Distributed Fiber-Optic Sensing in geophysical and engineering applications

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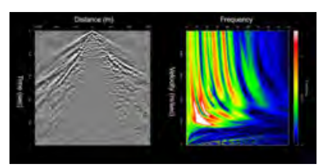
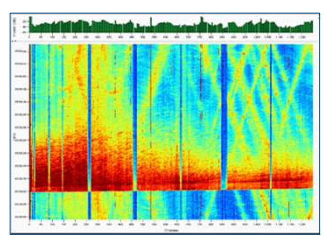
Oct 11, 2019 BC Geophysical Society

Outline





- Distributed Fiber-optic Sensing Concept
- Deployment Considerations
- Infrastructure Monitoring
- Near-surface
- Earthquake
- Landslides, slopes and geohazards

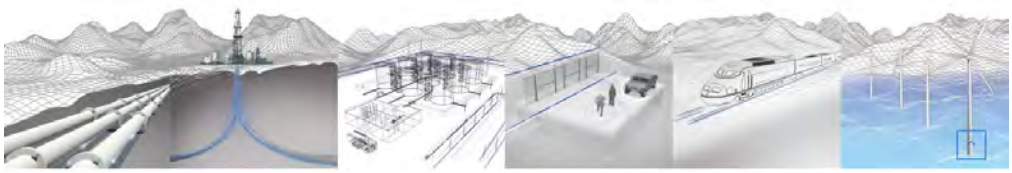
The Key Ingredients

Converting a fiber optic cable into a measurement device

Standard commercial off the shelf cable– up to 50 km (30 miles)

Interrogator: Laser, optical and electronic components

DAS Sensing on Infrastructure Fibers



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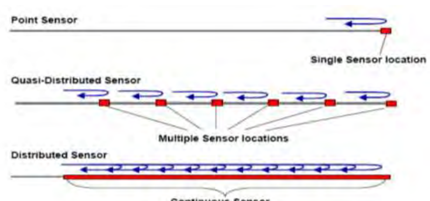
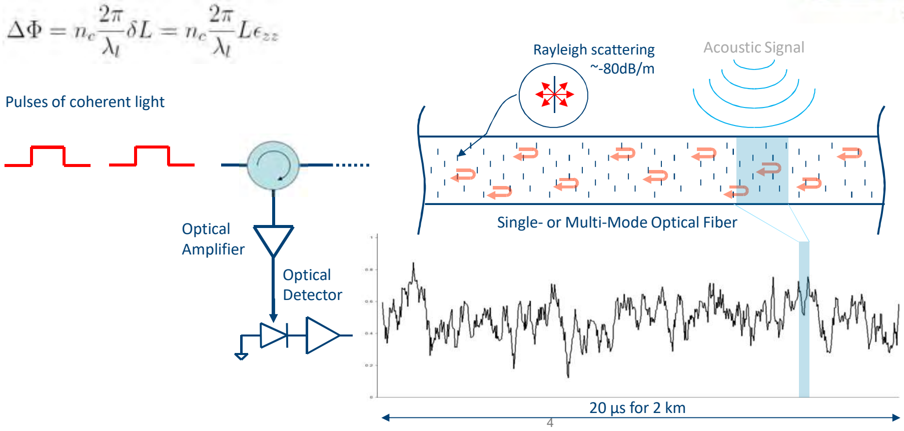
The DAS Measurement Principle

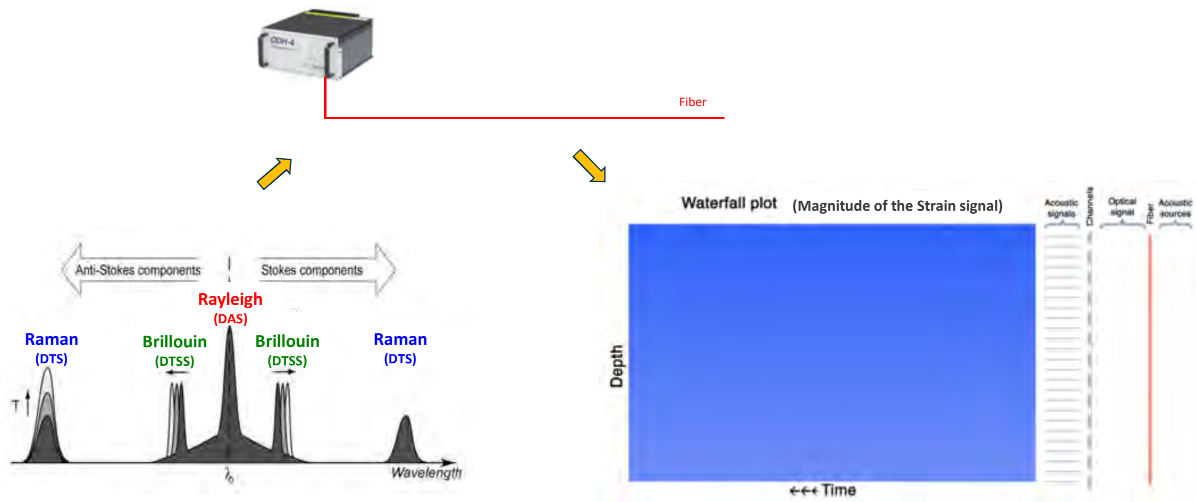
- Uses laser light pulses and the "Rayleigh scattering" effect to measure axial strains in the fiber
- Regular fiber optic cable turns into an array of acoustic sensors



$$\Delta\Phi = n_c \frac{2\pi}{\lambda_l}\delta L = n_c \frac{2\pi}{\lambda_l} L\epsilon_{zz}$$

