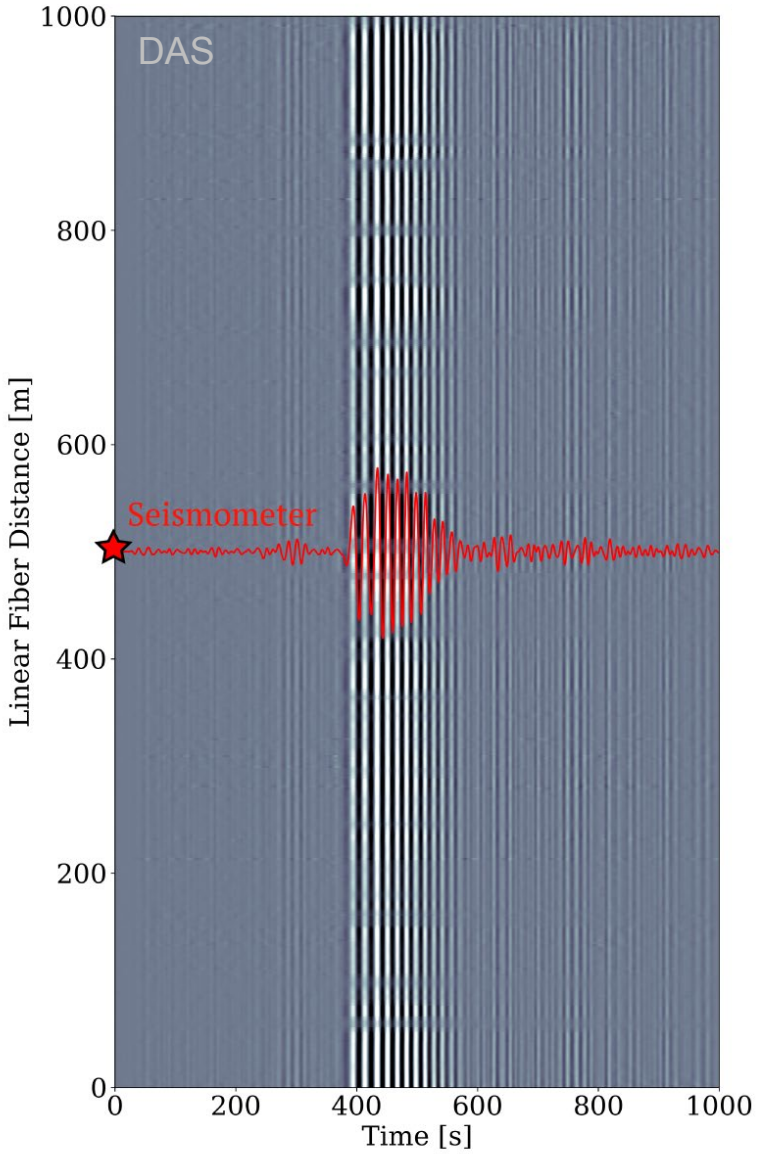


Broadband array seismology with fiber-optic DAS

Nate Lindsey, UC Berkeley

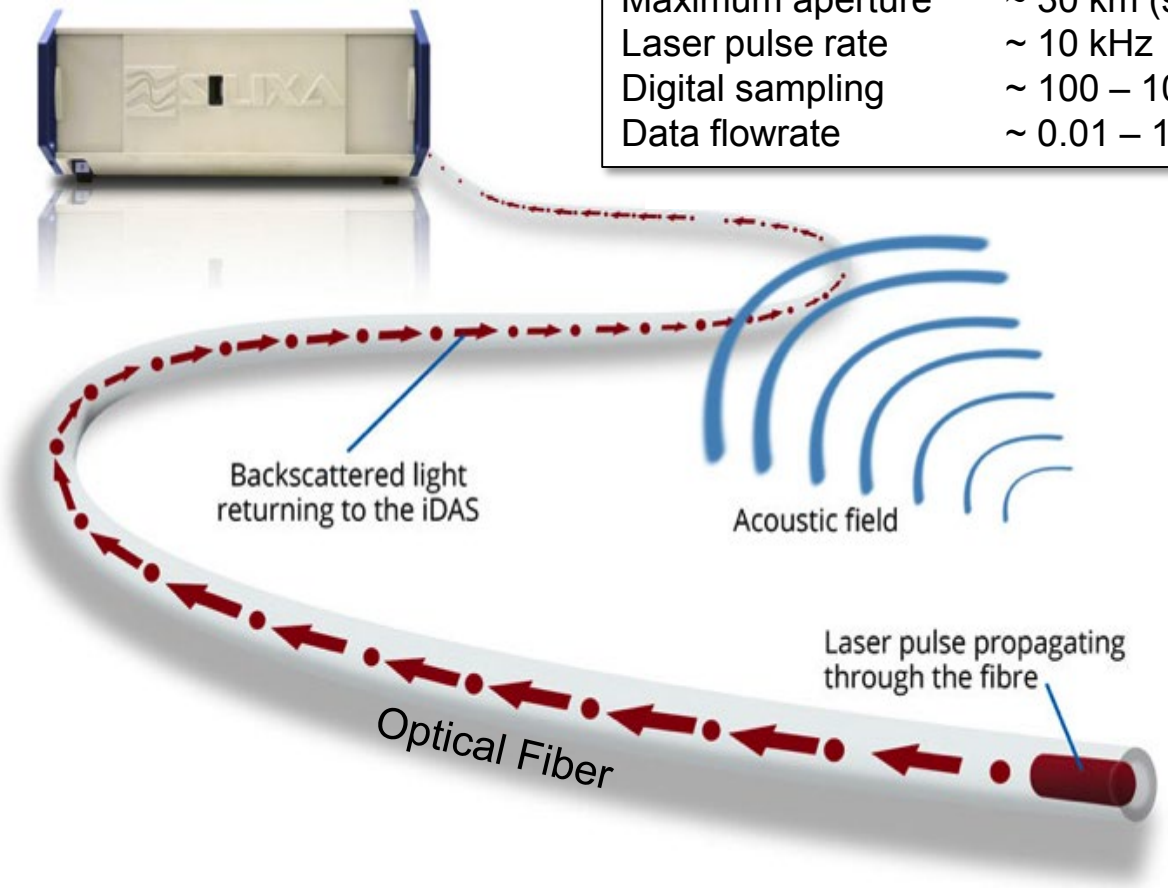
COSG 2019 Meeting
May 9, 2019

Aims

1. What is Distributed Acoustic Sensing?
2. How do we make DAS measurements?
3. Examples
4. Opportunities for research

What is DAS?

Laser pulse width	~ 10 – 40 ns
Spatial sampling	~ 10 m
Maximum aperture	~ 30 km (standard fiber)
Laser pulse rate	~ 10 kHz
Digital sampling	~ 100 – 1000 Hz
Data flowrate	~ 0.01 – 1 TB/day

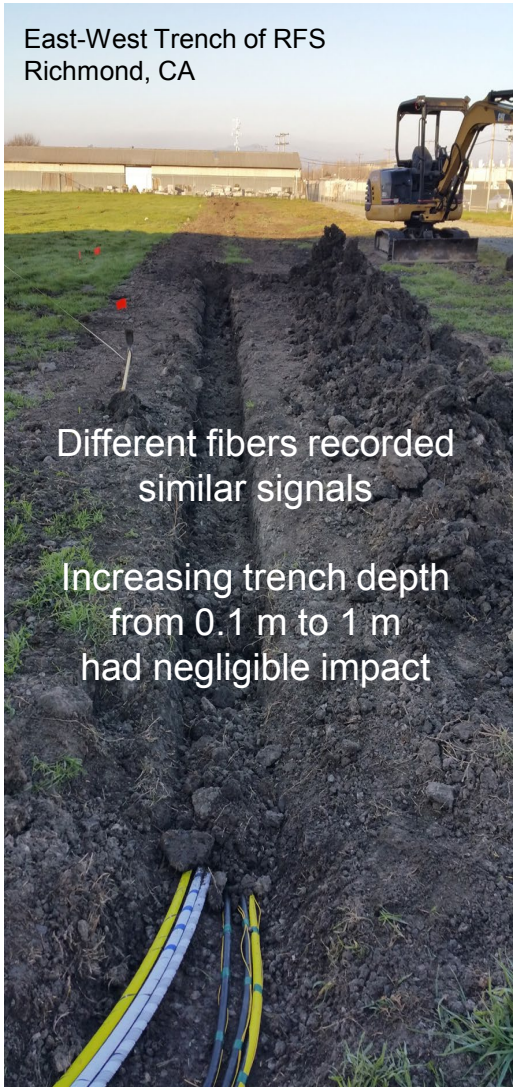


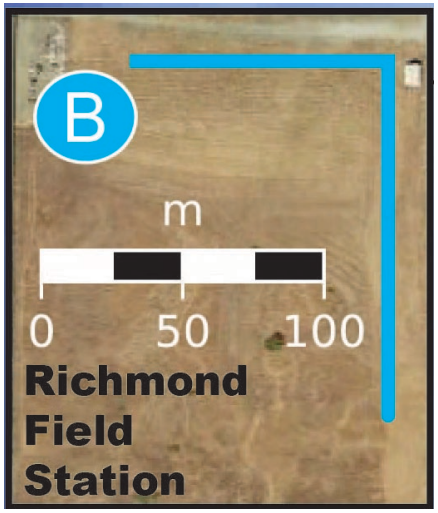
DAS turns a fiber-optic cable into a massive 1C seismic array.

(of strain-rate sensors)

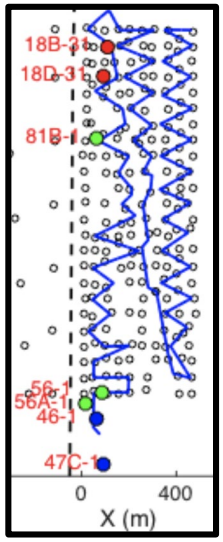
Making measurements

"Direct burial" of fiber-optic cables requires trenching and splicing.





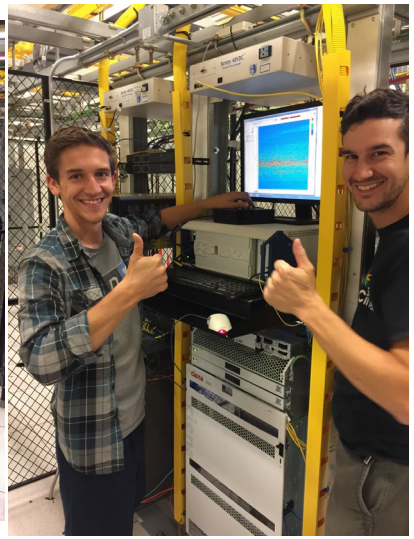
Lindsey et al., 2017

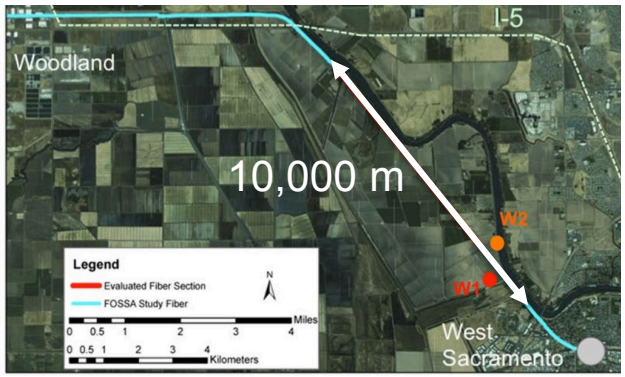


Wang et al., 2018

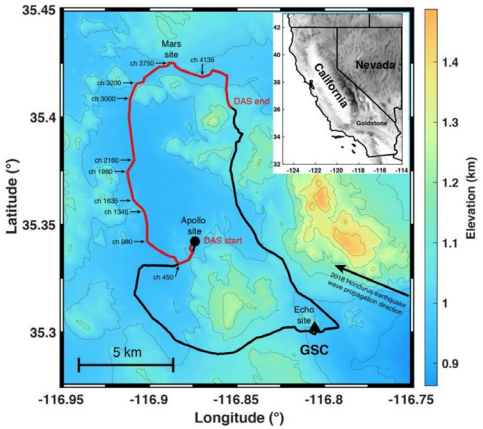
Making measurements

Using existing “dark fiber” in telecommunications cables requires access and leads to uncertainty in geometry and coupling.

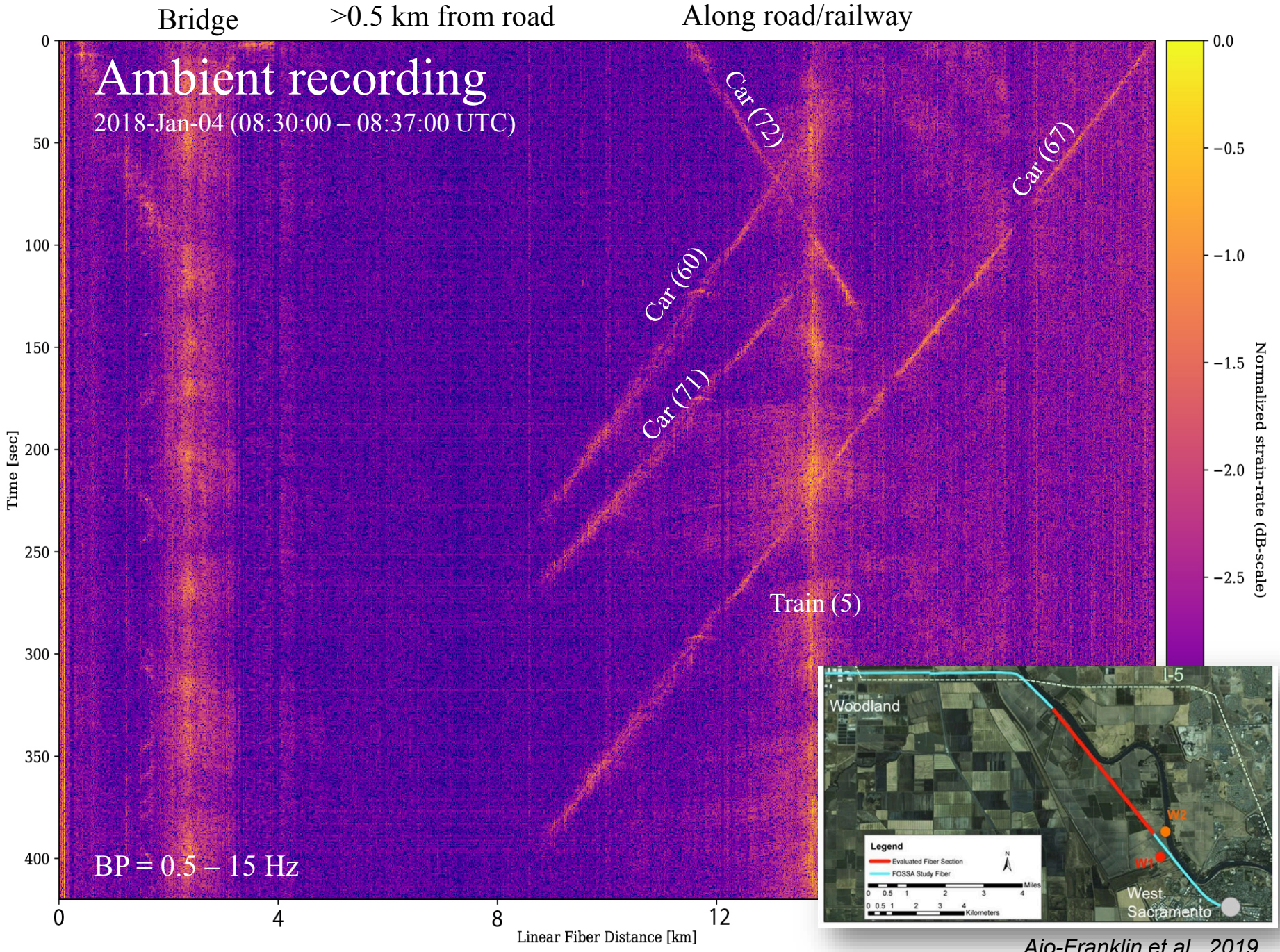




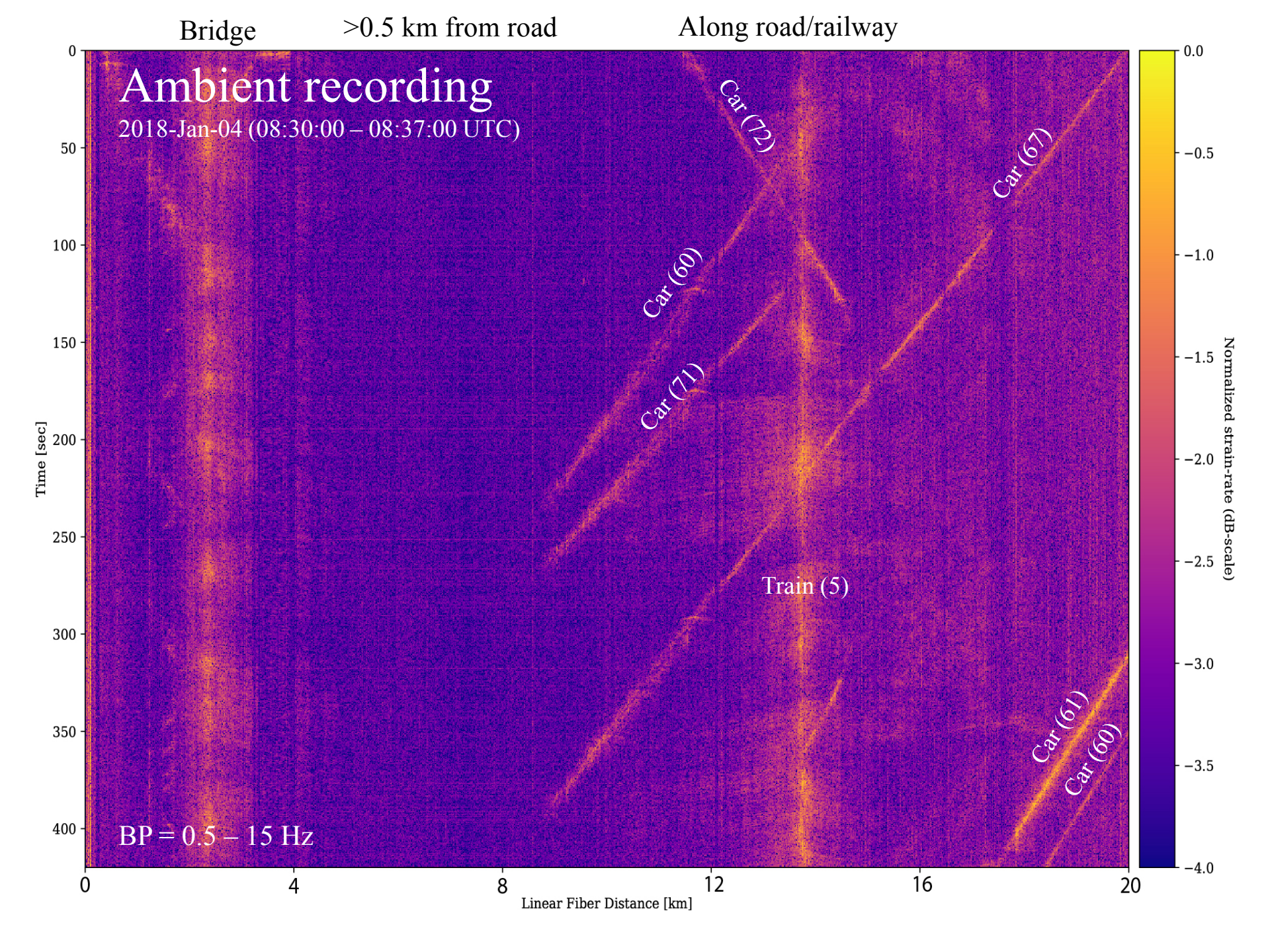
Ajo-Franklin et al., 2019



Yu et al., 2019



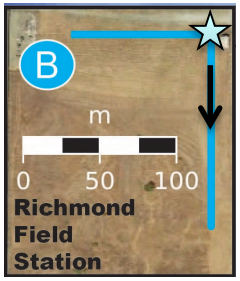
Ajo-Franklin et al., 2019


Bridge
>0.5 km from road
Along road/railway
Ambient recording
2018-Jan-04 (08:30:00 – 08:37:00 UTC)
Car (72)
Car (67)
Car (60)
Car (71)
Train (5)
Car (61)
Car (60)
BP = 0.5 – 15 Hz
Time [sec]
Linear Fiber Distance [km]
Normalized strain-rate (dB-scale)
0
50
100
150
200
250
300
350
400
4
8
12
16
20
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0

