Crossing the shoreline with fiber-optic Distributed Acoustic Sensing (DAS) in Monterey Bay

Nathaniel J. Lindsey[1,2], T. Craig Dawe[3], Horst Rademacher[1] , Veronica Rodriguez Tribaldos[2], Aleksei Titov[2], Julia Correa[2], Feng Cheng[4,2] & Jonathan Ajo-Franklin[4,2]

1. University of California, Berkeley
2. Lawrence Berkeley National Laboratory
3. Monterey Bay Aquarium Research Institute
4. Rice University

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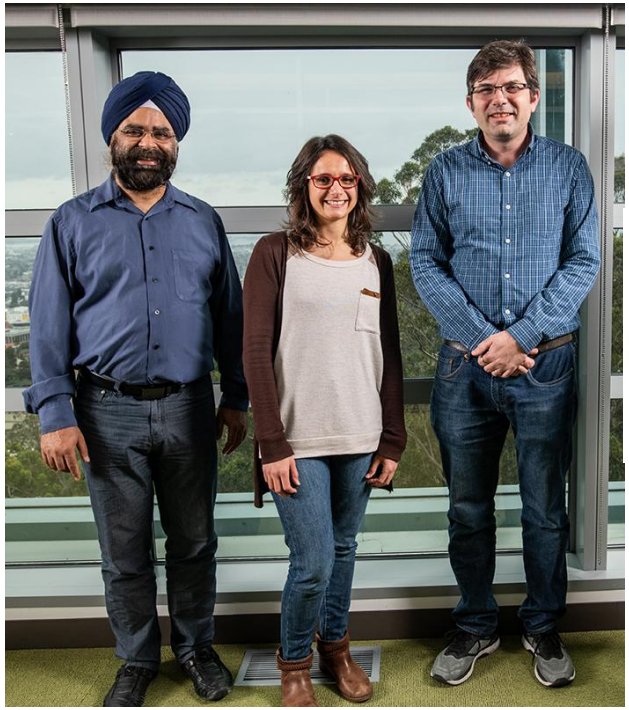
ENERGY SCIENCES NETWORK

Chris Tracy

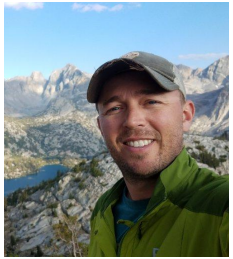


Inder Monga

Verónica Rodríguez Tribaldos

Jonathan Ajo-Franklin

Julia Correa



Craig Ulrich

MINES

Aleksei Titov

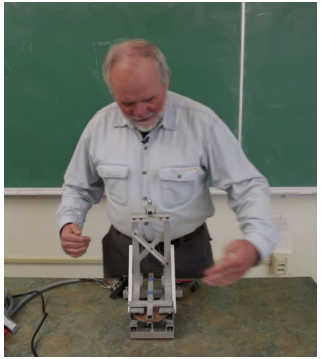
Feng Cheng

RICE

Michelle Robertson

Doug Dreger

Horst Rademacher



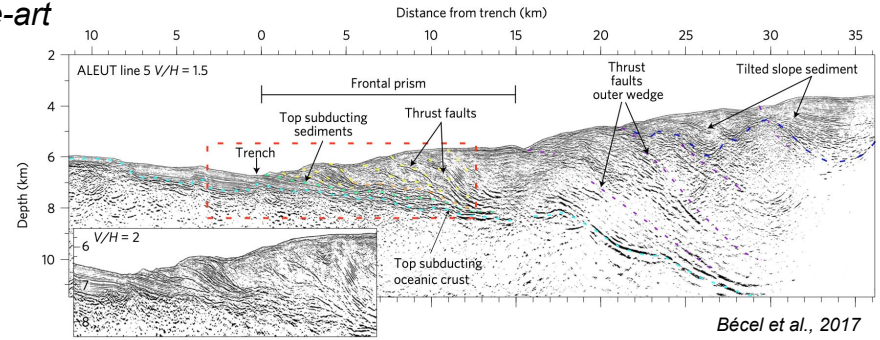
Berkeley
UNIVERSITY OF CALIFORNIA

Craig Dawe

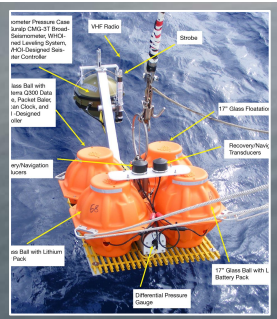
MBARI Monterey Bay Aquarium Research Institute

Marine Geophysics

State-of-the-art

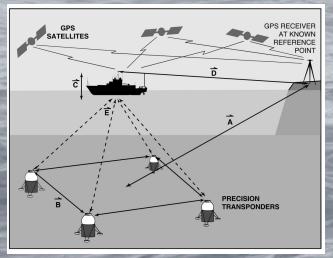


Bécel et al., 2017



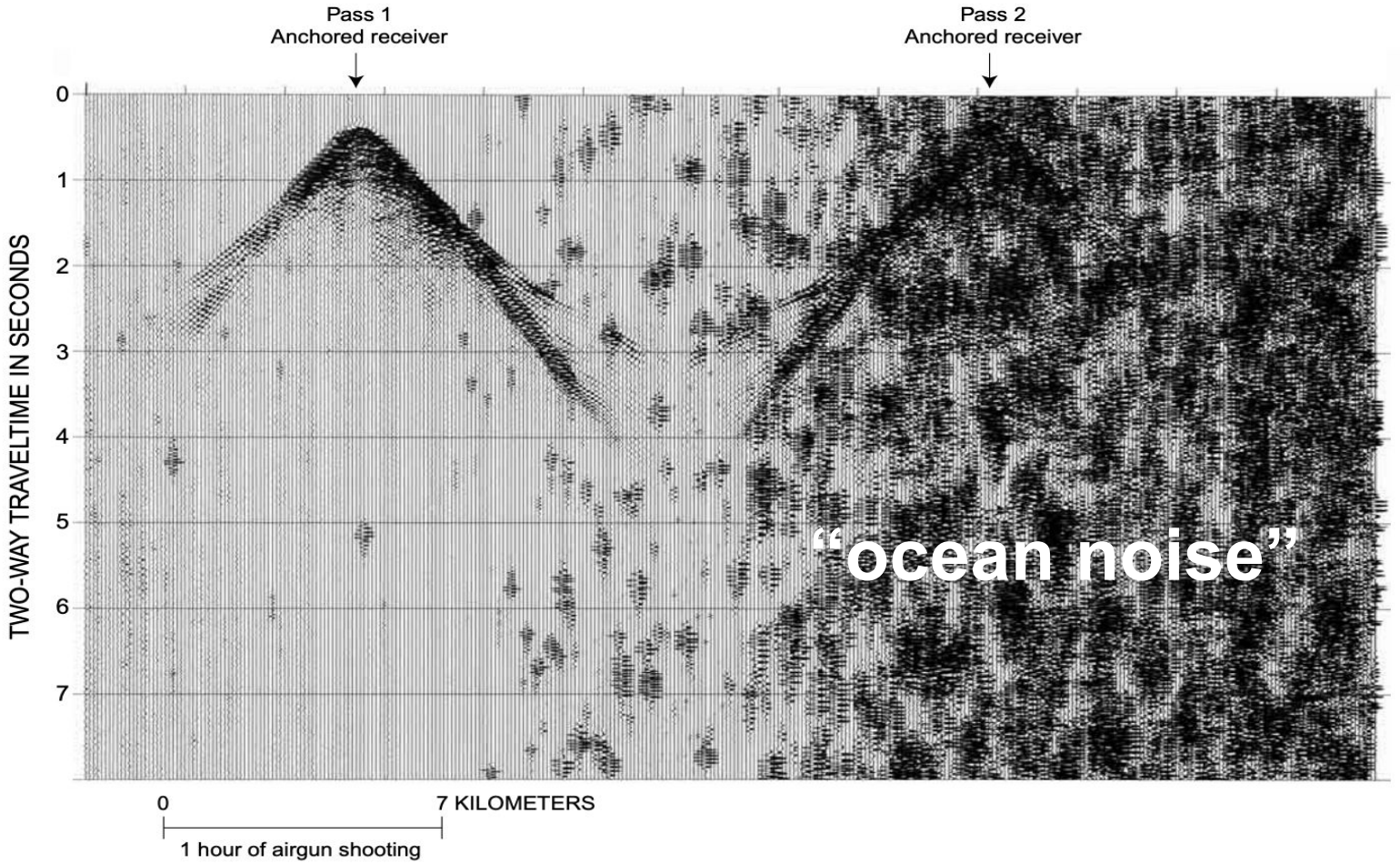
OBSIC

Image credit : Maya Tolstoy

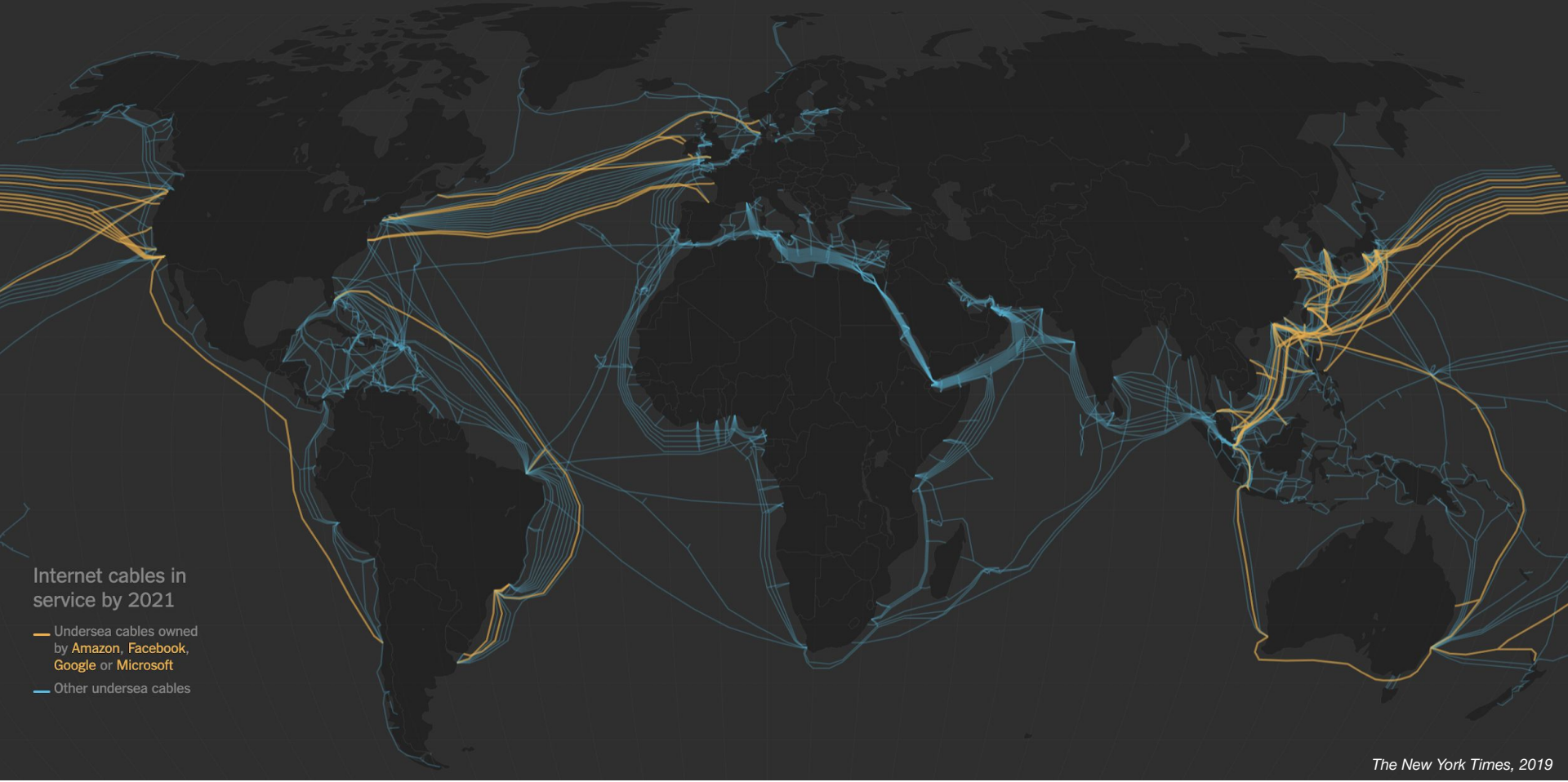


Chadwell and Spiess, 2008

Image credit : Florian Petersen

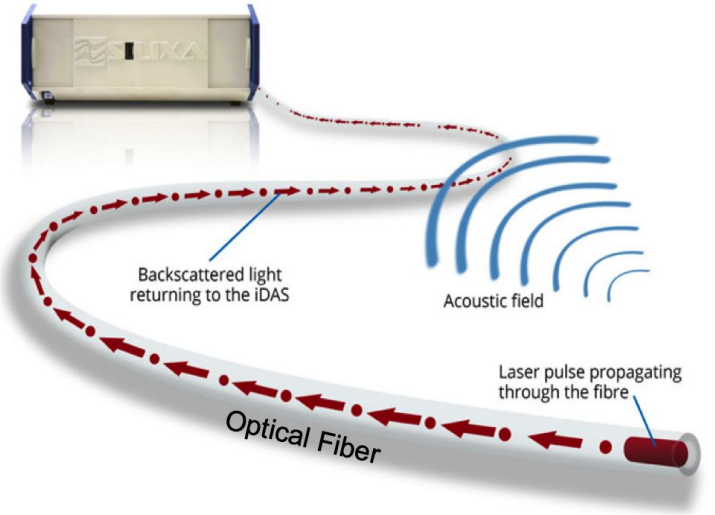


USGS BASIX-I Survey, 1991



Fiber-optic cables are everywhere

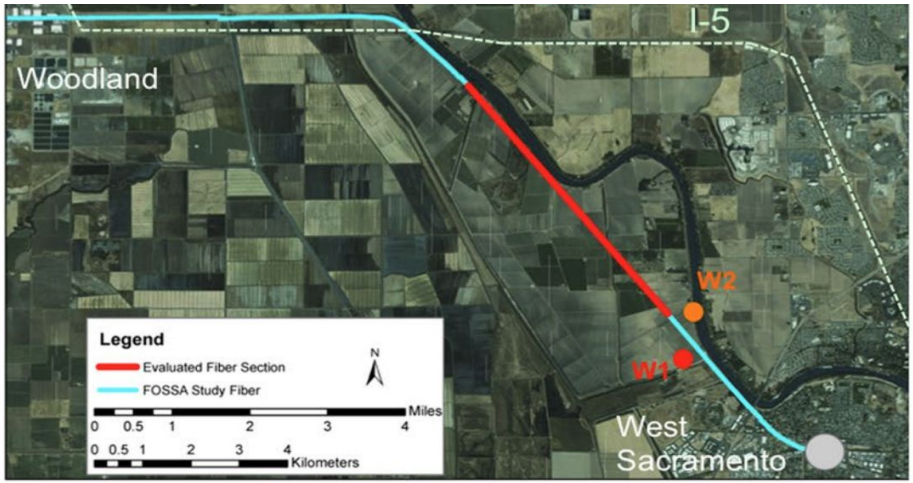
Distributed Acoustic Sensing



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

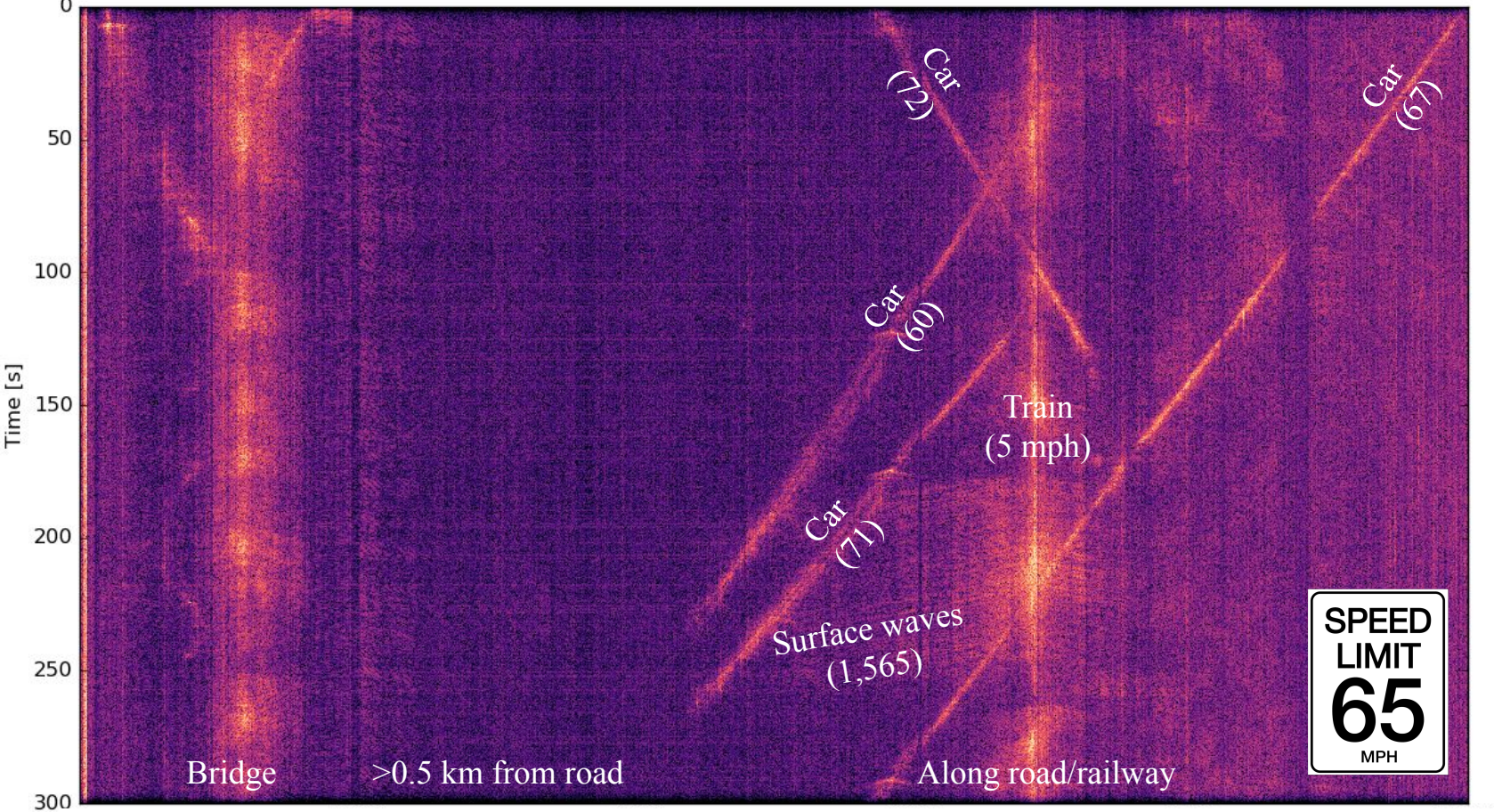
(of strain-rate sensors)

Image credit: Silixa



Ajo-Franklin et al., 2019

Ambient recording
2018-Jan-01 (08:30:00 – 08:35:00 UTC)



BP = 0.5 – 15 Hz

Questions at
Dec 2018 DAS workshop

How does an optical fiber couple to the seafloor?

Questions at
Dec 2018 AGU Fall Meeting

How can we use DAS to monitor submarine volcanoes and track whales?

Questions at
Dec 2018 DAS workshop

How do we store, transfer, share, analyze TB/day data volumes?

Questions at
Dec 2018 AGU Fall Meeting

How can we use DAS for earthquake early warning?

Aims for Today’s Talk

- What is DAS instrument response?
- What can we do offshore with DAS now?

