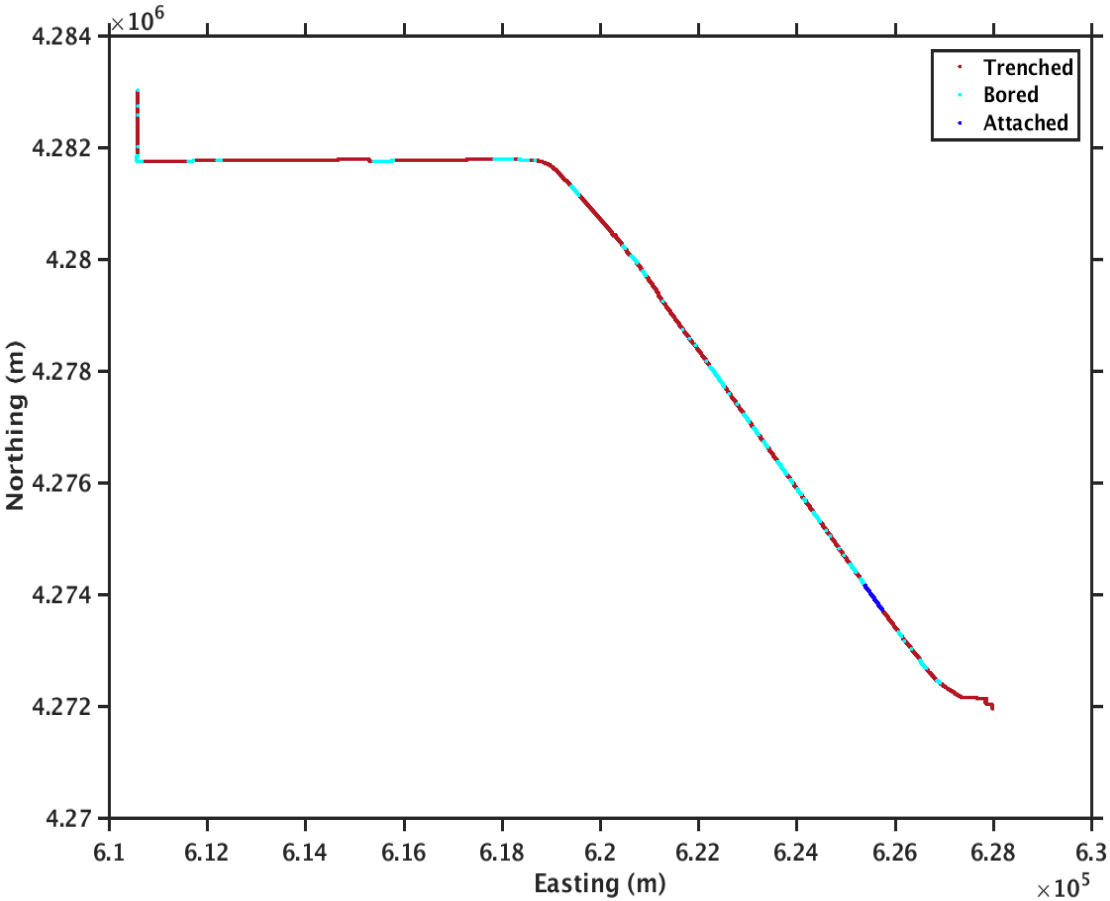
“Noise” in Space & Time

- Surface waves generated by trains are orders of magnitude larger than cars (not surprising)
- Train location/velocity can be easily tracked using DAS – freight runs are very slow, 10-20 mph
- Freight runs occur at irregular times, usually 2-4 runs/day



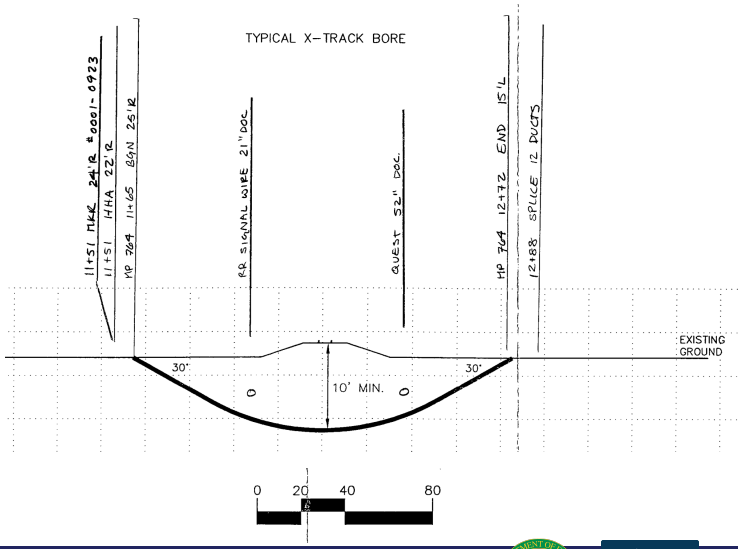
Different Installations?

- Mix of trenching (~60 cm), shallow horizontal bores, and bridge attached.
- Bore sections are short (10-50 m) and are usually used to navigate around infrastructure.



Impact on signal?

- Attached section unusable
- Bore/trench differences?
- On-going analysis effort



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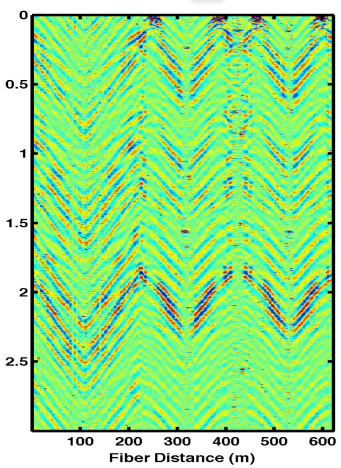
Concept : Turning Noise Into Soil Properties….

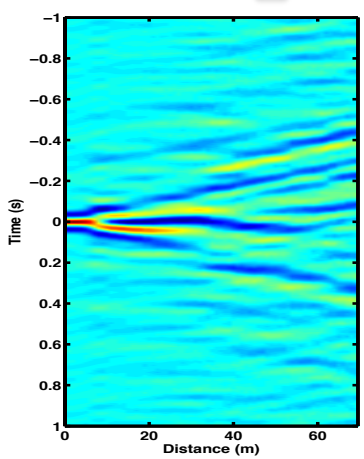
- Even with a dense network of sensors, we need a seismic source for imaging
- Source mobilization is expensive for infrastructure monitoring, also limits temporal resolution.

Solution : Use infrastructure noise (cars, trucks, trains) for seismic energy source!
How? : Some signal processing to turn random energy into something more ordered
Limits? : Limited by the bandwidth and energy of noise (can't get something for nothing).

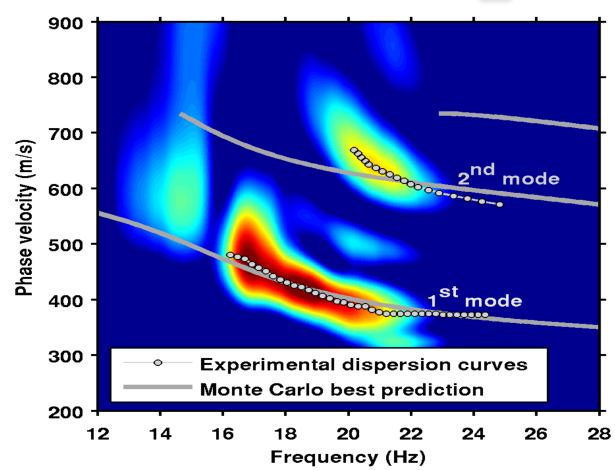
Pre-processing & Interferometry → **Dispersion Analysis** → **Surface Wave Inversion**



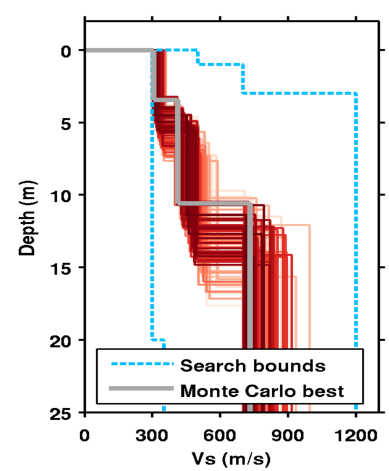
DAS Recorded Noise Gather



Interferometric Gather

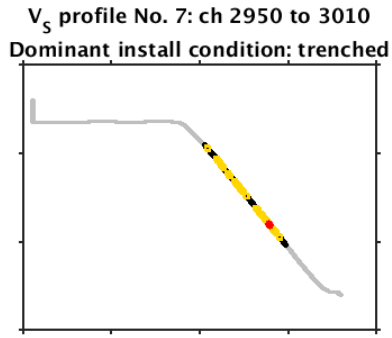


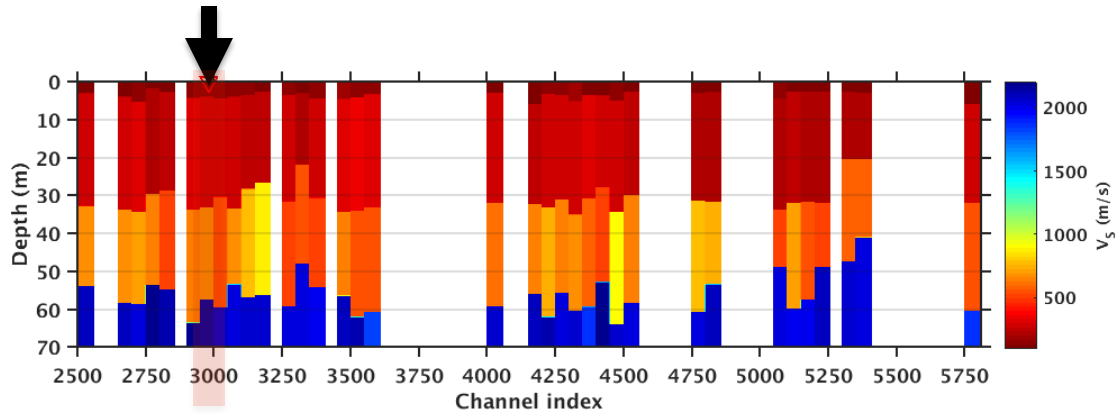
Dispersion Transform & Automatic Modal Picks



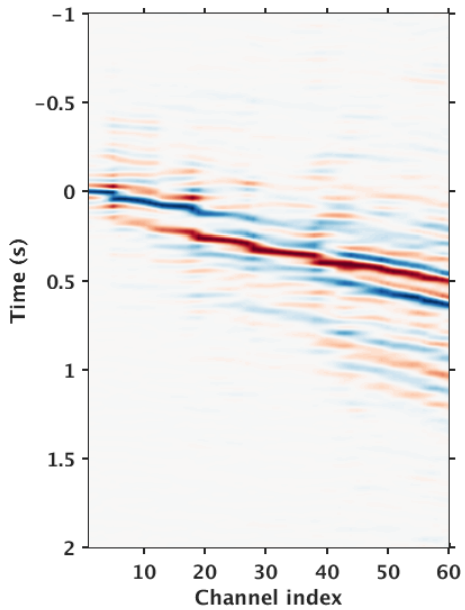
V_s Model [Soil Properties]