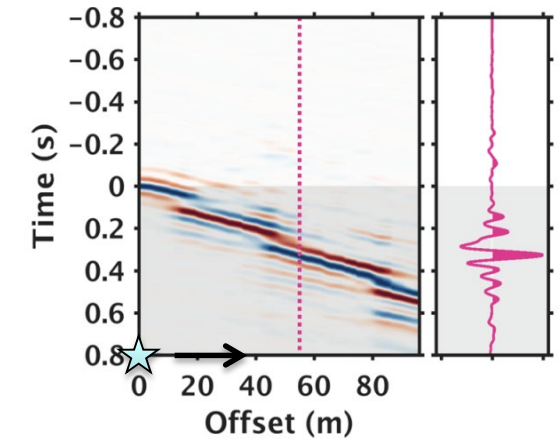
Examples

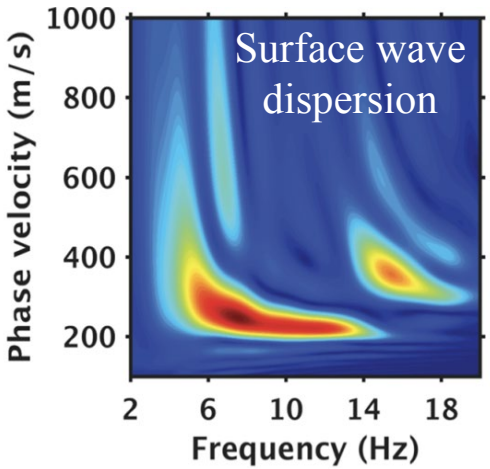
Ambient noise studies with DAS

Road ~50 m

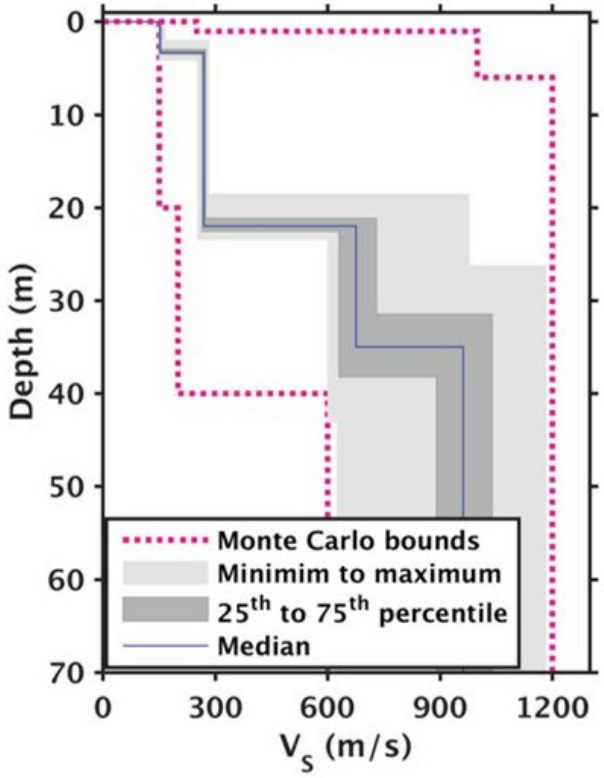


Noise correlations

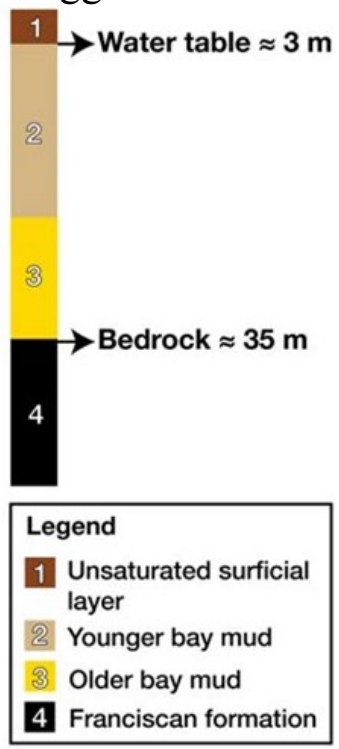




1-D Vs30 model over 100 m



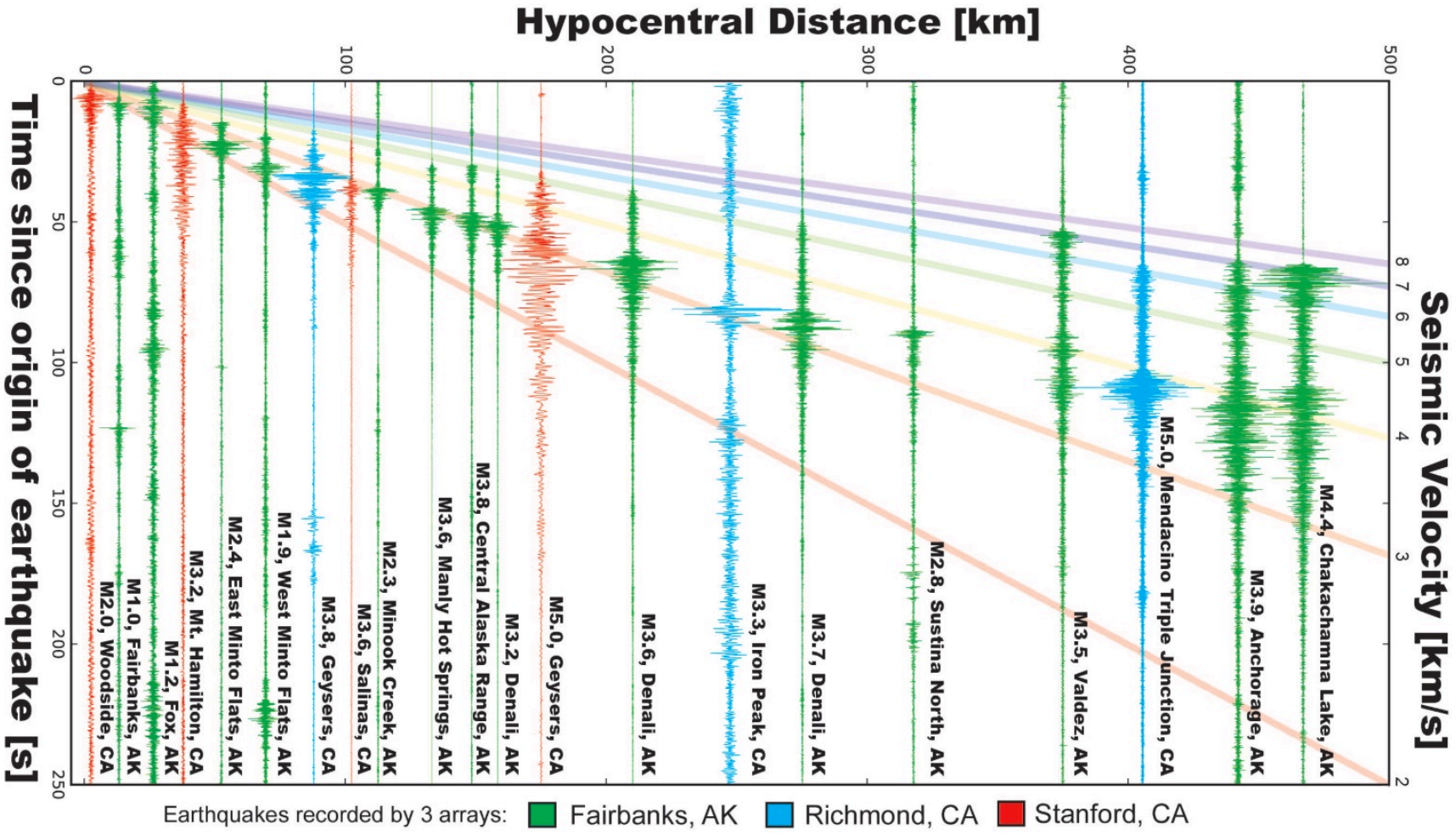
Logged borehole



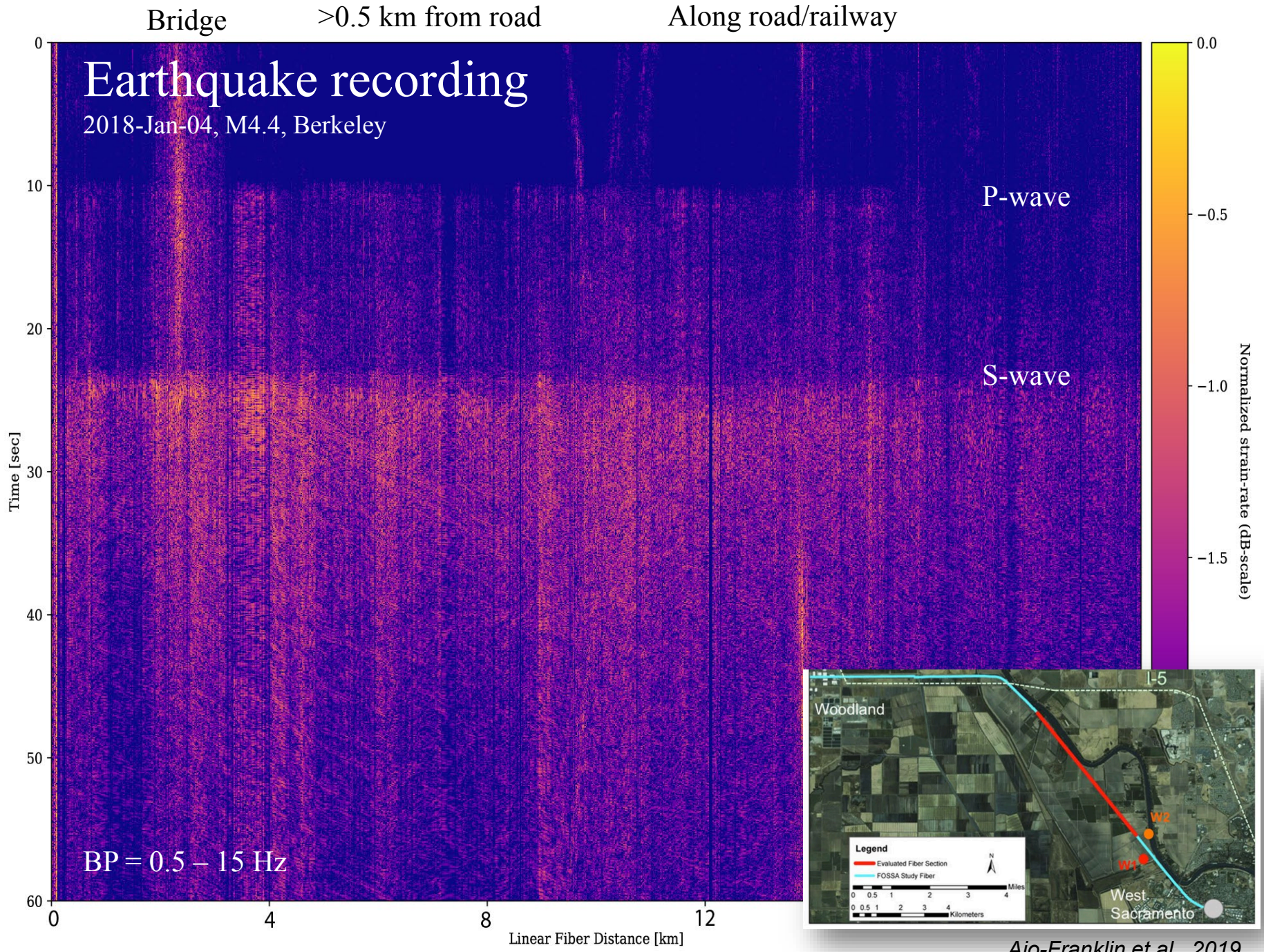
Dou et al., 2017; Zeng et al., 2017; Martin et al., 2018; Ajo-Franklin et al., 2019

Examples

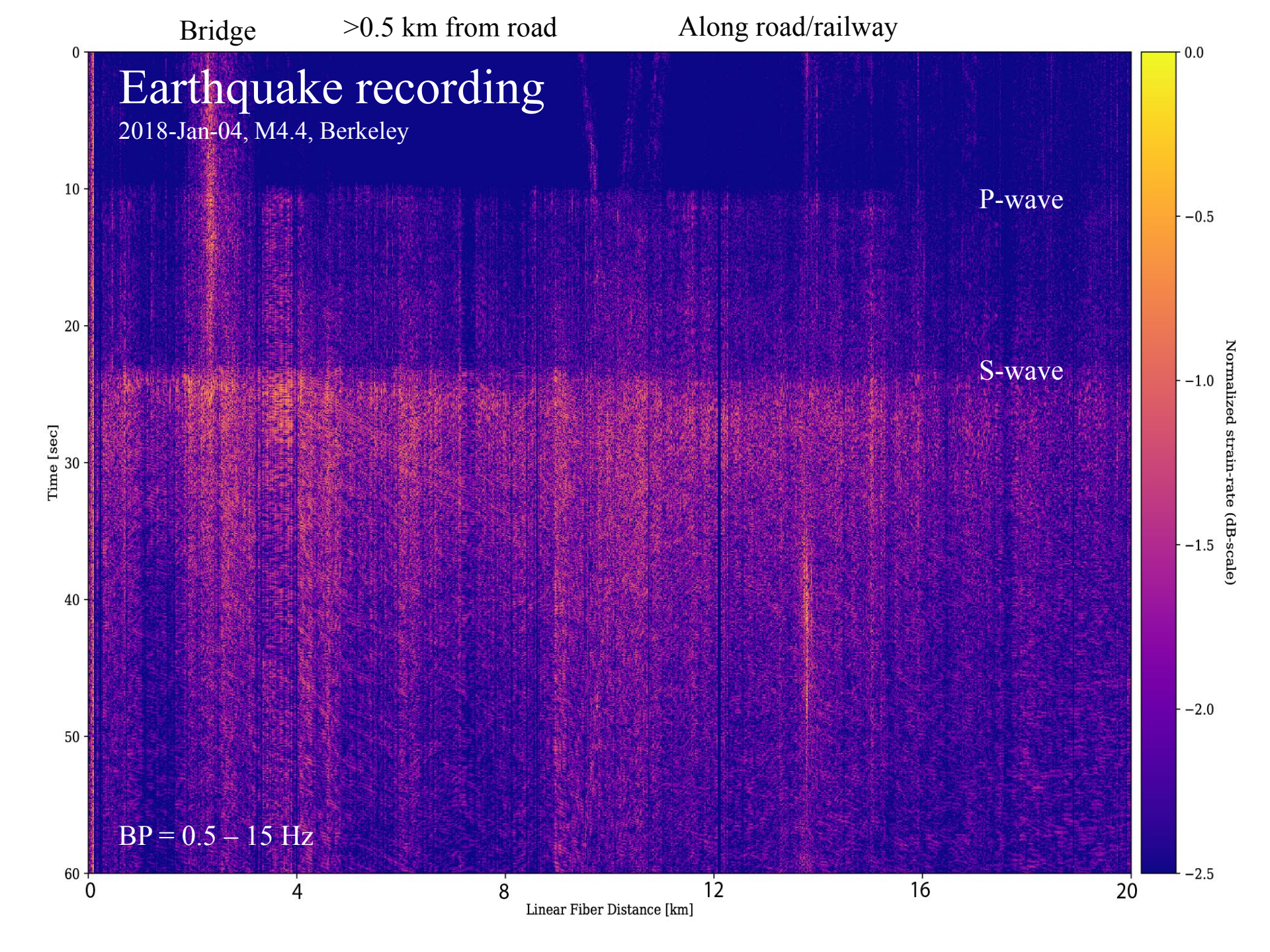
Earthquake studies with DAS



Lindsey et al., 2017; Wang et al., 2018; Li and Zhan, 2018; Jin and Roy, 2018; Jousset et al., 2018; Ajo-Franklin et al., 2019; Yu et al., 2019; Becker et al., 2019

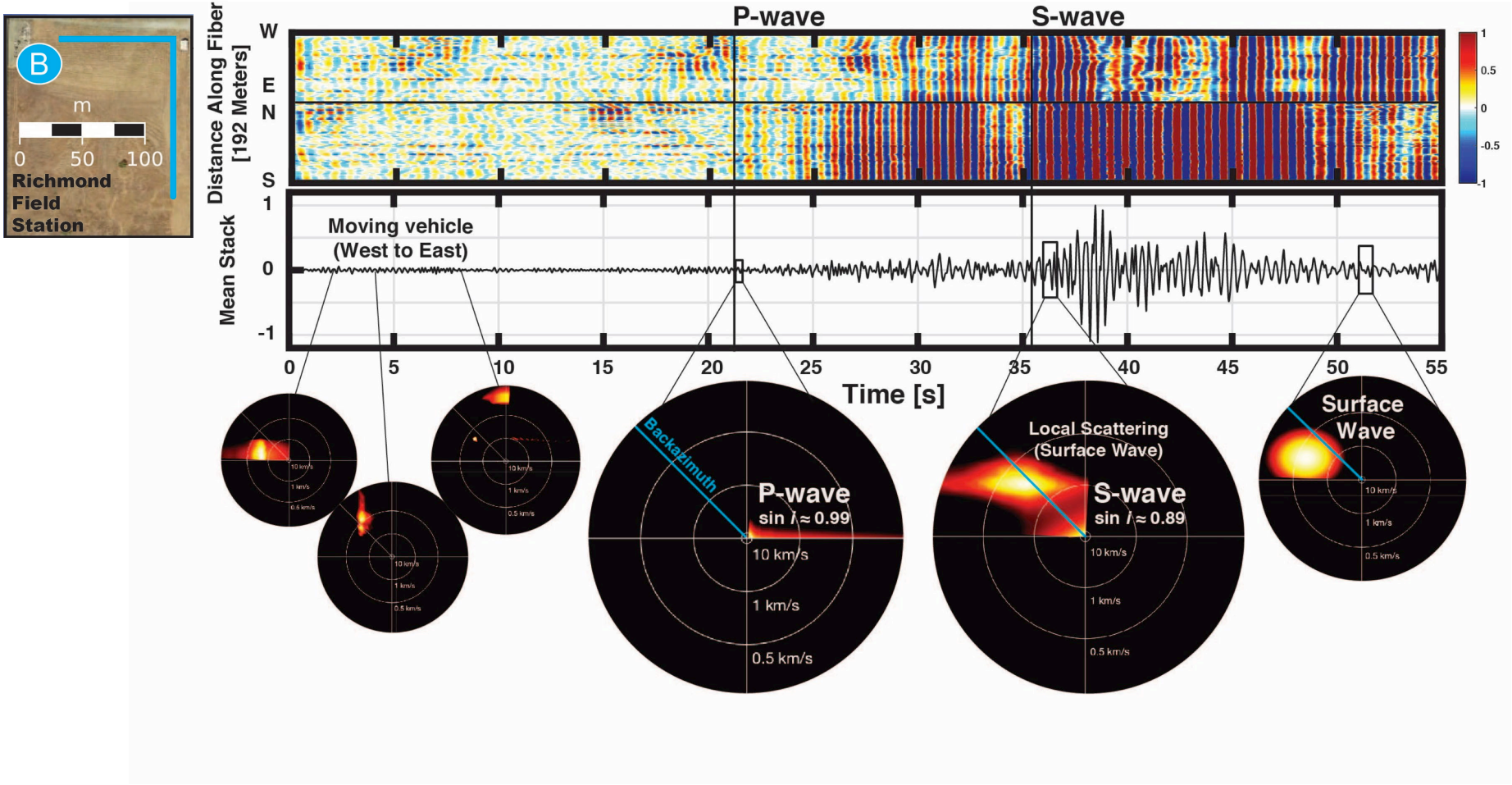


Ajo-Franklin et al., 2019


Bridge
>0.5 km from road
Along road/railway
Earthquake recording
2018-Jan-04, M4.4, Berkeley
P-wave
S-wave
BP = 0.5 – 15 Hz
Time [sec]
Linear Fiber Distance [km]
Normalized strain-rate (dB-scale)
0
10
20
30
40
50
60
0
4
8
12
16
20
0.0
−0.5
−1.0
−1.5
−2.0
−2.5