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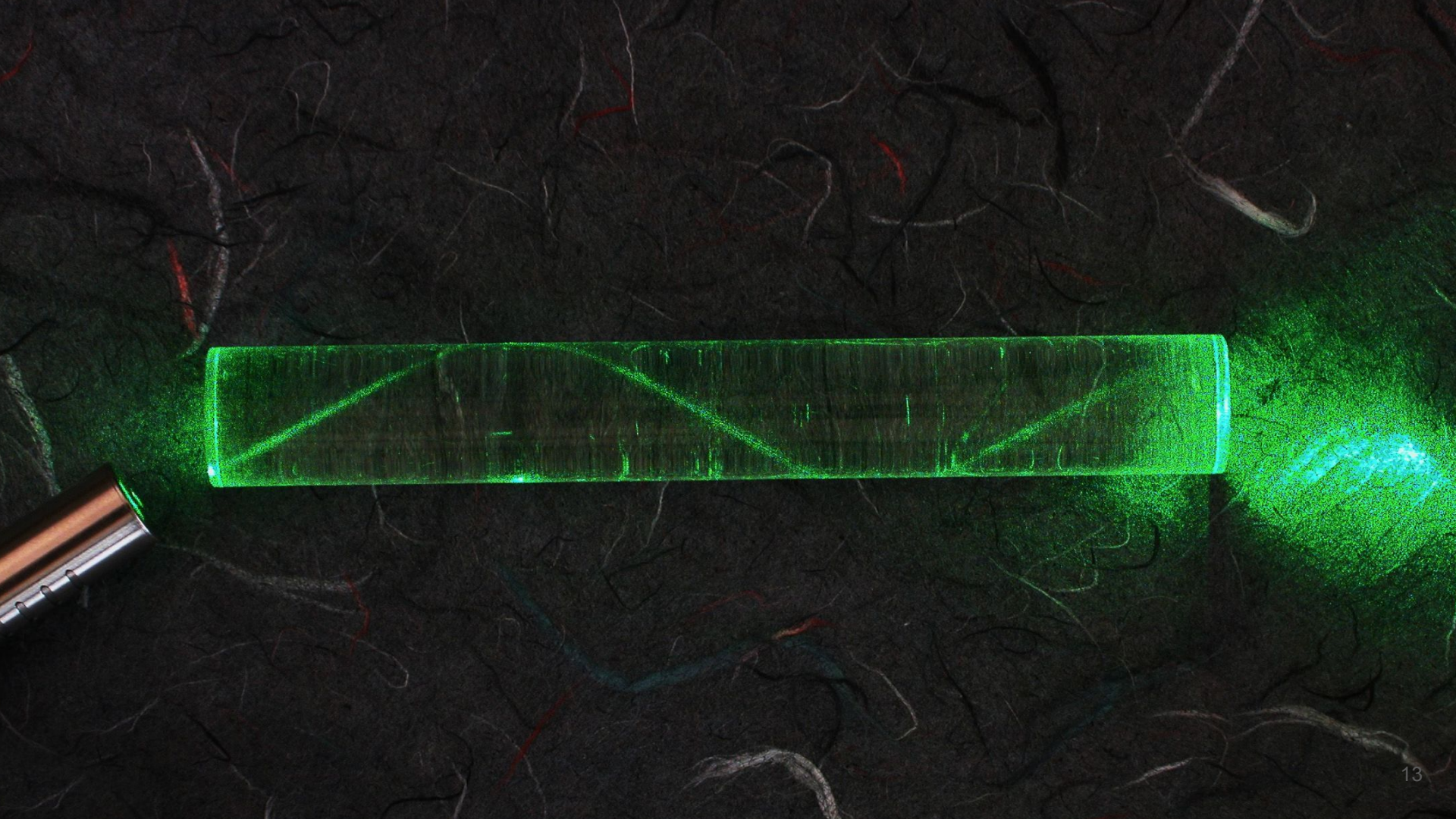
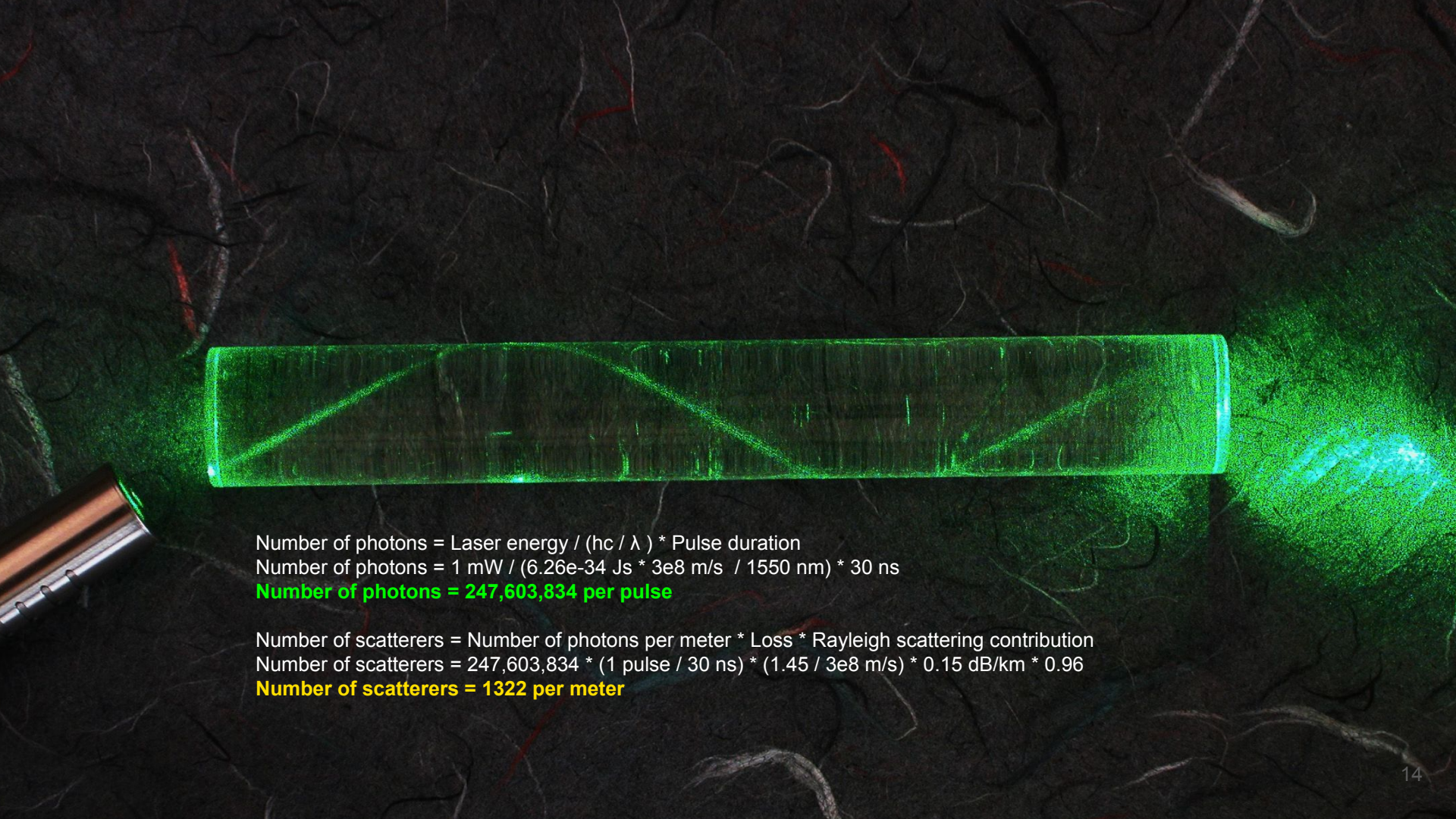
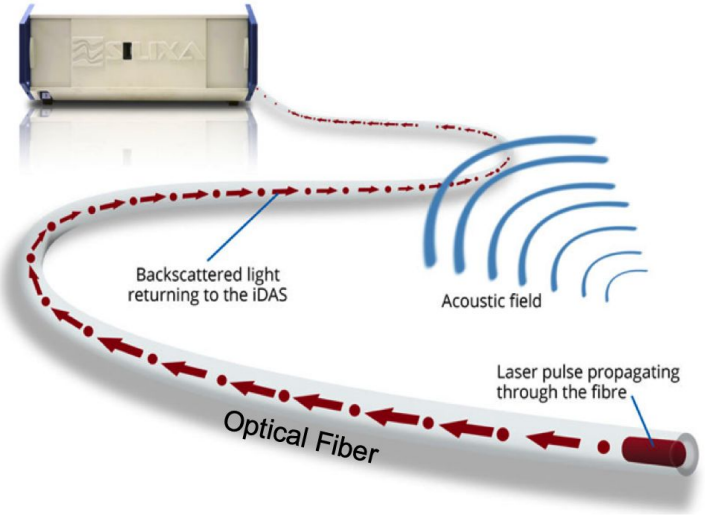


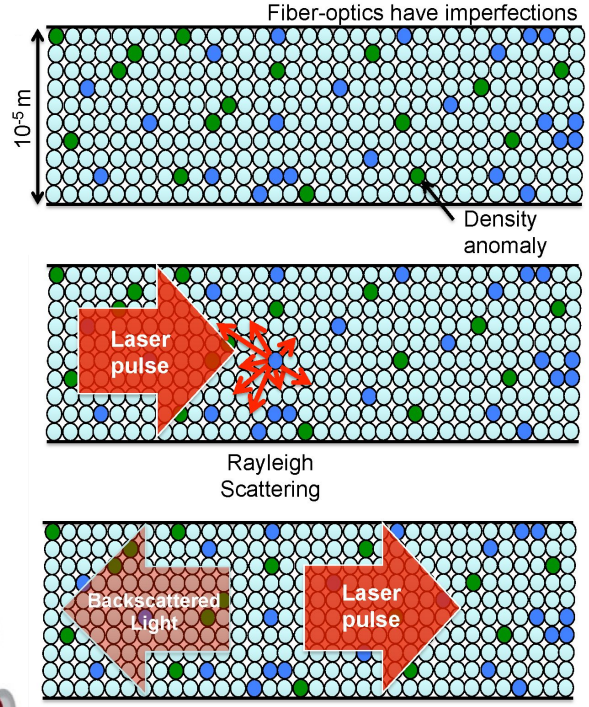


Number of photons = Laser energy / (hc / λ) * Pulse duration
Number of photons = 1 mW / (6.26e-34 Js * 3e8 m/s / 1550 nm) * 30 ns
Number of photons = 247,603,834 per pulse

Number of scatterers = Number of photons per meter * Loss * Rayleigh scattering contribution
Number of scatterers = 247,603,834 * (1 pulse / 30 ns) * (1.45 / 3e8 m/s) * 0.15 dB/km * 0.96
Number of scatterers = 1322 per meter

Distributed Acoustic Sensing





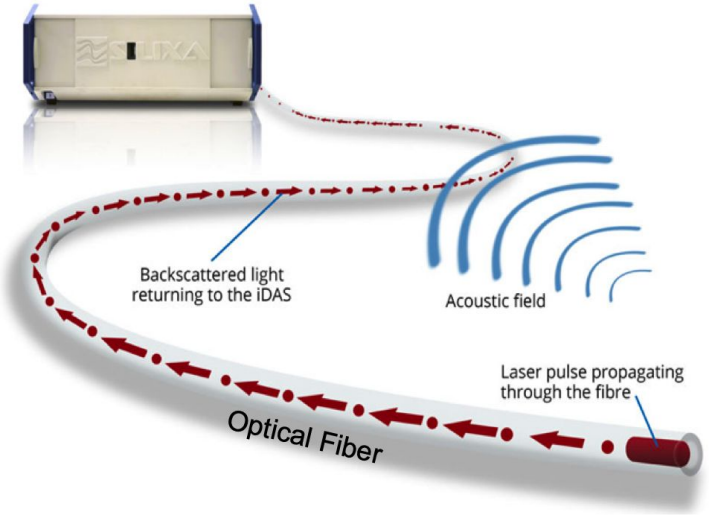
DAS turns a fiber-optic cable into a massive 1C seismic array.

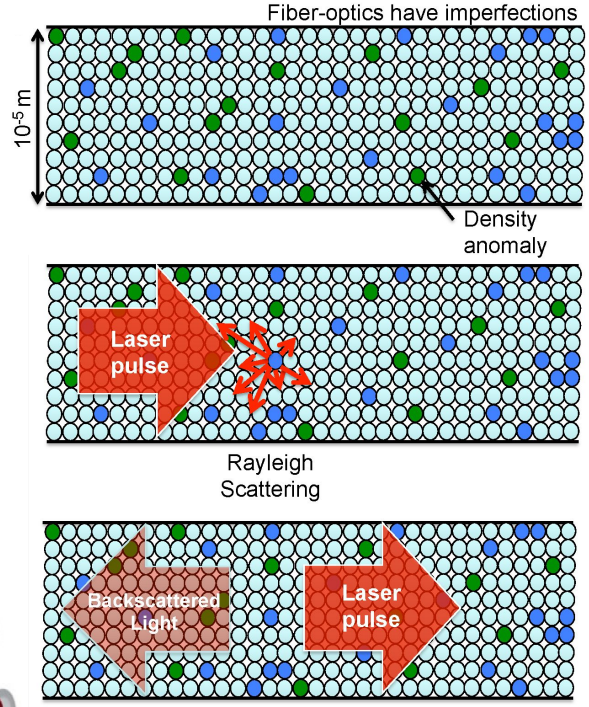
(of strain-rate sensors)

Image credit: Silixa

$$\epsilon_{xx}(t, x_j) = \frac{\lambda}{4\pi n L_G \zeta} \Delta\Phi = \frac{1550 \cdot 10^{-9}[m]}{4\pi \cdot 1.45 \cdot 10[m] \cdot 0.79} \Delta\Phi = 11.6 \cdot 10^{-9} \cdot \Delta\Phi[rad]$$

Distributed Acoustic Sensing





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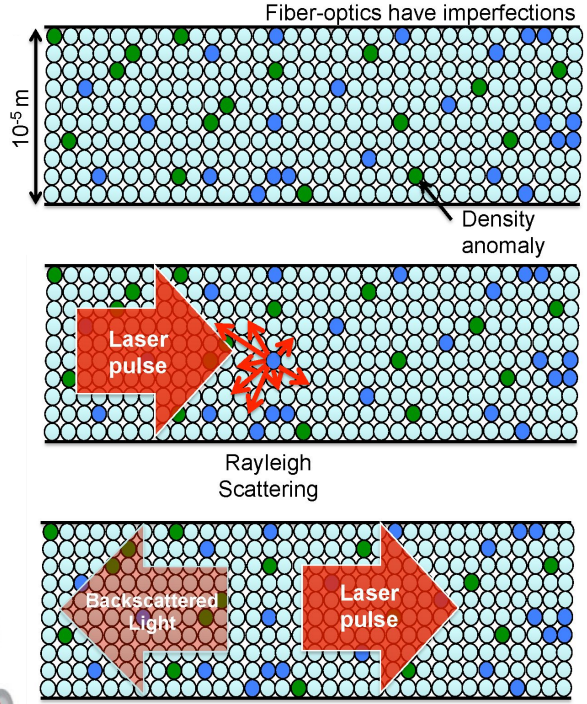
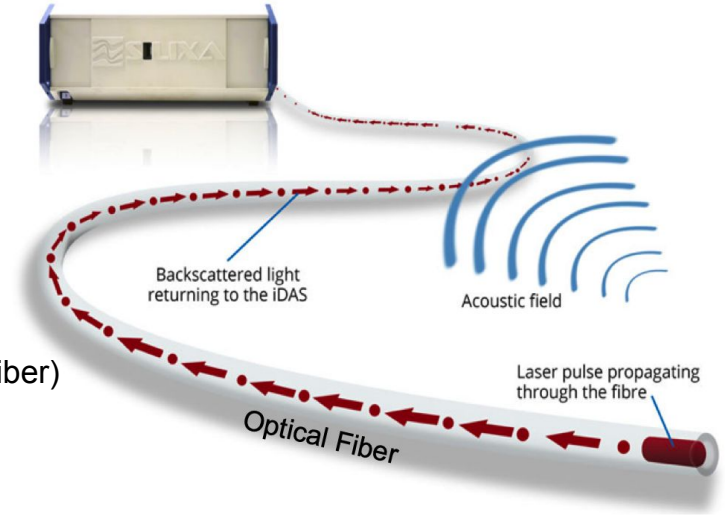




Laser pulse width ~ 10 – 40 ns
Spatial sampling (L_G) ~ 10 m
Maximum aperture ~ 30 km (standard fiber)
Laser pulse rate (t^{-1}) ~ 10 - 100 kHz
Digital sampling ~ 100 – 1000 Hz
Data flowrate ~ 0.01 – 10 TB/day

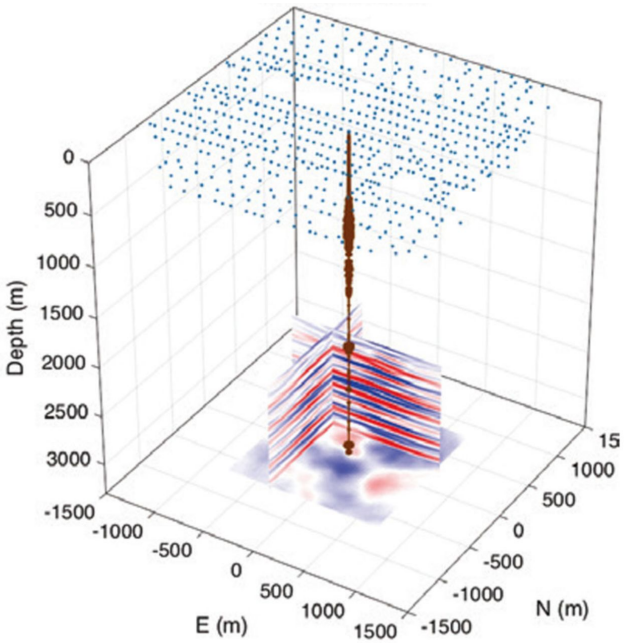
DAS turns a fiber-optic cable into a massive 1C seismic array.
(of strain-rate sensors)

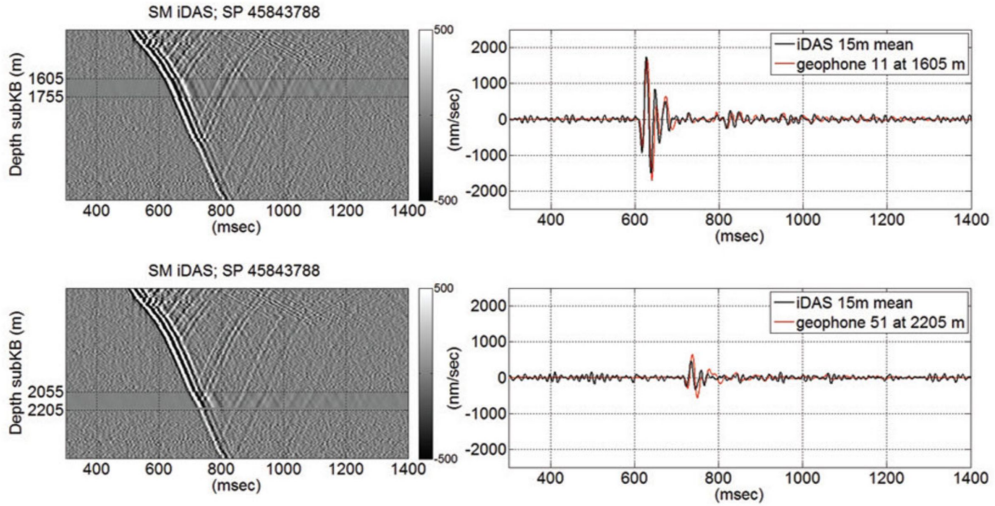
Image credit: Silixa

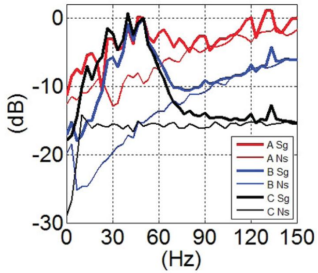
Making measurements

SEG Extended Abstracts for 2019 Meeting:
https://library.seg.org/doi/book/10.1190/segeab.38

99.9% of DAS experiments are in oil & gas industry







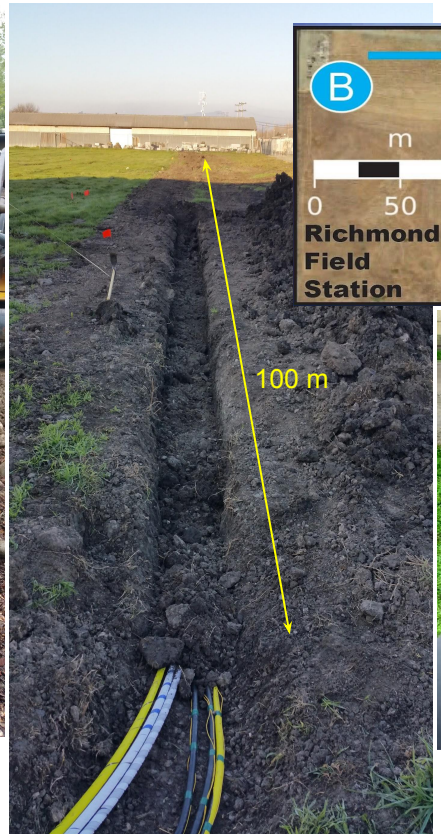
- Downhole Vertical Seismic Profiling (VSP)
- Production flow monitoring
- Frequency > 1 Hz
- Most comparisons are against geophones

Miller et al., 2016

Making measurements

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

Stephanie Saari
trenching in Fairbanks, AK



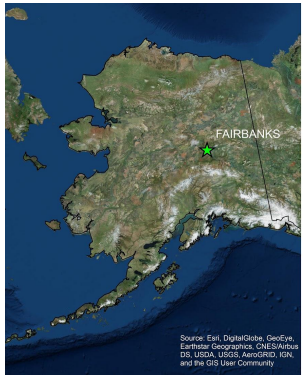
- Similar signals with different fibers f ~ 0.5 - 50 Hz
- No increase in SNR with trench depth >0.20 m

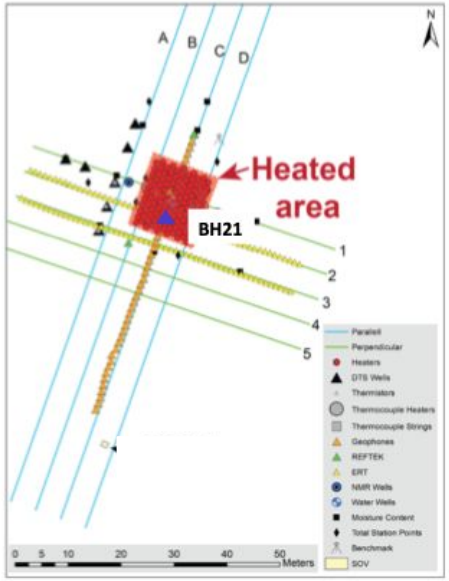
Dou et al., 2017

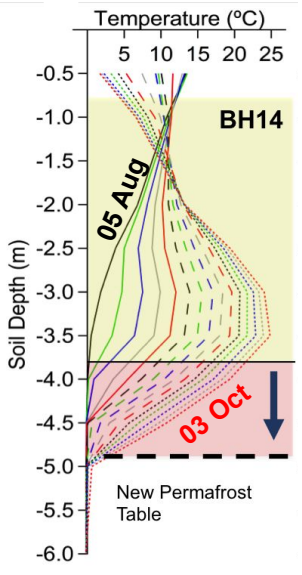
Making measurements

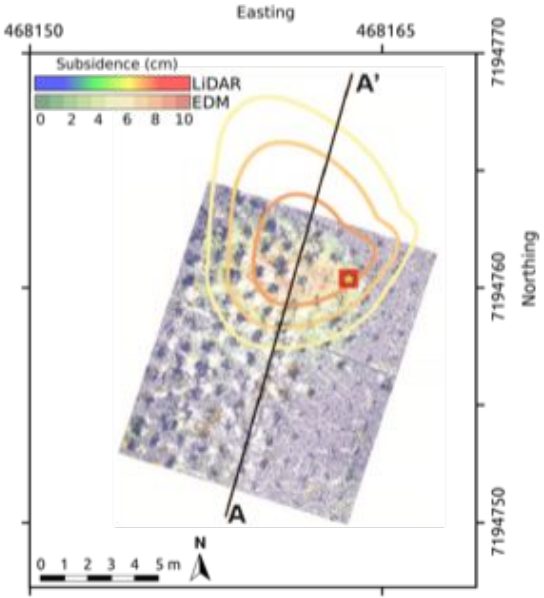
Fiber-optic geophysics for time > days?