FOSSA Example : One Location

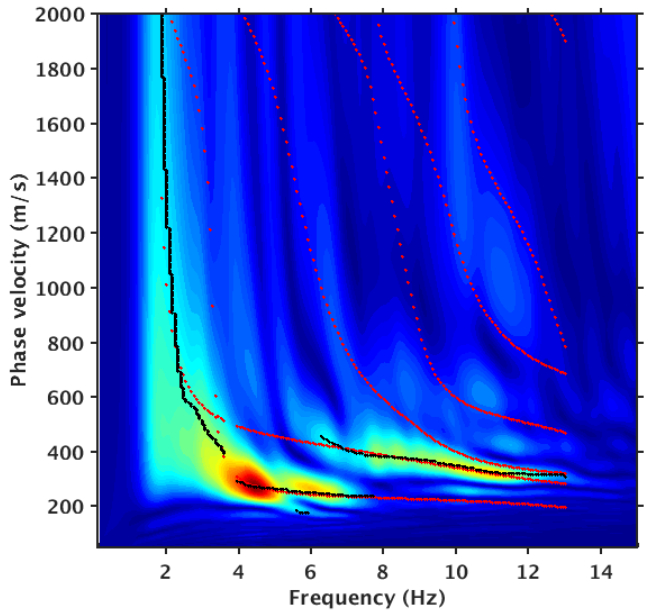




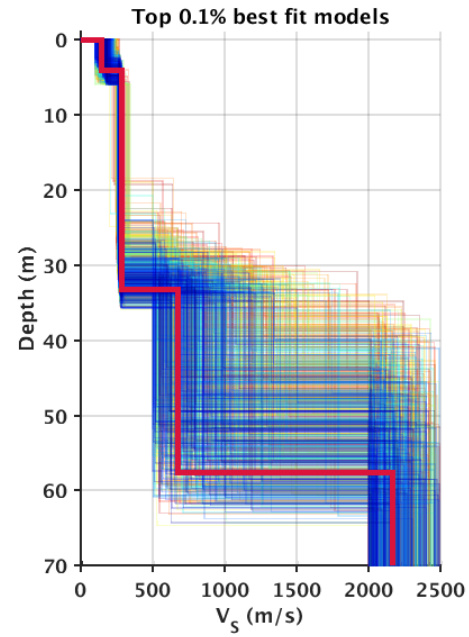
Interferometric Gather



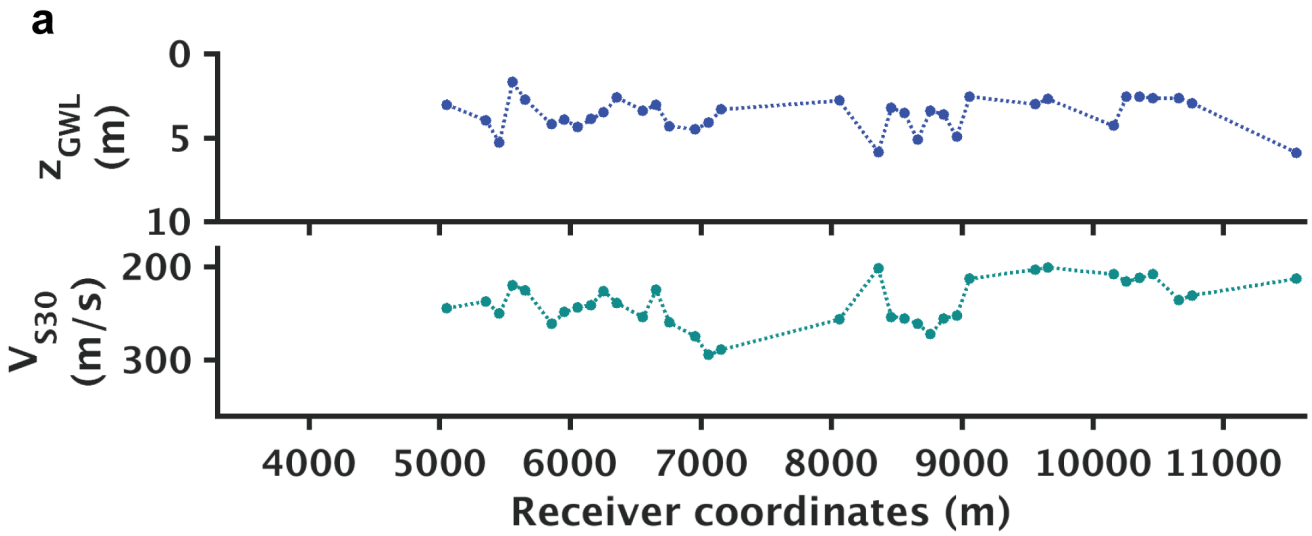
Dispersion Map



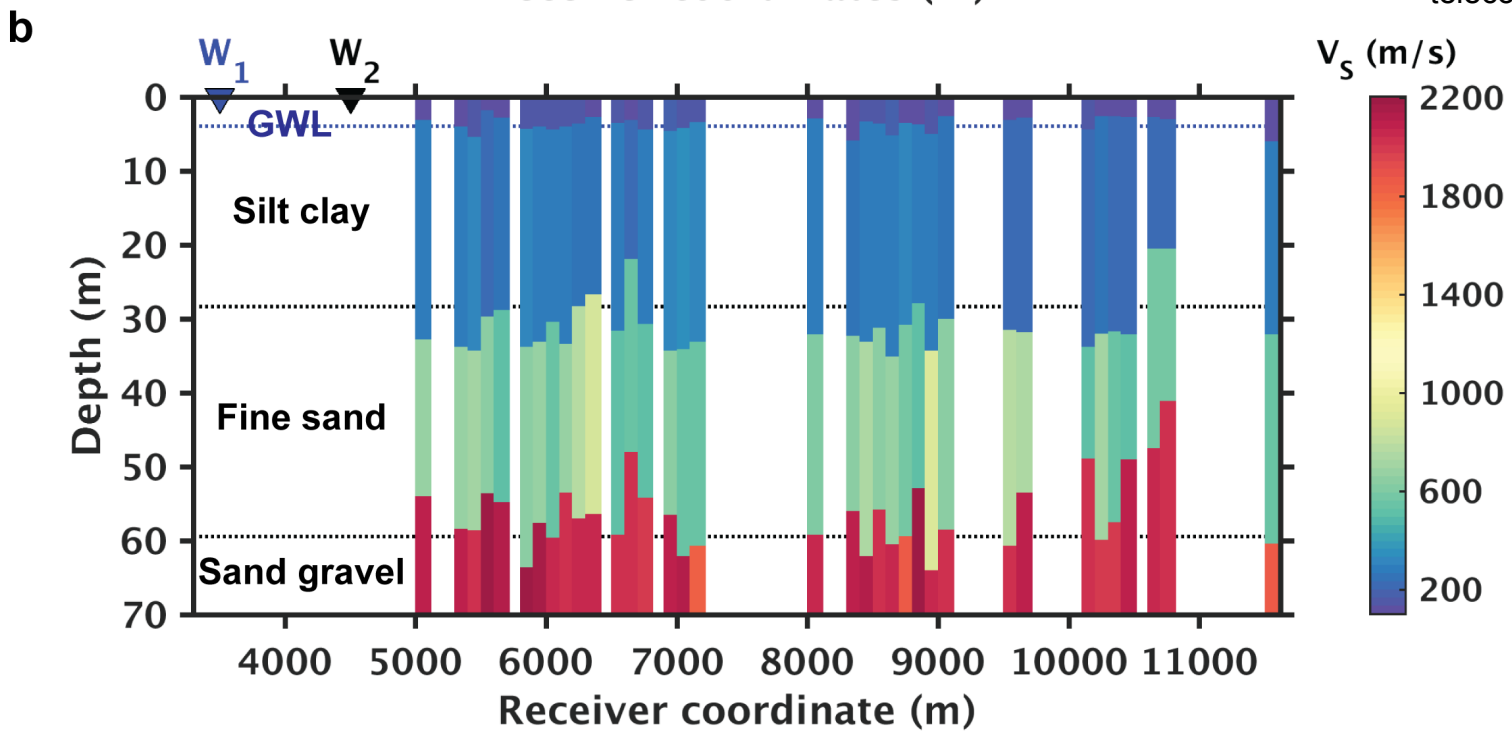
Surface Wave Inversion



Shallow Structure at 10 km Scale



- Example of a 6 km of inverted data.
- Confirmed top interface against CASGEM water table monitoring well (rock physics?)
- Silt/Sand/gravel transitions confirmed against driller's logs.
- First example of large scale imaging/monitoring using telecom infrastructure.



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- Observations of Regional and Teleseismic Events

Next Steps & Challenges :

DAS for EQ Seismology?

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL075722

Key Points:
- Distributed acoustic sensing (DAS) transforms fiber optics into dense seismic arrays (1 sensor/meter) using laser scattering
- Earthquake observations indicate that DAS and seismometer sensitivity is similar at 0.8-1.6 Hz
- Fiber installed in telecommunication conduit shows sensitivity to propagating seismic waves

Supporting Information:
- Supporting Information S1

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natelindsey@berkeley.edu

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Fiber-Optic Network Observations of Earthquake Wavefields

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Abstract Our understanding of subsurface processes suffers from a profound observation bias: seismometers are sparse and clustered on continents. A new seismic recording approach, distributed acoustic sensing (DAS), transforms telecommunication fiber-optic cables into sensor arrays enabling meter-scale recording over tens of kilometers of linear fiber length. We analyze cataloged earthquake observations from three DAS arrays with different horizontal geometries to demonstrate some possibilities using this technology. In Fairbanks, Alaska, we find that stacking ground motion records along 20 m of fiber yield a waveform that shows a high degree of correlation in amplitude and phase with a colocated inertial seismometer record at 0.8–1.6 Hz. Using an L-shaped DAS array in Northern California, we record the nearly vertically incident arrival of an earthquake from The Geysers Geothermal Field and estimate its backazimuth and slowness via beamforming for different phases of the seismic wavefield. Lastly, we install a fiber in existing telecommunications conduits below Stanford University and show that little cable-to-soil coupling is required for teleseismic *P* and *S* phase arrival detection.

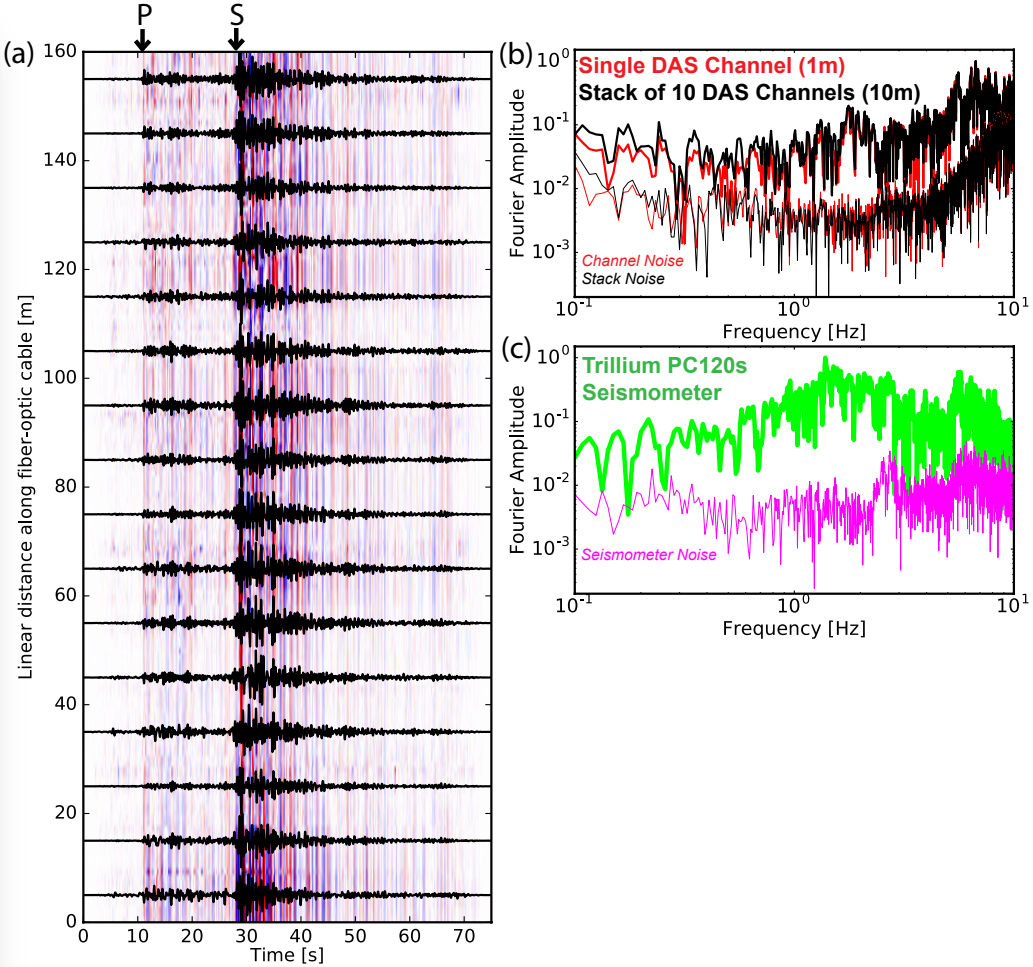
Plain Language Summary A new seismic recording technology, called distributed acoustic sensing (DAS), turns common telecommunications fiber-optic cables into a very long (tens of kilometers) array of single-component seismometers. We catalog and analyze earthquake observations from three different DAS experiments and demonstrate some of the possibilities of using this technology for earthquake seismology. We compare DAS records with a conventional seismometer and then show how the array style response of DAS enables recording of additional information such as the direction of the seismic energy. We also install a fiber in a typical telecommunications conduit below Stanford University, as opposed to directly burying the fiber in soil, and show that main seismic waves are still detected despite the hypothesized decrease in coupling between the fiber and the ground.

1. Introduction

Massive seismometer arrays in "large-N" geometries have quickly become a fundamental tool for modern earthquake seismology (Lin et al., 2013; Rost & Thomas, 2002; Schmandt & Lin, 2014); however, such experiments are difficult to maintain over months to years (so-called "large T"), especially in offshore and urban settings. Low-cost sensors and smartphone arrays have the potential to circumvent many of these logistical limitations but are currently much less sensitive than seismometers (Kong et al., 2016; Laine & Mougenot, 2014). Here we consider how a new type of seismic measurement approach, fiber optic-based distributed acoustic sensing (DAS), might be used in earthquake seismology to deliver meter-scale seismic wavefield information over tens of kilometers with a single instrument operating at one end of the fiber.

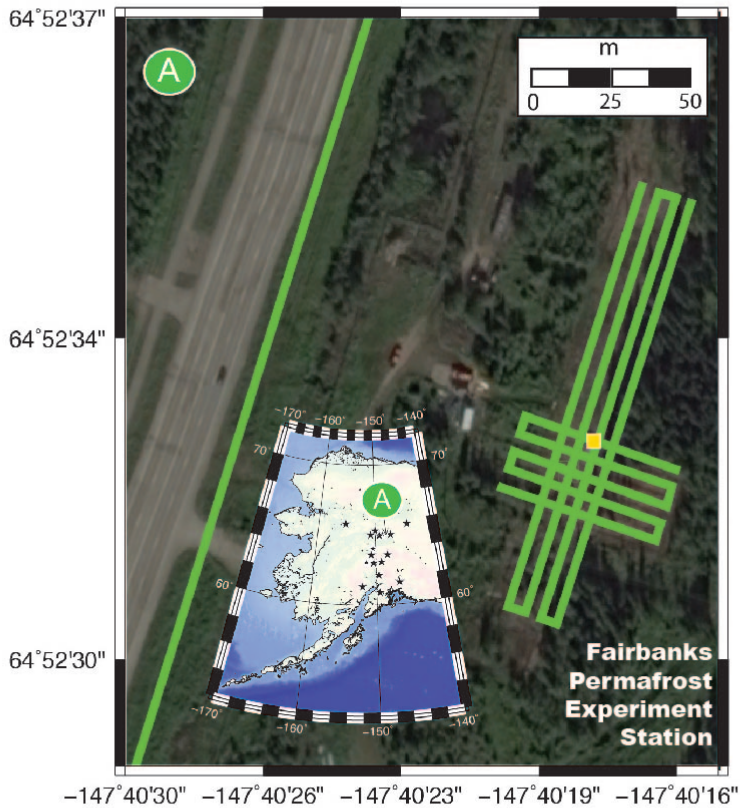
DAS repurposes standard telecommunication fiber-optic cables as a long series of single-component, in-line strain or strain-rate sensors, with sensing point separations as fine as 1 m or less. The DAS method employs a laser interrogator unit located at one end of the fiber whose purpose is to illuminate the fiber with short pulses and then perform high-rate optical interferometry of the Rayleigh backscattered light. Backscattered photons return to the interrogator unit at a time proportional to the linear fiber distance traveled by the photon. The retrieved phase shift from interferometry is quasi-linearly proportional to the change in strain (Grattan & Meggitt, 2000). This means that DAS essentially probes the motion of the entire fiber optic at each time

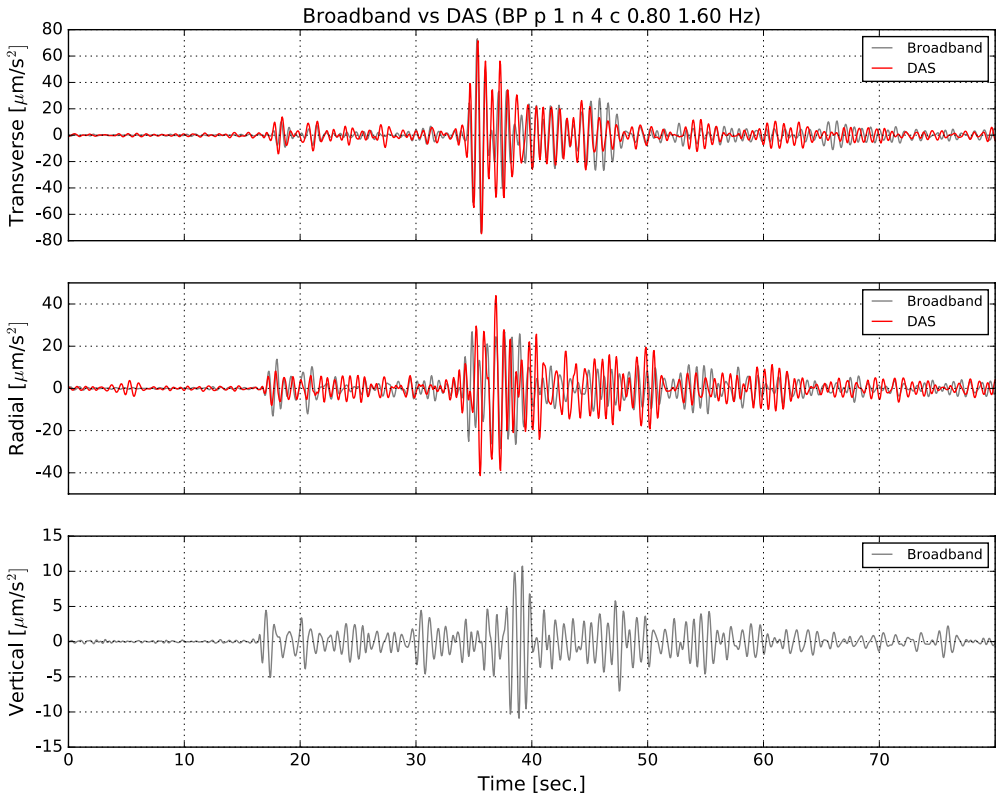
LINDSEY ET AL. FIBER-OPTIC EARTHQUAKE OBSERVATIONS 1



Lindsey et al., 2017

DAS for EQ Seismology?