Examples

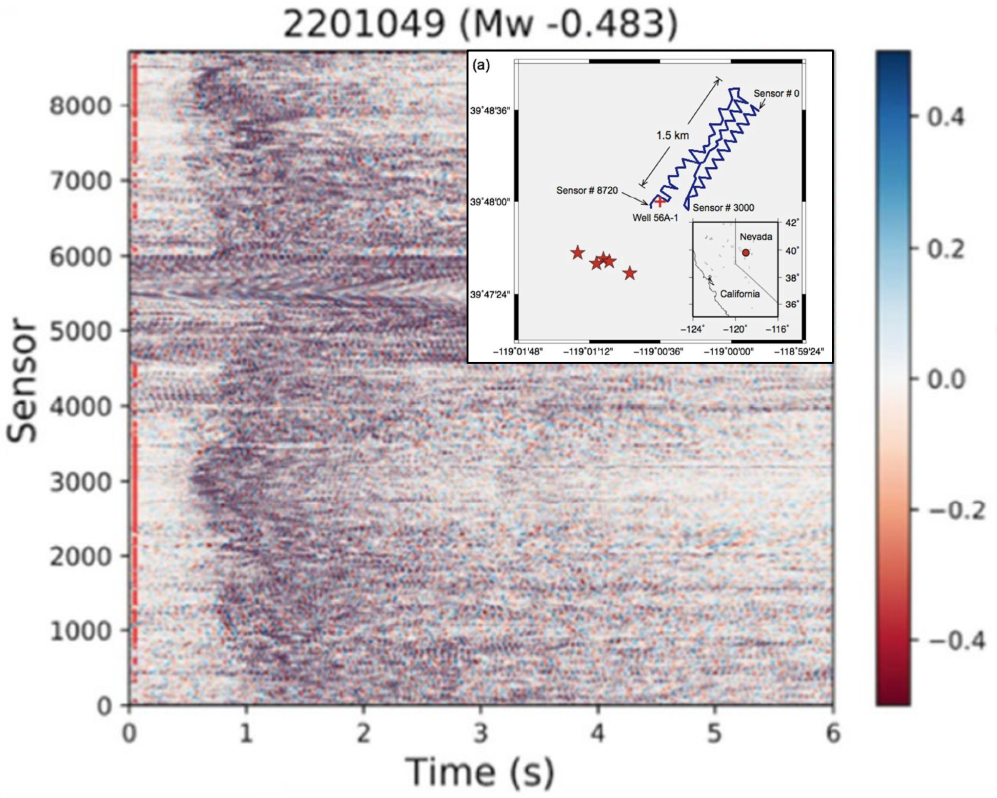
Array beamforming with DAS

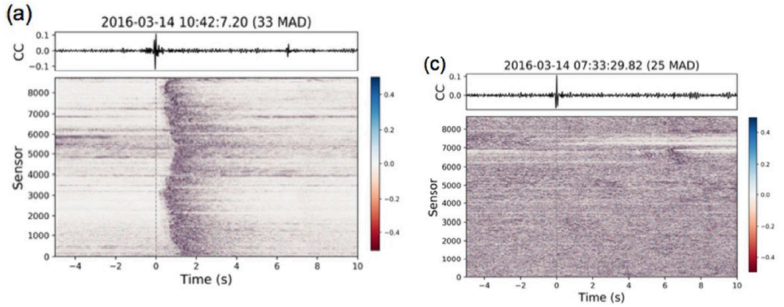


Lindsey et al., 2017; Wang et al., 2018; Li and Zhan, 2018; Jin and Roy, 2018; Jousset et al., 2018; Ajo-Franklin et al., 2019; Yu et al., 2019; Becker et al., 2019

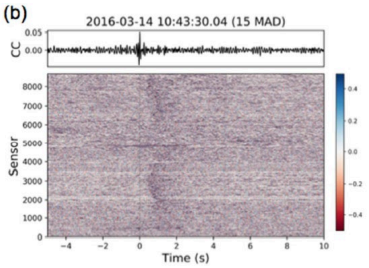
DAS Examples

Template matching with earthquakes at shut-in





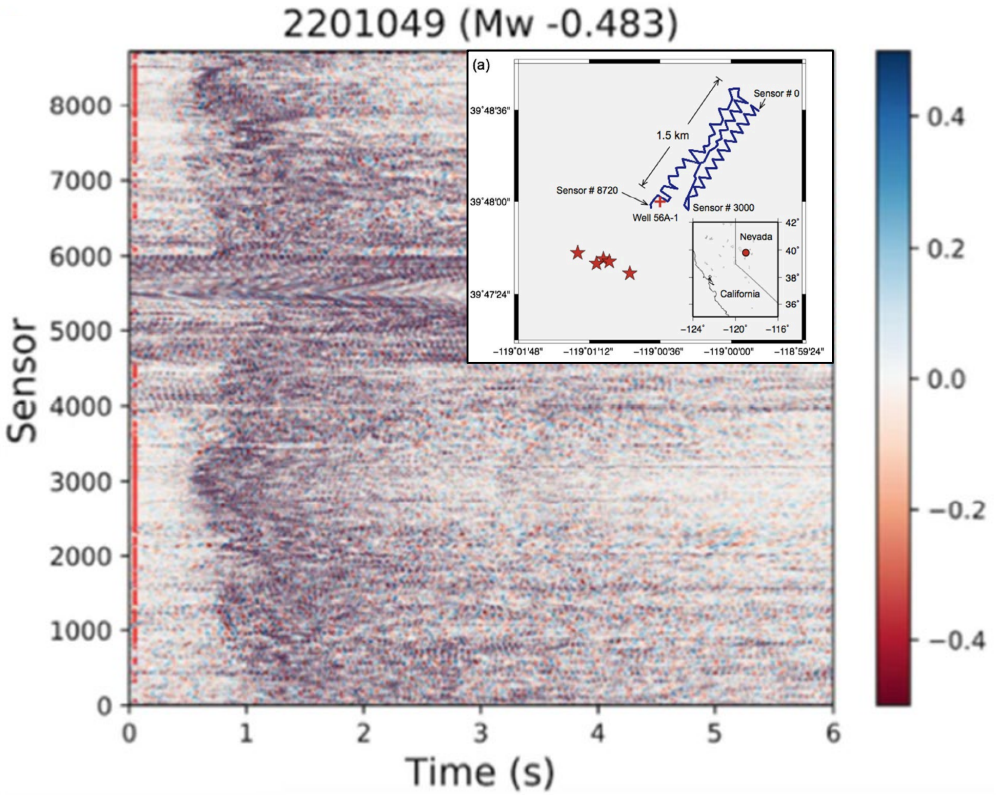
High Confidence Matches

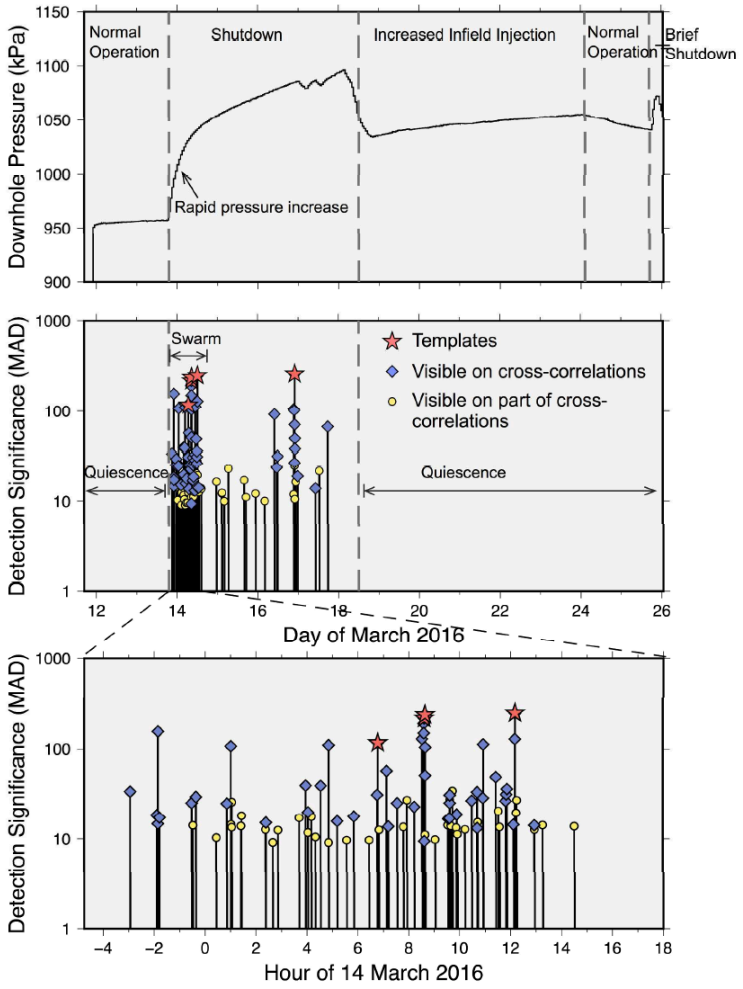


Lindsey et al., 2017; Wang et al., 2018; Li and Zhan, 2018; Jin and Roy, 2018; Jousset et al., 2018; Ajo-Franklin et al., 2019; Yu et al., 2019; Becker et al., 2019

DAS Examples

Template matching with earthquakes at shut-in

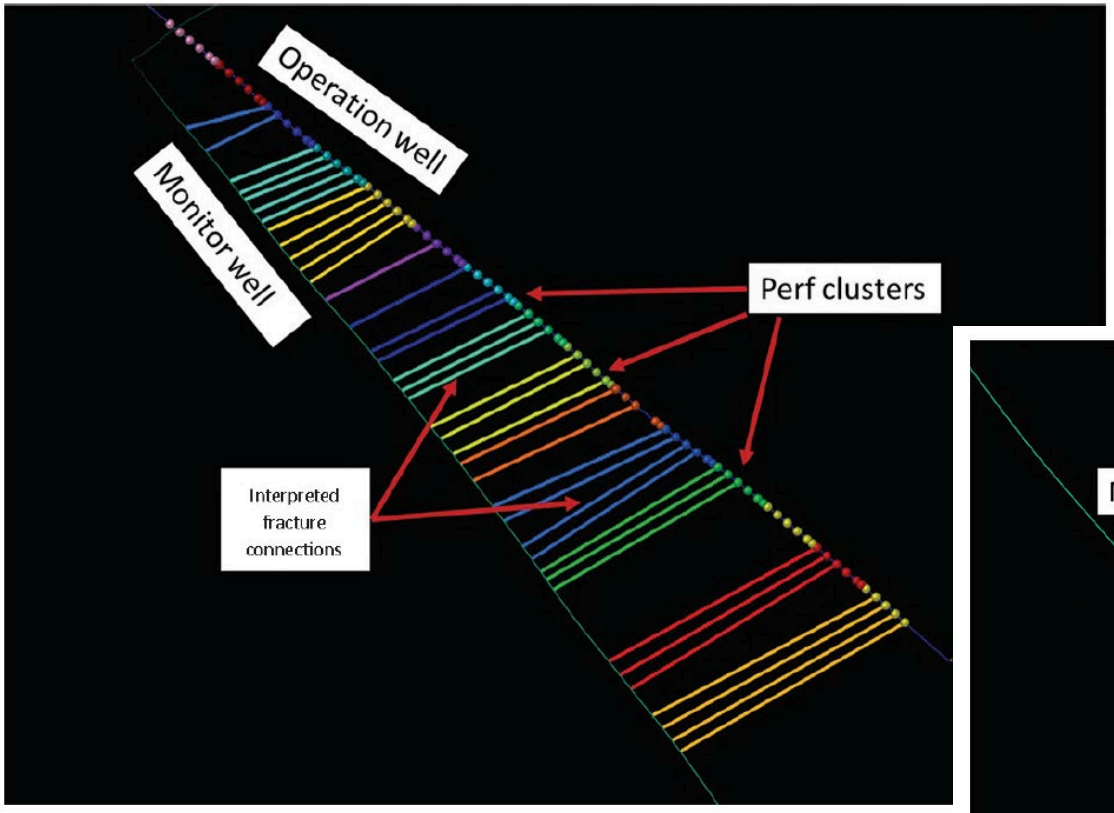


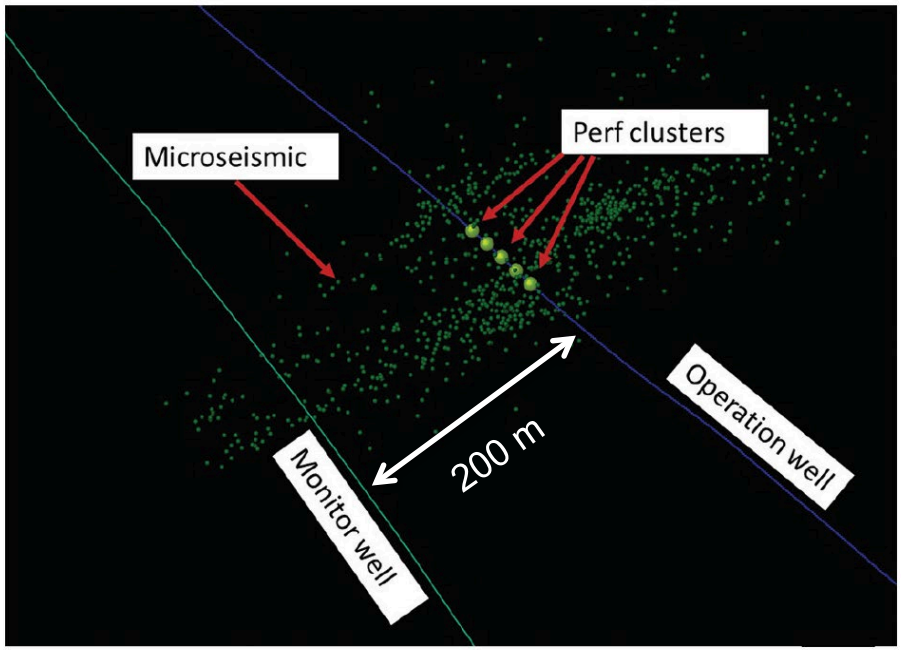


Lindsey et al., 2017; Wang et al., 2018; Li and Zhan, 2018; Jin and Roy, 2018; Jousset et al., 2018; Ajo-Franklin et al., 2019; Yu et al., 2019; Becker et al., 2019

DAS Examples

Strain and EQ detection during hydraulic fracturing

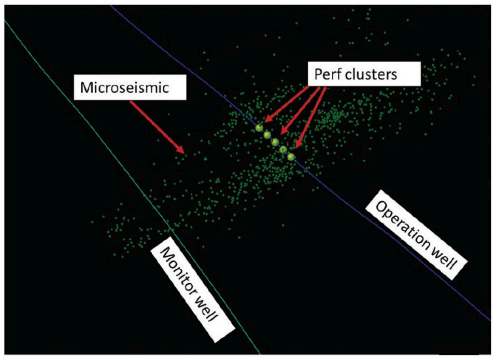


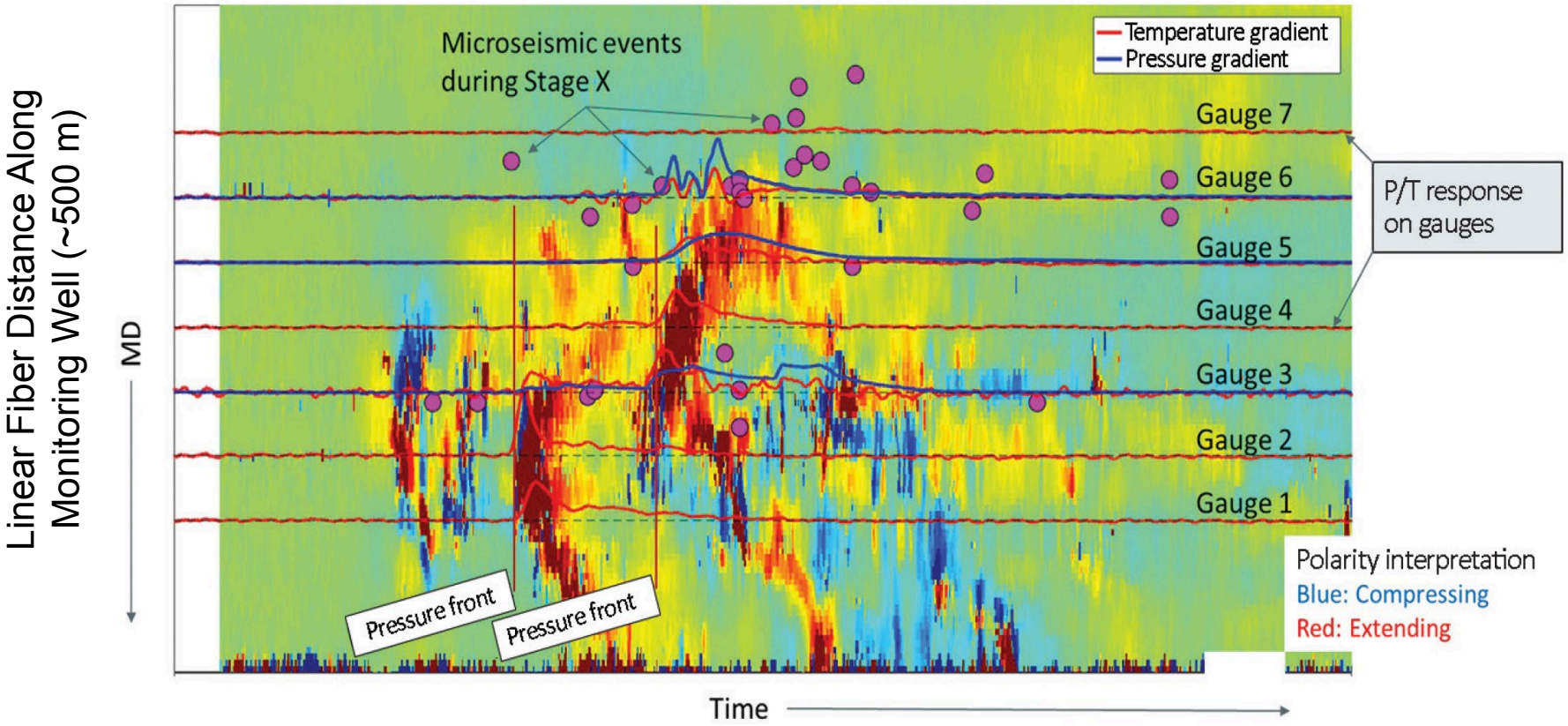


Lindsey et al., 2017; Wang et al., 2018; Li and Zhan, 2018; Jin and Roy, 2018; Jousset et al., 2018; Ajo-Franklin et al., 2019; Yu et al., 2019; Becker et al., 2019

DAS Examples

Strain and EQ detection during hydraulic fracturing



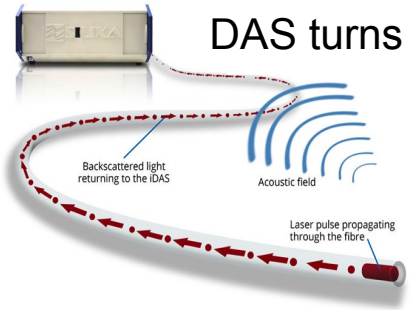


Lindsey et al., 2017; Wang et al., 2018; Li and Zhan, 2018; Jin and Roy, 2018; Jousset et al., 2018; Ajo-Franklin et al., 2019; Yu et al., 2019; Becker et al., 2019