Permafrost degradation experiment
(Wagner, et al., 2018, *Scientific Reports)*









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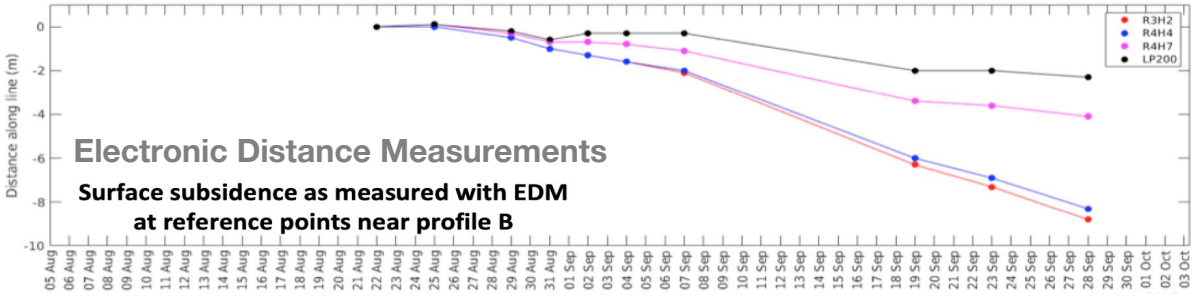
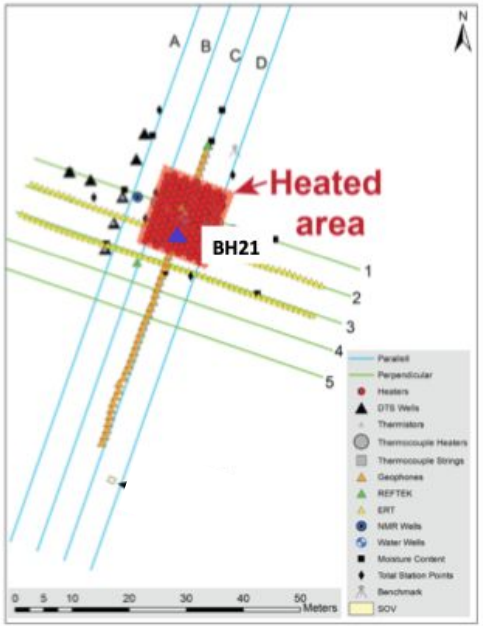
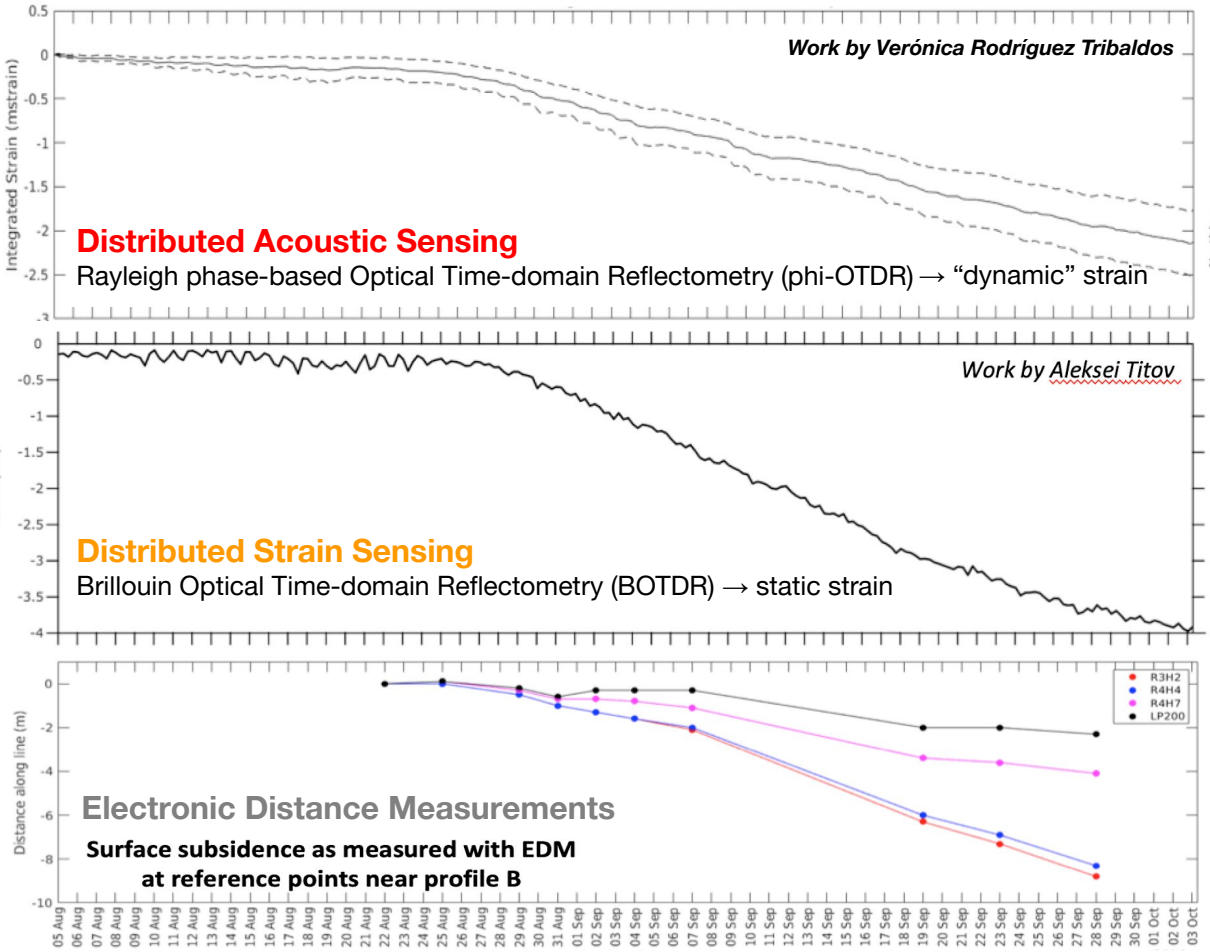


Making measurements

Fiber-optic geophysics for time > days?

Distributed fiber-optic measurements of strain due to subsidence during permafrost degradation experiment

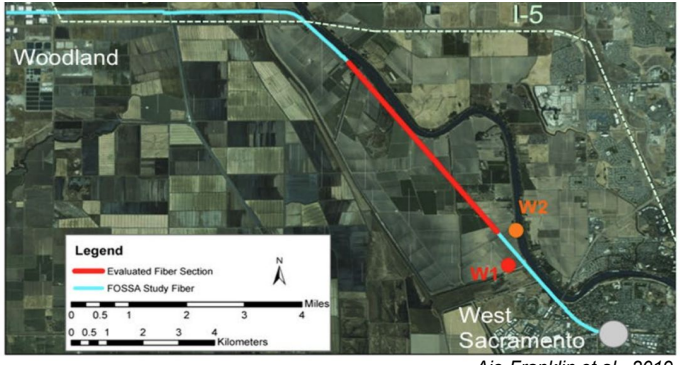




Making measurements

Using existing "**dark fiber**" in telecommunications cables requires access and leads to greater uncertainty in geometry and coupling, but is more efficient.

Craig Ulrich tap-testing in Sacramento, CA



Ajo-Franklin et al., 2019

Connecting to ESNet in Sacramento, CA

“Three conditions for a seismometer”

Lay and Wallace, 1995, *Modern Global Seismology*

1. Timing
2. Known instrument response
3. Coupled sensor

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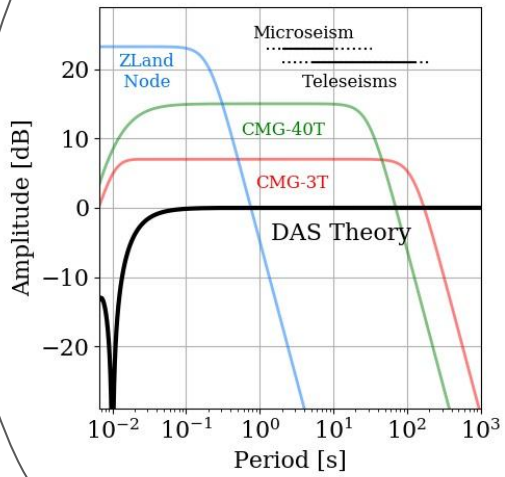
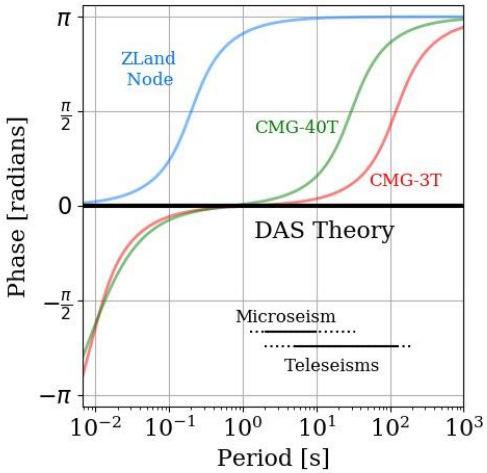
What is DAS instrument response?





Lindsey et al., in review [JGR]

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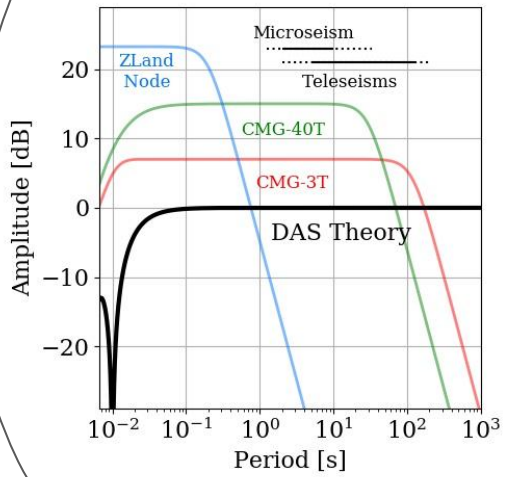
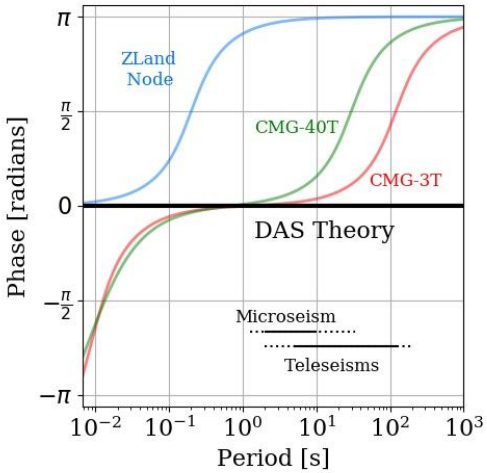




Lindsey et al., in review [JGR]

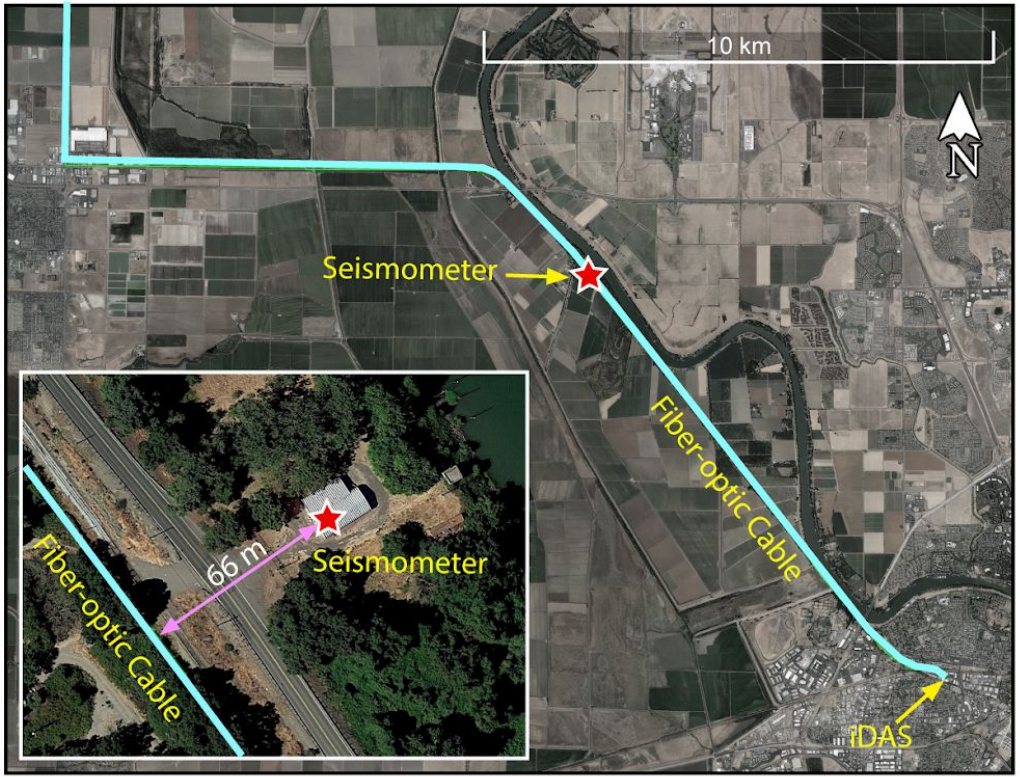
Measuring DAS Performance Parameters

SEAFOM MSP-02 (https://seafom.com/?mdocs-file=1270)

- Dynamic range
- **Frequency response**
- **Fidelity**
- Self-noise
- Spatial Resolution
- Cross-talk
- Loss budget

What is DAS instrument response?

Empirical evaluation using teleseismic earthquakes



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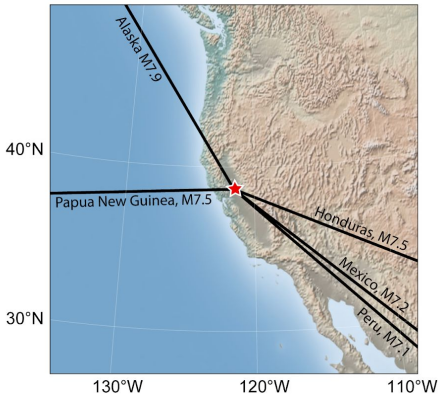
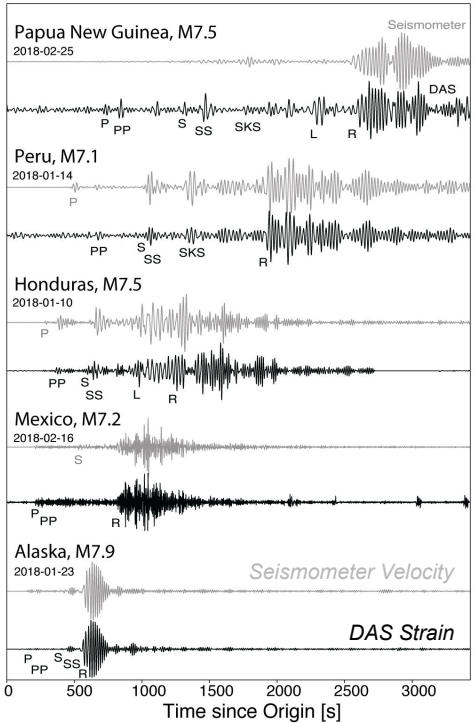
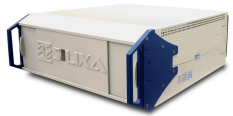




Guralp CMG-3T



Silixa iDAS, v2

Lindsey et al., in review [JGR]

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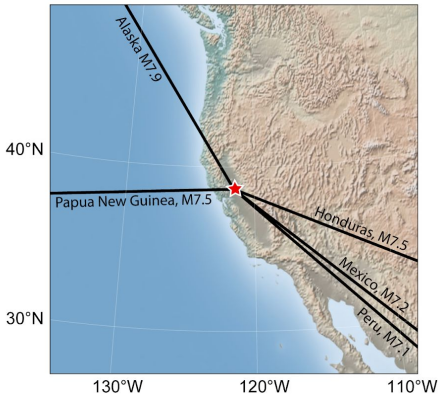

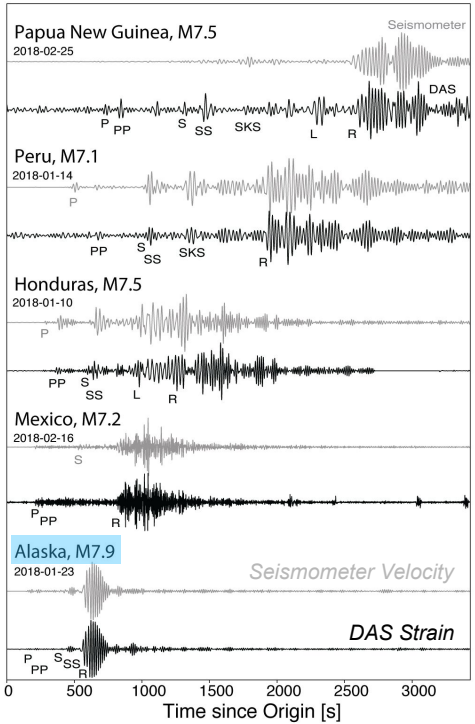

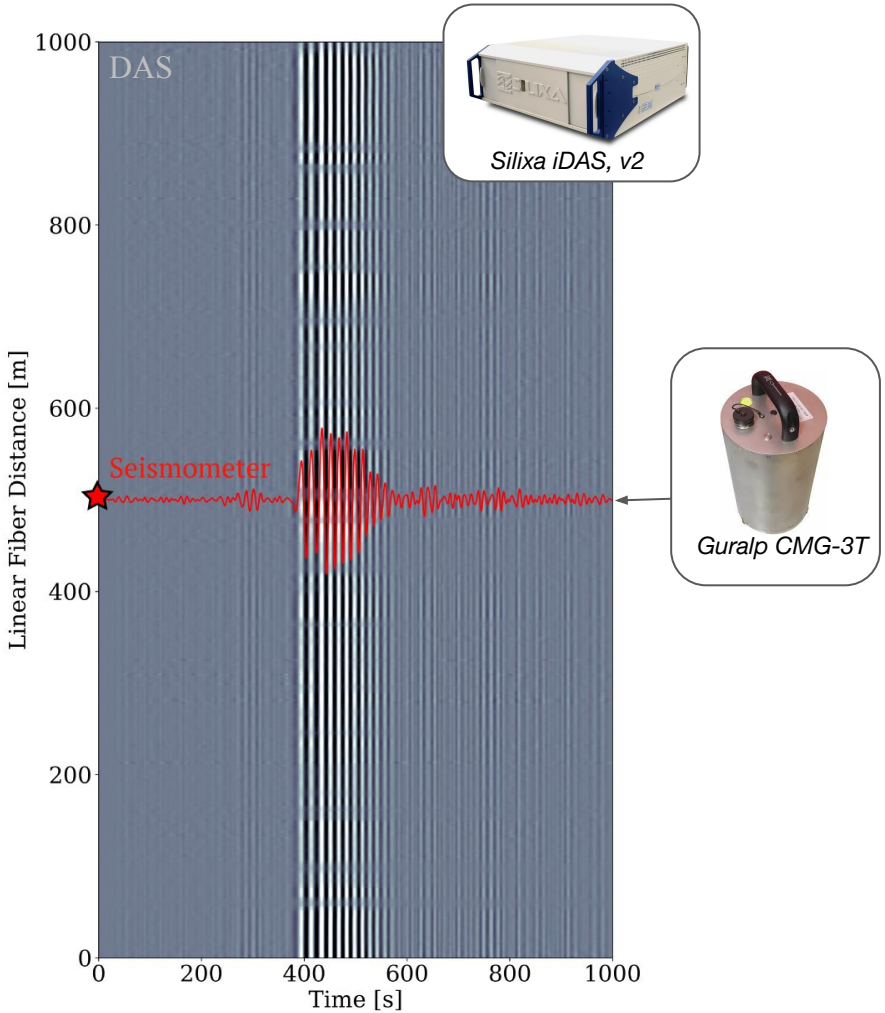

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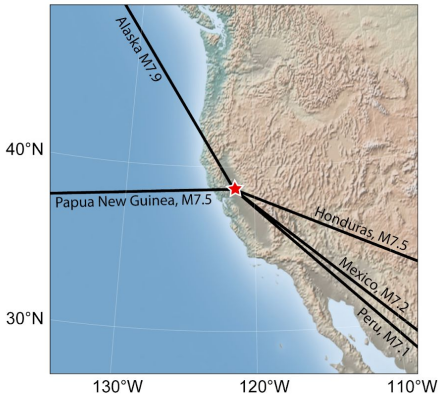

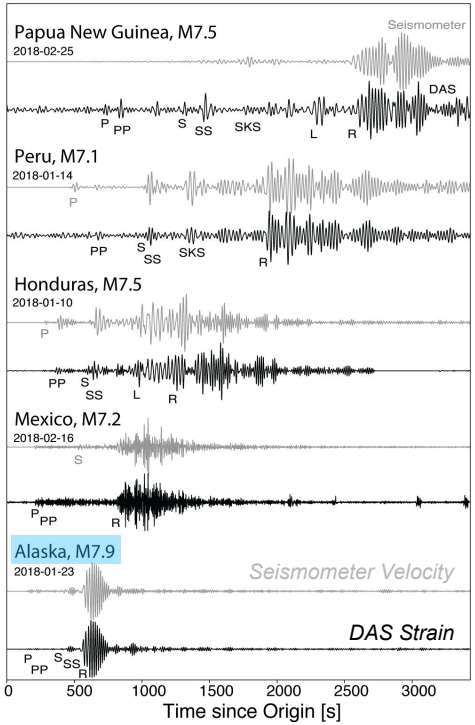

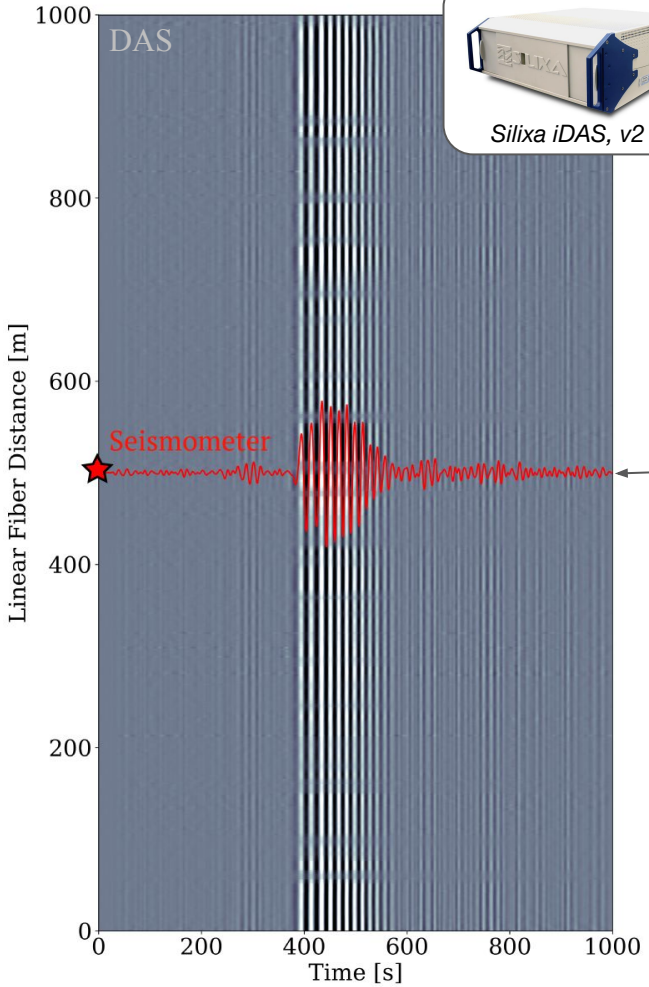

Converting DAS strain to particle velocity in FK domain over 500 channel subarray (1 km)...