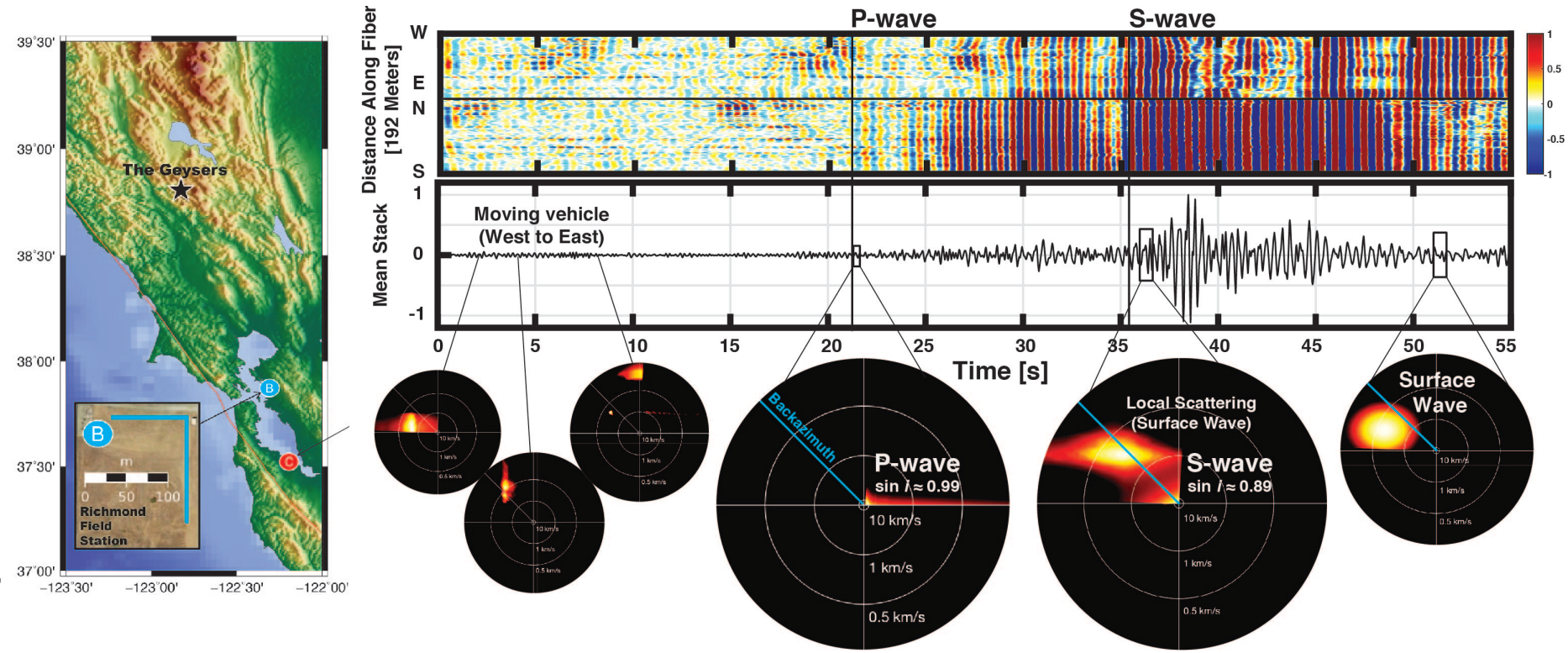




Lindsey et al., 2017

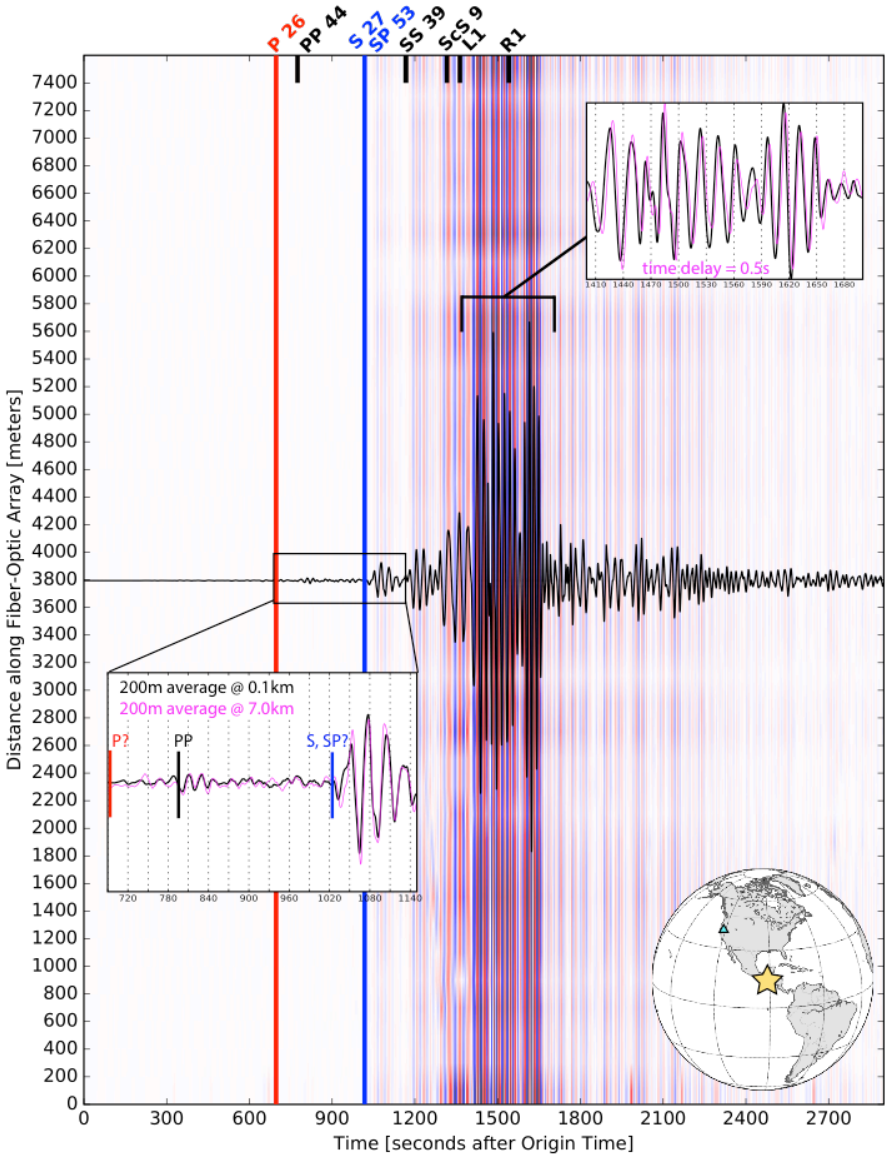
DAS for EQ Seismology?

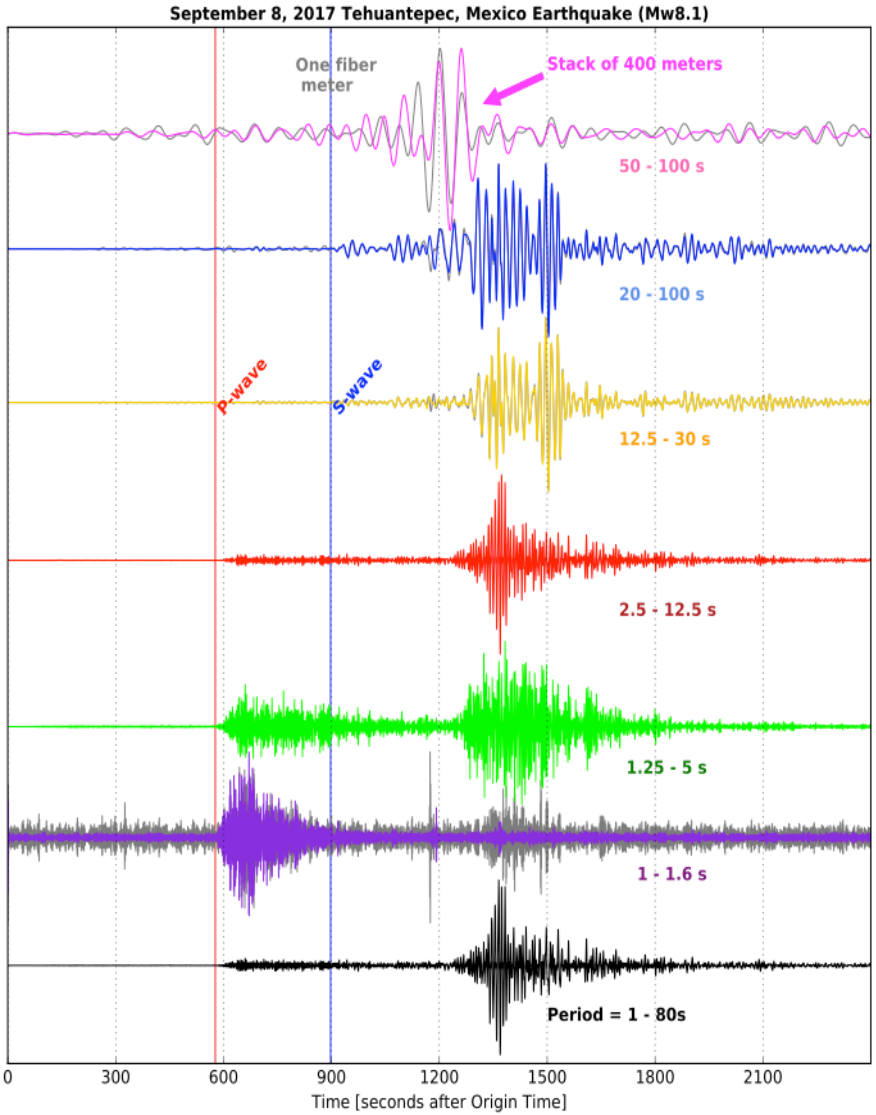
- Large DAS arrays are also potentially useful for beamforming applications
- Example from RFS pilot experiment (Lindsey et al 2017)



Lindsey et al., 2017

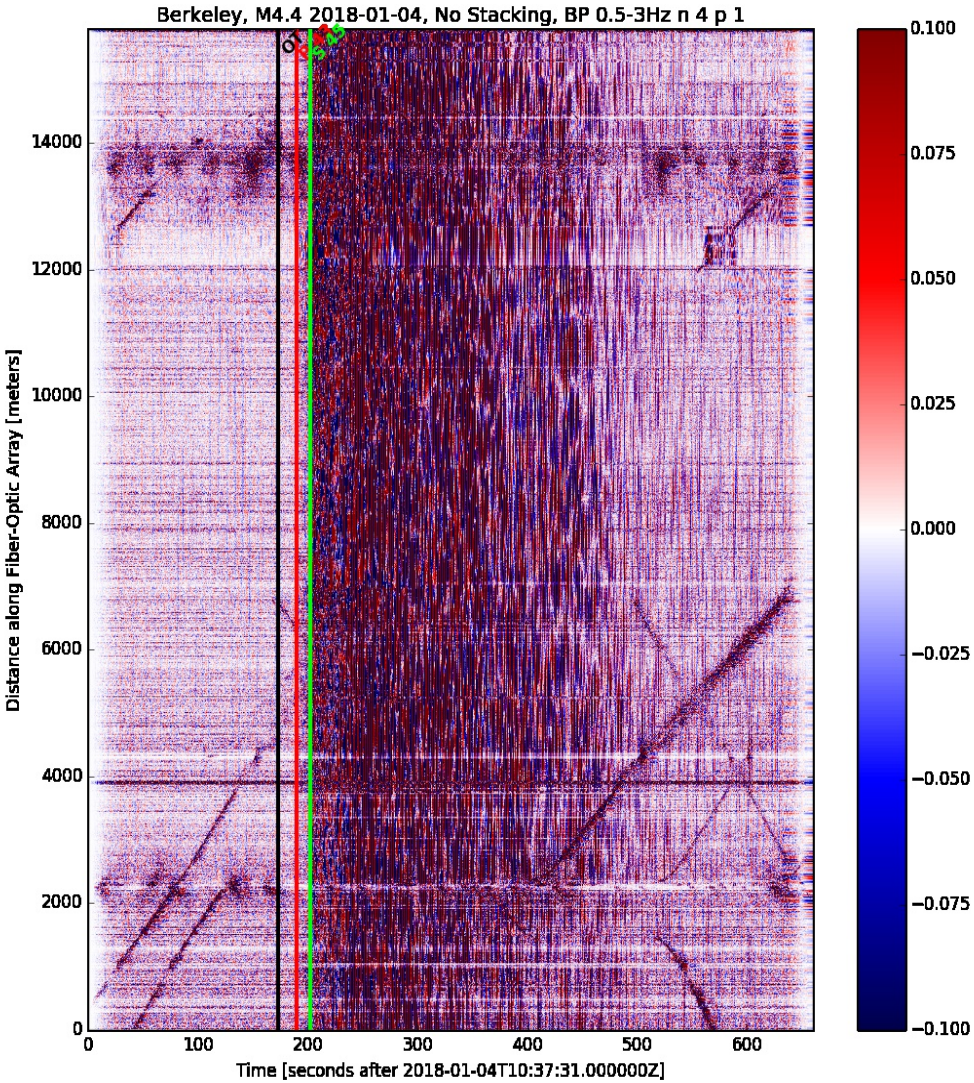
Observations of Mexico M8.1 Earthquake (Teleseismic)

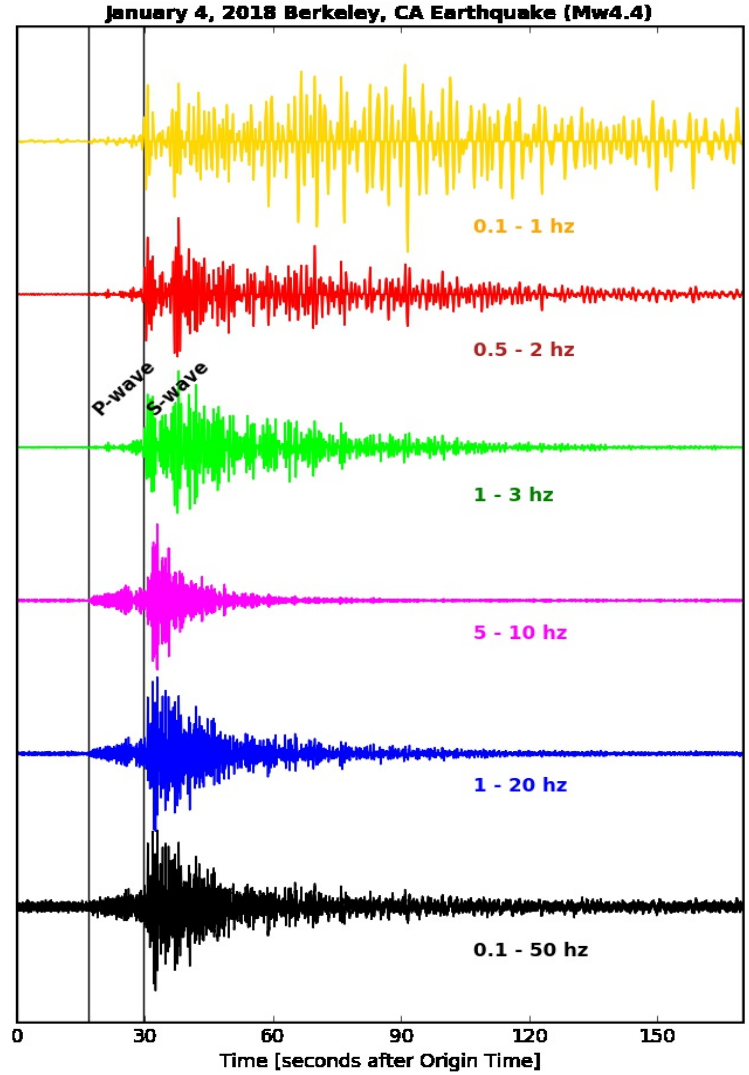




Berkeley, CA M4.4, Jan. 4th, 2018 (Regional)

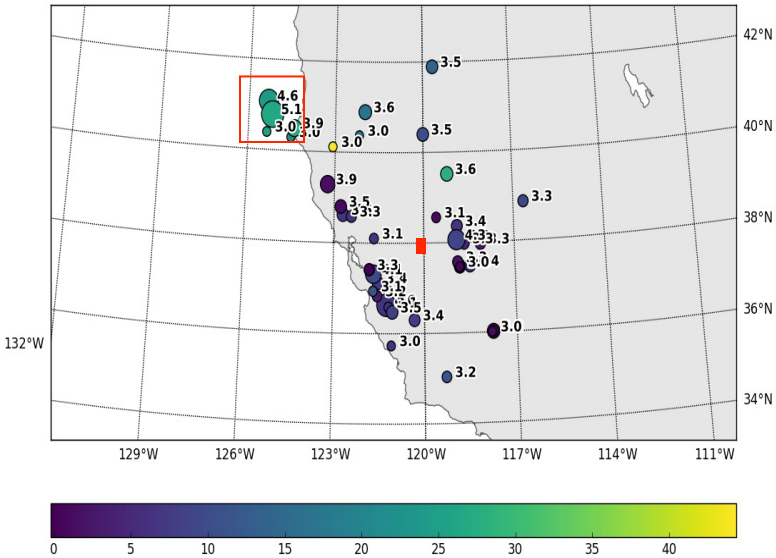
Left : Note vehicle traffic has a different moveout and array excitation pattern.
Right : A single channel - good performance for smaller regional events.