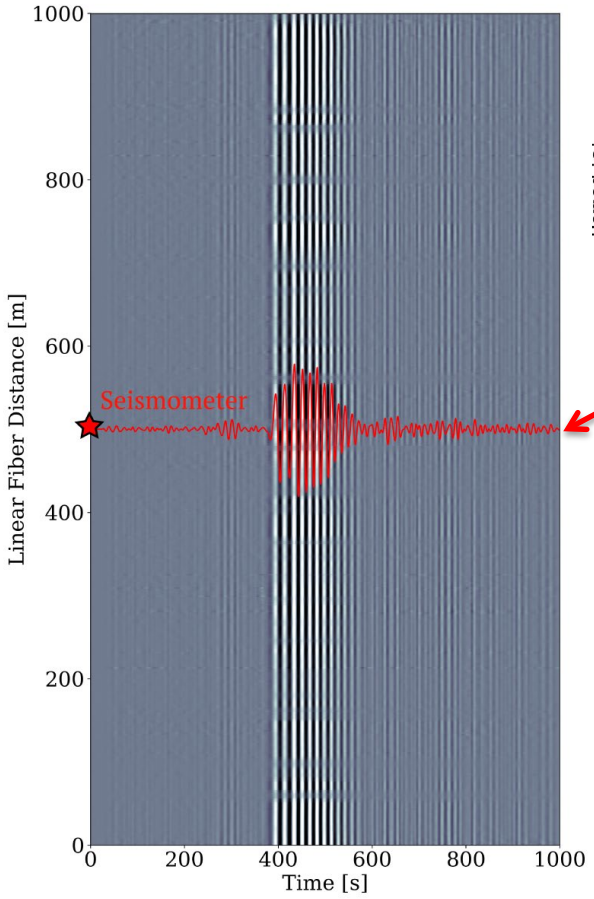
Opportunities for research

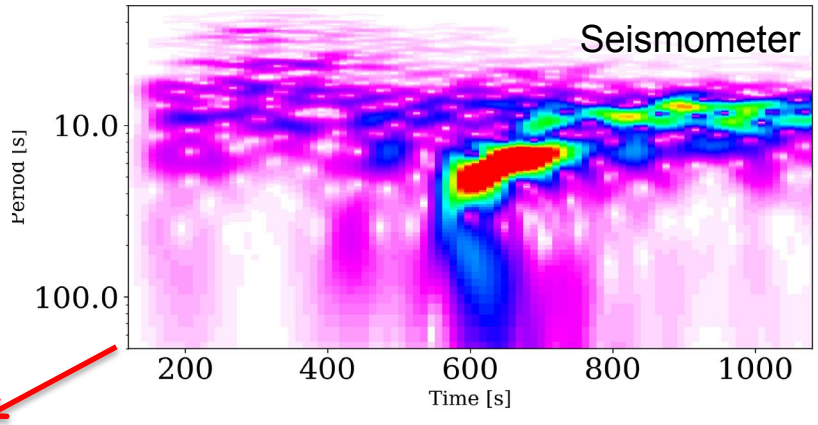
- Arrays of opportunity…bridging network gaps
- Time-lapse decadal (“Large T”) recording
- Urban seismology
- Offshore array seismology
- “Zero latency” offshore earthquake early warning
- Instrumentation (photonics/seismology)

Summary

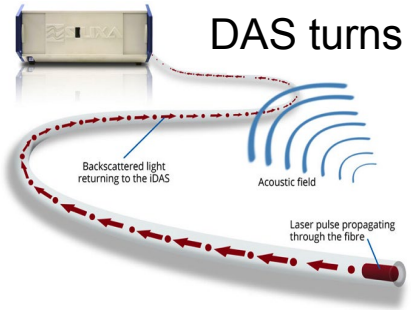


DAS turns a fiber-optic cable into a massive 1C seismic array





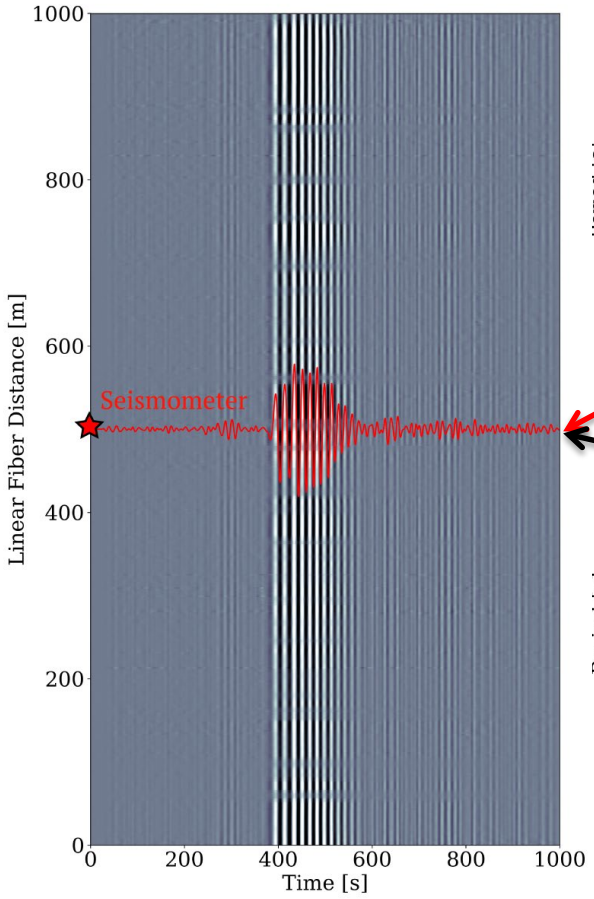
Summary

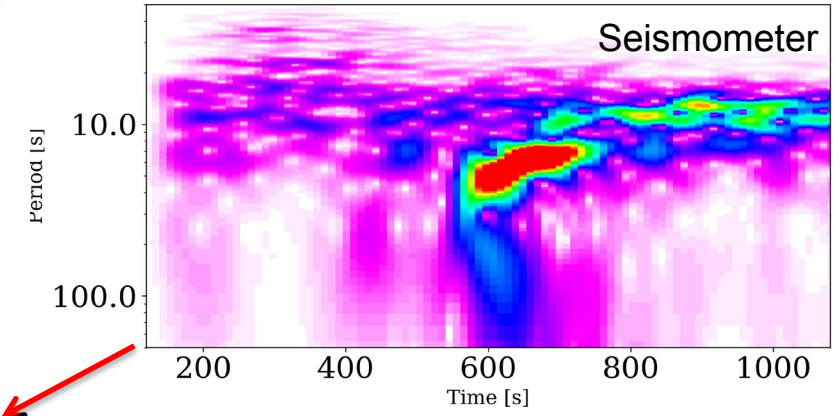


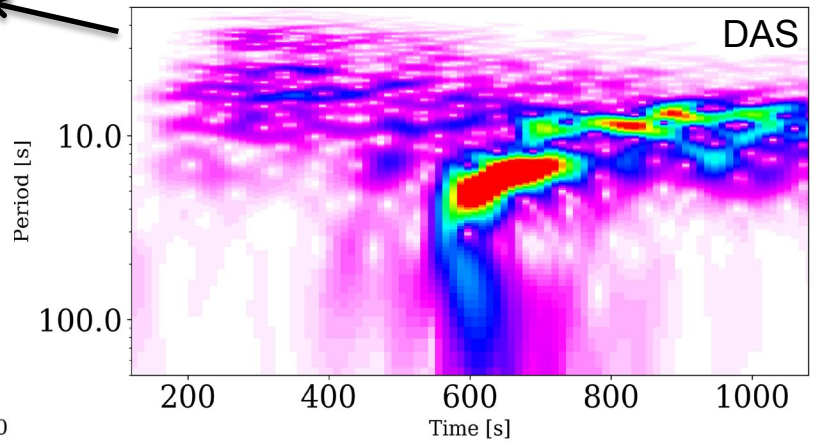
DAS turns a fiber-optic cable into a massive 1C seismic array

^

broadband

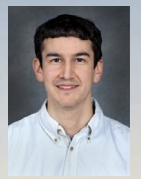







Horst Rademacher


Doug Dreger


Chris Tracy


Inder Monga


Nate Lindsey
(PhD student
UC Berkeley/LBNL)

Jonathan Ajo-Franklin

Tom Daley

Barry Freifeld

Michelle Robertson

Craig Ulrich


Eileen Martin
(Assistant Prof. Virginia Tech)


Verónica Rodríguez Tribaldos


Shan Dou


Xiaoye (Sherry) Li

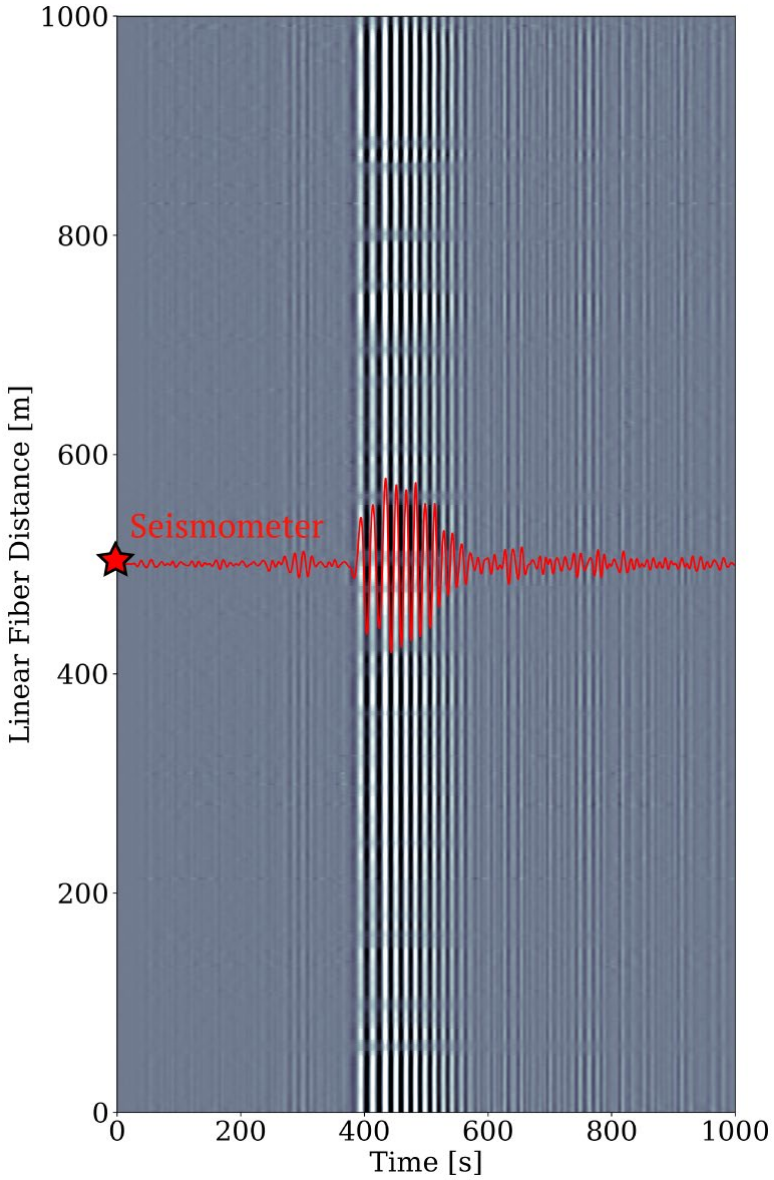

Chris Tracy

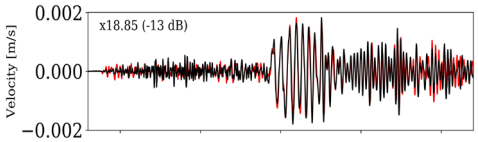

Inder Monga

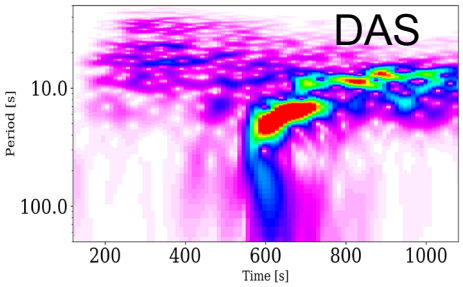

Aleksei Titov
(PhD student
Colorado School of Mines)

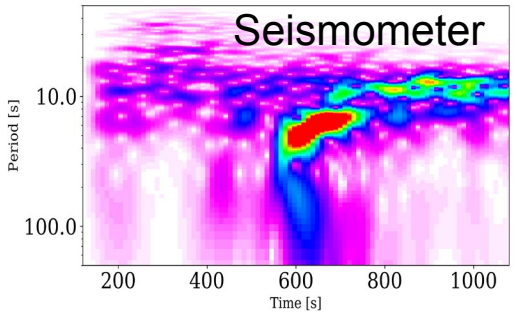
Supplementary slides

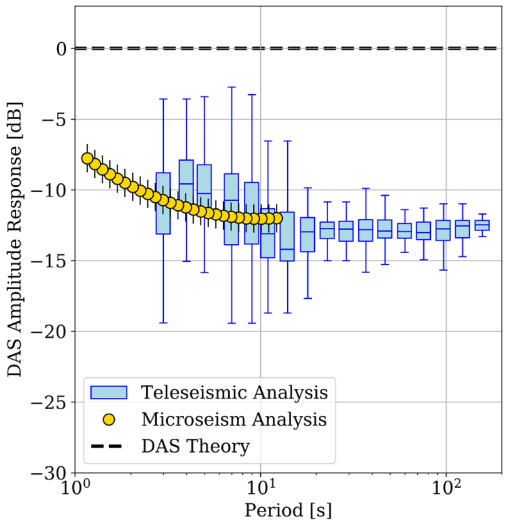
Towards an instrument response function for DAS

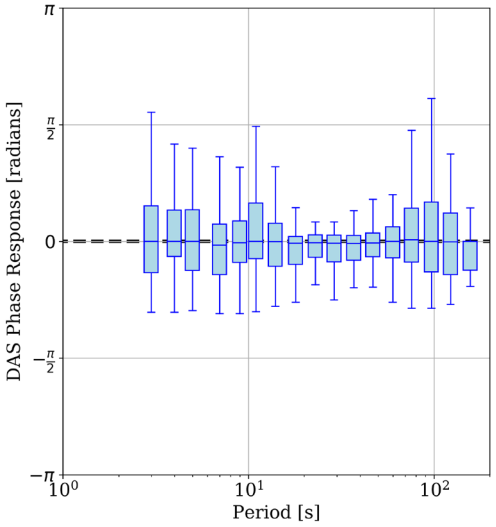








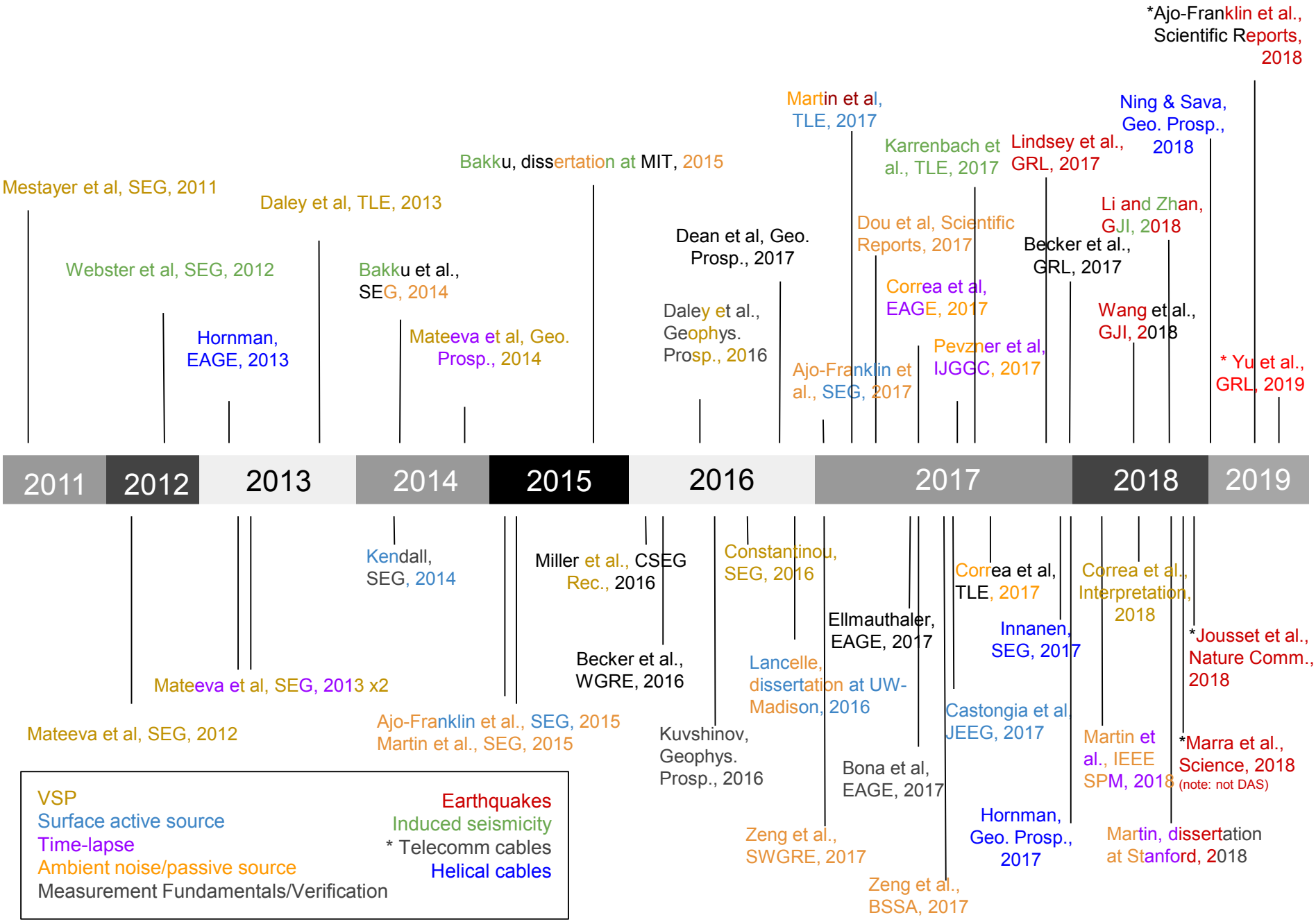




Lindsey et al., submitted

Projected market value in 2025 is $2B

"Key Players of the Global Distributed Acoustic Sensing Market", Review Health World (May 2019).


*Ajo-Franklin et al., Scientific Reports, 2018
Martin et al, TLE, 2017
Ning & Sava, Geo. Prosp., 2018
Karrenbach et al., TLE, 2017
Lindsey et al., GRL, 2017
Bakku, dissertation at MIT, 2015
Mestayer et al, SEG, 2011
Daley et al, TLE, 2013
Li and Zhan, GJI, 2018
Dou et al, Scientific Reports, 2017
Dean et al, Geo. Prosp., 2017
Becker et al., GRL, 2017
Webster et al, SEG, 2012
Bakku u et al., SEG, 2014
Correa et al, EAGE, 2017
Daley et al., Geophys. Prosp., 2016
Wang et al., GJI, 2018
Hornman, EAGE, 2013
Mateeva et al, Geo. Prosp., 2014
Pevzner et al, IJGGC, 2017
* Yu et al., GRL, 2019
Ajo-Franklin et al., SEG, 2017
2011
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Kendall, SEG, 2014
Miller et al., CSEG Rec., 2016
Constantinou, SEG, 2016
Correa et al, TLE, 2017
Correa et al., Interpretation, 2018
Ellmauthaler, EAGE, 2017
Innanen, SEG, 2017
*Jousset et al., Nature Comm., 2018
Becker et al., WGRE, 2016
Lancelle, dissertation at UW-Madison, 2016
Mateeva et al, SEG, 2013 x2
Castongia et al, JEEG, 2017
Martin et al., IEEE SPM, 2018
*Marra et al., Science, 2018 (note: not DAS)
Ajo-Franklin et al., SEG, 2015
Martin et al., SEG, 2015
Kuvshinov, Geophys. Prosp., 2016
Mateeva et al, SEG, 2012
Bona et al, EAGE, 2017
Hornman, Geo. Prosp., 2017
Zeng et al., SWGRE, 2017
Martin, dissertation at Stanford, 2018
Zeng et al., BSSA, 2017
VSP
Surface active source
Time-lapse
Ambient noise/passive source
Measurement Fundamentals/Verification
Earthquakes
Induced seismicity
* Telecomm cables
Helical cables

Many unresolved instrument questions…

"Please—no technology questions!"