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

Aki and Richards (1980)

Lindsey et al., in review [JGR]

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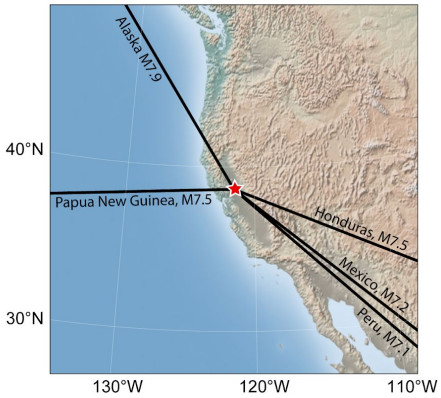

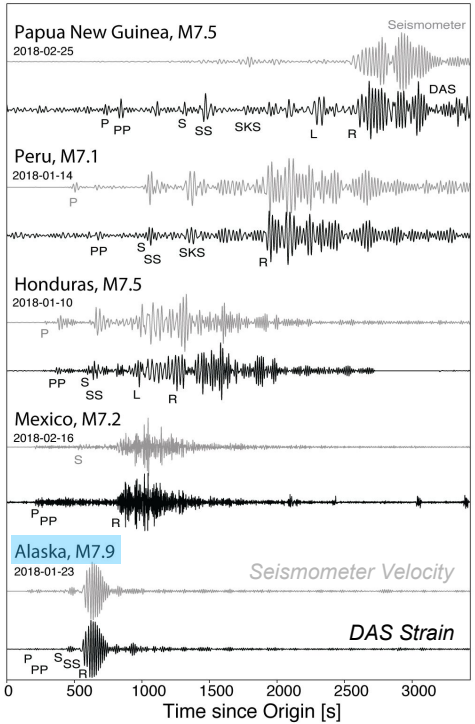

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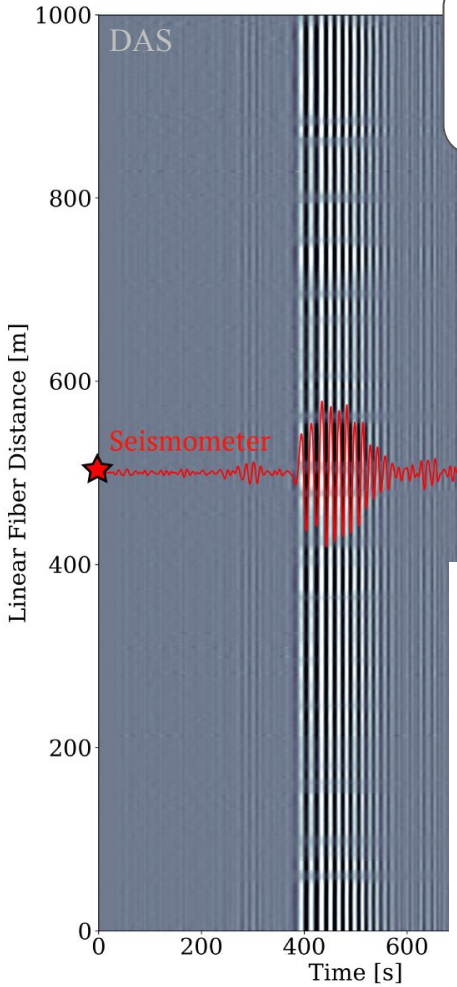


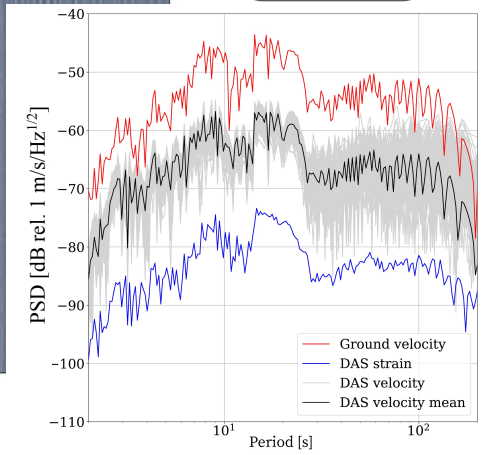
Silixa iDAS, v2

Converting DAS strain to particle velocity in FK domain over 500 channel subarray (1 km)...

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

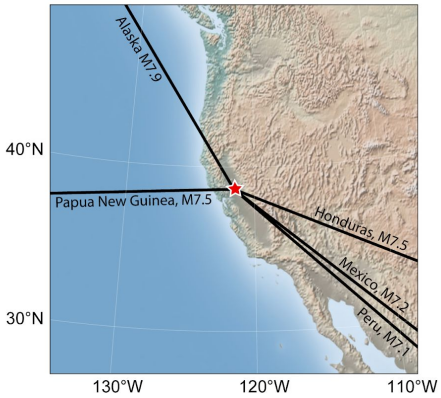
Aki and Richards (1980)

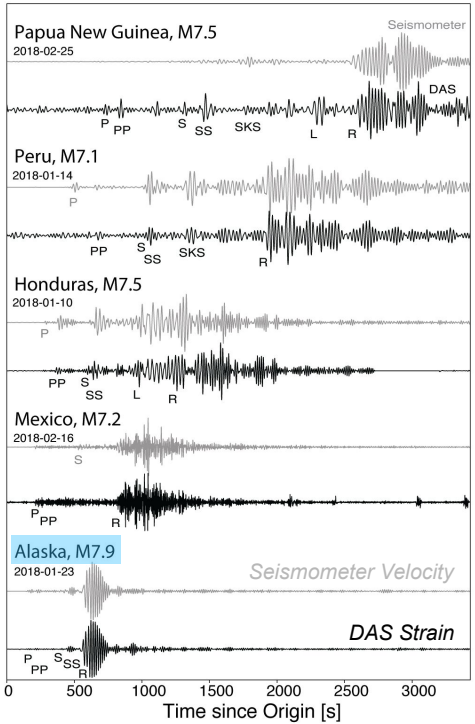
Guralp CMG-3T



What is DAS instrument response?

Empirical evaluation using teleseismic earthquakes





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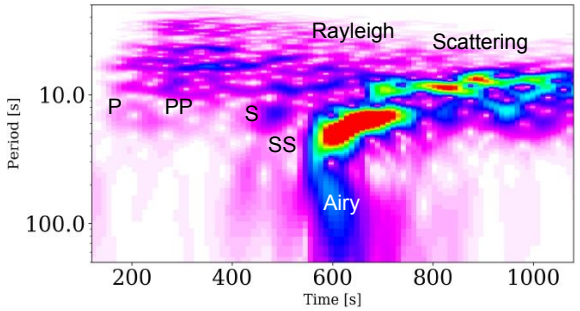

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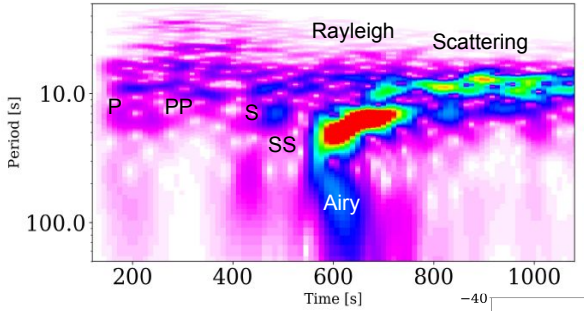

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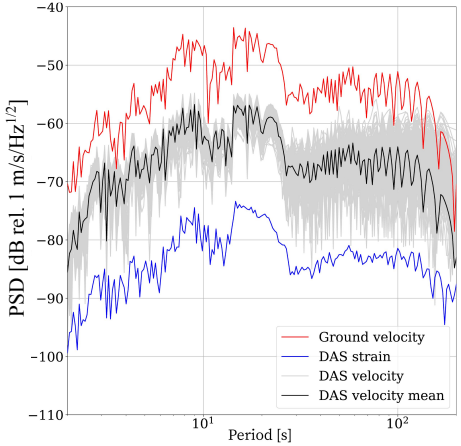

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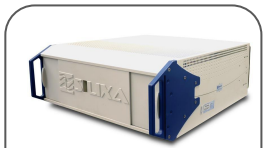

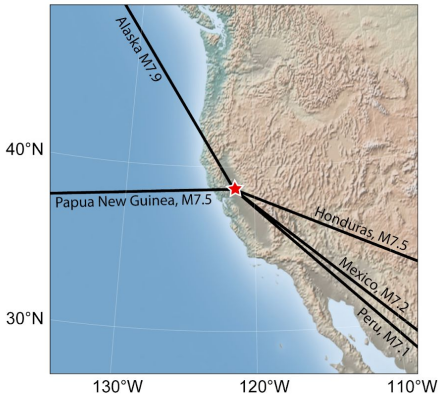

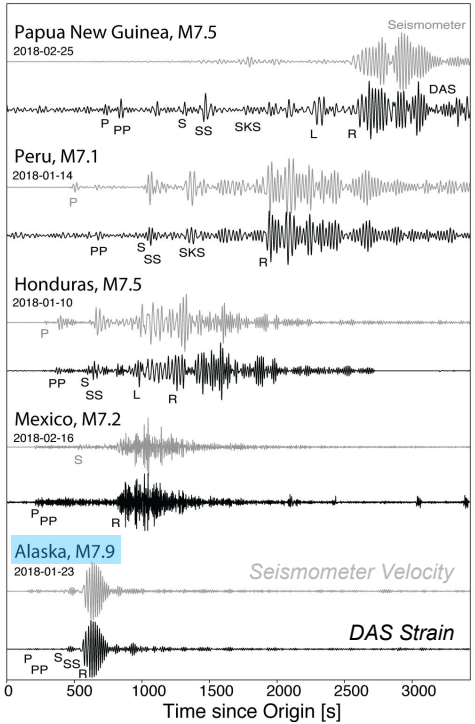

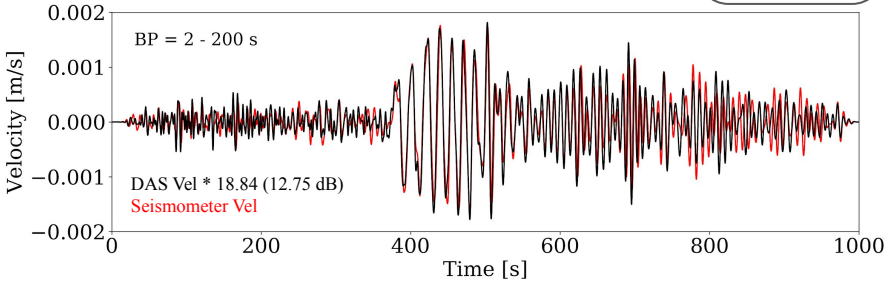

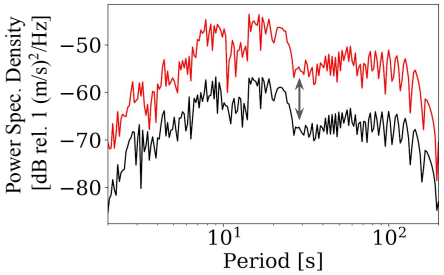

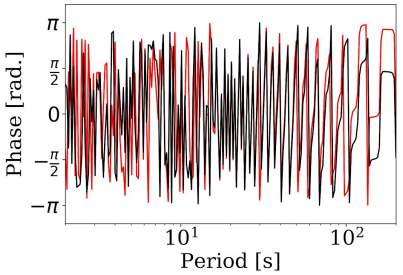

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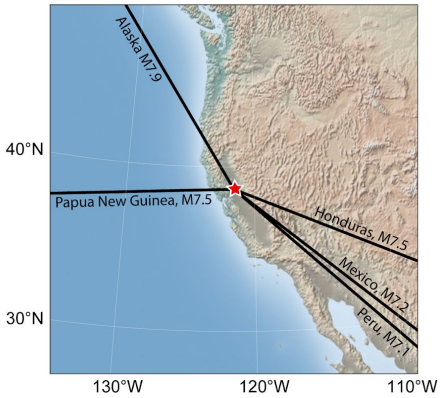

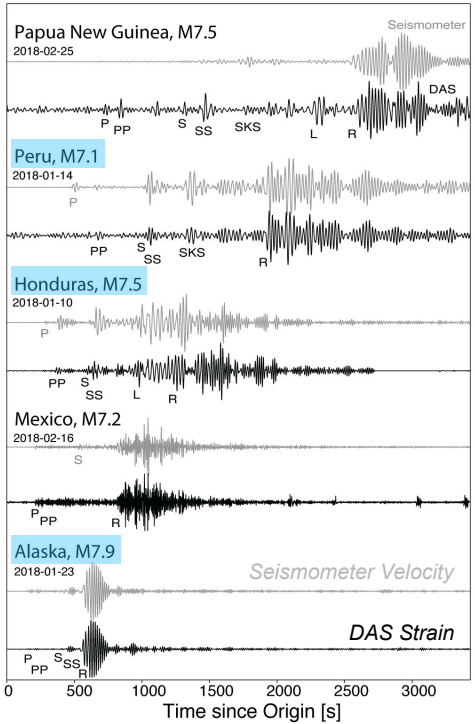

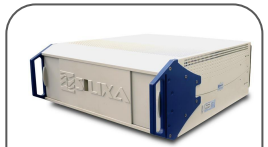
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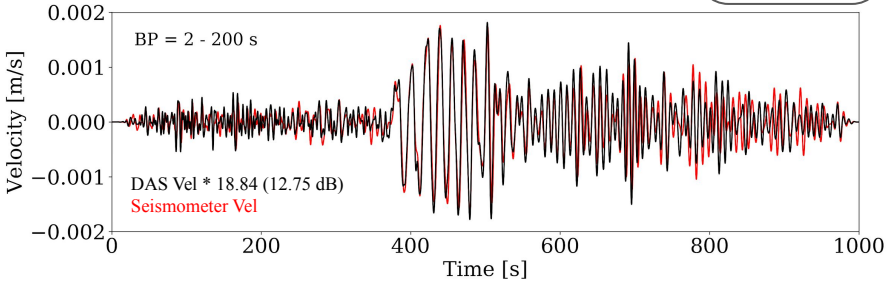
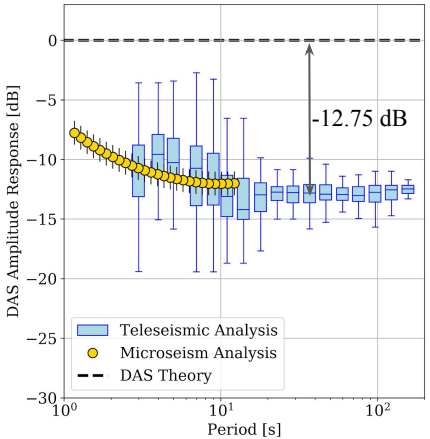
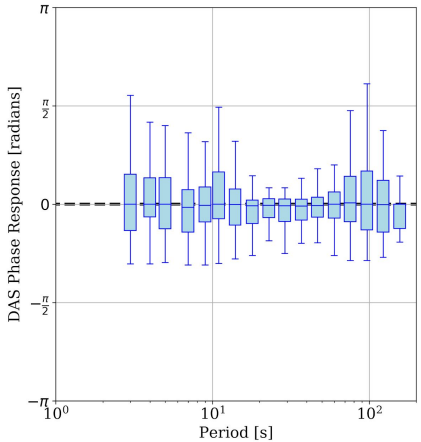


Result of Deconvolution

As broadband as seismometer, flat phase, reduced amplitude...coupling? photonic?





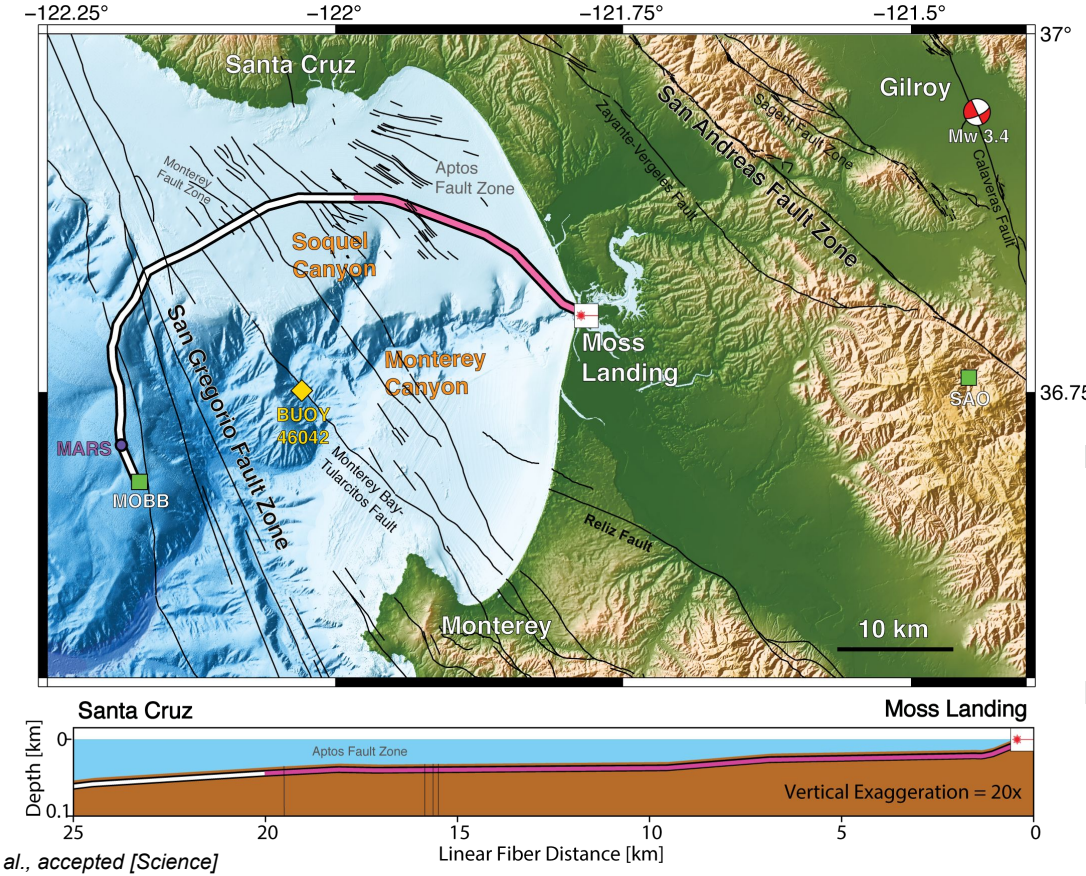
Lindsey et al., in review [JGR]

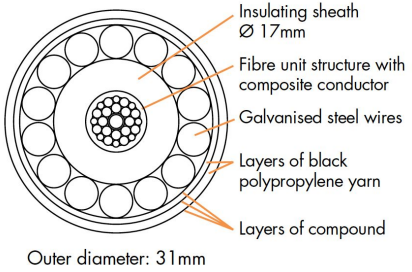
Aims for Today’s Talk

- What is DAS instrument response?
- What can we do offshore with DAS now?