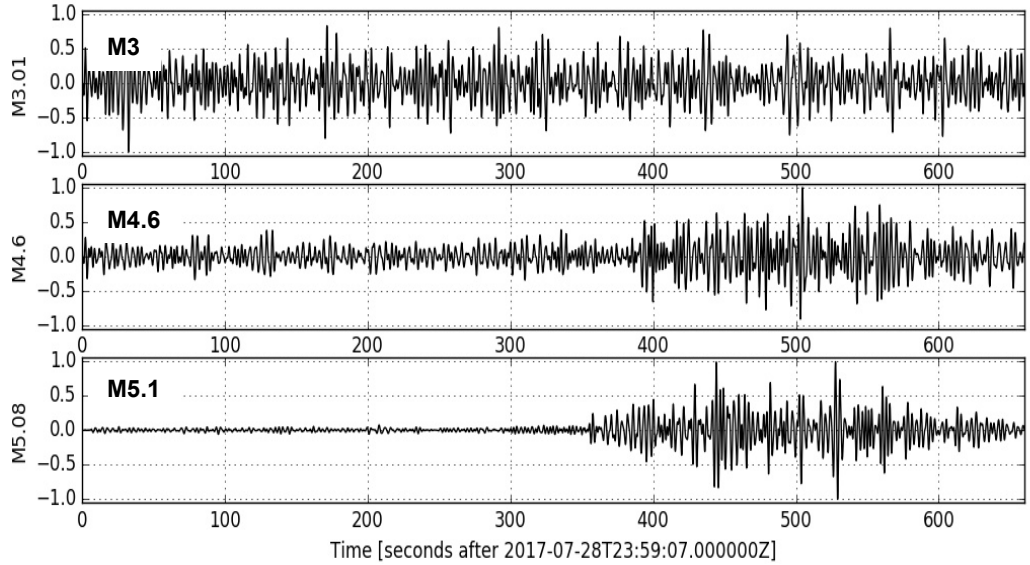




Mendocino Aftershock Sequence : Sensitivity?

- Starting more quantitative sensitivity tests.
- Using sequence from M5.1 and after-shock sequence as sensitivity test
- Events from M5.1 to M1 available with very similar ray paths
- M5.1 clear, events in the M4 range detectable but noisy, M3s are below noise threshold
- Examples below for single channel (2 m) : examining optimal stacking to improve threshold
- Early data lacked reference stations …

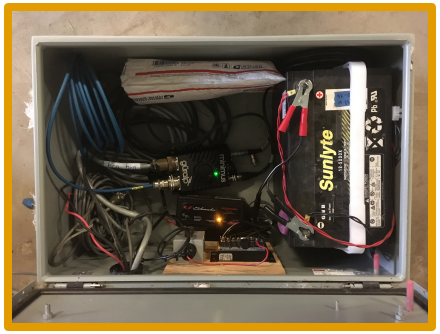


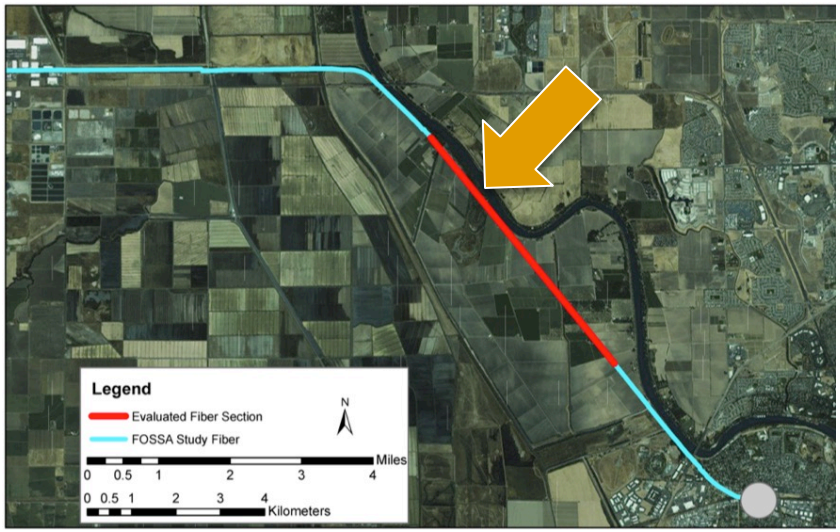


Understanding What We Are Recording ….

- Optimally, use well-calibrated sensor for comparisons.
- Now have 3 months of Guralp CMG-3T data for future evaluation.
- Thanks to local volunteer fire dept!

November 13, 2017
Installed Guralp CMG-3T
Broadband Seismometer
at FOSSA





Berkeley Seismological Laboratory

w. Horst Rademacher

A Story In Several Parts

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Next Steps & Challenges :

Looking Towards an Applied Geophysics Superfacility?

Challenge :

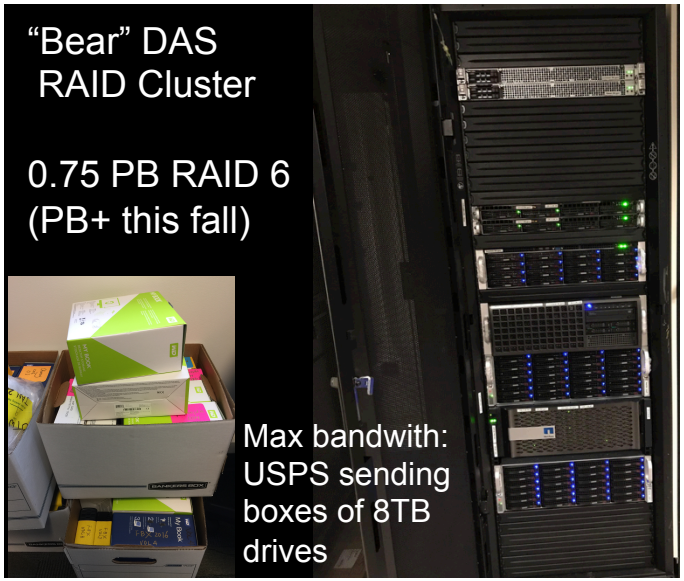
- Data acquisition is only part of the puzzle.
- DAS data volumes are large (to 10s of TB/day) and growing
- Data needs to be transported, processed, archived, analyzed.
- Need real-time feedback in some cases
- Often data ***is*** the experimental bottleneck.

Example

- Sacramento Dark Fiber array generates 8-16 TB/week.
- Current dataset is 192 TB of raw field records (a RAID shelf)
- We have 4 units in the field at the moment.
- Last 2 years, more LBNL DAS acquisition then the full IRIS archive (0.75 PB).
- ***Not sustainable with current project structures***.

Solutions? :

- A superfacility combining observation (DAS), data transport (ESnet), and storage/analysis (NERSC)?
- Precedence for such combinations
- Also require scalable + flexible environment for experimental seismology with non-standard processing approaches.
- Machine learning approaches? Need techniques which function on large unlabeled datasets (no cats!).
- DAS is new enough that we are in an exploration phase.



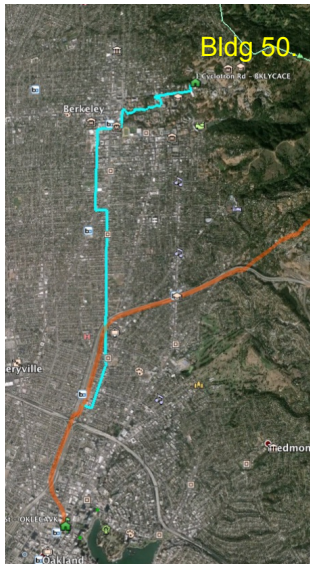
HPPS
Tape
Robot

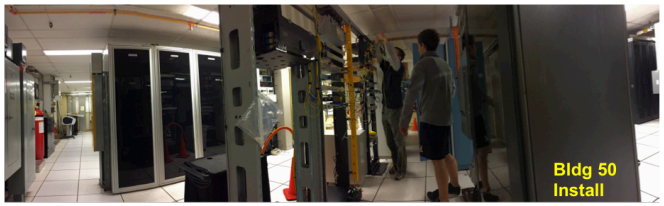
NERSC's
Cori :
152832 cores

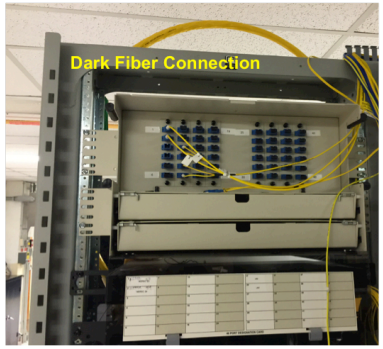
What Can We Do With Urban Fiber Infrastructure?

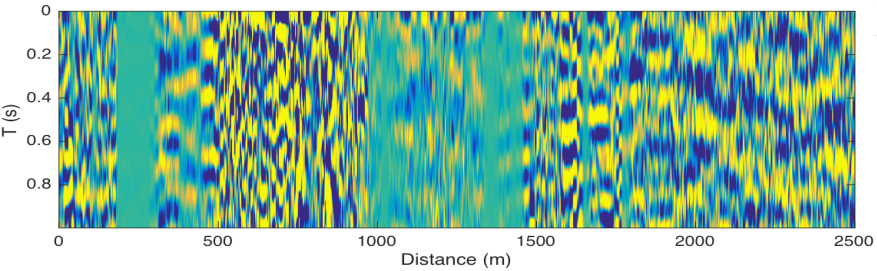
Piggy-back acquisition of Dark Fiber/DAS data on Esnet Bldg. 50->NERSC Oakland fiber.

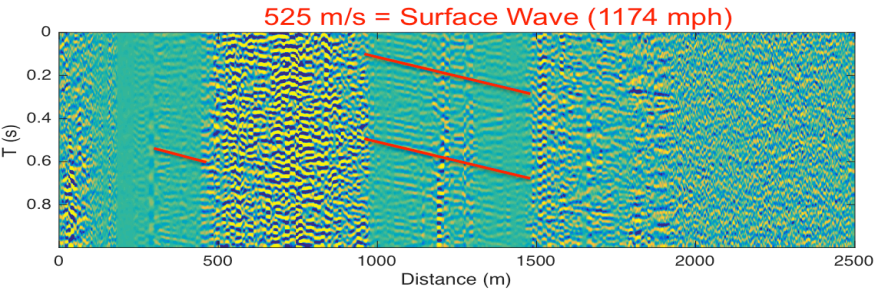
- Of 12 km cable, highly variable data quality.
- ***Detected*** **:** infrastructure signatures (BART/trains/trucks) and seismic surface waves.
- Still exploring our first "Berkeley/Oakland" Dark Fiber dataset − unclear on what drives differences in signal.

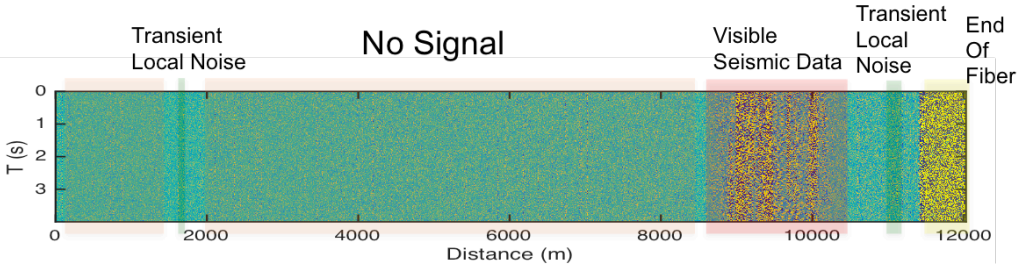


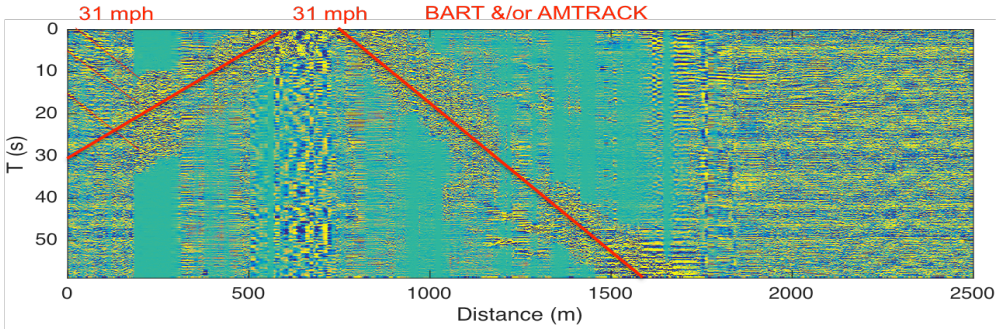












Next Steps for Dark Fiber...

1. Looking for approaches to understanding where fiber is installed (burial conditions, conduit, etc) and as a result, what we can measure...

2. What kind of environmental information can we pull from Dark Fiber beyond surface wave velocities?

   - Local soil moisture?
   - Soil temperature?
   - Deep aquifer properties

3. How can EQ seismic measurements on dark fiber be most effectively utilized?

   - Earthquake early warning? (P-waves closer to epicenter)
   - More accurate hypocenters?
   - Information on small events in zones of poor coverage?
   - Information on induced seismicity?

4. How can urban (vs. rural) dark fiber be most effectively leveraged for sensing beyond prior topics? Transit sensing? Leaking pipes? Many possibilities.

Thanks!