Instrument response function?

Self-noise? What is the minimum sensitivity?

Dynamic range? At what amplitude will DAS data saturate or "clip"?

Are f > 1 Hz measurements actually representative of ground motion?

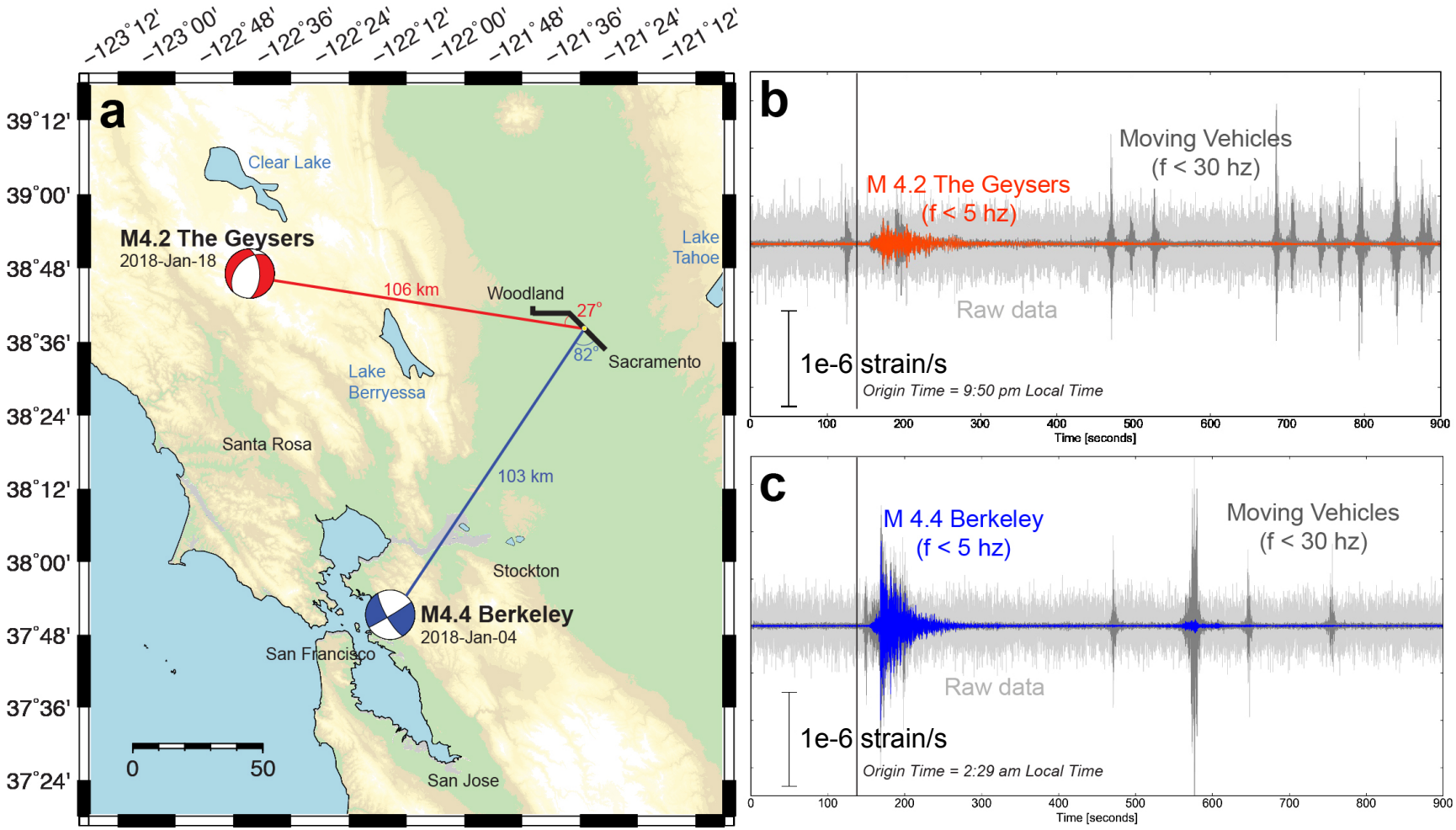
Consequences of recording strain/strain-rate instead of displacement/velocity?

How well do fiber-optic cables couple to the Earth?

How do different install conditions affect DAS response?

Can telecommunications cables be augmented to improve response?

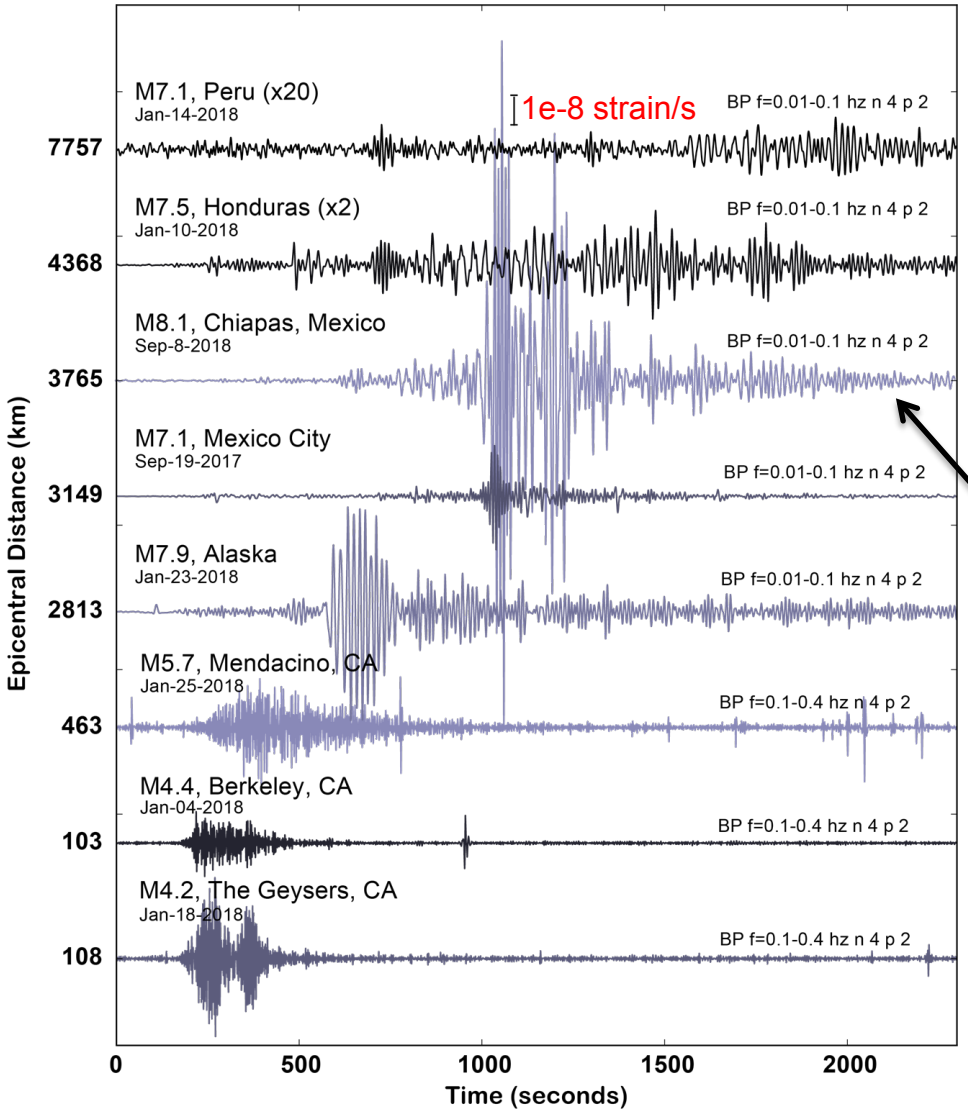
DAS can record earthquakes



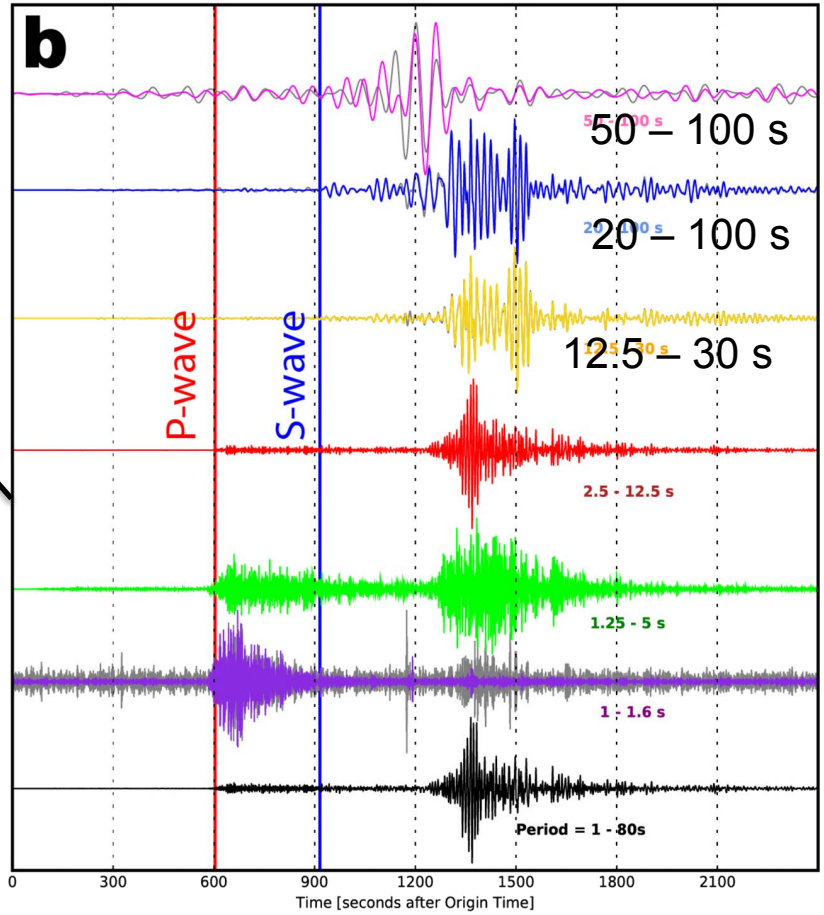
Lindsey et al., 2017 [GRL];
Ajo-Franklin, Dou, Lindsey et al., 2019 [Nature, Sci Rep]

DAS can record GLOBAL earthquakes

Teleseismic observations at Sacramento

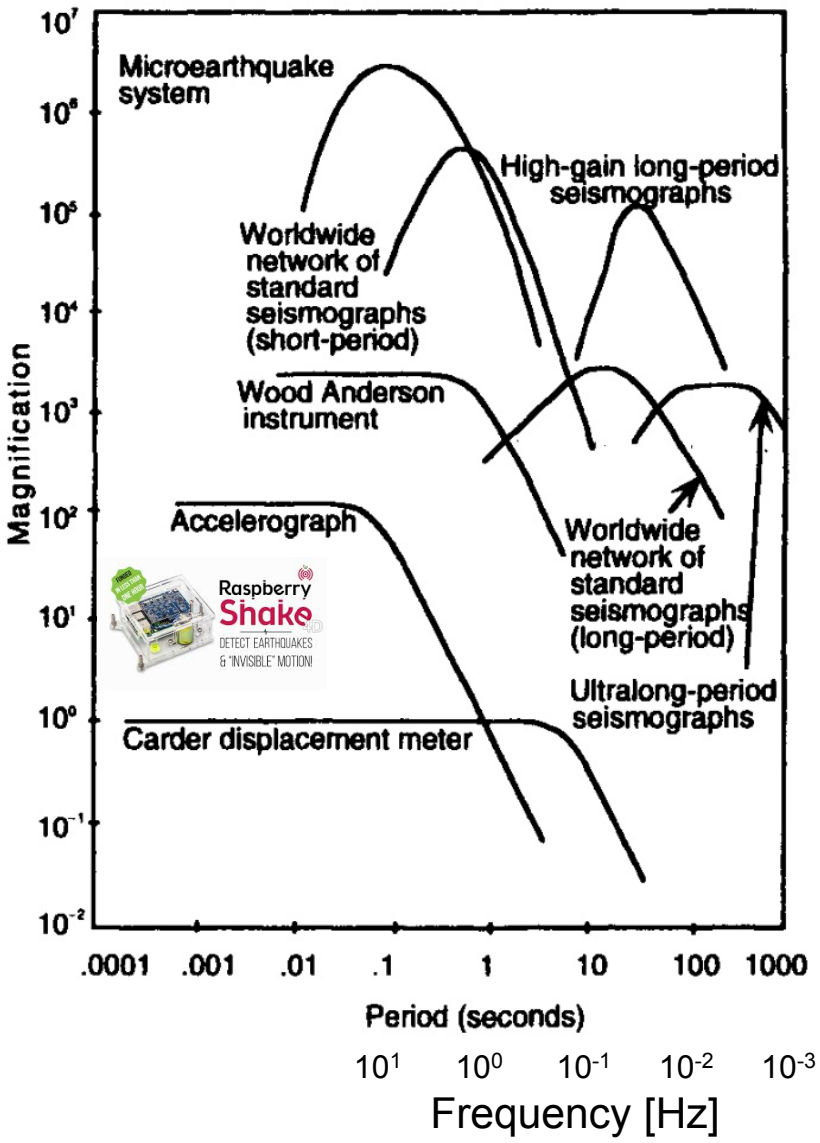


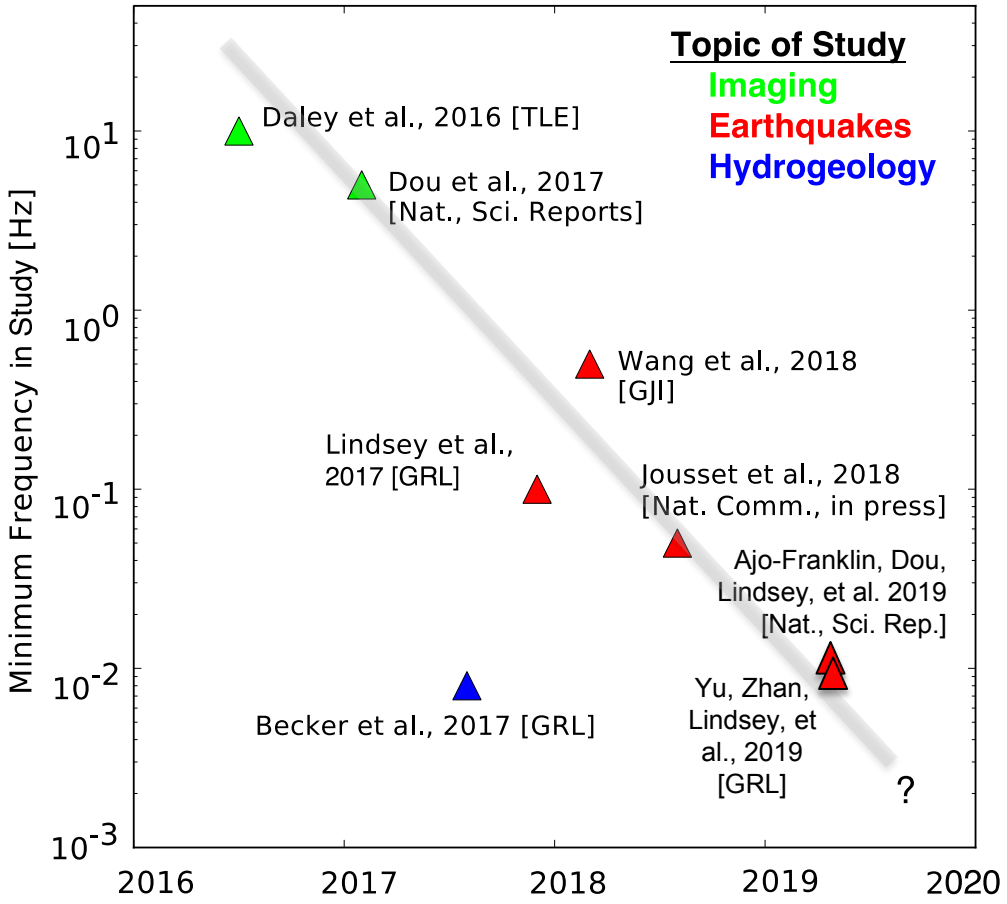
M8.1 Chiapas, Mexico 2018



Ajo-Franklin, Dou, Lindsey et al., 2019 [Nature, Sci Rep]

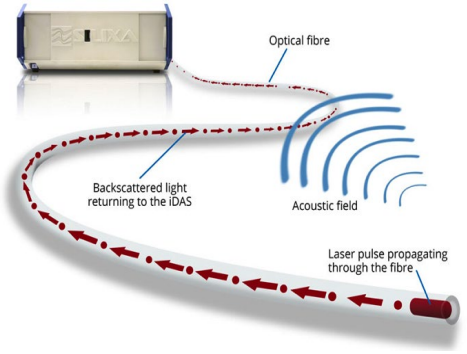
What is DAS instrument response?





f > 1 Hz is useful...but how low can DAS go?

What is DAS instrument response?

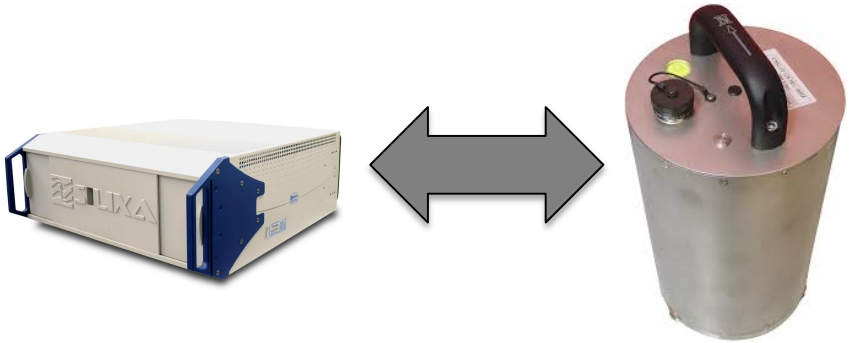


The Silixa iDAS measures

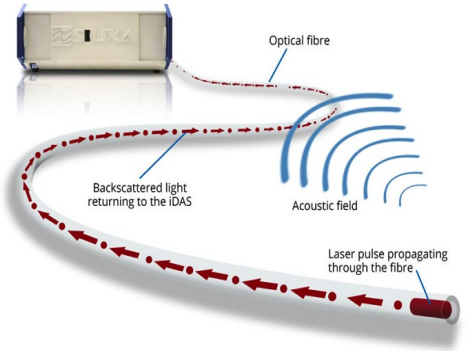
$$\Delta\dot{\Phi} \approx \dot{\epsilon_{zz}} = \frac{\partial}{\partial t}\left(\frac{\partial u}{\partial z}\right) = \frac{\partial}{\partial t}\left(\frac{u\left(z+\frac{dz}{2}\right) - u\left(z-\frac{dz}{2}\right)}{dz}\right)$$

How can we test the hypothesis that
DAS has a broadband “flat-to-DC” instrument response?

Teleseismic earthquakes generate
T ~ 2 – 200 s
Use a broadband seismometer



What is DAS instrument response?