Crossing the shoreline

DAS-MARS Cable Experiment





OALC4 Single Armoured Cable (SA)

MARS cable laid in 2006 (UC Berkeley/MBARI)

- 52 km long, 0.5-1 m deep
- Provides power/comm to seafloor node
- Continuous operation 2006 - 2019
- No unused fiber
- Routine node maintenance 3 - 4 days / year

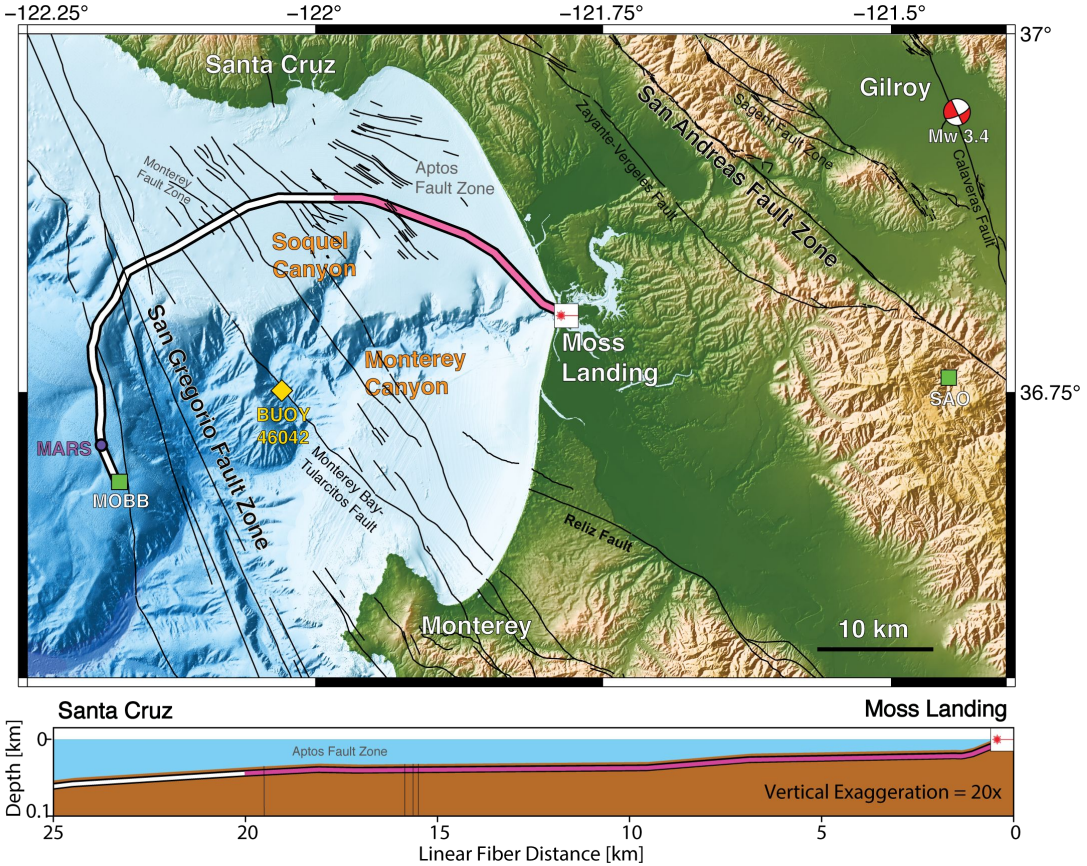
DAS-MARS cable experiment 2018

- 3.5 days
- Occupied 1 SMF from shore with Silixa iDAS
- 9,984 DAS @ dt=0.002 s, dx=2 m, L_G=10 m
- Total collected DAS data volume = 3.45 TB

Lindsey et al., accepted [Science]

Crossing the shoreline

DAS-MARS Cable Experiment



Questions:

- Seafloor DAS sensitivity
  ...ocean acoustics? solid earth signals?
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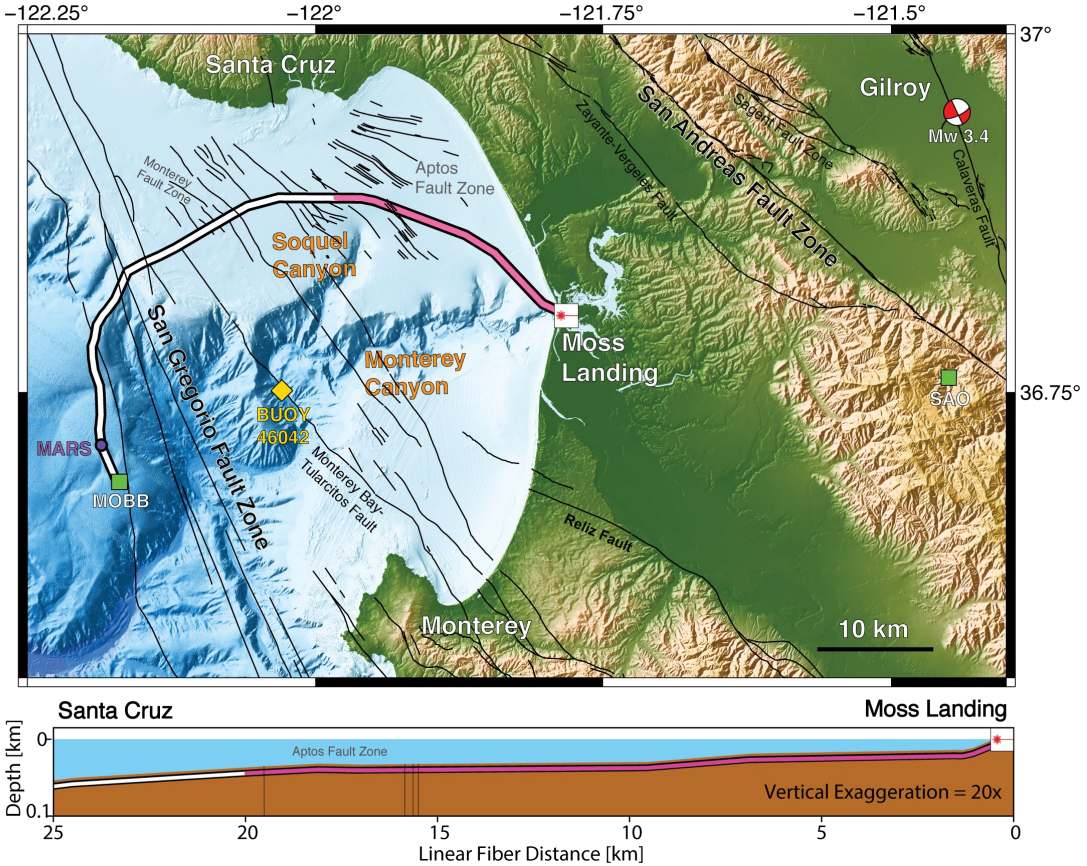

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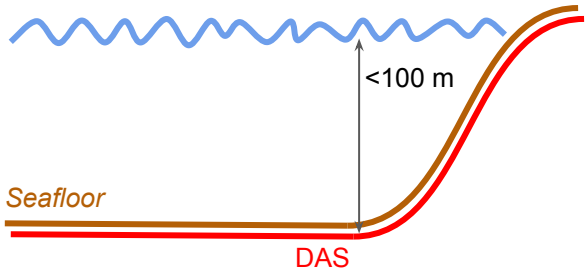
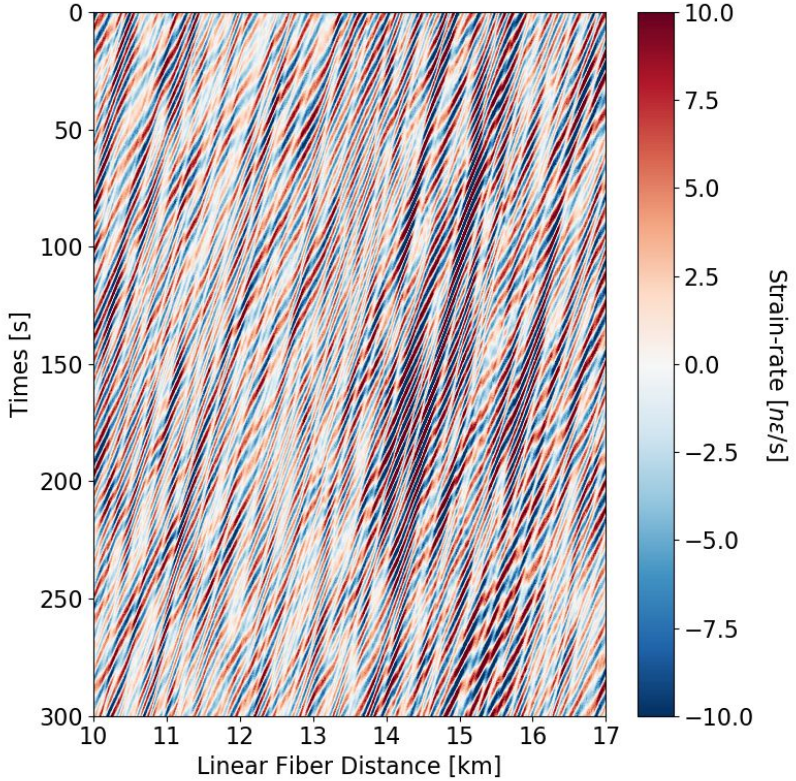
What does it mean to record seafloor DAS data? Sensitivity to ocean signals?

DAS-MARS Cable Experiment





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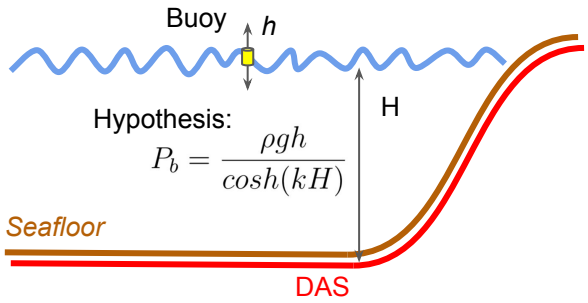

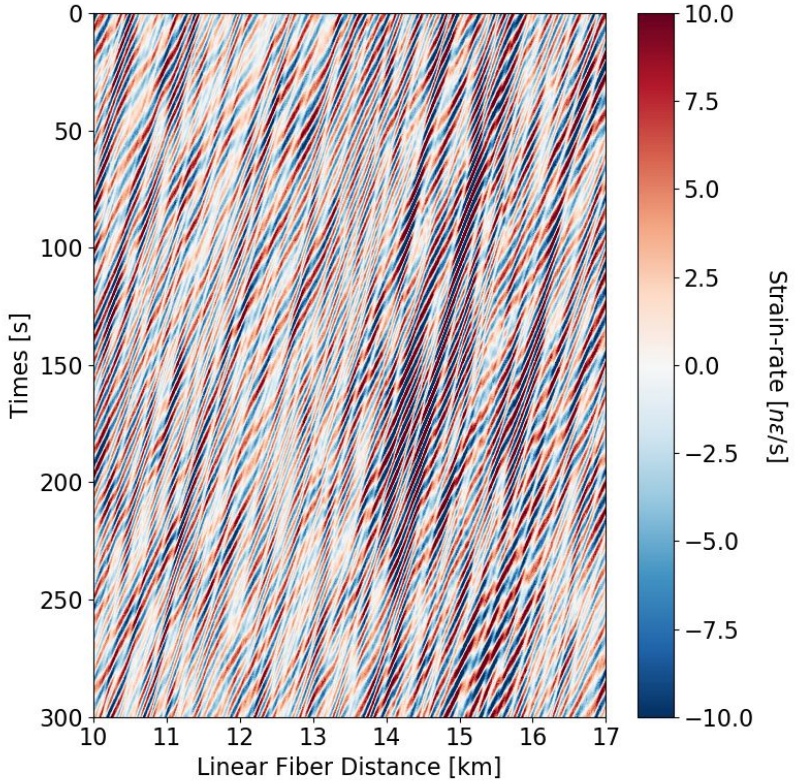

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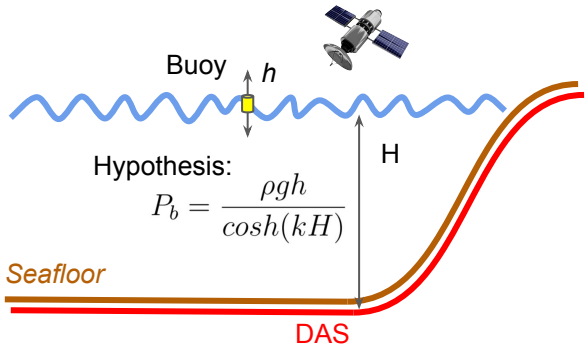

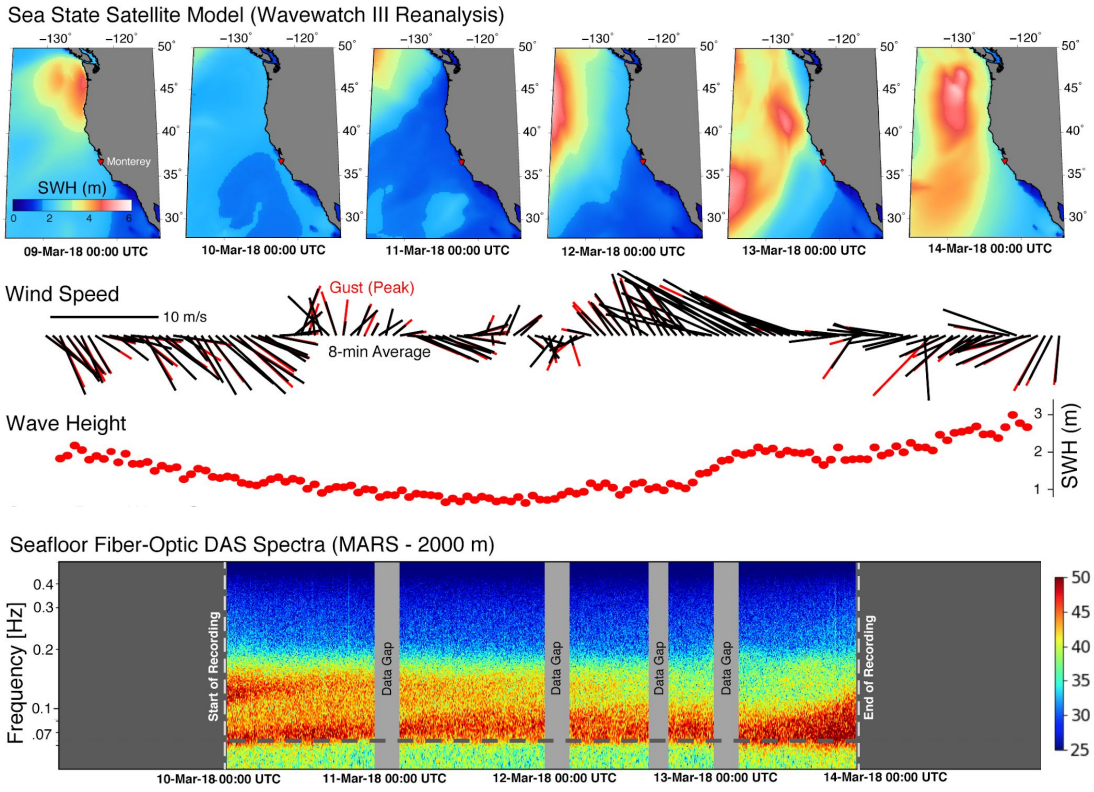

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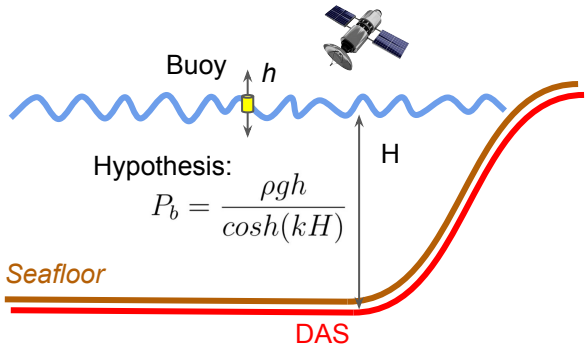
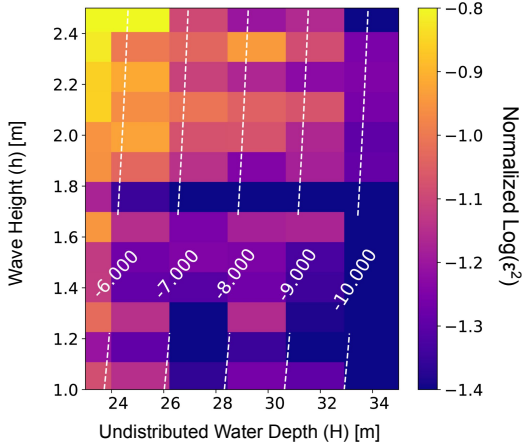
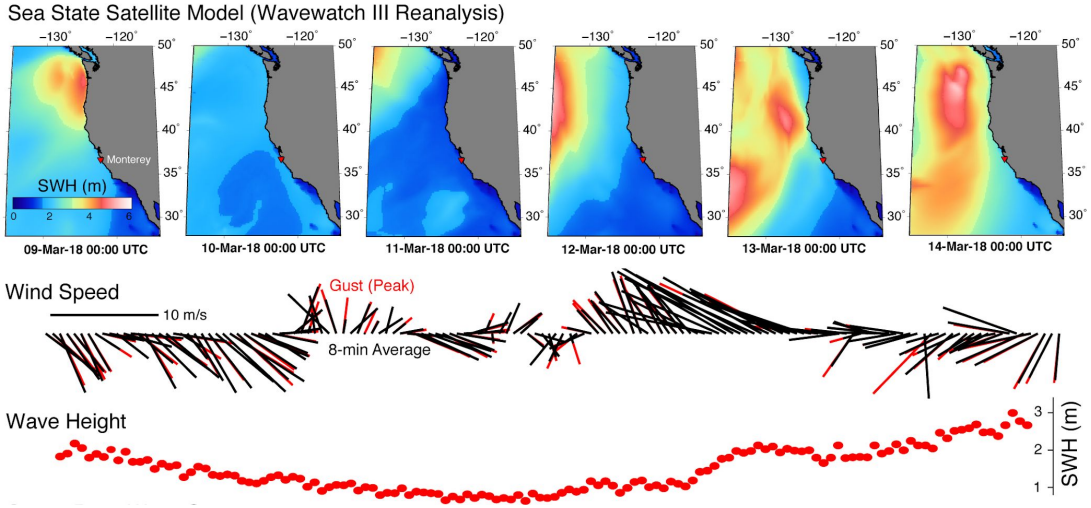
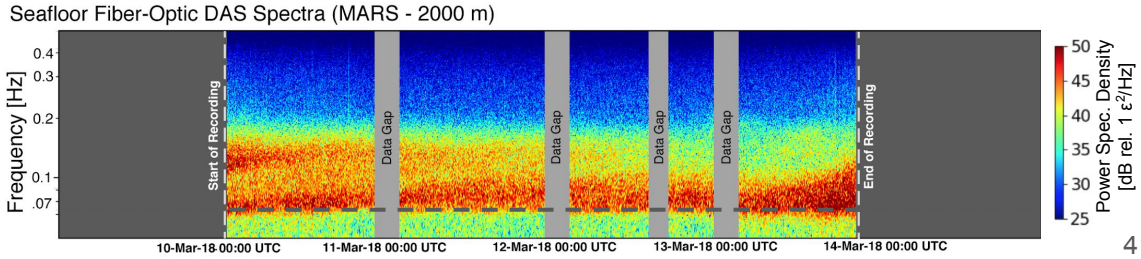


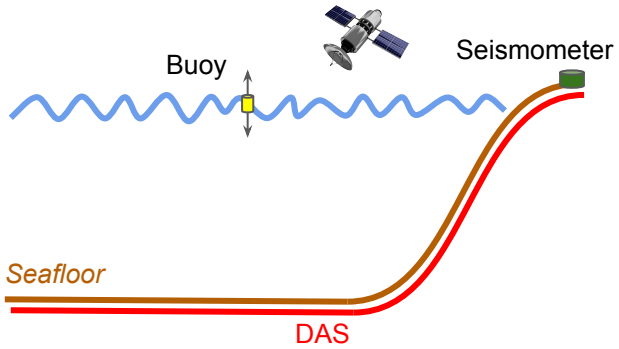


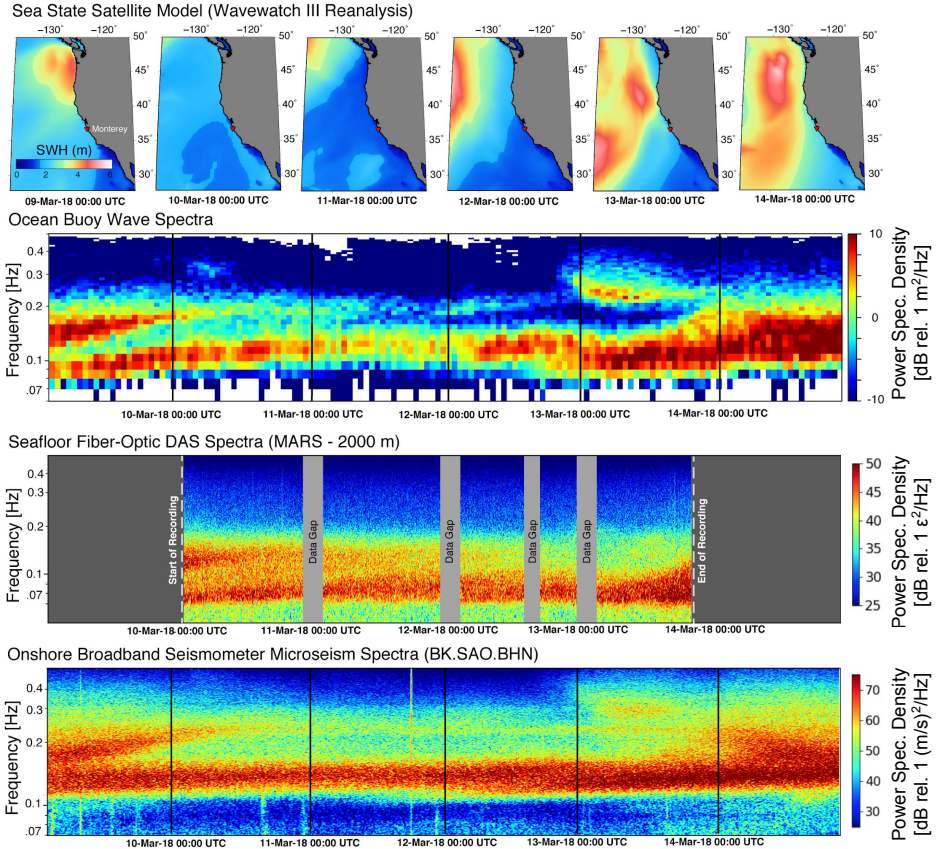




How is microseism energy partitioned at the ocean-solid earth interface?