Support From

1. **Early work SERDP/DoD**

Strategic Environmental Research and Defense Program

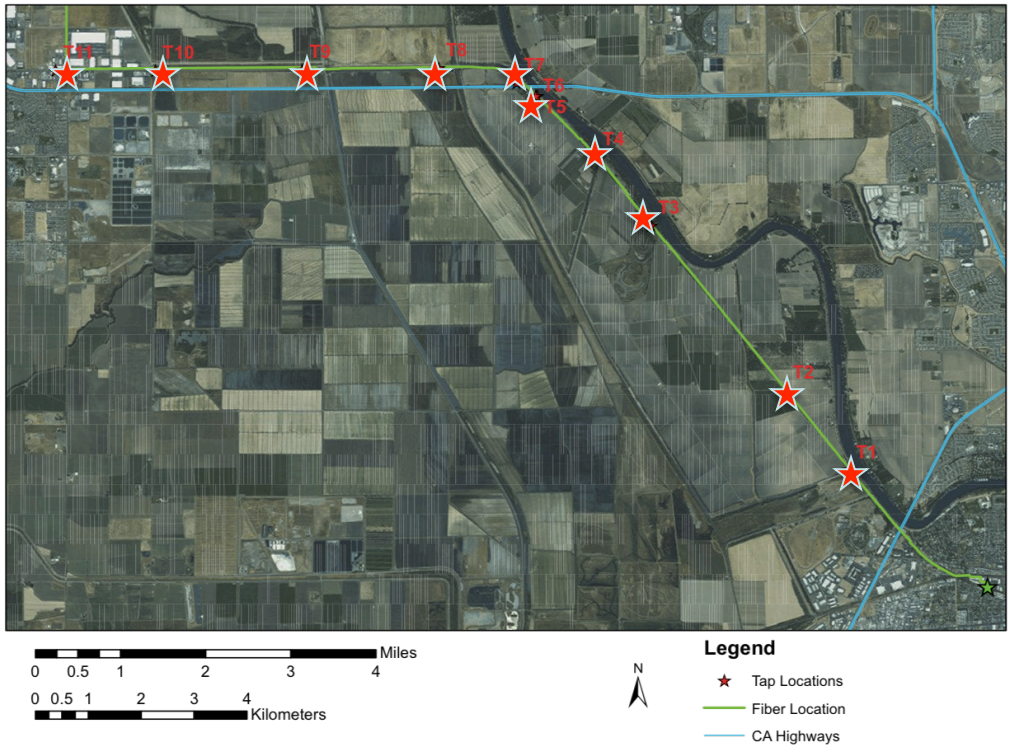
2. **Dark Fiber project : LBNL LDRD**

Lawrence Berkeley National Laboratory
Laboratory Directed Research & Development program
LDRD

BACKUP

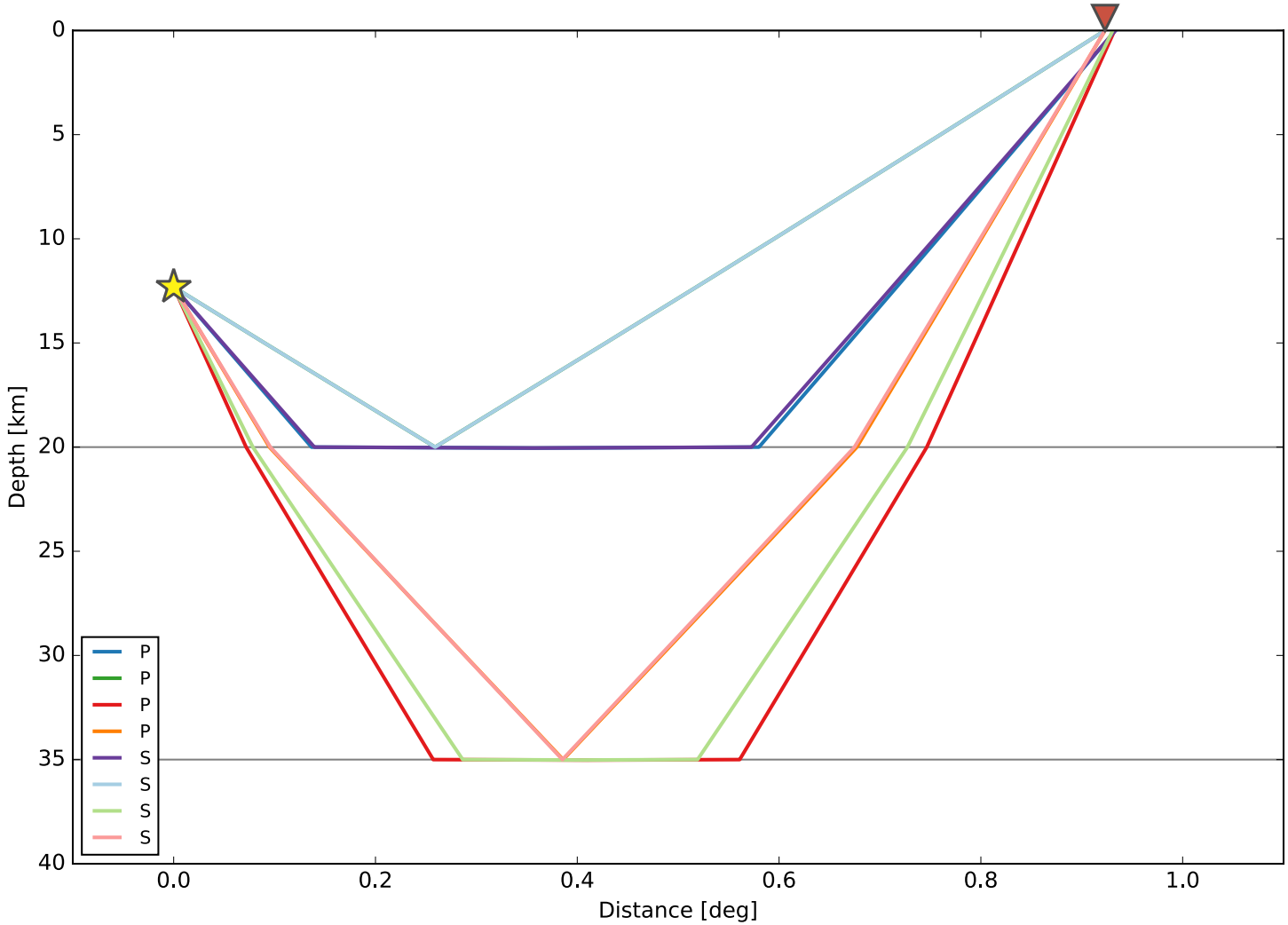
Building Geometry

- ***Challenge*** : Mapping between linear fiber location and true X/Y/Z (have to know where you are!).
- ***Issue*** : telecom install procedure with slack + surveying practices results in uncertain mapping.
- Vertical hammer test with GPS location/timing was used to calibrate physical location of fiber run.
- Used to develop mapping between linear fiber distance and X/Y coordinates, accurate to within 2-5 m.



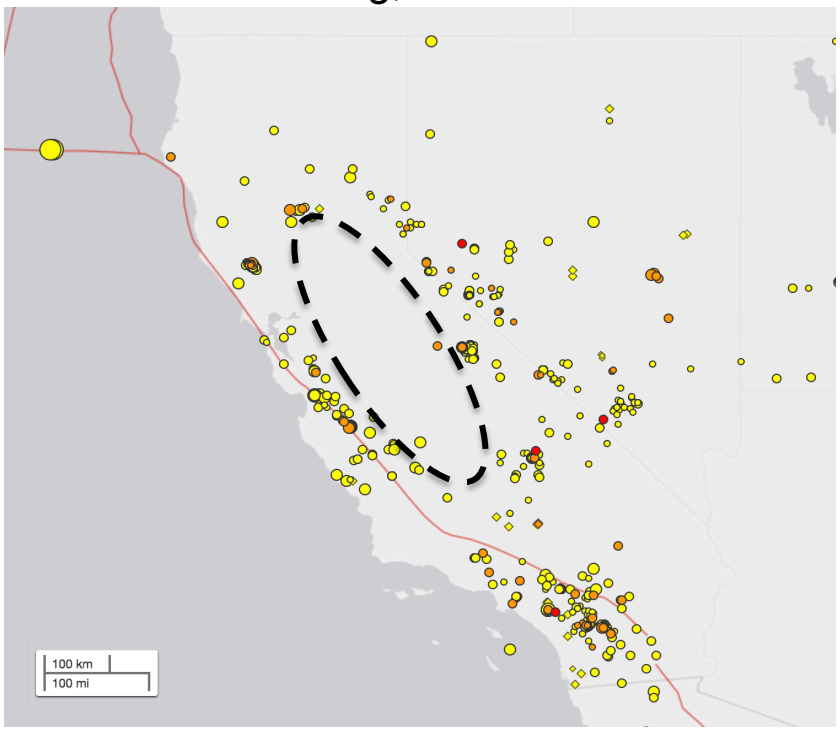
Berkeley, CA M4.4, Jan. 4th, 2018 (Regional)

Comment : Body waves (P,S) are arriving at high angle regardless of azimuthal array orientation (ray-tracing through IASPEI model)



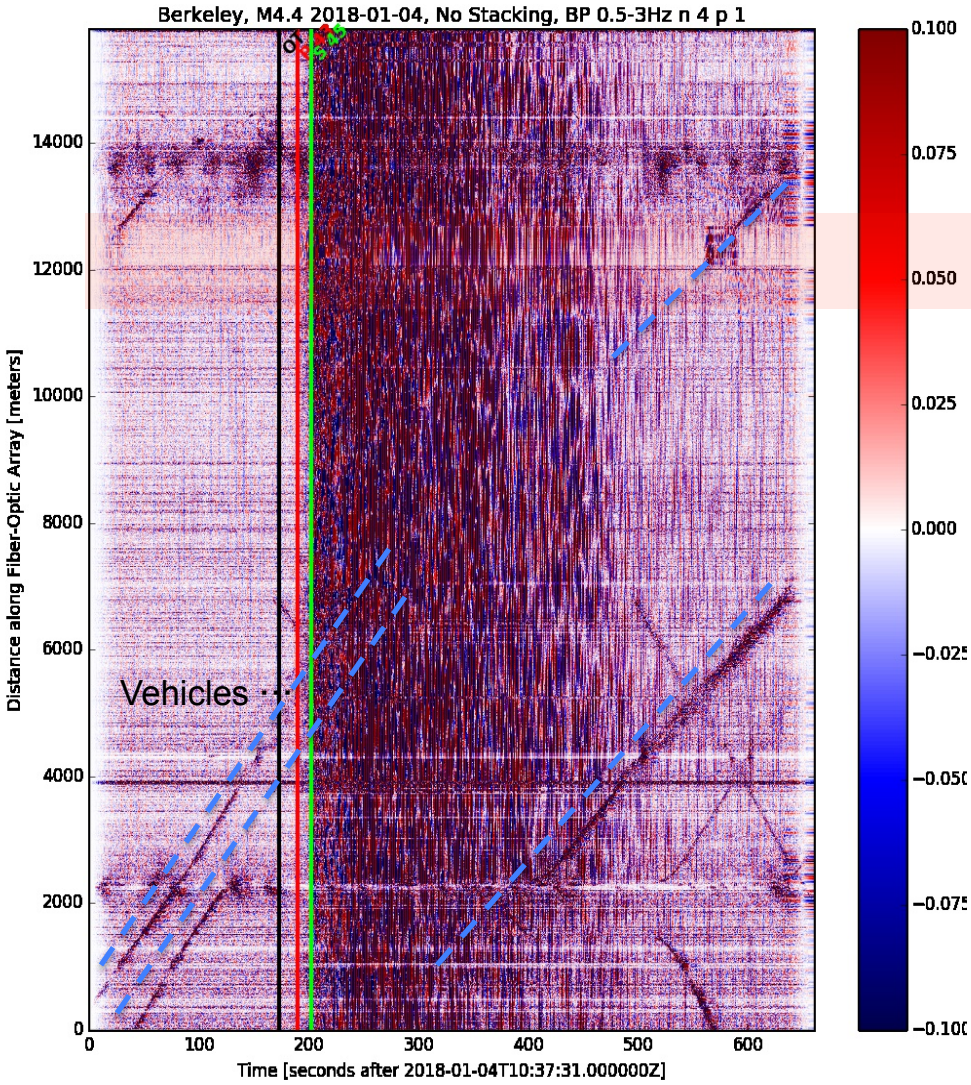
Gaps in CAs Seismic Catalog?