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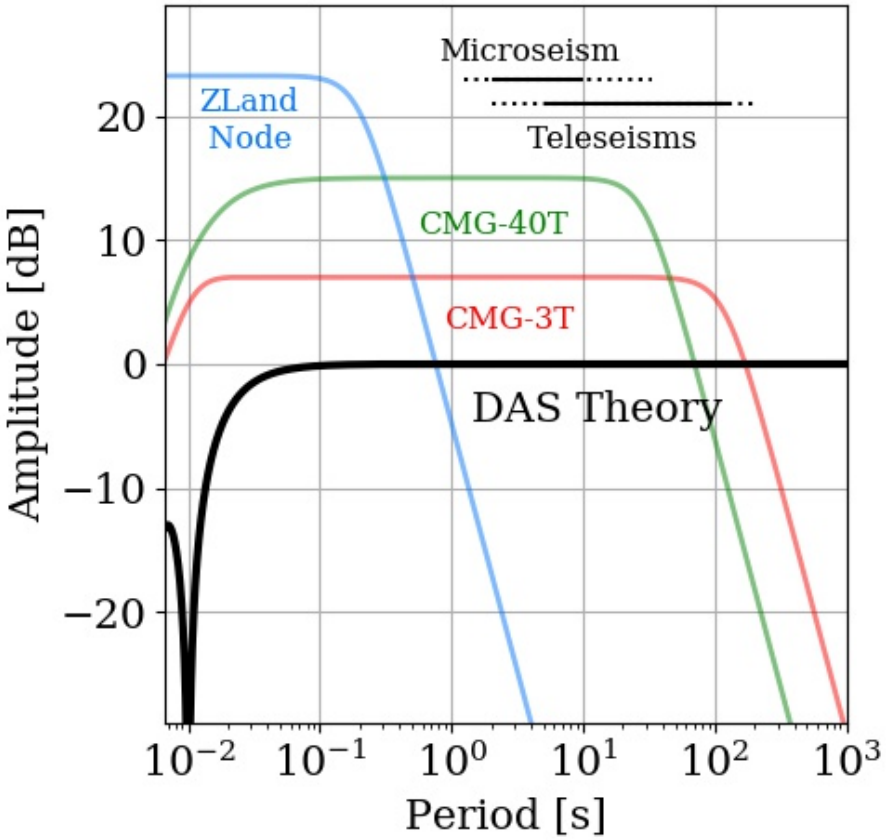
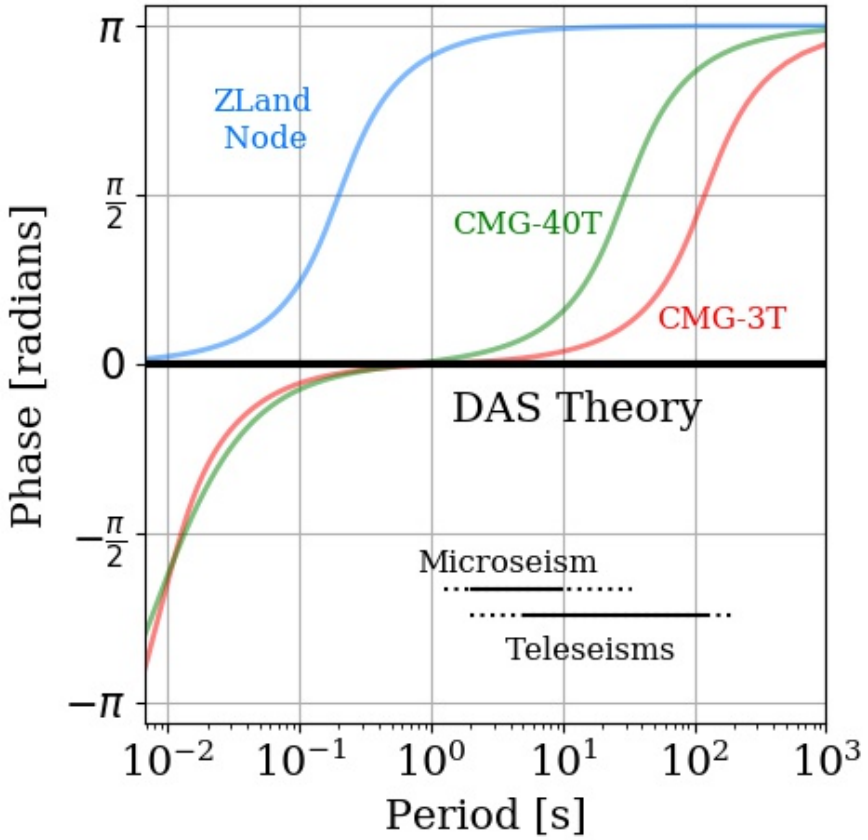
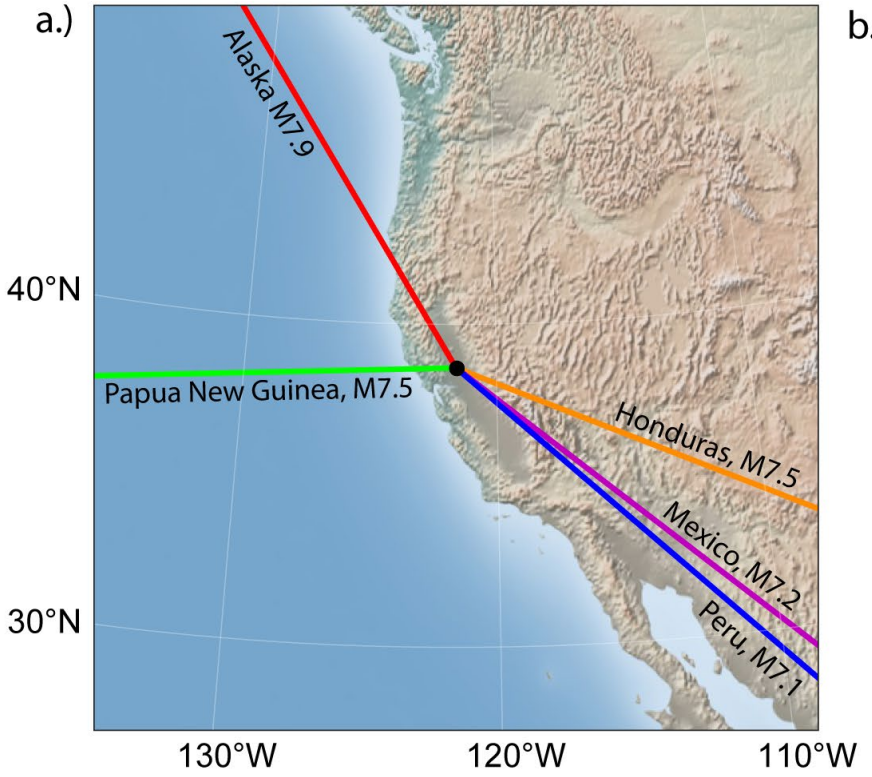
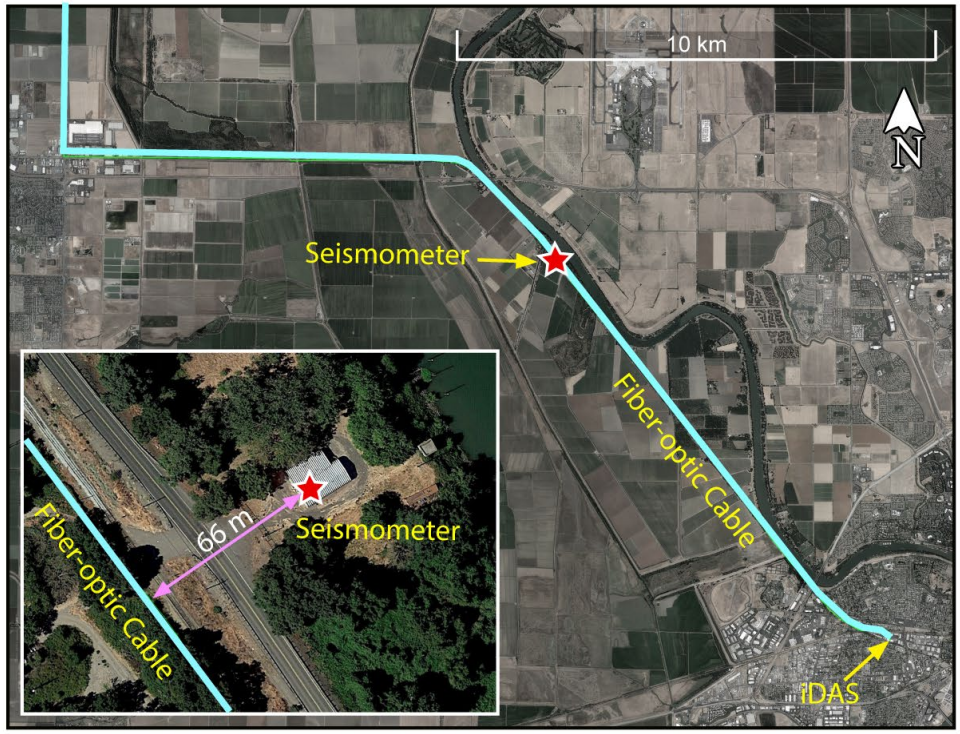




Field Experiment

Guralp CMG-3T





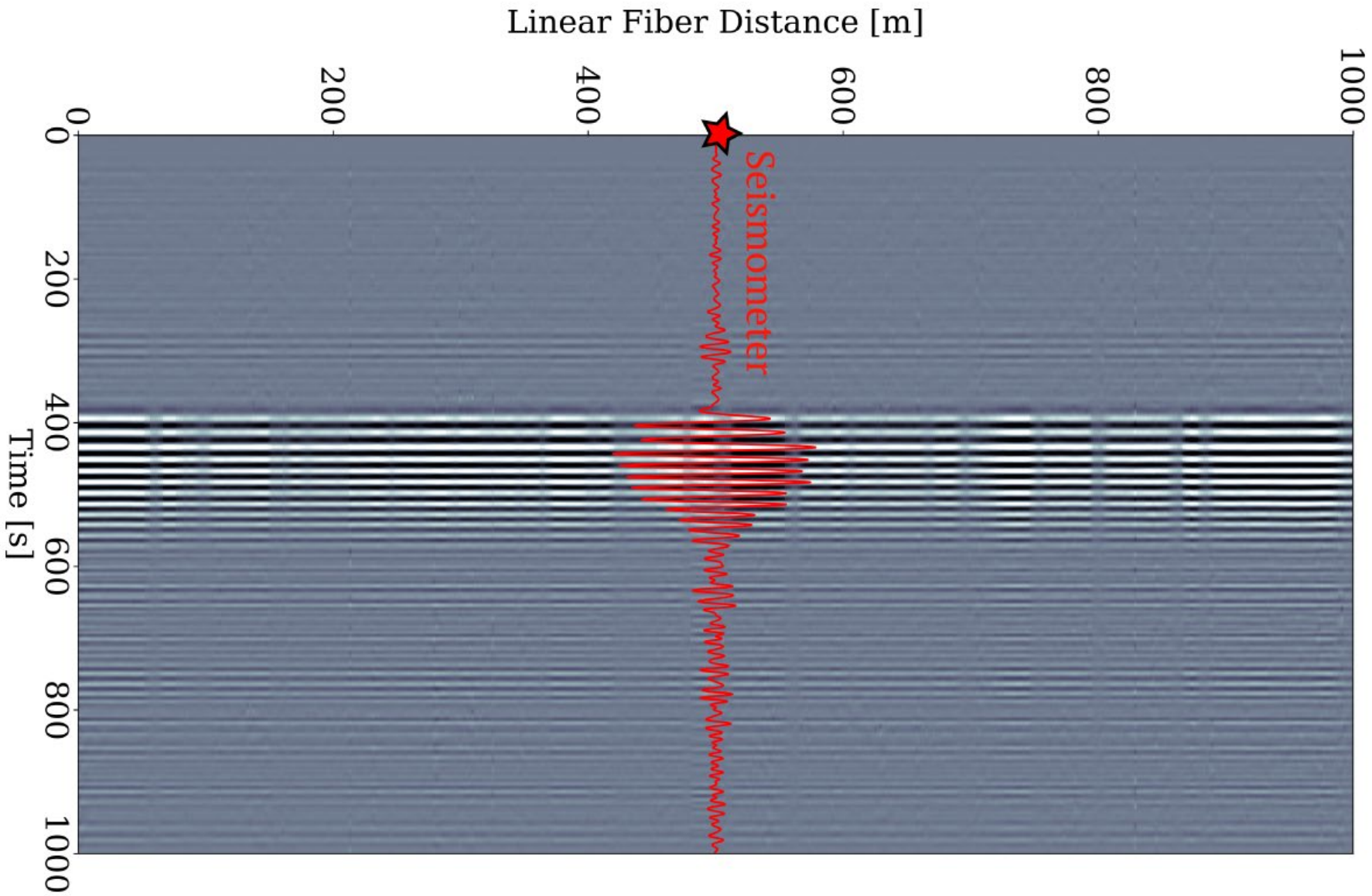
Measure true ground velocity at fiber location using broadband seismometer

Data

Teleseismic recording

Alaska M7.9

Jan-23-2018; 2778 km

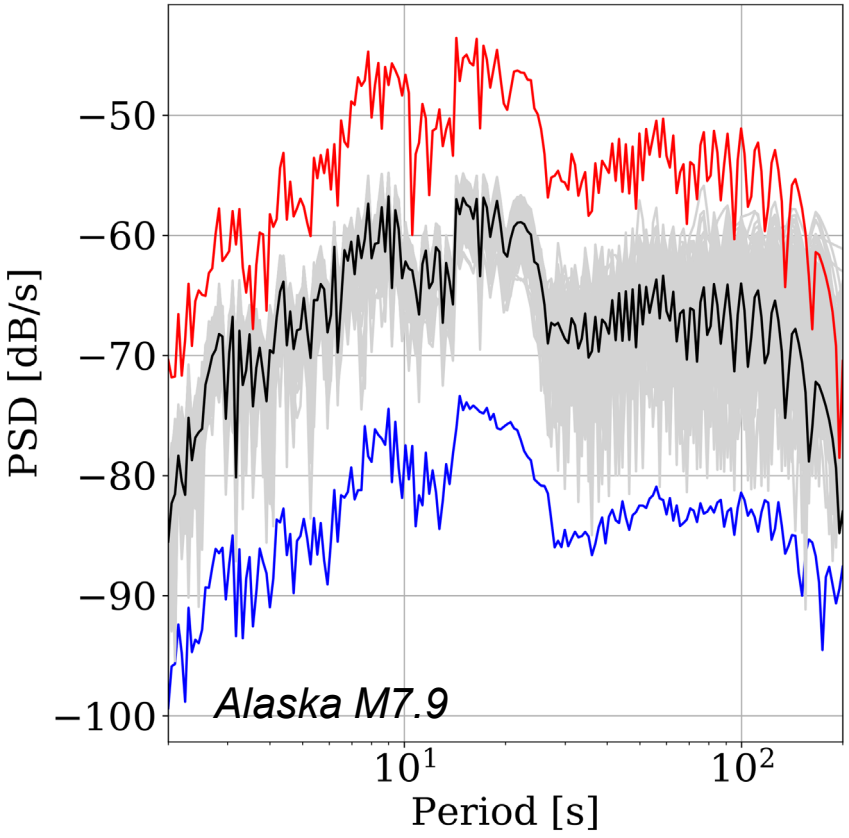


Data Processing

FK-domain rescale

$$\frac{\partial u}{\partial t} = \left(-\frac{\omega}{k}\right)\frac{\partial u}{\partial x}$$

Aki and Richards, (1980)



Ground Velocity
(after instrument response removal)

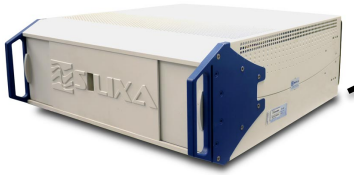
DAS Velocity
(average over 1 km or 500 channels)

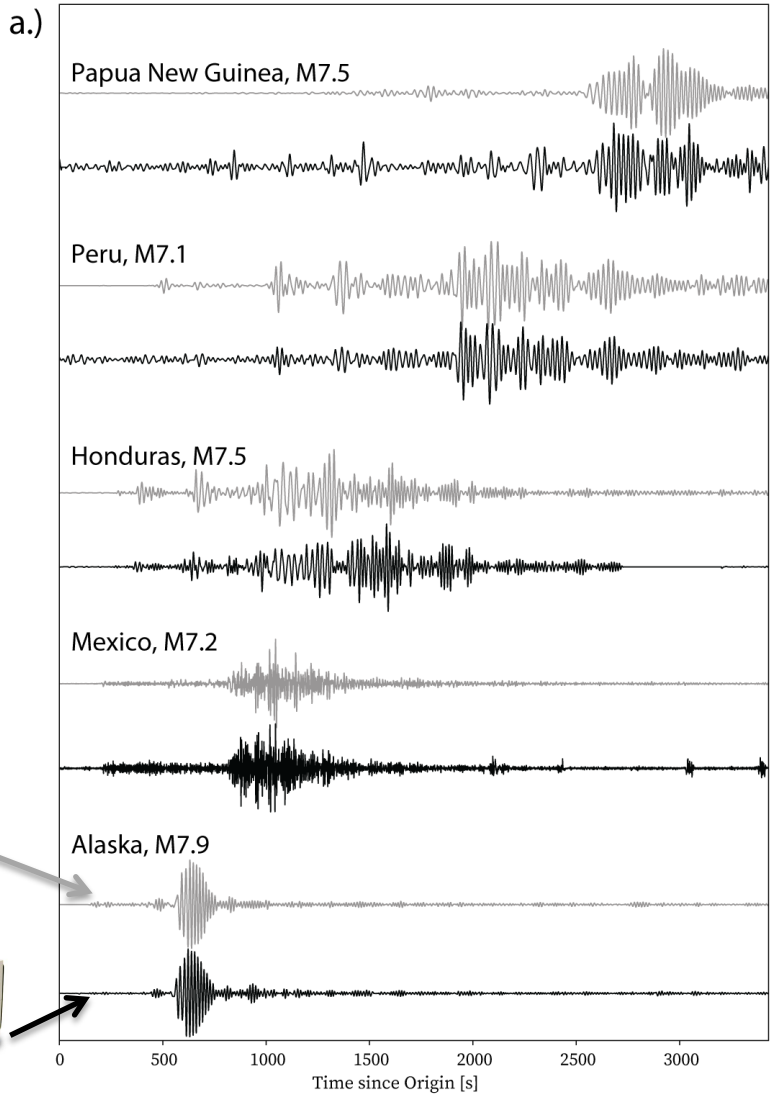
DAS Strain

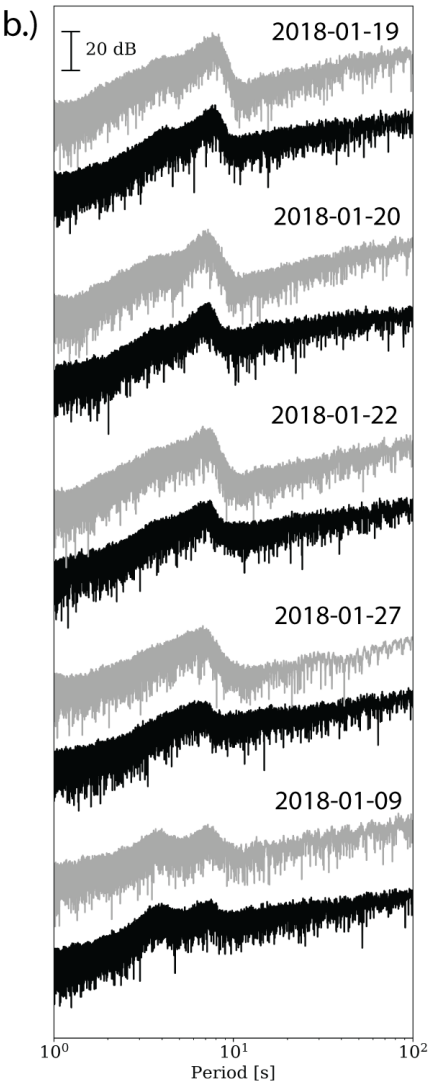
Alaska M7.9
Jan-23-2018; 2778 km

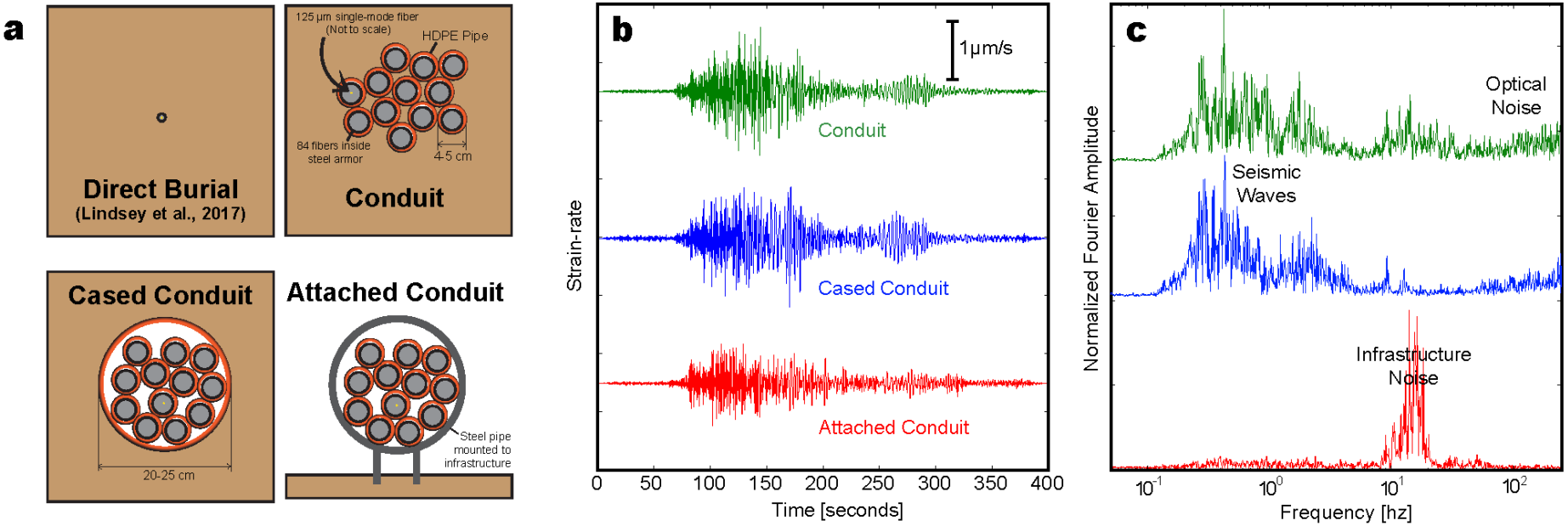
Data Processing

Teleseismic recording evaluation (we also capture microseism noise)