DAS-MARS Cable Experiment





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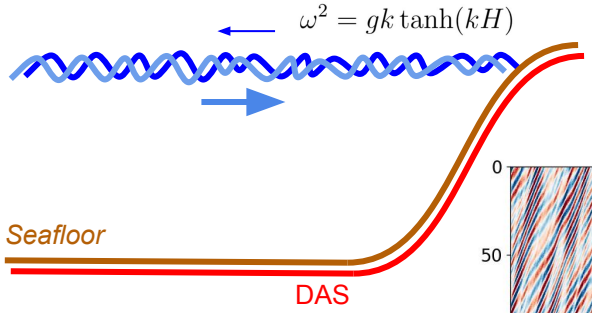

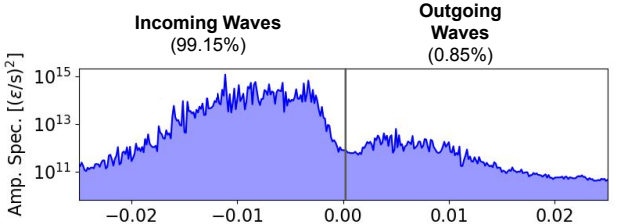

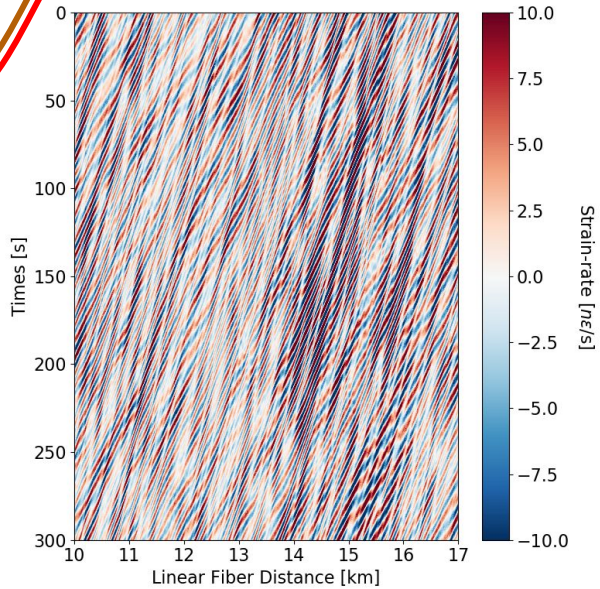

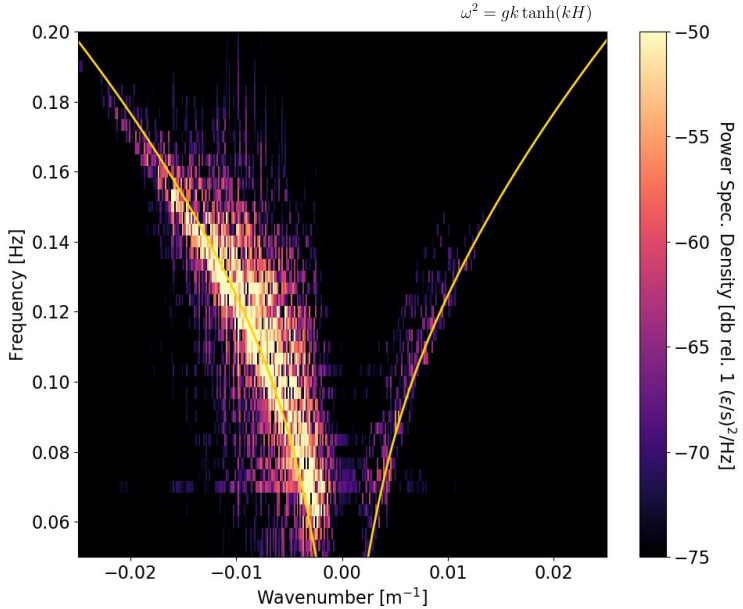

- PM : f = .05 - 0.2 Hz; asymmetric

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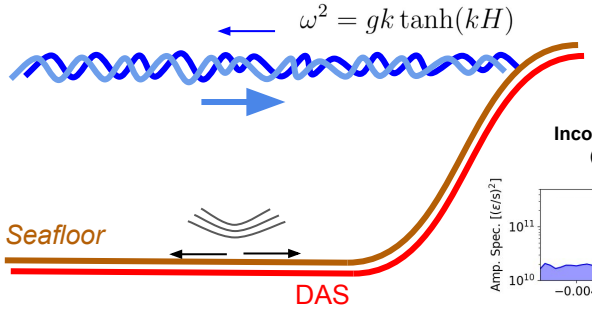
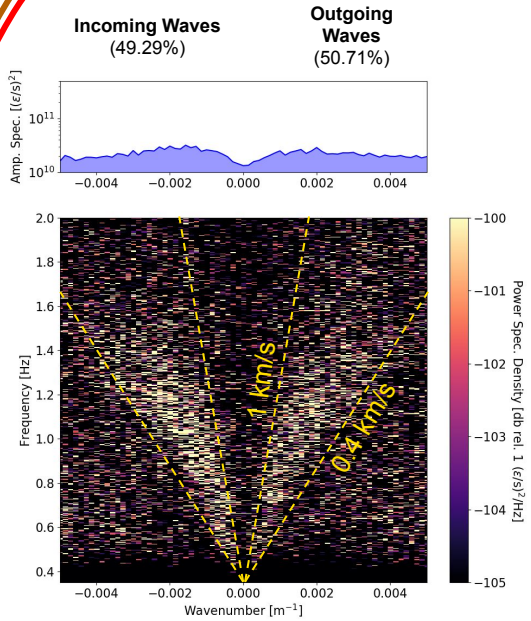
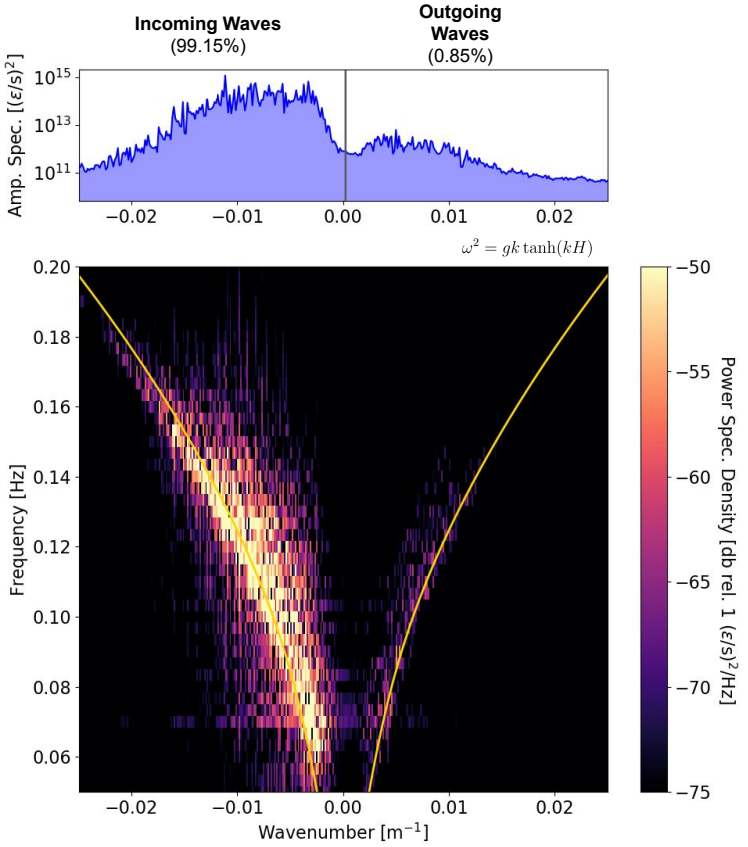




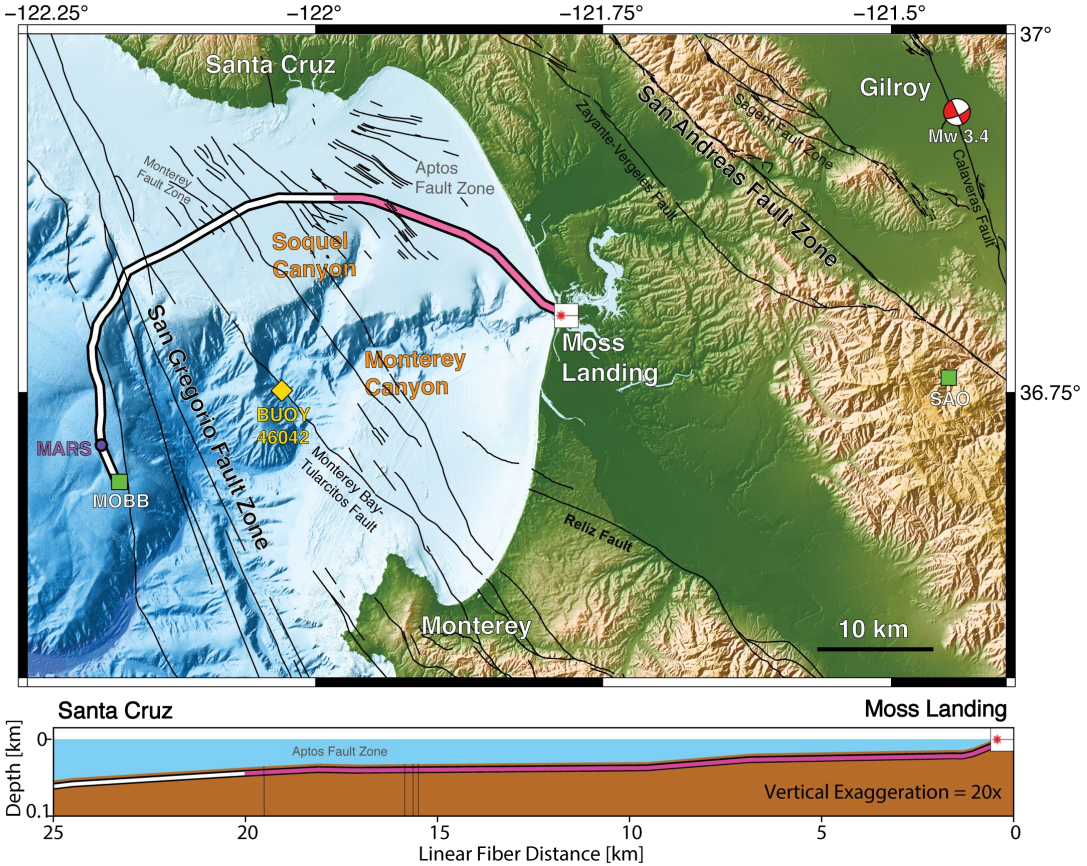


- PM : f = .05 - 0.2 Hz; asymmetric
- SM : f = .03 - 2 Hz; symmetric (fast)
- Energy PM >> SM in shallow water

Longuet-Higgens, 1950; Hasselmann, 1963

Crossing the shoreline

DAS-MARS Cable Experiment



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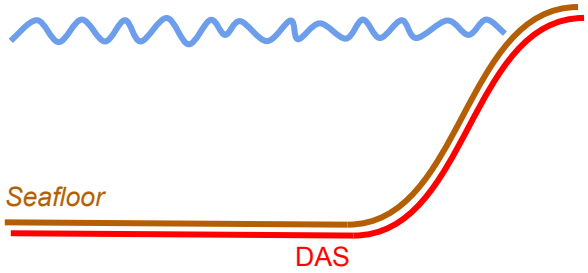
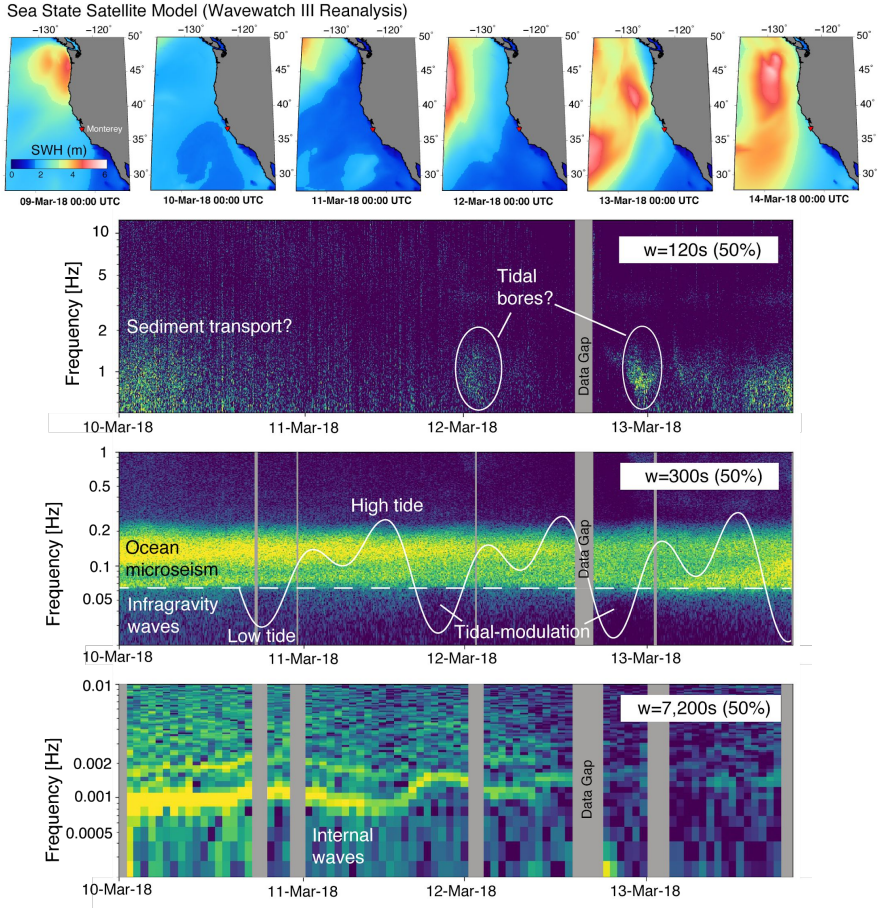
Long period DAS response to hydrodynamic signals?

DAS-MARS Cable Experiment



- Infragravity waves tidally modulated
- Post-low tide bore migration
- Field evidence of DAS response T~1000 s



Dolenc et al., 2005; Cazenave 2008; Colosi et al., 2018; Becker et al., 2017

Crossing the shoreline

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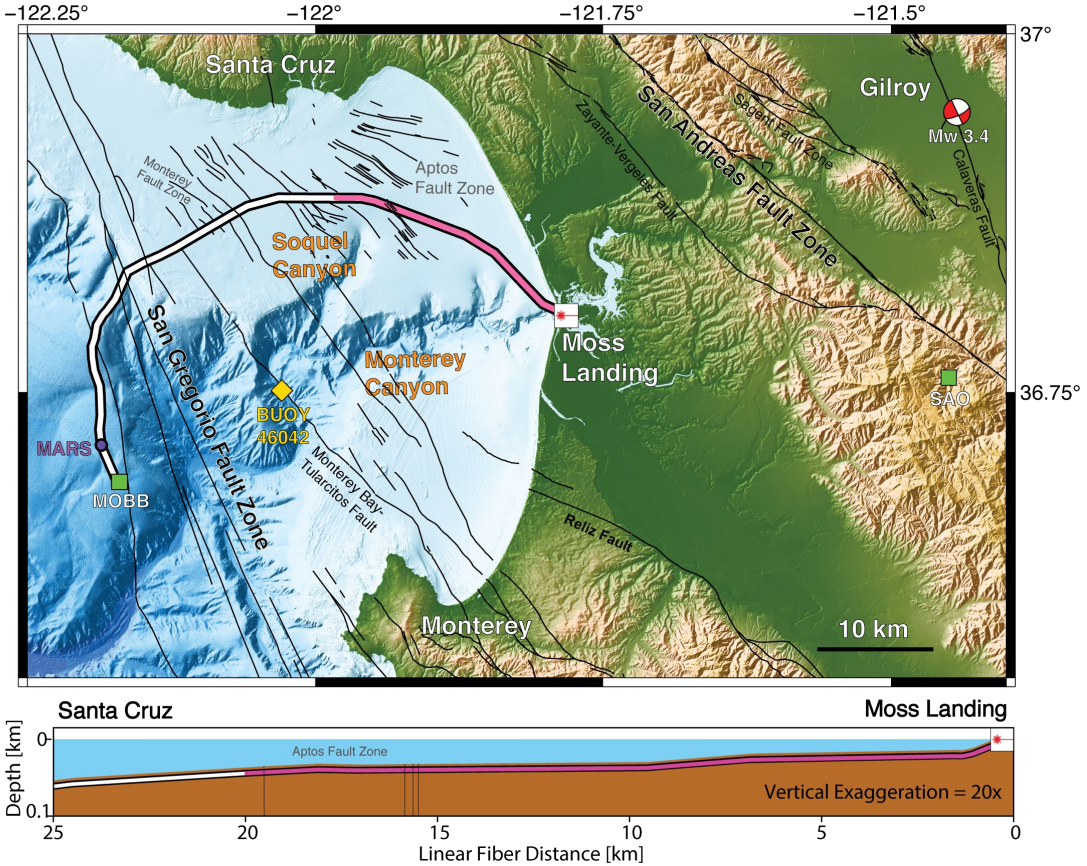

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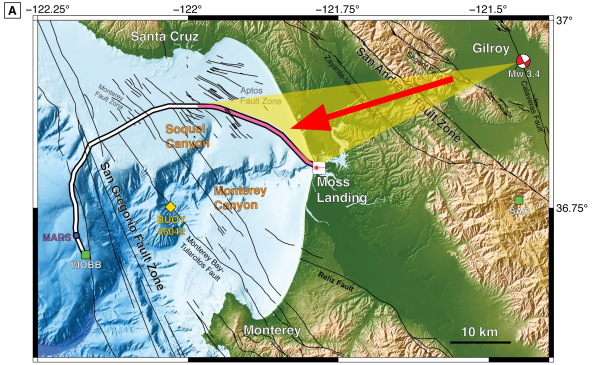
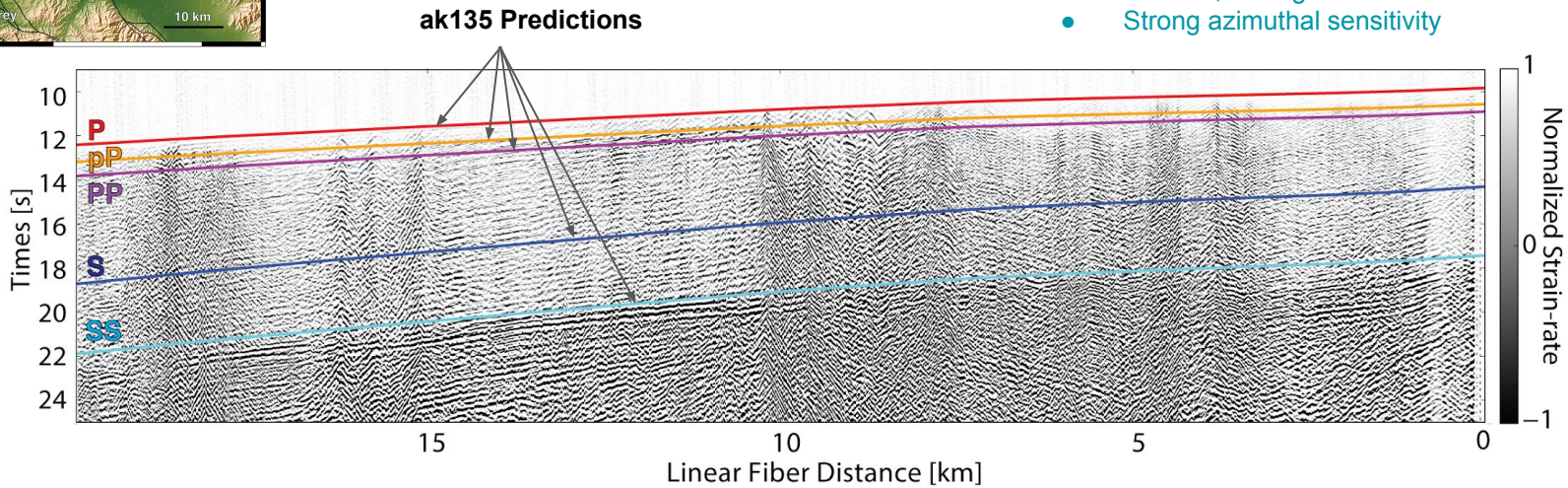


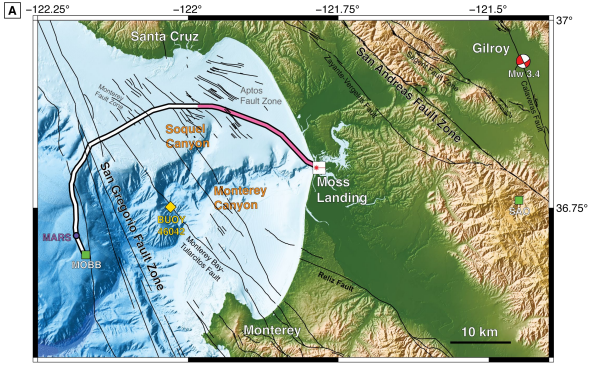
- Mw 3.4
- 2.87 km depth
- Weak P; Stronger SS than S
- Strong azimuthal sensitivity

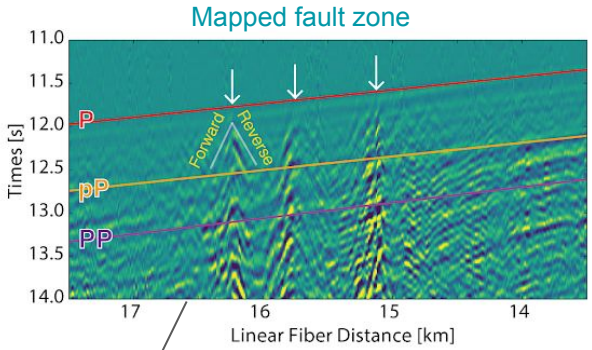


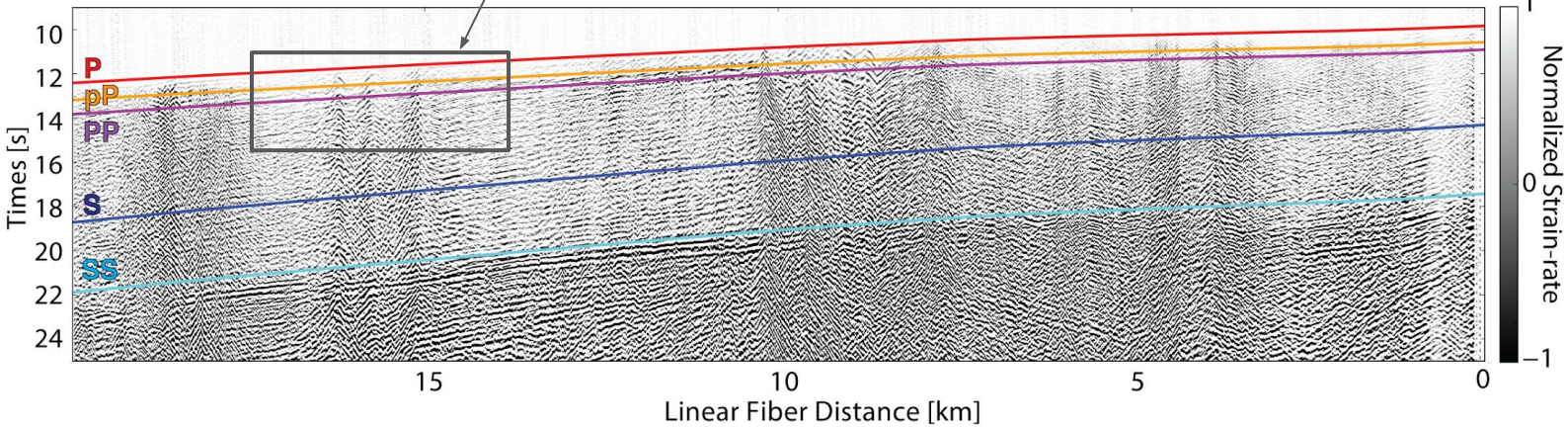
Can we use DAS to study seafloor fault properties?