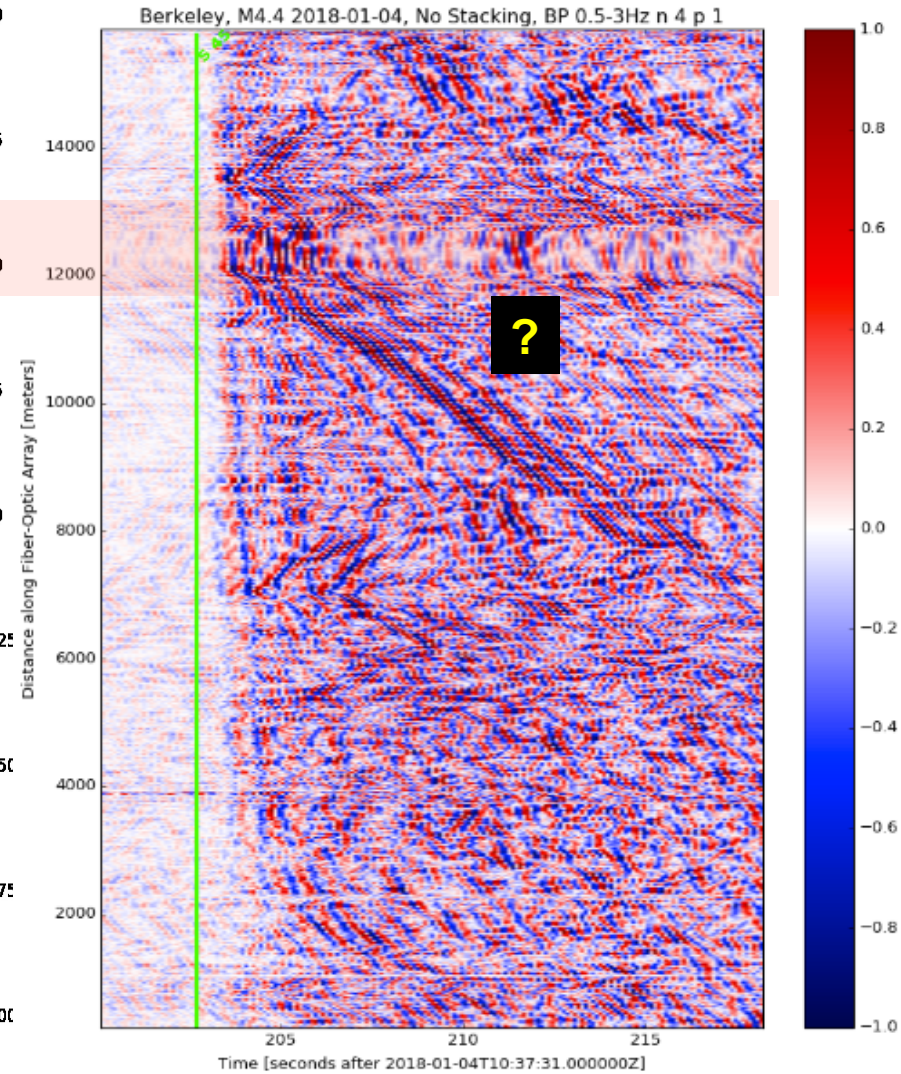
Detected catalog, week of Jan. 22-29



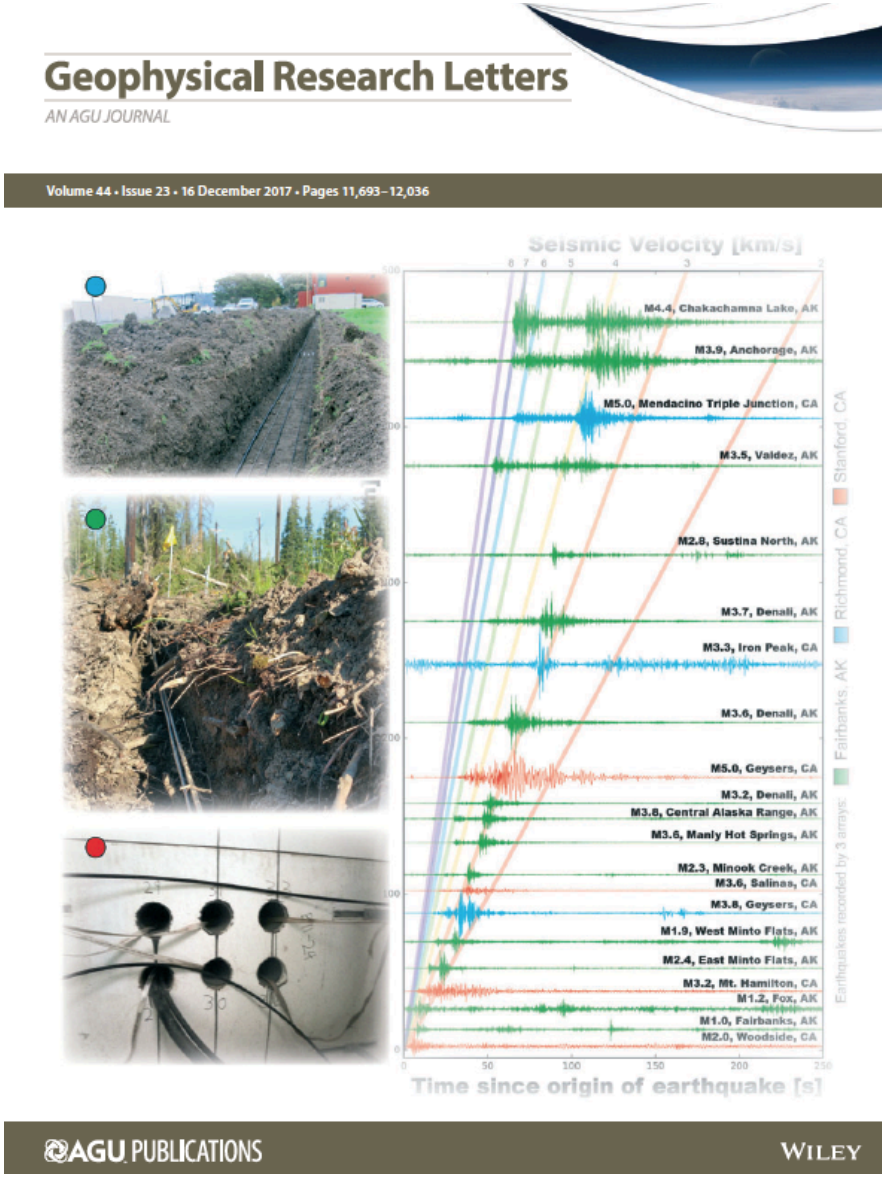
Berkeley, CA M4.4, Jan. 4th, 2018 : Unusual Scattering?

Comment : Unusual scattered events near S body wave arrival − linear surface wave moveout. Unclear source but visible at 4 km offsets (!).

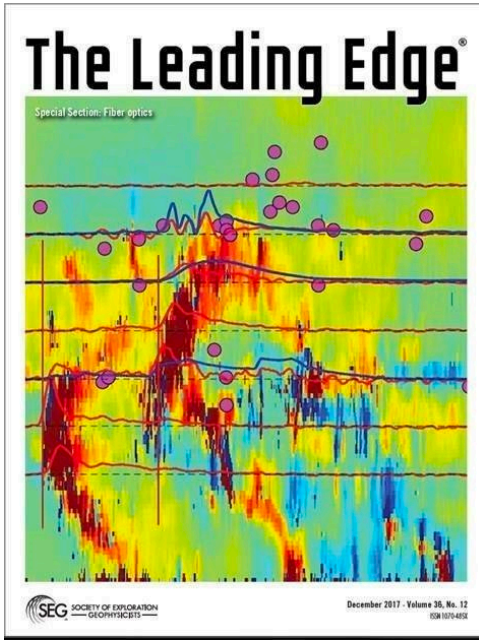




Recent DAS Fiber Highlights : Ambient Noise & EQ Studies

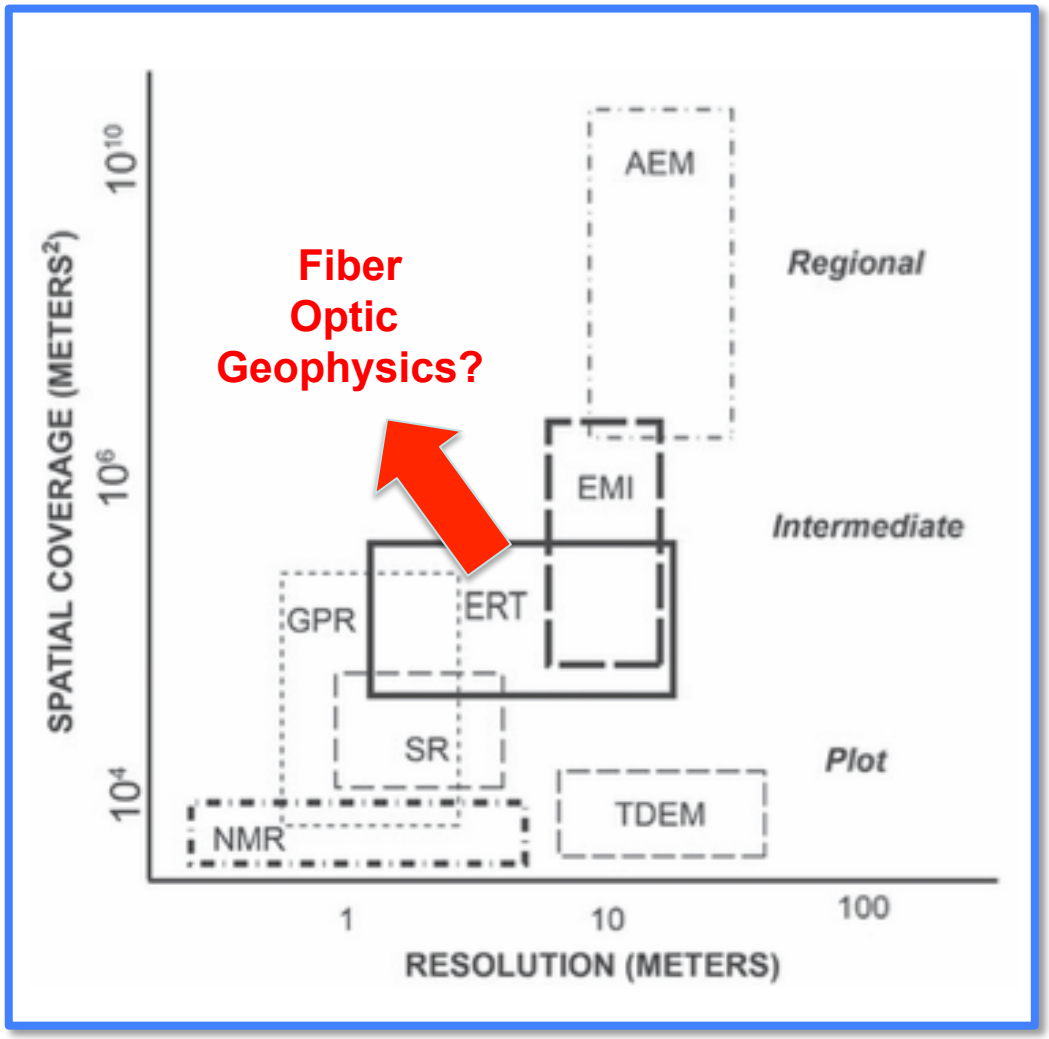


Academic : GRL Cover Article, Dec. 2017
Press/Media : ABC7, Photonics, Scientific American, Physics Today, Fast Company, Smithsonian, Science

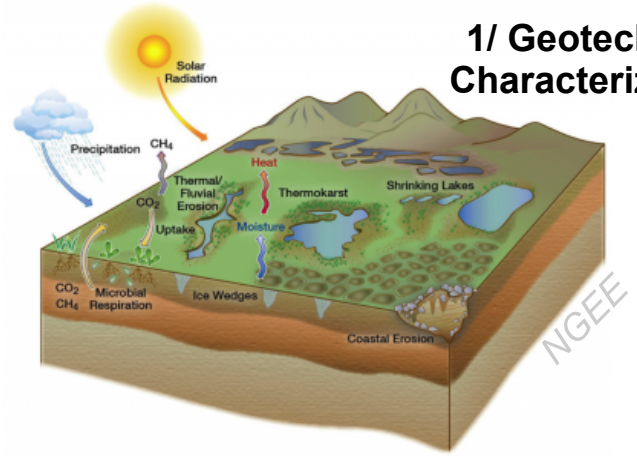


http://abc7news.com/science/fiber-optic-cables-could-help-us-understand-earthquakes/2853012/

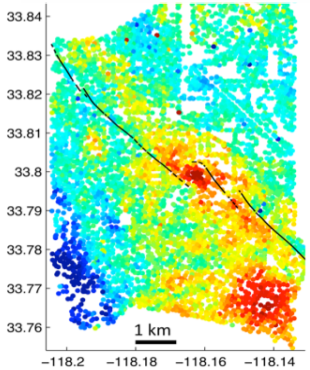
Observation bias in earth science



Walvoord and Kurylyk, 2016



1/ Geotechnical Characterization



2/ Earthquake Seismology

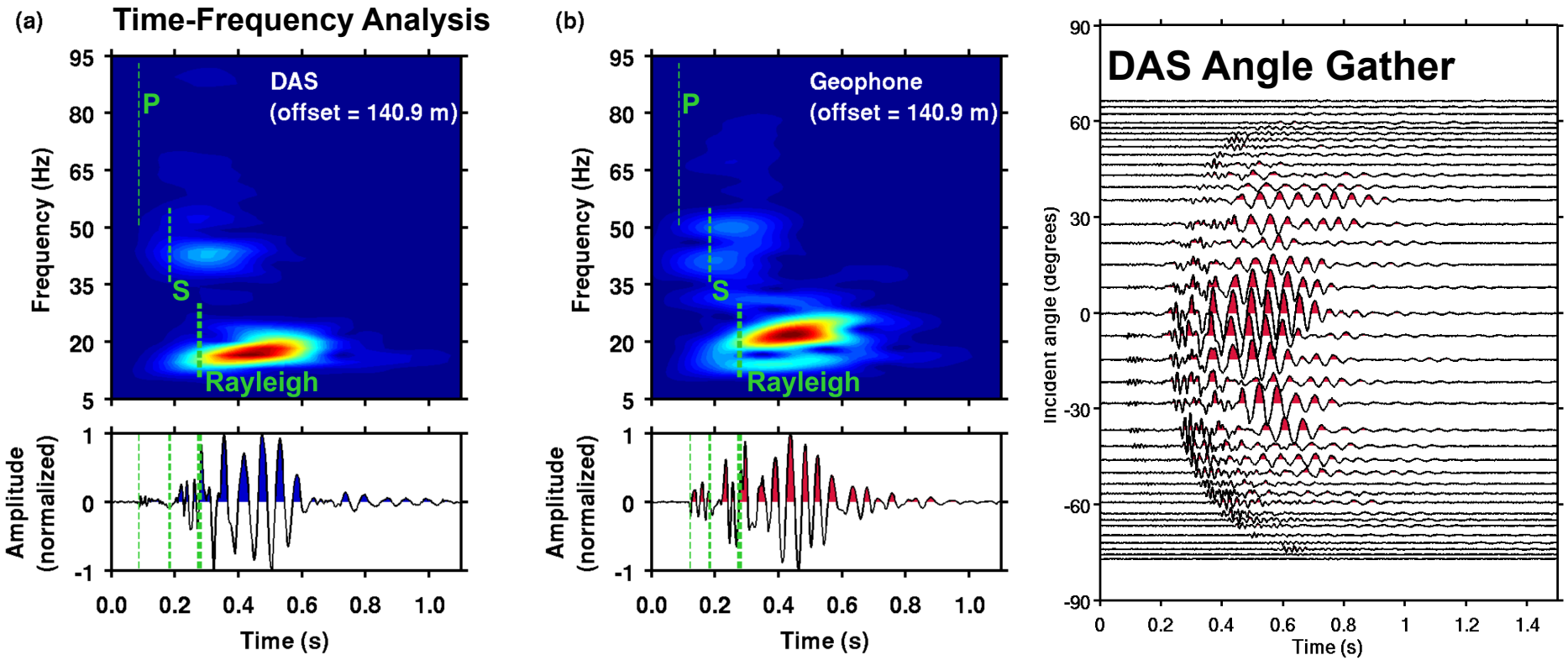
Long Beach Seismic Array

(Schmandt and Clayton, 2013)

3/ Basin Scale Structural Imaging

Characteristics of DAS Recording : Directionality

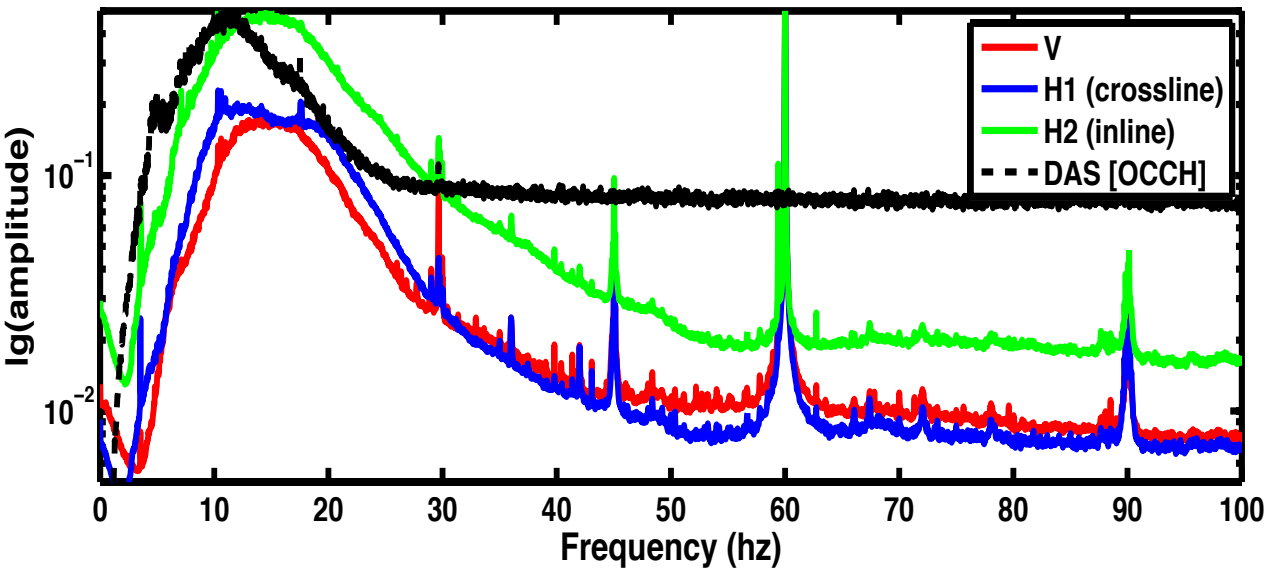
- Straight fibers + DAS most sensitive to extensional strain rate (vector)
- Strong angular sensitivity, P-waves at ~ $\cos^2$ of incidence angle
- Result, excellent Rayleigh wave response, reasonable S, poor P in surface geometries
- Example below : Otway GCS surface line, yields $\cos^3$ response.
- Can be improved through novel cable design (helical, twisted sin, etc).
- True 3C systems still theoretical.