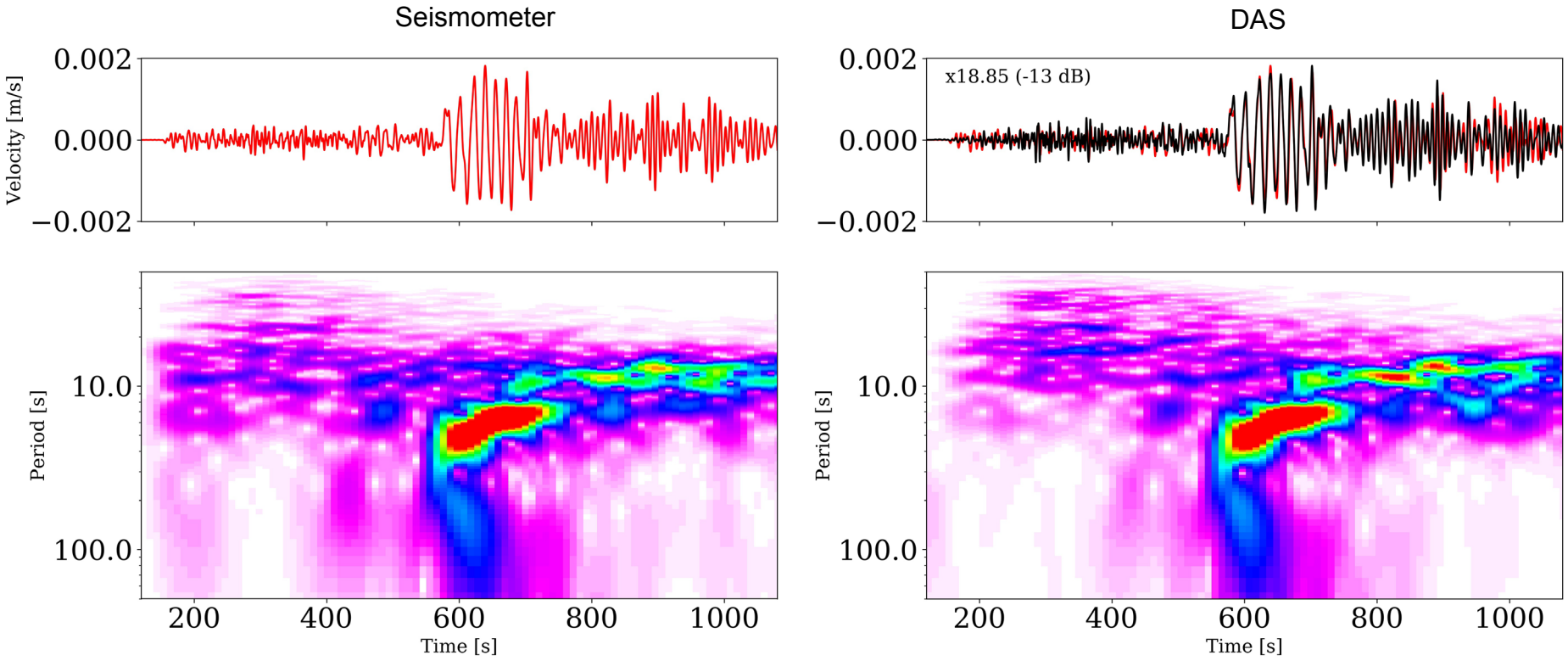


Ajo-Franklin et al., 2019 (Nat. Sci. Rep)

Results

Recording comparison

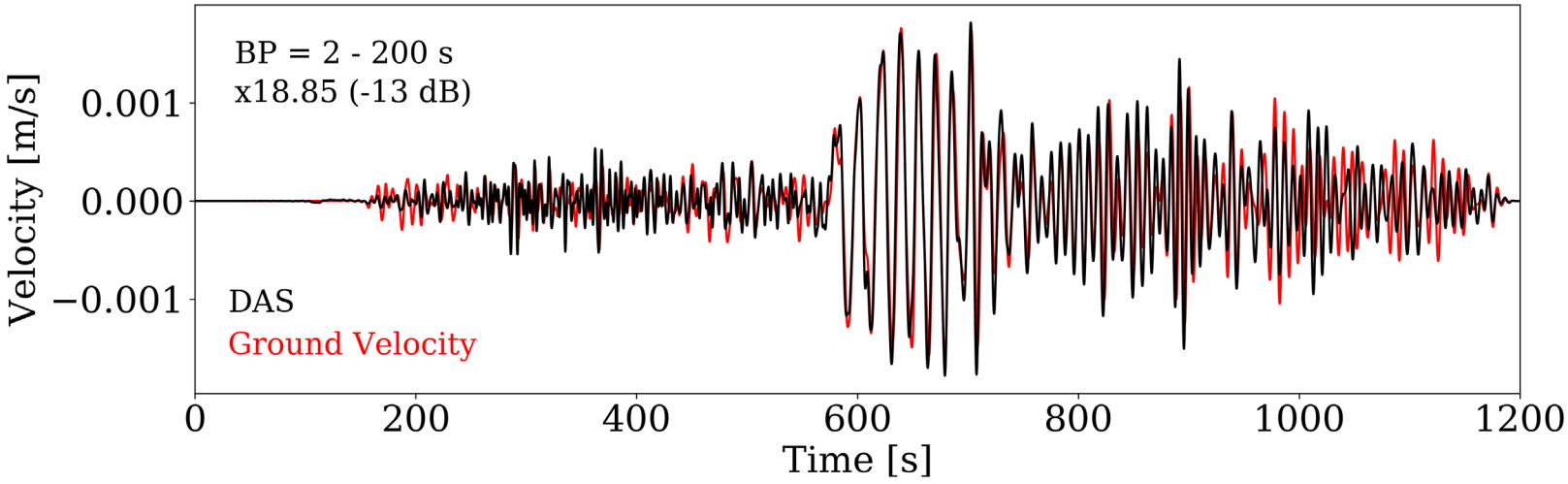
Alaska M7.9
Jan-23-2018; 2778 km

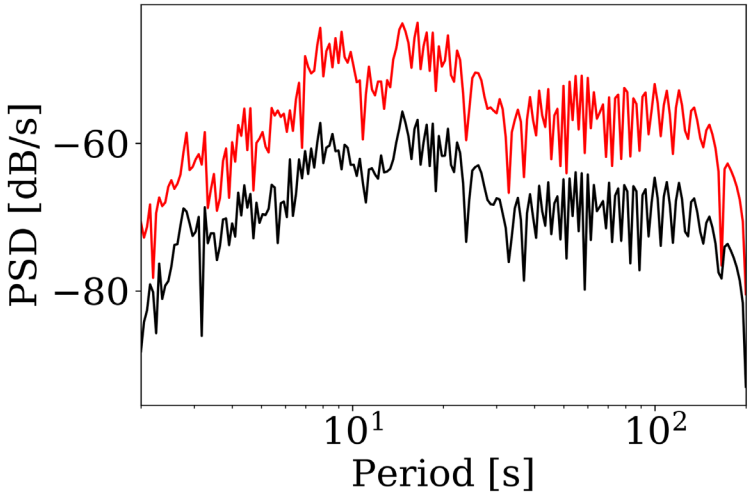


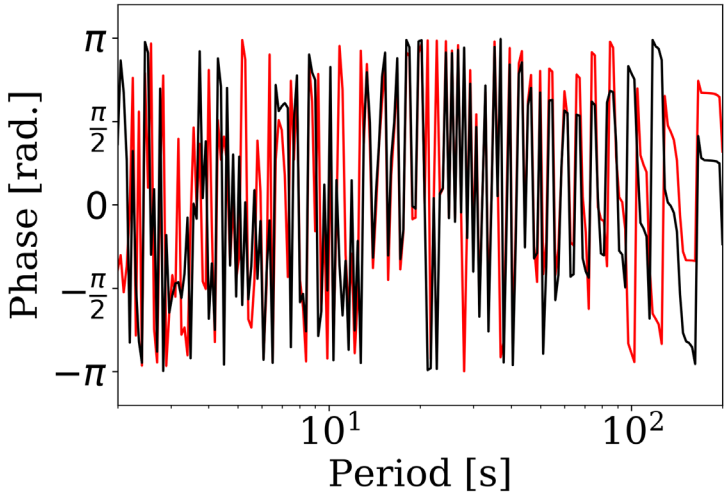
Alaska M7.9
Jan-23-2018; 2778 km

Results

Recording comparison

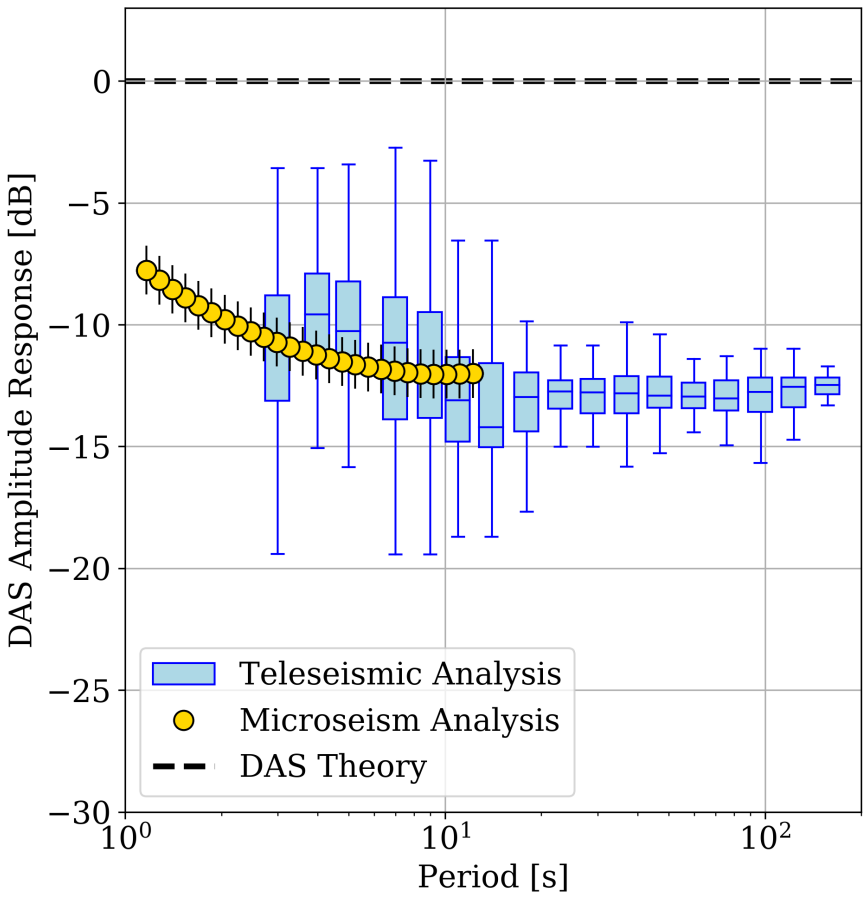


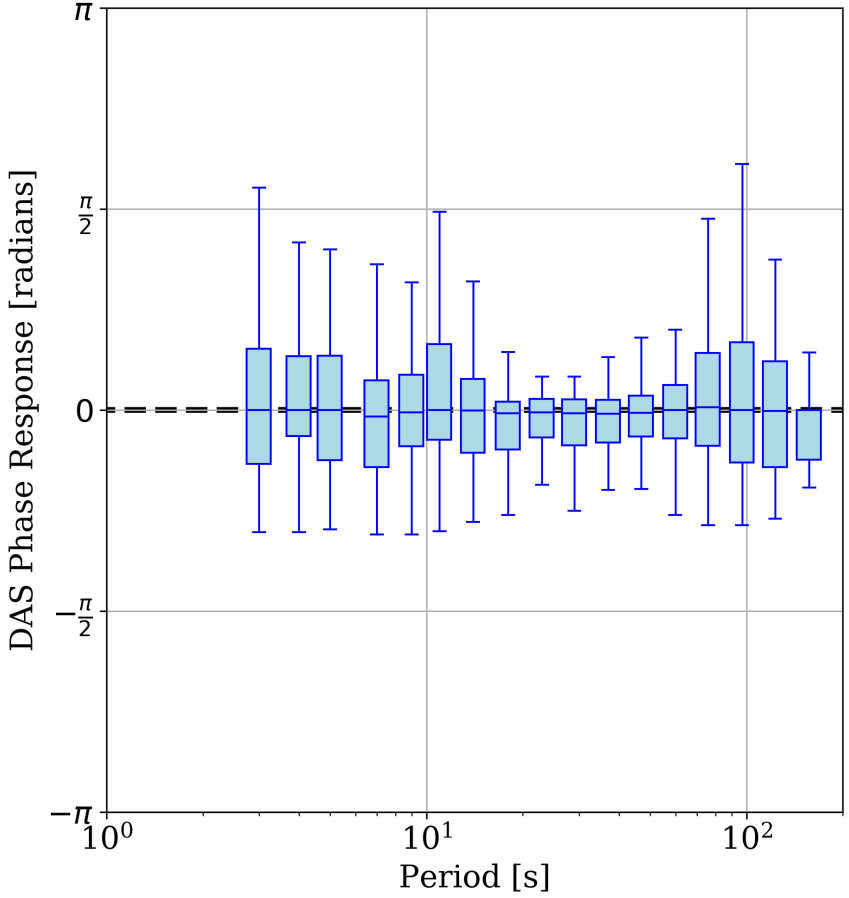




Results

DAS instrument response function





Lindsey et al., in prep

Fiber-optics Beyond Communications

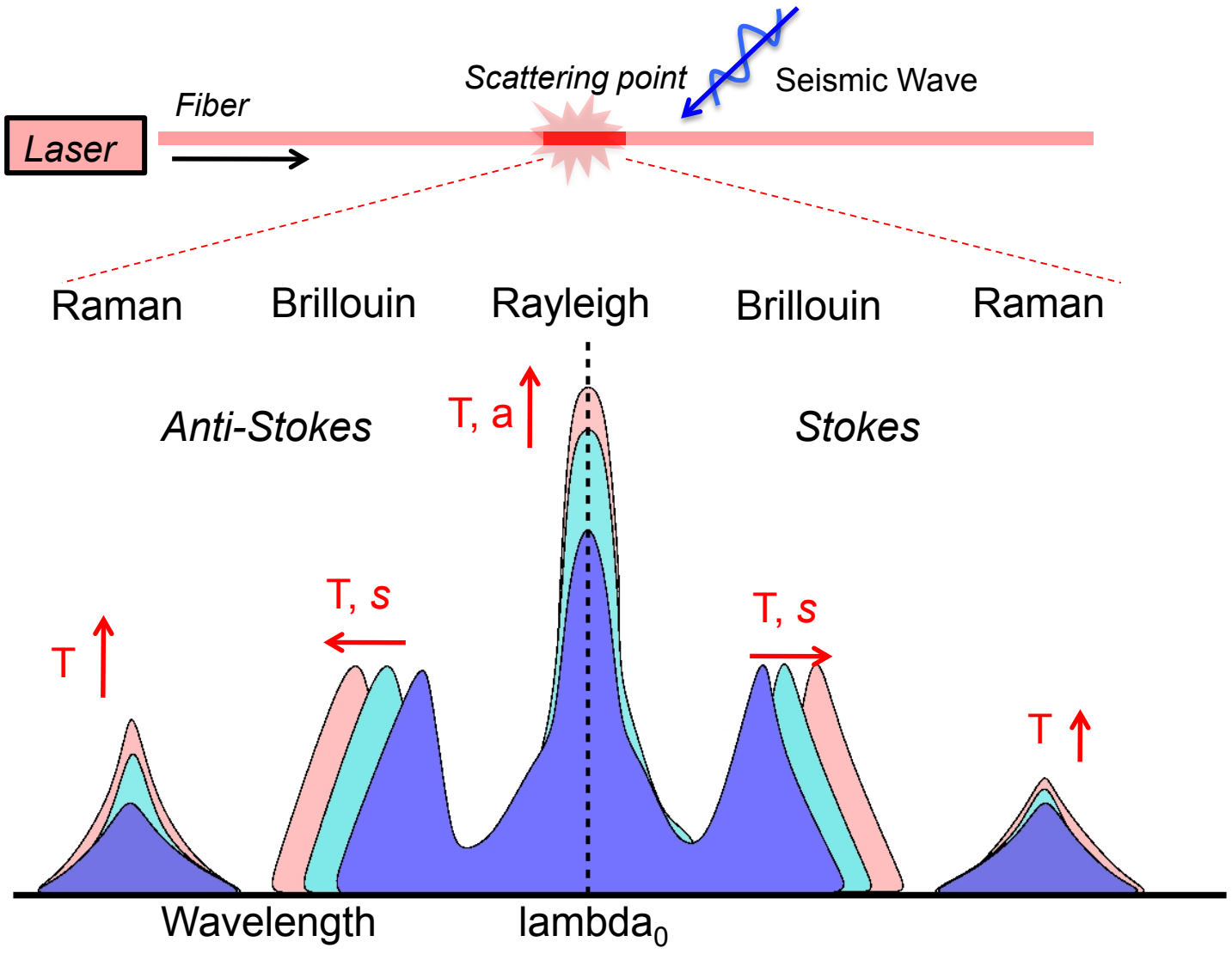
Concept :
Measure scattering from every point along a continuous fiber