DAS-MARS Cable Experiment

- FK-filter removes microseism
- Aptos Fault Zone recently mapped with dense 3-D seismic reflection (CSMP).
- Point scattering of body waves into 400-800 m/s surface waves.







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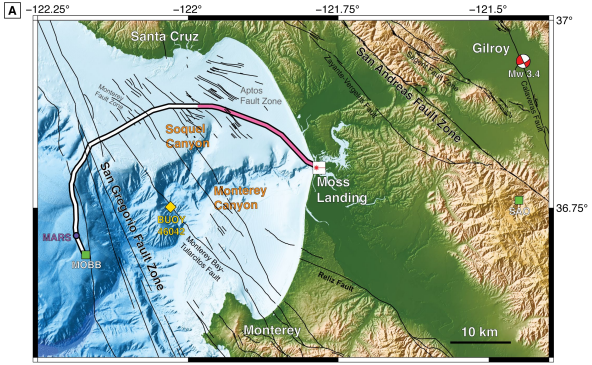
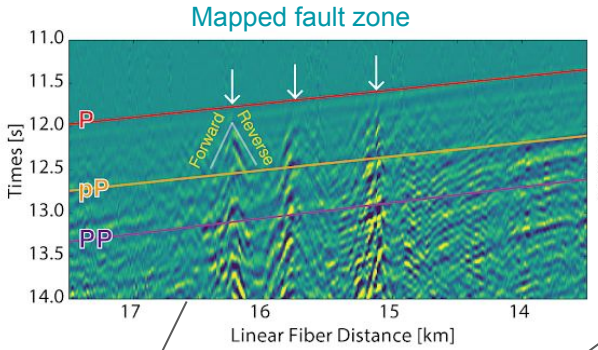
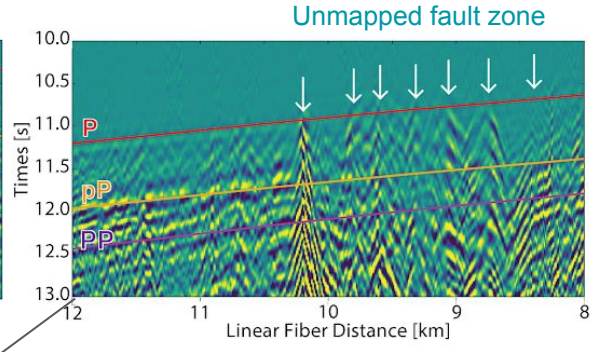
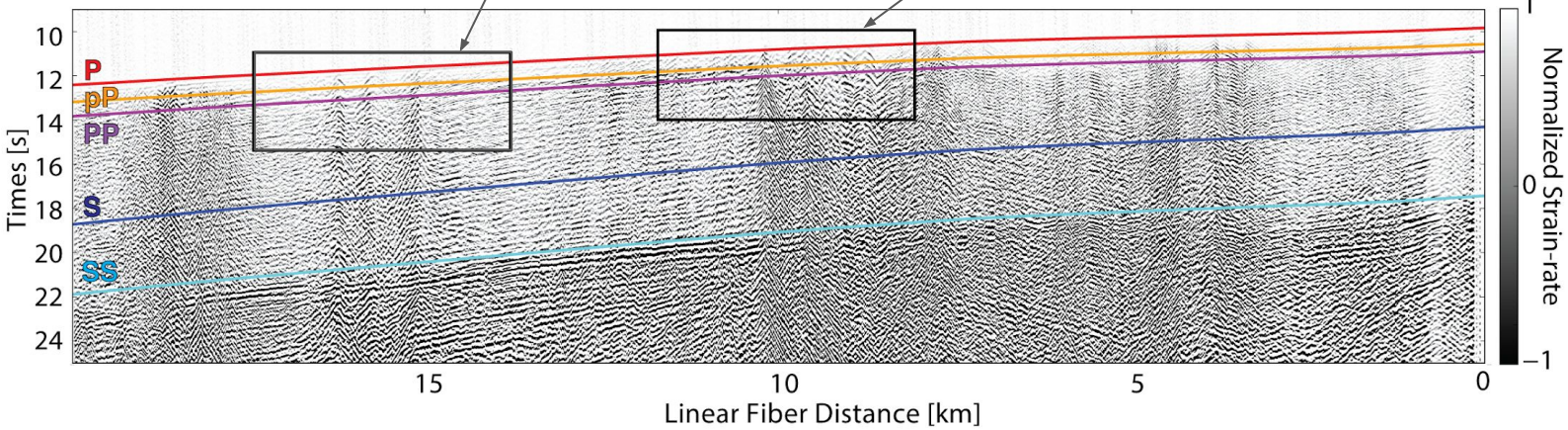




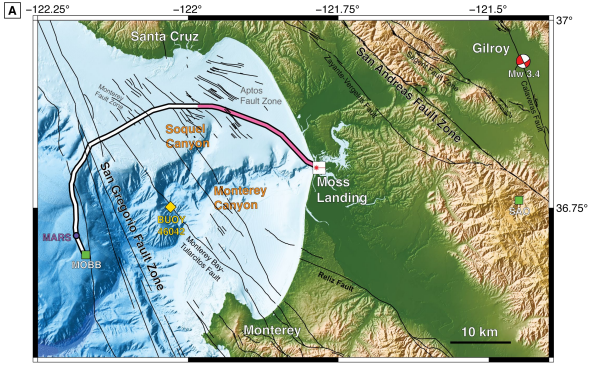


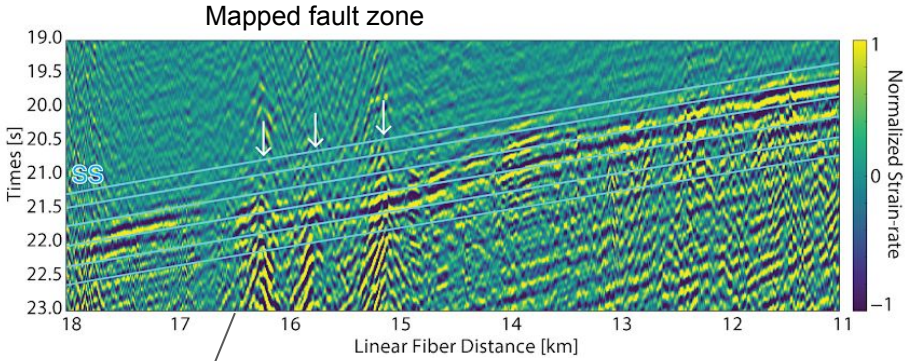


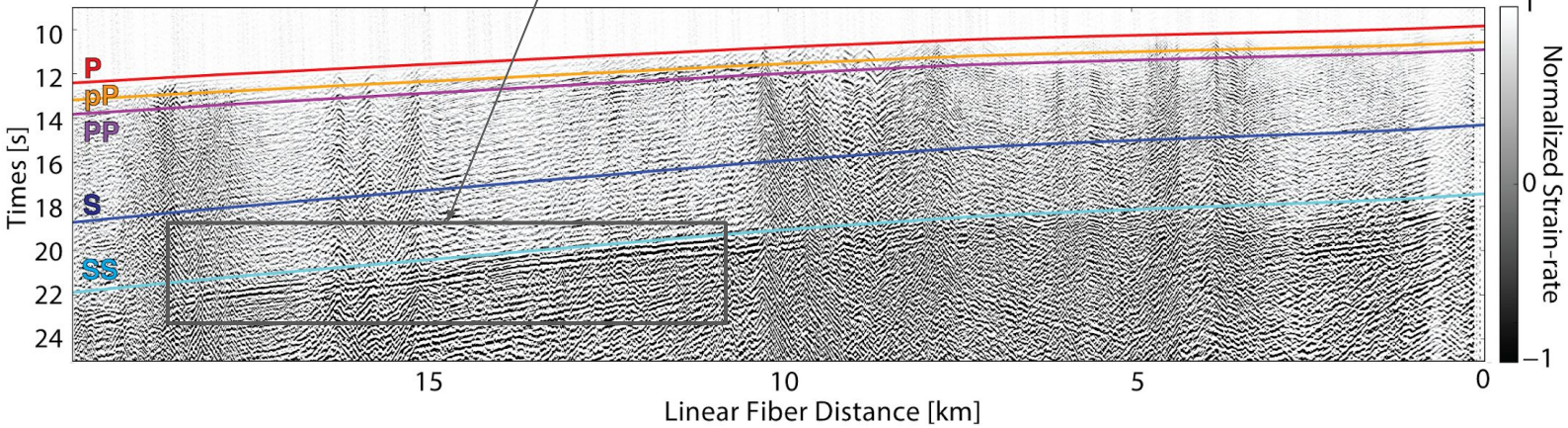
Can we use DAS to study seafloor fault properties?

DAS-MARS Cable Experiment

- FK-filter removes microseism
- Aptos Fault Zone recently mapped with dense 3-D seismic reflection (CSMP).
- Point scattering of body waves into 400-800 m/s surface waves.
- Wavefront delay = 0.5 s







Further reading in pre-print, press...

Instrument response

- Becker, M.W. and Coleman, T. (2019). Distributed Acoustic Sensing of Strain at Earth Tide Frequencies. *Sensors 19*(9), 1975; https://doi.org/10.3390/s19091975.

Seafloor DAS

- Williams, E., Fernandez-Ruiz, M. R., Magalhaes, R., Vanthillo, R., Zhan, Z., Gonzalez-Herraez, M., & Martins, H. F. (2019). Teleseisms and Microseisms on an Ocean-Bottom Distributed Acoustic Sensing Array. EarthArXiv; https://eartharxiv.org/kg7q4/ (in review, *Nat Comm.).*

- Sladen, A., Rivet, D., Ampuero, J. P., Hello, Y., Calbris, G., and Lamare, P. (2019). Distributed sensing of earthquakes and ocean-solid Earth interactions on seafloor telecom cables. *EarthArXiv*; https://eartharxiv.org/ekrfy/ (in review, *Nat Comm.).*

- Lindsey, N., Dawe, T.C., & Ajo-Franklin, J. (2019). Photonic seismology in Monterey Bay: Dark fiber DAS illuminates offshore faults and coastal ocean dynamics. *EarthArXiv*; https://eartharxiv.org/7bf92/ (accepted, *Science).*

Thank you for your attention!

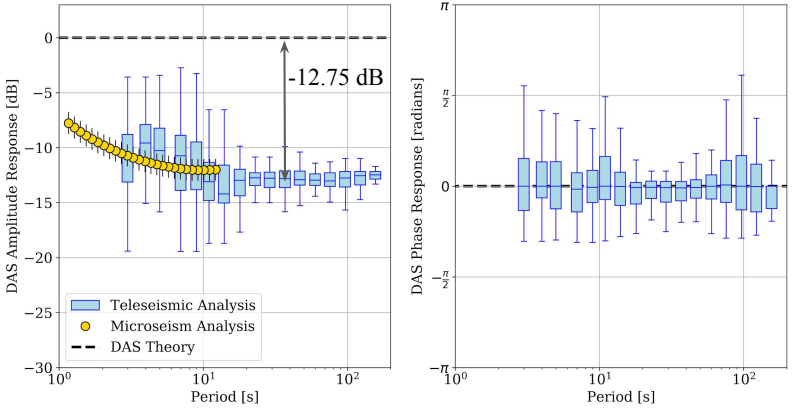
Nate Lindsey
natelindsey@berkeley.edu

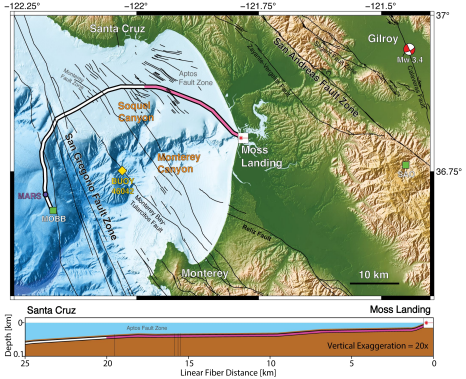
- ## What is DAS instrument response?

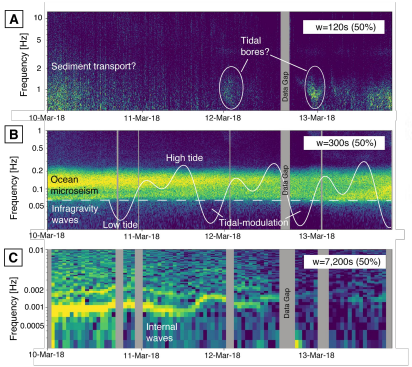
  As broadband as seismometer, flat phase, reduced amplitude...coupling? photonic?
  Are all fibers and instruments the same? Need cross-validation and calibration.
  Many more open aspects to investigate...self-noise, dynamic range, cross-talk.

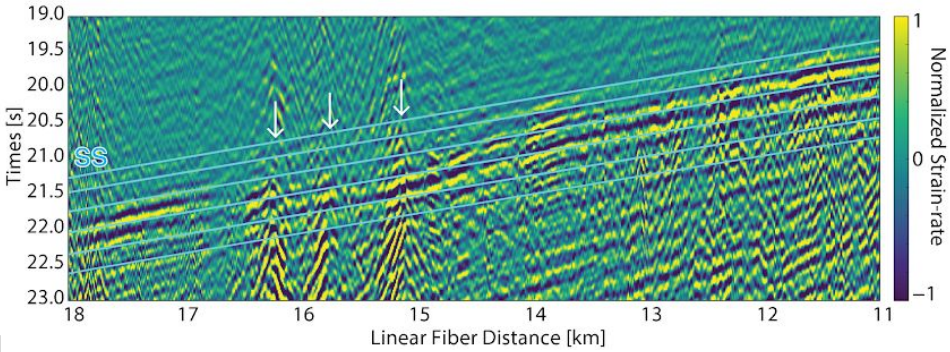
- ## What can we do offshore with DAS now?

  DAS has sensitivity to nearshore ocean noises and solid earth seismic signals.
  Examine microseism partitioning, nearshore soundscape, seafloor fault properties.



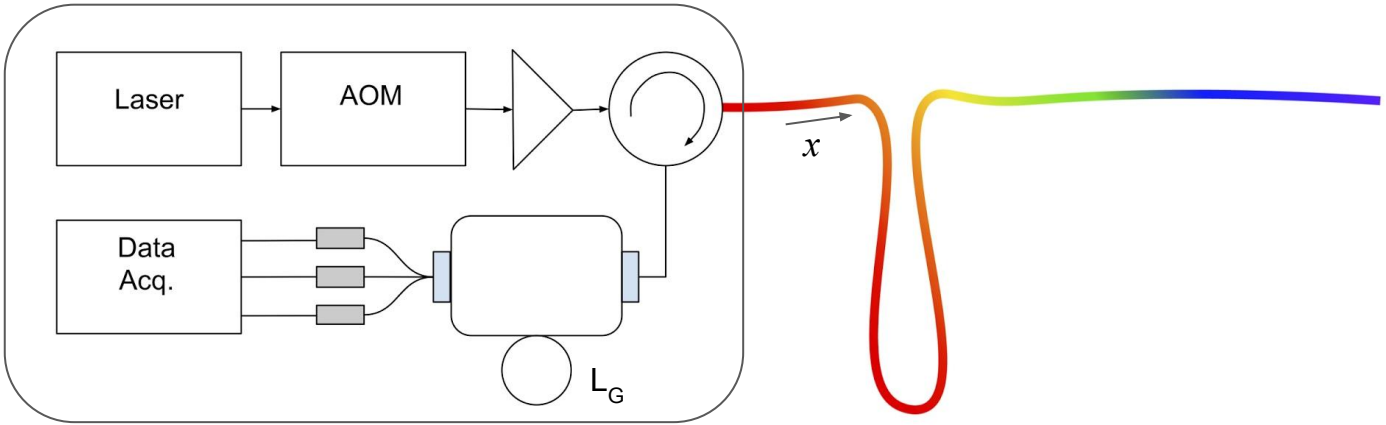






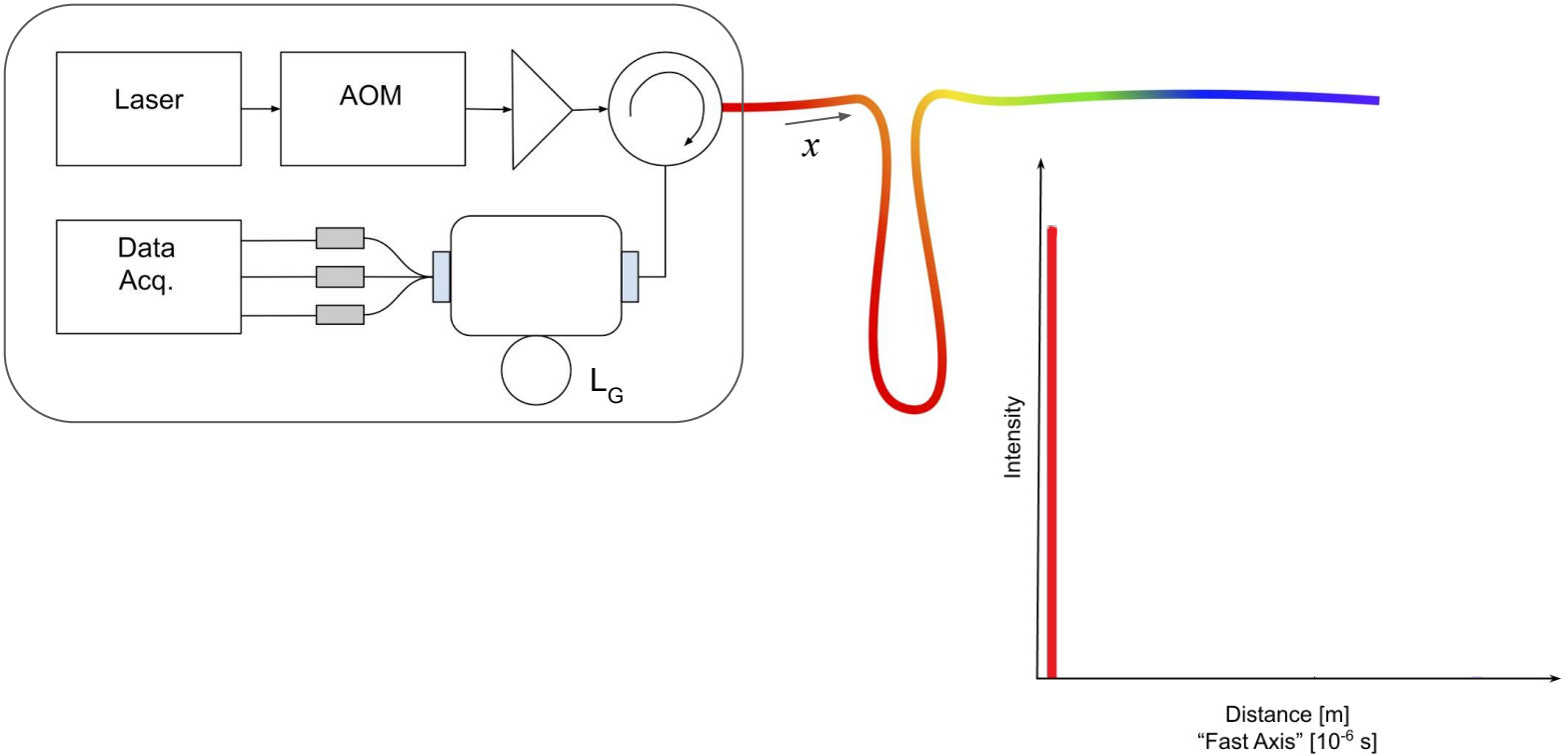
Supplementary Slides

Distributed Acoustic Sensing



after Posey 2000; Masoudi and Newsom, 2016; Hartog, 2017

Distributed Acoustic Sensing



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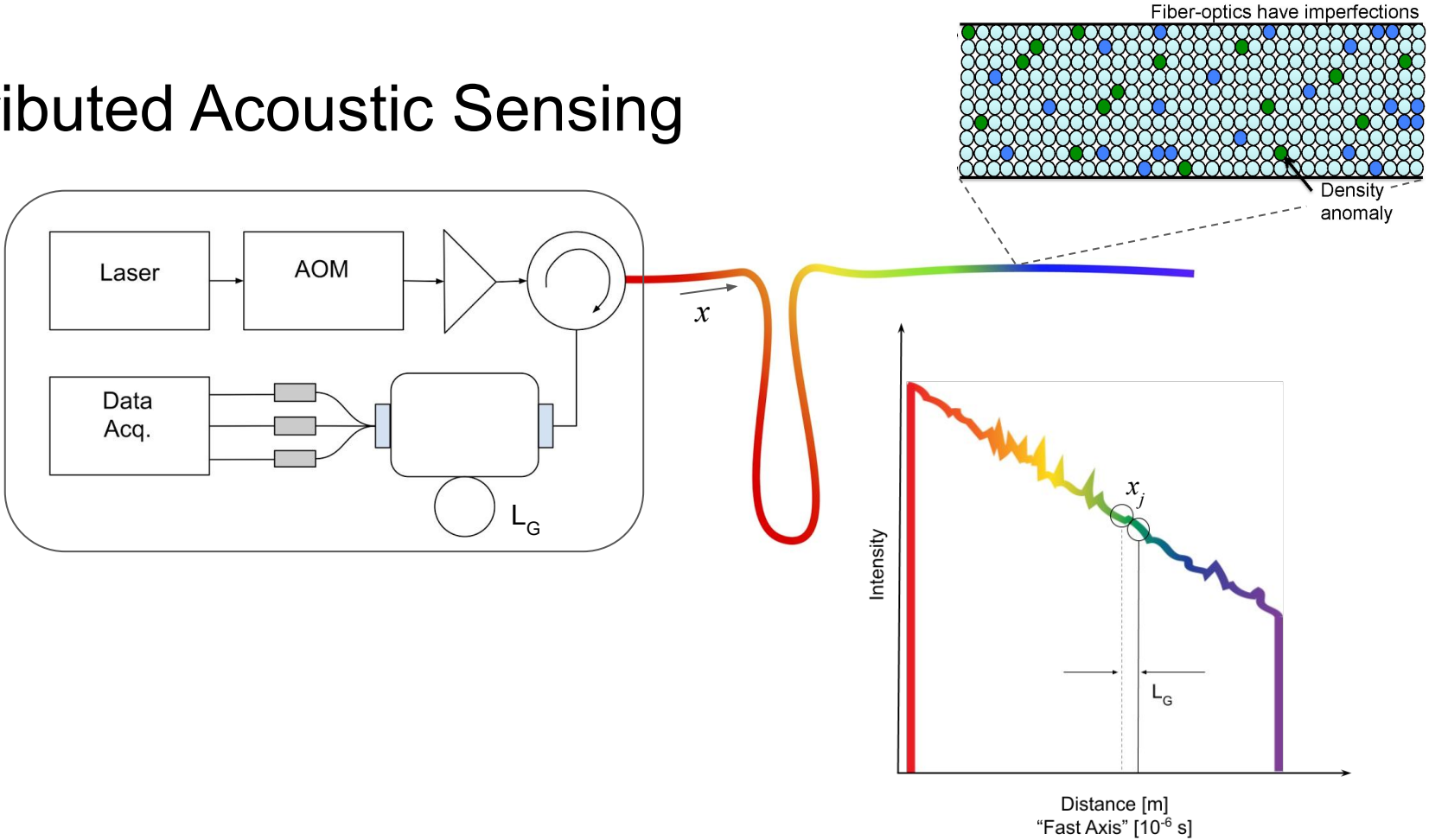
Distributed Acoustic Sensing