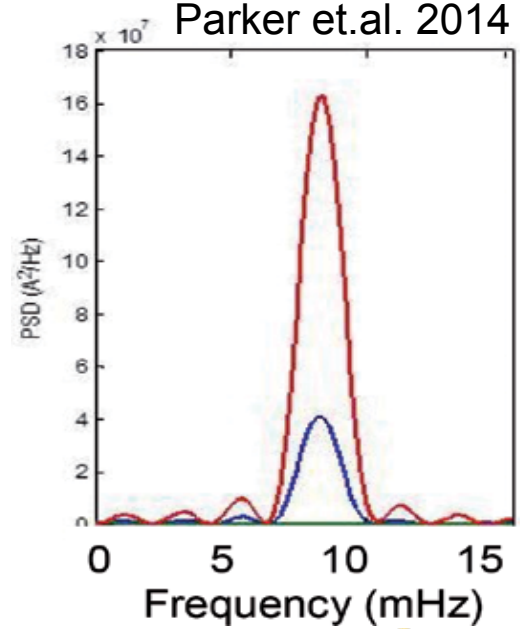
Characteristics of DAS Recording: Bandwidth

- Frequency response dependent both on interrogator type and fiber used.
- Digitization out to 100 kHz (fast lasers)
- ***High end*** : optical noise significant f > 200 Hz, low S/N measurements to 50 kHz
- ***Low end*** : drop off in response but signals visible in the mHz (100 s) range
- Good quality data 1 Hz to 100 Hz, S/N worse than geophone data by 10-20 db
- Note insensitivity to electrical noise, but some box vibration induced noise.

LBNL RFS Tests (2014)

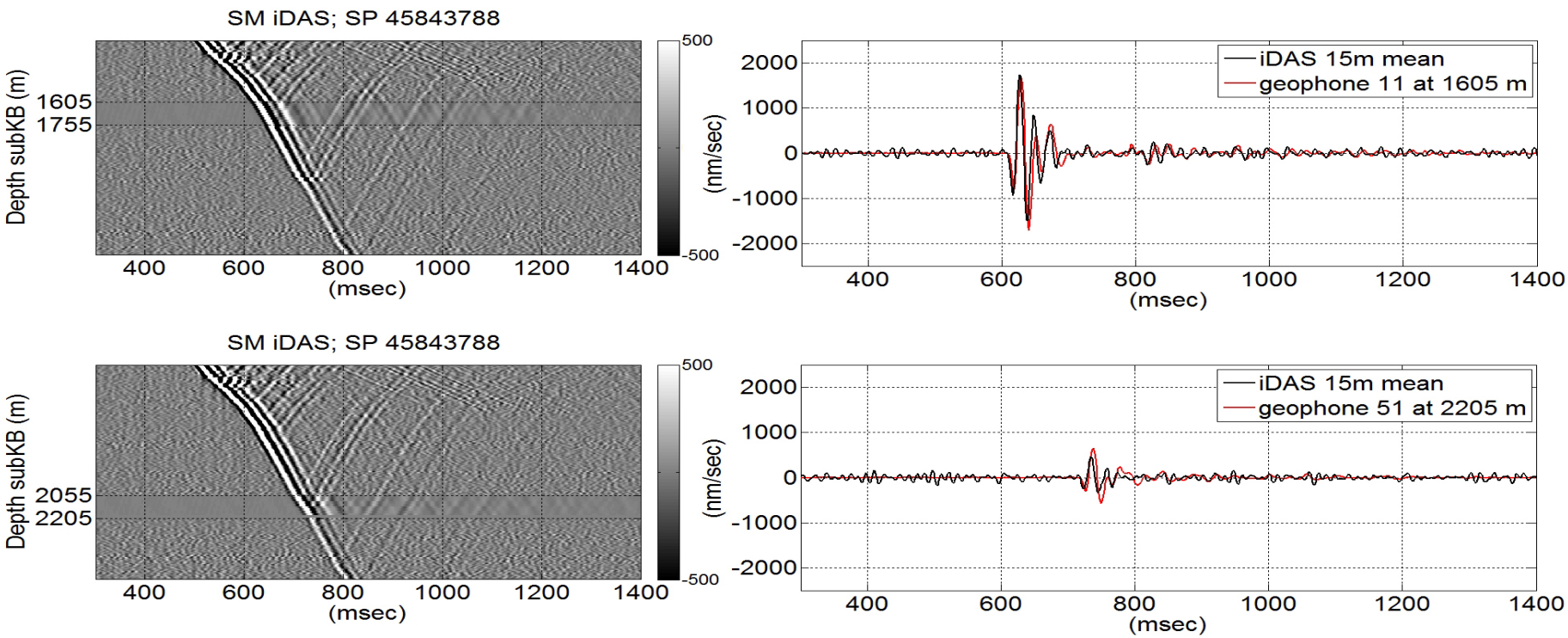


Parker et.al. 2014



Comparable to Geophone Data?

- 3C borehole geophone vs. fiber cemented behind casing (Aquistore VSP – Miller et al 2016)
- One challenge : native unit conversion, strain rate to particle velocity.
- After conversion, wiggle-to-wiggle comparison to co-located geophone data
- Over exploration bandwidth (7-70 Hz), slightly worse S/N on sensor/sensor comparison
- Subsequent comparisons (e.g. Correa et al 2017) have yielded similar results.

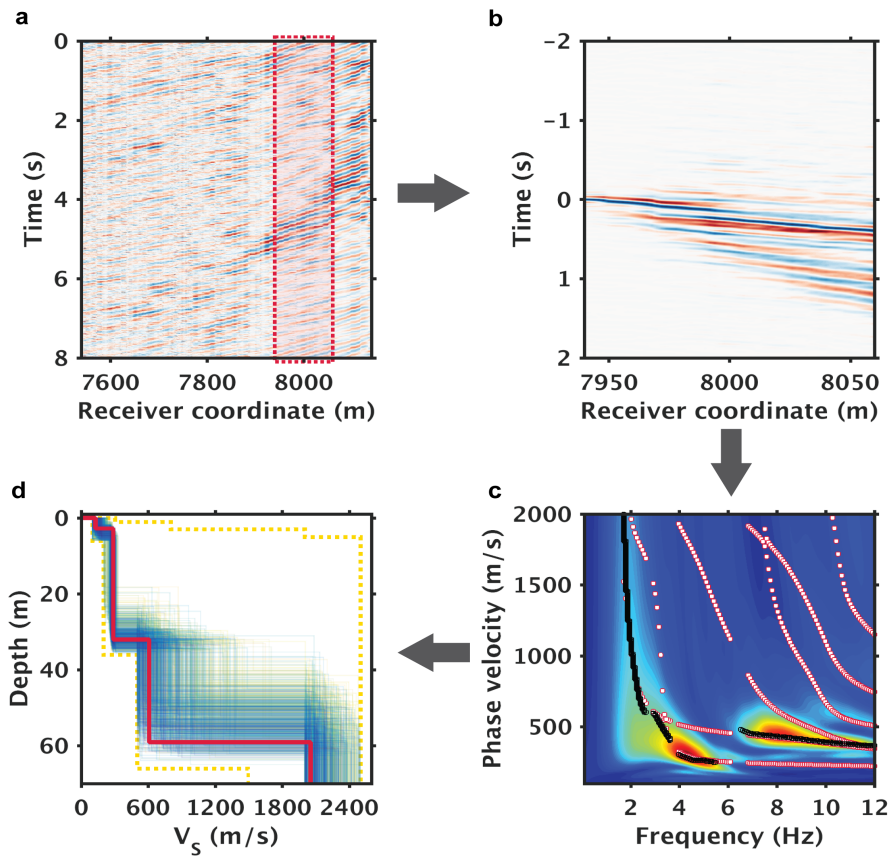


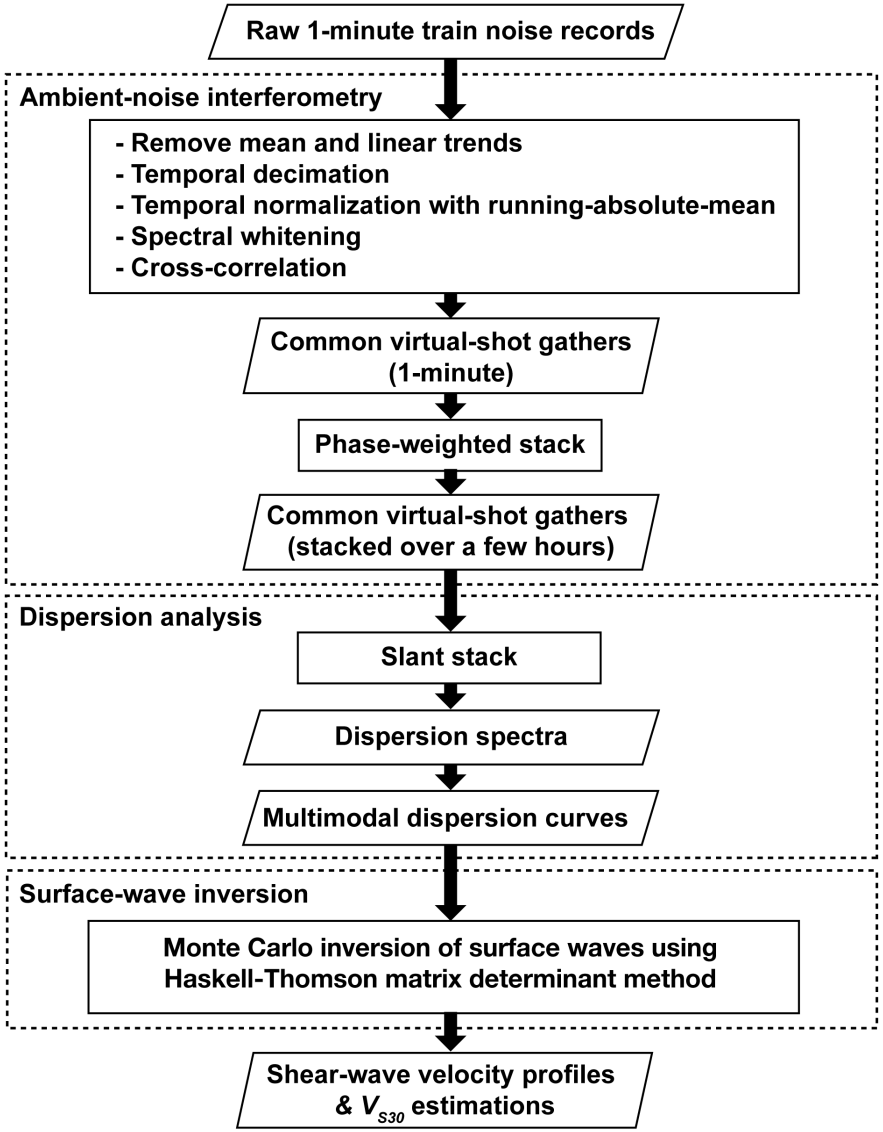
Miller, Daley, et al, 2016

Ambient Noise Processing : Details

Unusual steps :

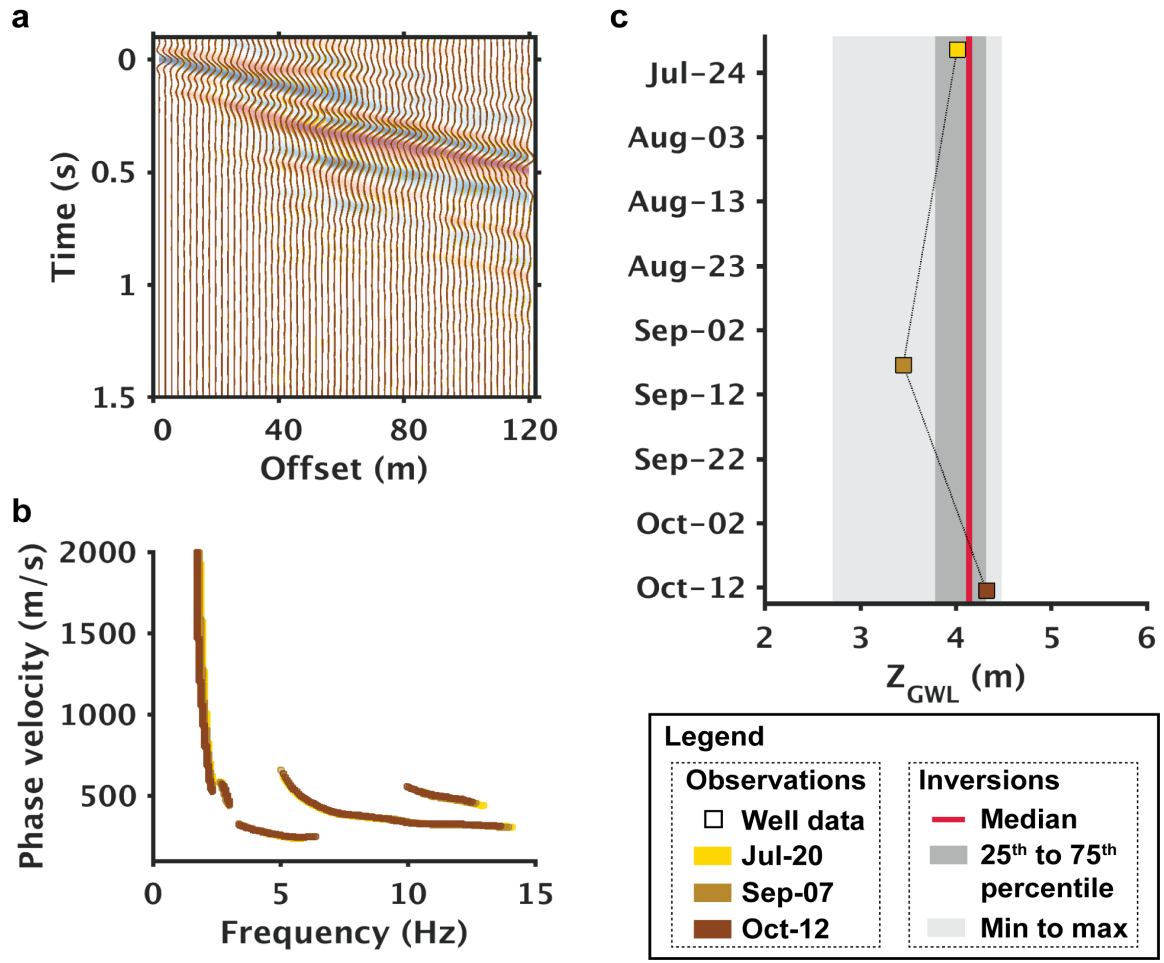
- Train record selection
- Phase weighted stack
- MC inversion using HT determinant method (Foti et al.)