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

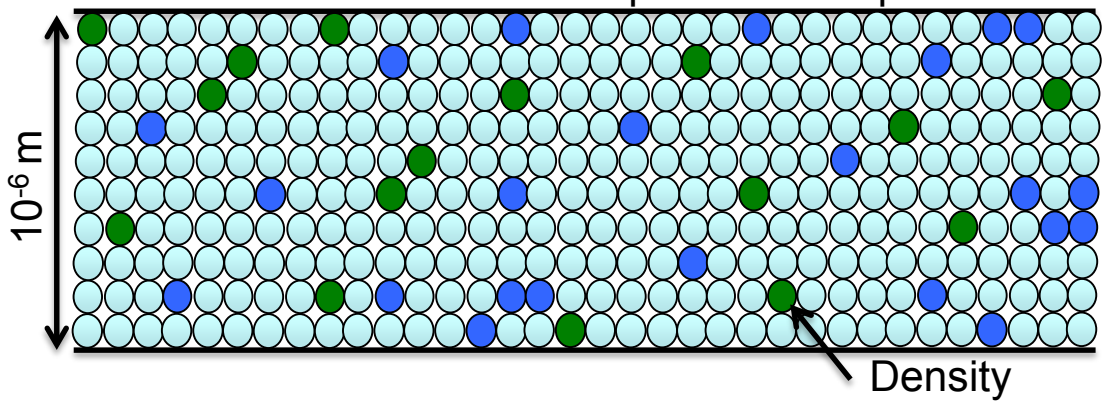
Raman : (DTS)
Strong T dependence

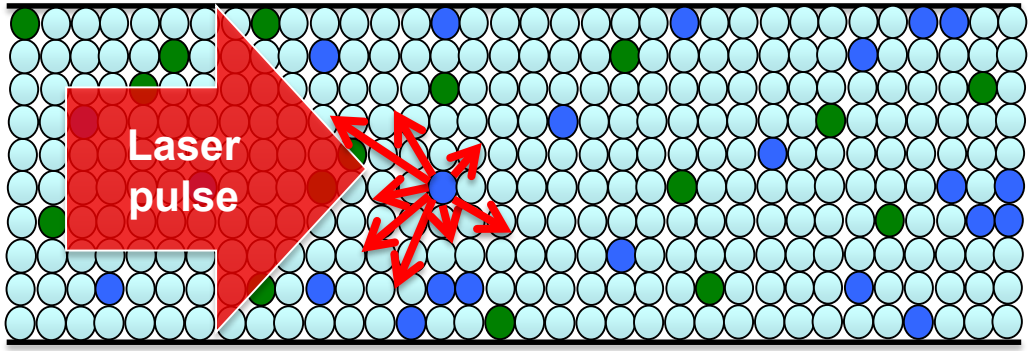
Brillouin : (DTS,DSS)
Wavelength shift during strain and T variation

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



Fiber-optics have imperfections

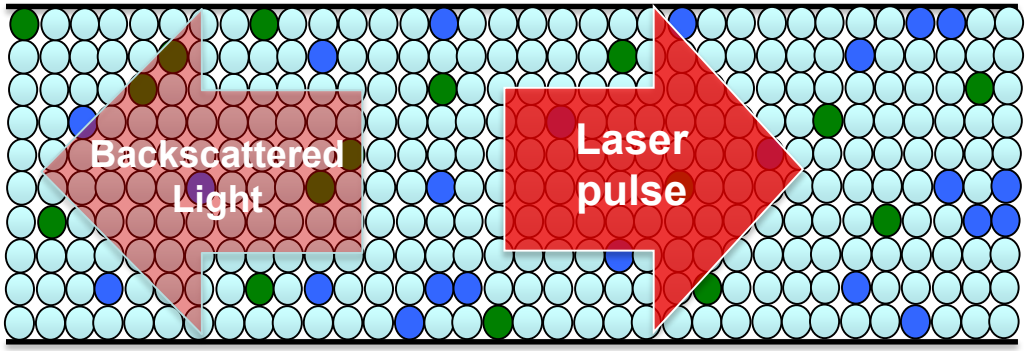




Rayleigh Scattering

Optical Time Domain Reflectometry

$z = v * t / 2$



z?

Where does strain to optical phase come from?

Coherent optical phase:

$$\Phi = \frac{4\pi n_c z}{\lambda}$$

Silixa iDAS measures changes in optical phase:

$$\Delta\Phi = \frac{\partial\Phi}{\partial z}\Delta z + \frac{\partial\Phi}{\partial n_c}\Delta n_c + \frac{\partial\Phi}{\partial\lambda}\Delta\lambda,$$

$\Delta n_c \to 0$ (Seismic timescale)

$\Delta\lambda \to 0$ (Rayleigh scattering)

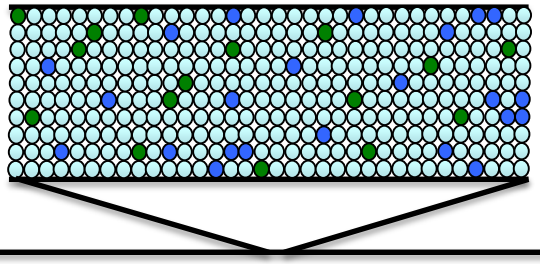
Optical phase change directly proportional to in-line strain:

$$\epsilon_{zz} = \frac{\lambda}{4\pi n_c z_g \psi}\Delta\Phi = \frac{1550 \cdot 10^{-9}[m]}{4\pi \cdot 1.45 \cdot 10[m] \cdot 0.79}\Delta\Phi = (11.6 \cdot 10^{-9})\Delta\Phi[rad].$$

Strain is the difference of displacement separated by gauge length:

$$\epsilon_{zz} = \frac{\partial u}{\partial z} = \frac{u\left(z + \frac{dz}{2}\right) - u\left(z - \frac{dz}{2}\right)}{dz}$$

Gauge length

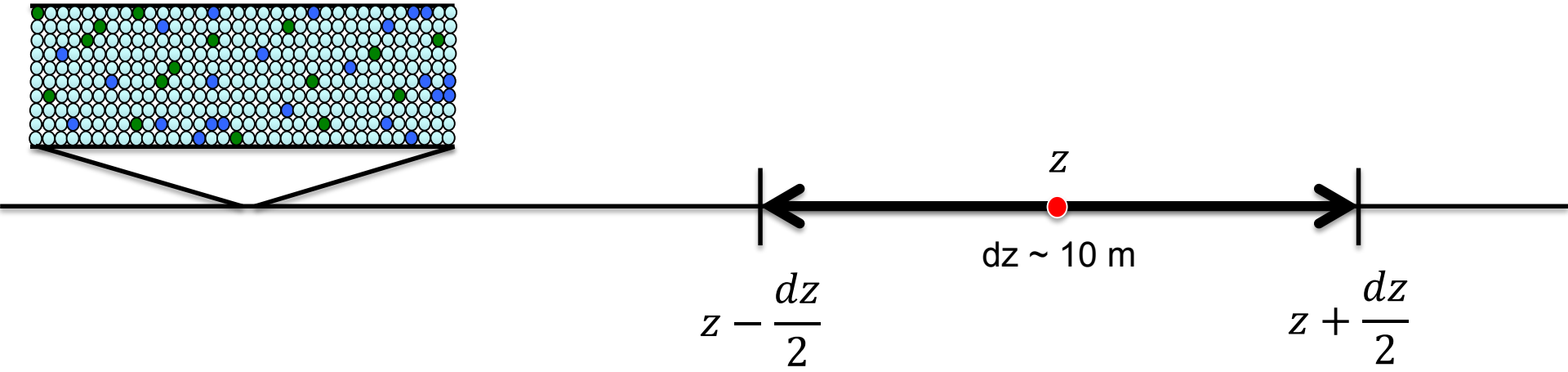


Optical phase rate

$$\Delta\dot{\Phi} \approx \dot{\epsilon_{zz}} = \frac{\partial}{\partial t}\left(\frac{\partial u}{\partial z}\right) = \frac{\partial}{\partial t}\left(\frac{u\left(z+\frac{dz}{2}\right)-u\left(z-\frac{dz}{2}\right)}{dz}\right)$$

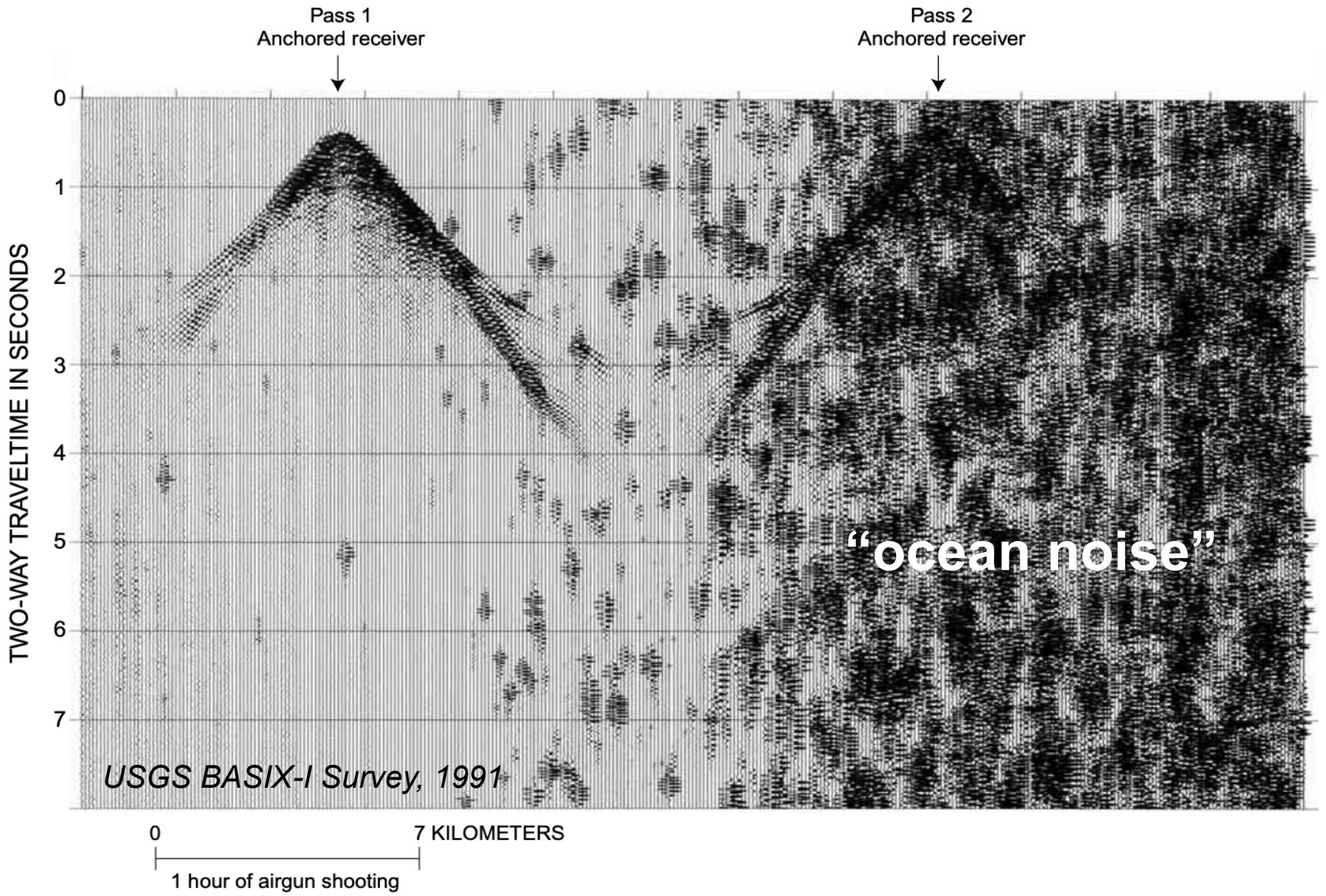
Axial strain rate

Gauge length



The Silixa iDAS measures $\frac{\partial}{\partial t}\left(\frac{u\left(z+\frac{dz}{2}\right)-u\left(z-\frac{dz}{2}\right)}{dz}\right)$ at each channel.

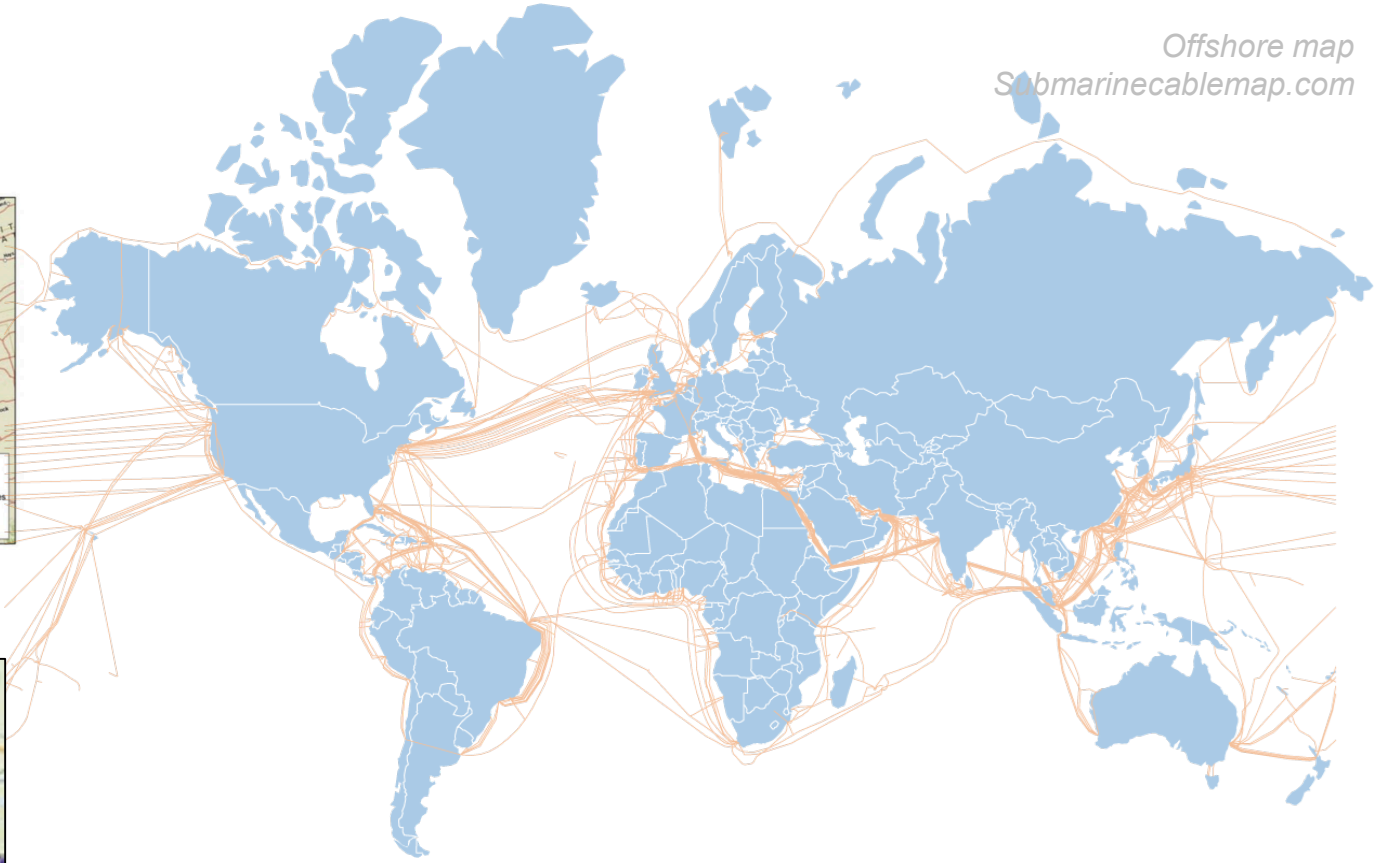

Newhall Pass (I-5) after the 1971 Northridge M6.7
200 m


Pass 1
Anchored receiver
Pass 2
Anchored receiver
TWO-WAY TRAVELTIME IN SECONDS
0
1
2
3
4
5
6
7
"ocean noise"
USGS BASIX-I Survey, 1991
0
7 KILOMETERS
1 hour of airgun shooting

Fiber-optic cables are everywhere

LBNL ESNet
Western US Longhaul

Zayo's
SF Bay Metro
Dark Fiber

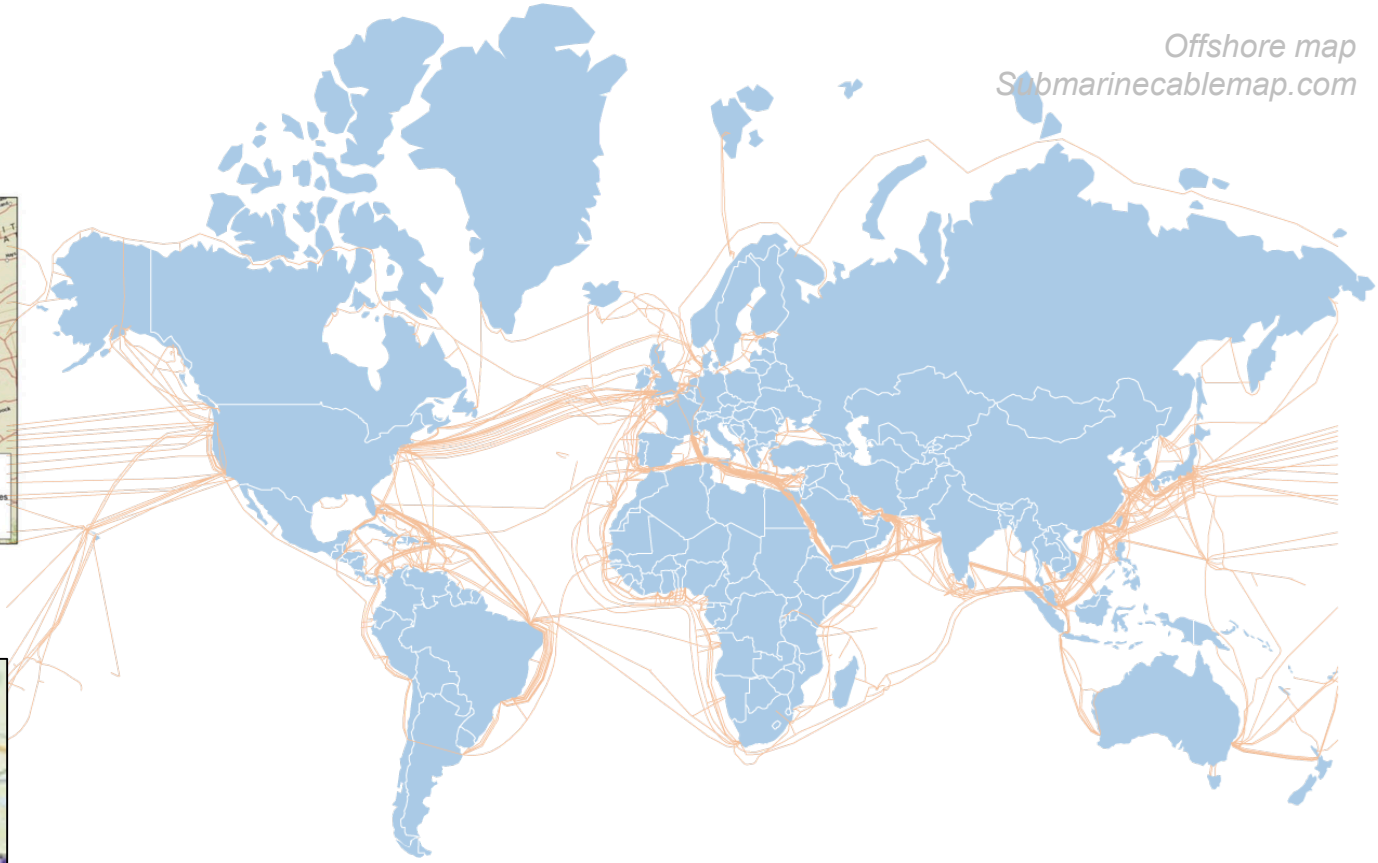


"dark fiber" = unlit telecommunications capacity

Fiber-optic cables are everywhere

LBNL ESNet
Western US Longhaul

Zayo's
SF Bay Metro
Dark Fiber



Where do we really need DAS?

"Field to watershed" scale
typically spatially-aliased
difficult to access long term.