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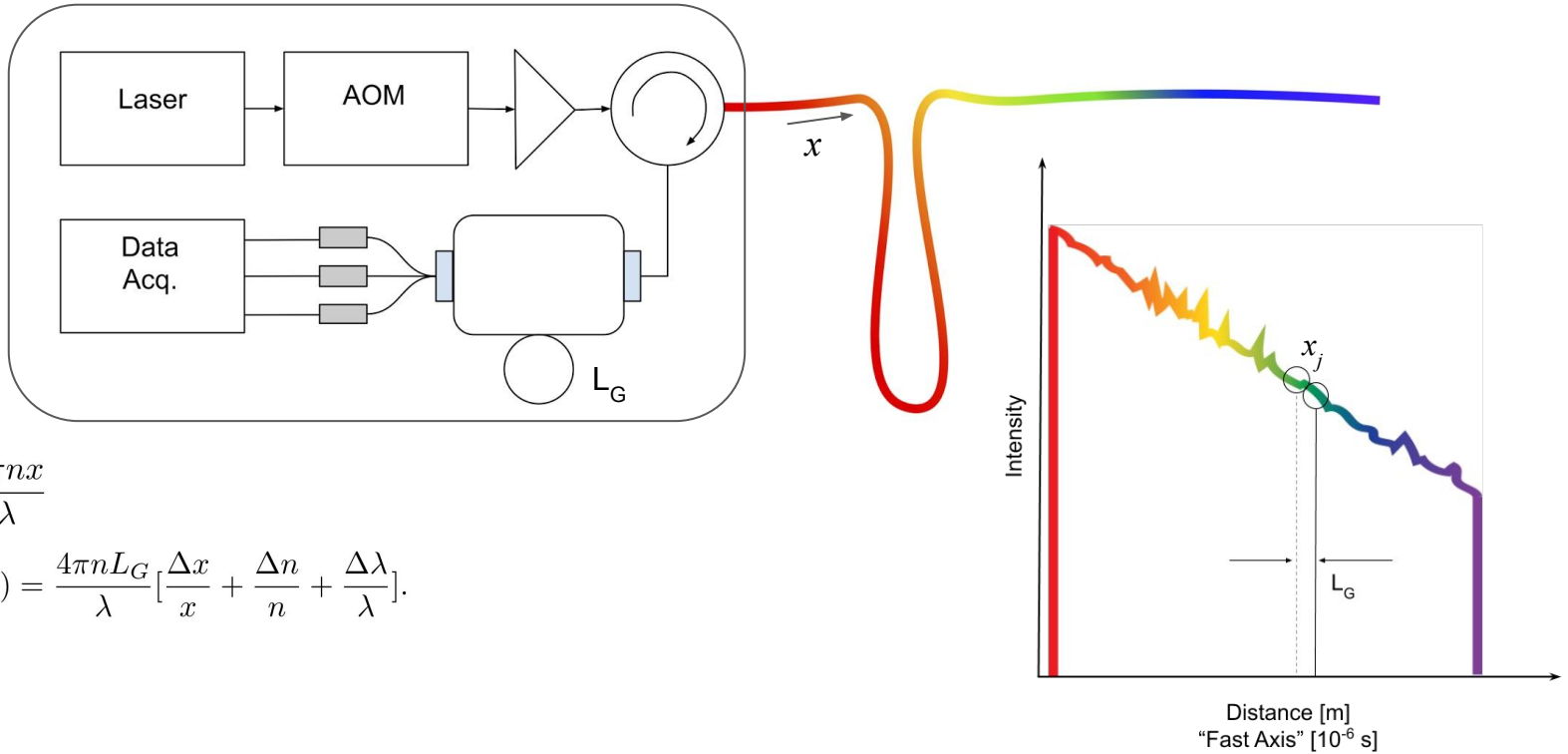
Distributed Acoustic Sensing

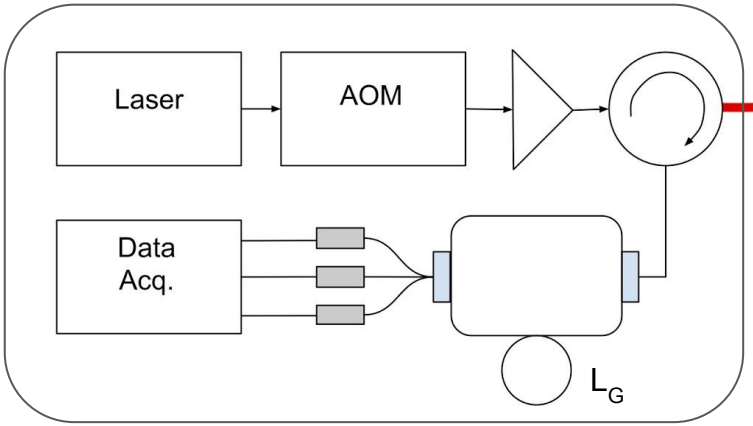


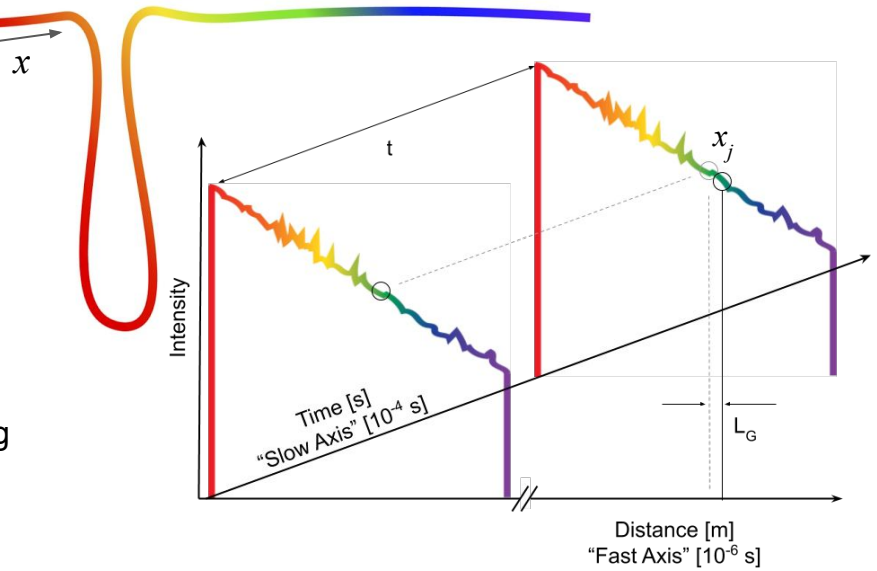
$$\Phi = \frac{4\pi n x}{\lambda}$$

$$\Delta\Phi(t, x_j) = \frac{4\pi n L_G}{\lambda}\left[\frac{\Delta x}{x} + \frac{\Delta n}{n} + \frac{\Delta\lambda}{\lambda}\right].$$

after Posey 2000; Masoudi and Newsom, 2016; Hartog, 2017

Distributed Acoustic Sensing





$$\Phi = \frac{4\pi n x}{\lambda}$$

~0.79 on seismic timescale

0 for Rayleigh backscattering

$$\Delta\Phi(t, x_j) = \frac{4\pi n L_G}{\lambda}[\frac{\Delta x}{x} + \cancel{\frac{\Delta n}{n}} + \cancel{\frac{\Delta \lambda}{\lambda}}].$$

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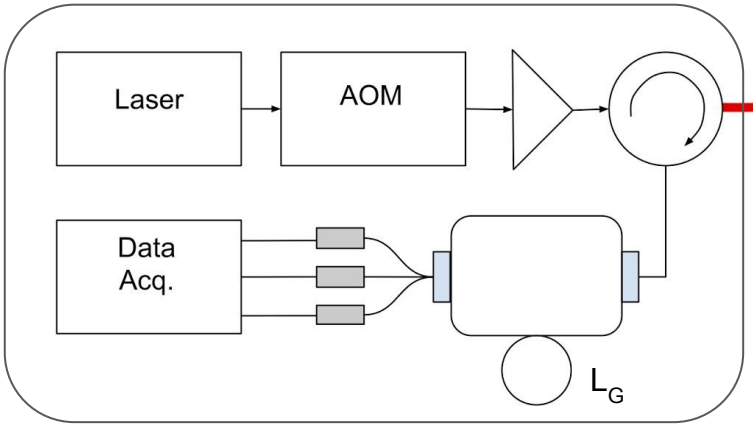
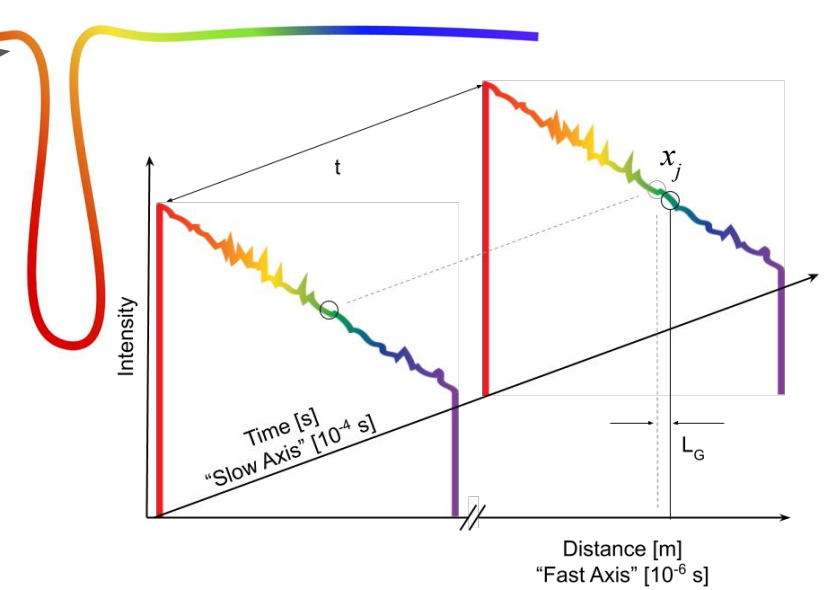
Distributed Acoustic Sensing





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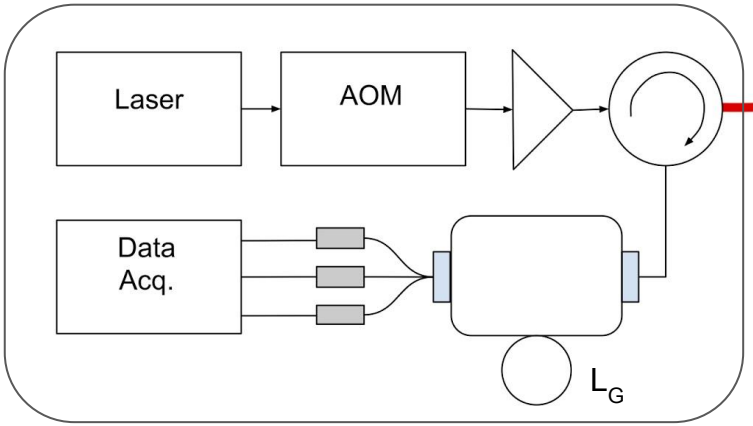
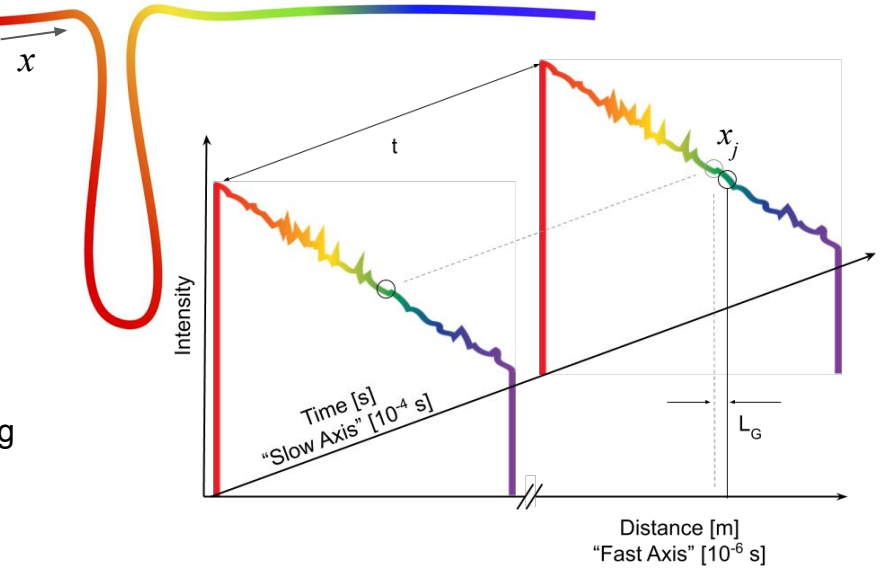
$$\epsilon_{xx}(t, x_j) = \frac{\lambda}{4\pi n L_G \zeta}\Delta\Phi = \frac{1550 \cdot 10^{-9}[m]}{4\pi \cdot 1.45 \cdot 10[m] \cdot 0.79}\Delta\Phi = 11.6 \cdot 10^{-9} \cdot \Delta\Phi[rad]$$

after Posey 2000; Masoudi and Newsom, 2016; Hartog, 2017

Distributed Acoustic Sensing

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





$$\Phi = \frac{4\pi n x}{\lambda}$$

~0.79 on seismic timescale
0 for Rayleigh backscattering

$$\Delta\Phi(t, x_j) = \frac{4\pi n L_G}{\lambda}\left[\frac{\Delta x}{x} + \frac{\Delta n}{n} + \frac{\Delta\lambda}{\lambda}\right].$$

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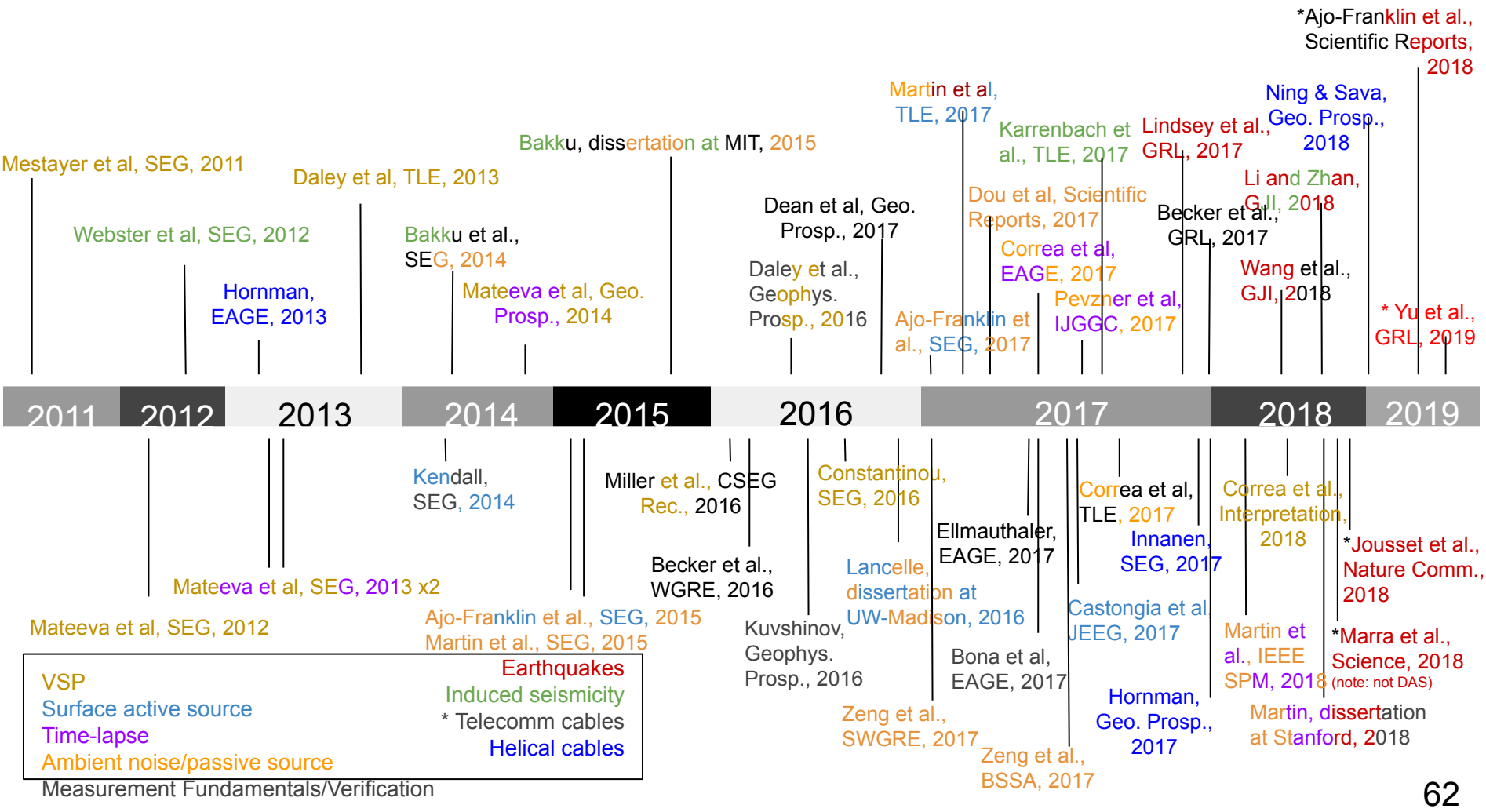
Mestayer et al, SEG, 2011
Webster et al, SEG, 2012
Hornman, EAGE, 2013
Daley et al, TLE, 2013
Bakku et al., SEG, 2014
Mateeva et al, Geo. Prosp., 2014
Bakku, dissertation at MIT, 2015
Dean et al, Geo. Prosp., 2017
Daley et al., Geophys. Prosp., 2016
Martin et al, TLE, 2017
Ajo-Franklin et al., SEG, 2017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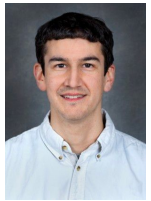
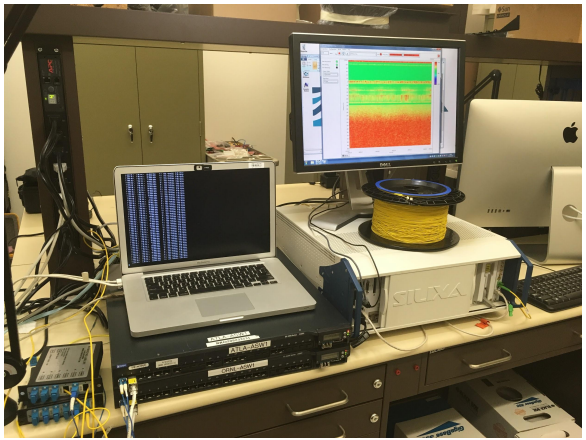
Mateeva et al, SEG, 2012
Mateeva et al, SEG, 2013 x2
Kendall, SEG, 2014
Ajo-Franklin et al., SEG, 2015
Martin et al., SEG, 2015
Miller et al., CSEG Rec., 2016
Becker et al., WGRE, 2016
Kuvshinov, Geophys. Prosp., 2016
Constantinou, SEG, 2016
Lancelle, dissertation at UW-Madison, 2016
Zeng et al., SWGRE,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

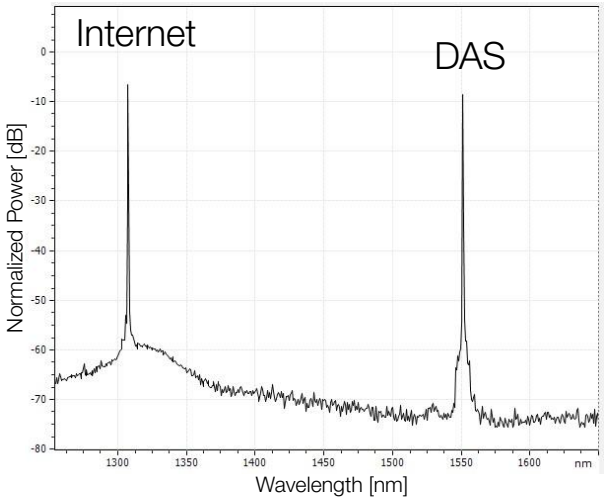
Making measurements

Also works in “lit fiber” telecommunications geometries...stay tuned


Aleksei Titov


Chris Tracy





- Full fidelity DAS recording
- 1310 nm 100baseT Ethernet connection reported 0 packet loss when sharing fiber

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ENERGY SCIENCES NETWORK

Lindsey, Titov, Tracy, in prep.