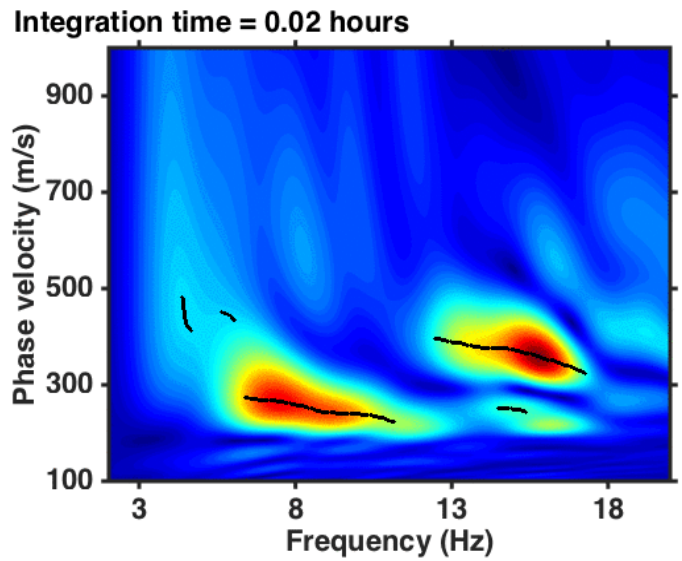
Temporal Stability?

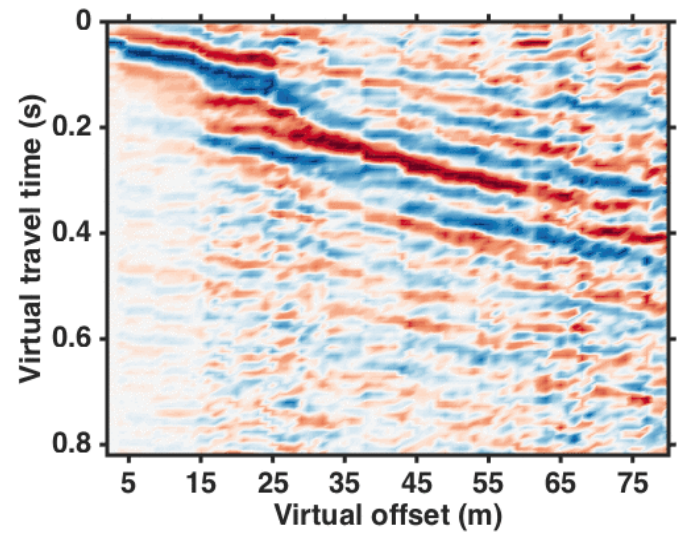
- Timelapse surface wave analysis was also conducted using a rolling stack of 40 train events.
- Time-domain interferometric gathers (right, a) exhibited a high degree of stability over the July-Oct period over which minimal variation in water table occurred.
- Auto-picked dispersion curves (right b) were also stable with less than 2% variation month to month in well-sampled frequency bands.
- Stability suggests that interface tracking is a reasonable target if large excursions occur.
- Waiting for large fluctuations of water table; winter rainy season.

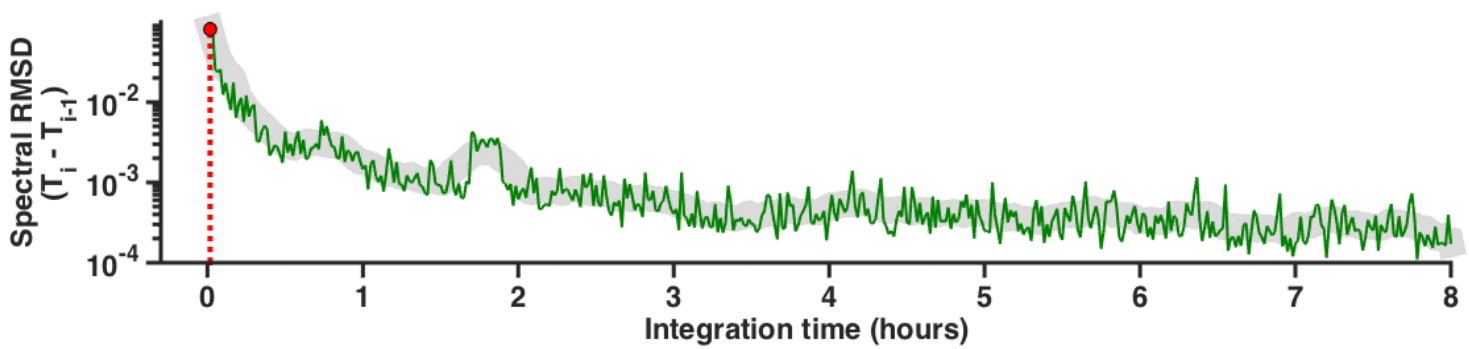


Modest Integration times typically sufficient for ambient noise analysis (RFS example)

1. Stacking example from earlier RFS pilot
2. Contrast with lower frequency AN studies
3. Spectral RMSD is a measure of how the dispersion image is changing with sequential stacks.

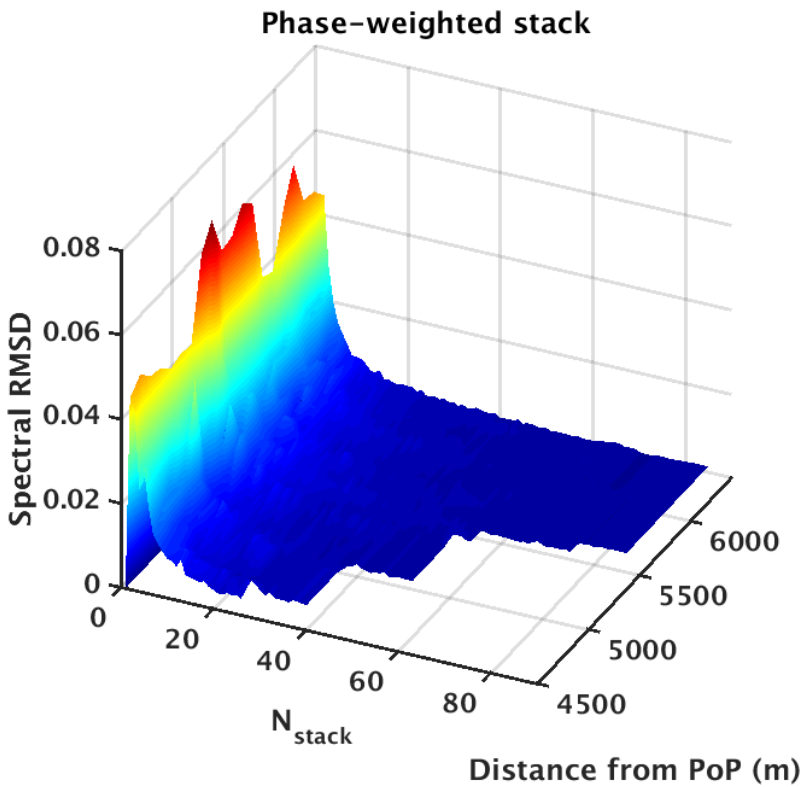


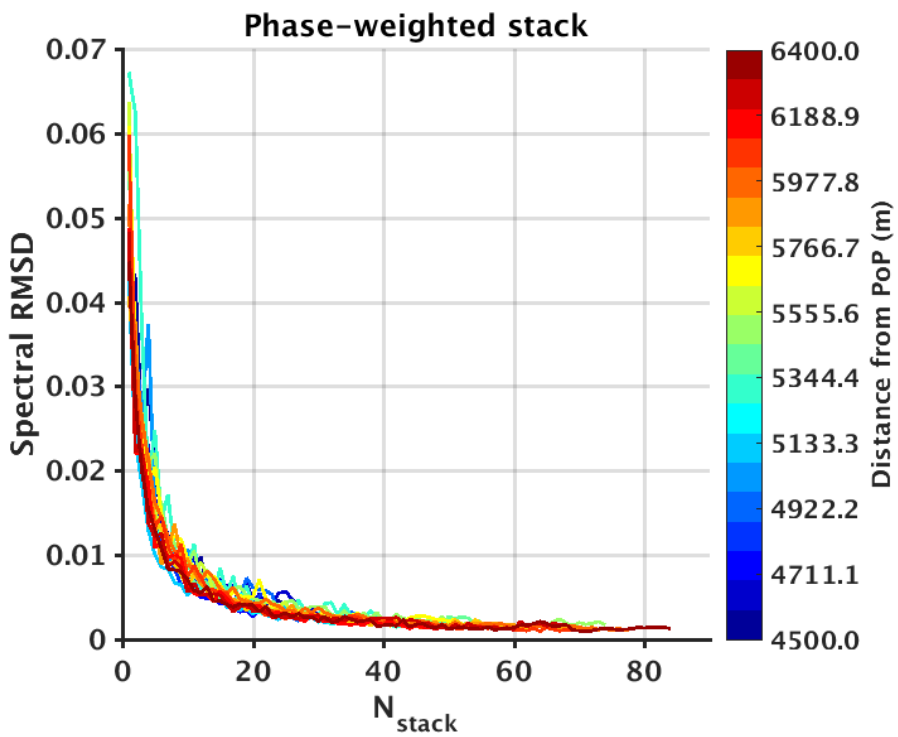




FOSSA : Adding Data from Train Passes

- Virtual gathers typically converge after a relatively small number of passes (20-40).
- Results in temporal sampling on the 1-2 week scale with excellent S/N.
- Exact temporal sampling impacted by daily train schedule (!).





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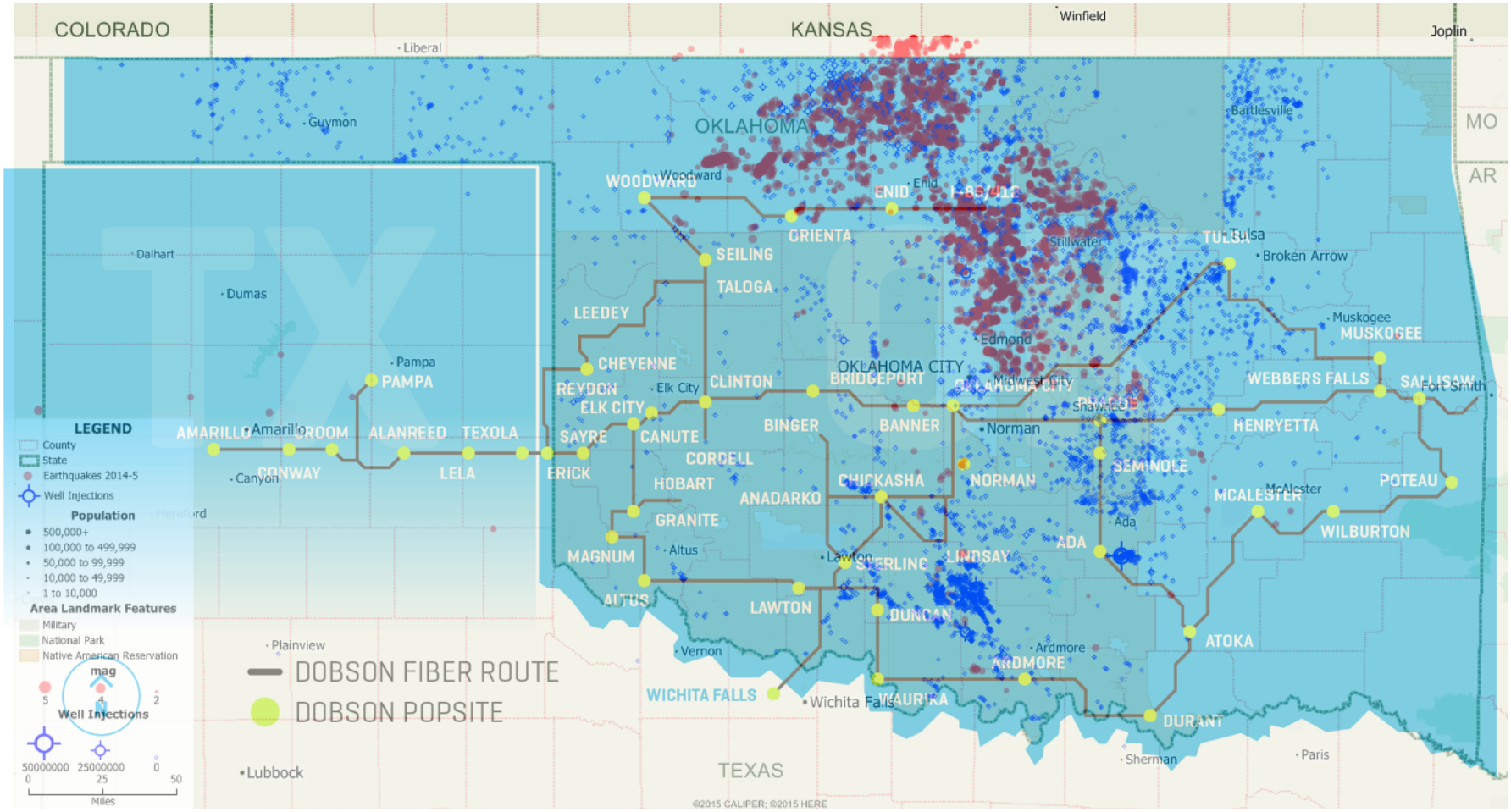
Dark Fiber and Seismicity in OK?



Looking Towards an Applied Geophysics Superfacility?

Challenge :

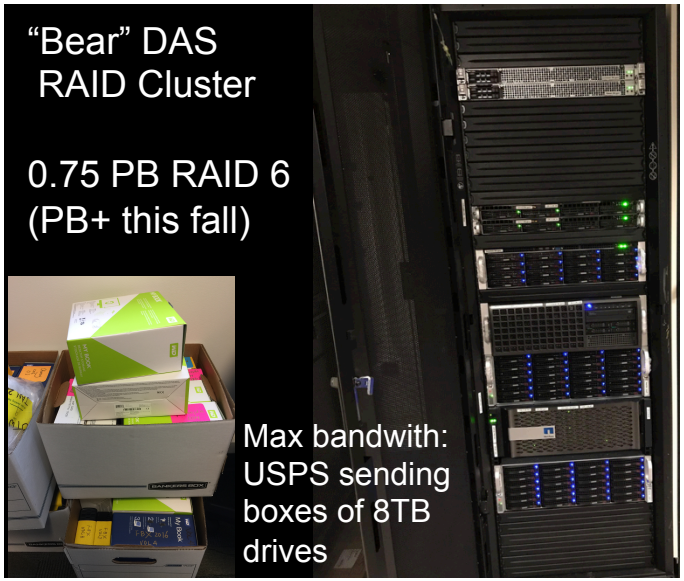
- Data acquisition is only part of the puzzle.
- DAS data volumes are large (to 10s of TB/day) and growing
- Data needs to be transported, processed, archived, analyzed.
- Need real-time feedback in some cases
- Often data ***is*** the experimental bottleneck.

Example

- Sacramento Dark Fiber array generates 8-16 TB/week.
- Current dataset is 192 TB of raw field records (a RAID shelf)
- We have 4 units in the field at the moment.
- Last 2 years, more LBNL DAS acquisition then the full IRIS archive (0.75 PB).
- ***Not sustainable with current project structures***.

Solutions? :

- A superfacility combining observation (DAS), data transport (ESnet), and storage/analysis (NERSC)?
- Precedence for such combinations (Craig Tull's SPOT framework – ALS->NERSC).
- Also require scalable + flexible environment for experimental seismology with non-standard processing approaches.
- Machine learning approaches? Need techniques which function on large unlabeled datasets (no cats!).
- DAS is new enough that we are in an exploration phase.



HPPS
Tape
Robot

NERSC's
Cori :
152832 cores