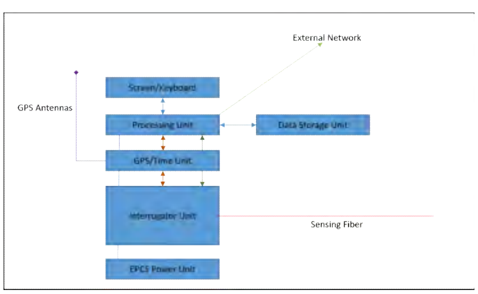


DAS: Coherent Rayleigh Backscatter Effects



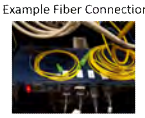
A Distributed Fiber-optic System

Deployment Options



Interrogator

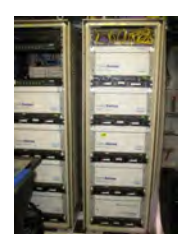
Example Fiber Connection



Temporary Deployment in Transport Case

Rugged Field Cases

Permanent Deployment in Rack

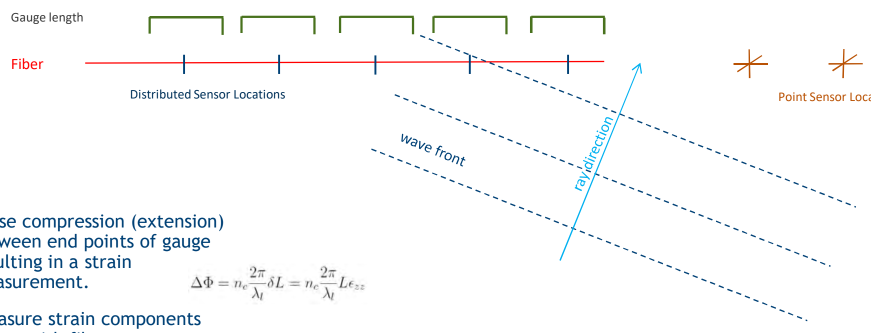


Distributed Sensors

10000's of sensors

Point Sensors

100's of sensors



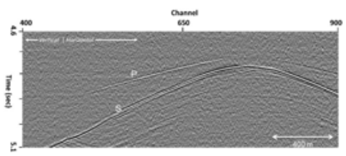
Sense compression (extension) between end points of gauge resulting in a strain measurement.

$$\Delta\Phi = n_c \frac{2\pi}{\lambda_l}\delta L = n_c \frac{2\pi}{\lambda_l} L\epsilon_{zz}$$

Measure strain components inline with fiber.

Sense at a single point particle velocity or acceleration.

Measure particle velocity / accelerations direction vector.



Reception characteristic is different between a DAS fiber sensor and a geophone/accelerometer.

Measurements can be converted from one to the other.

DAS sensitivity depends on several factors

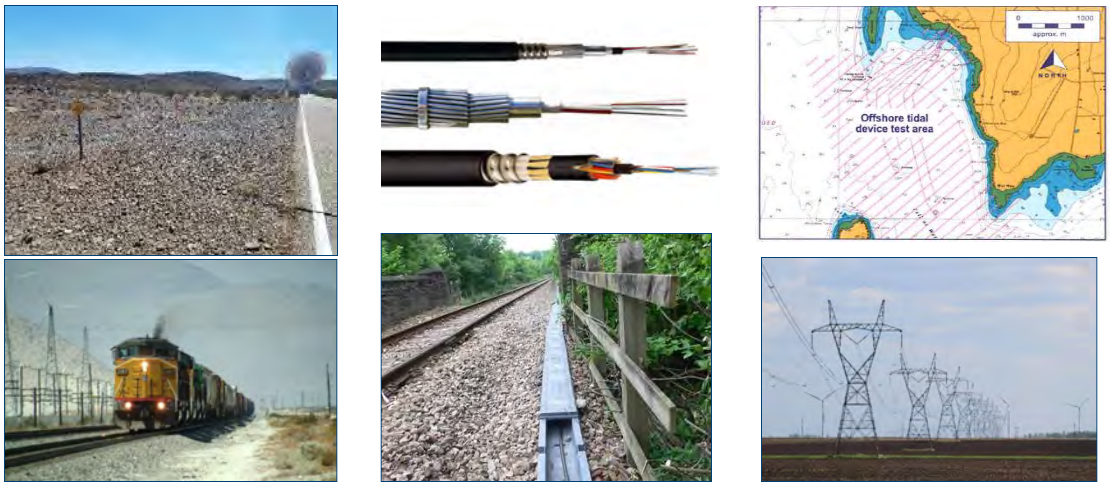
- Factors impacting sensitivity:
  - Fiber types X dB → Optical properties of fiber core materials
  - Cable types Y dB → Fiber arrangement, geometry, packaging
  - Interrogator types Z dB → Optical, electronic hardware systems

System Performance: **(X+Y+Z)** dB

- Yields:
  - Higher signal-to-noise ratio
  - Wider sensor pattern
  - Farther monitoring distances
  - Strain components
  - Additional physical effects

The Infrastructure Monitoring Challenge

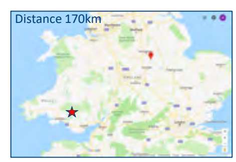
How well are we coupled ?



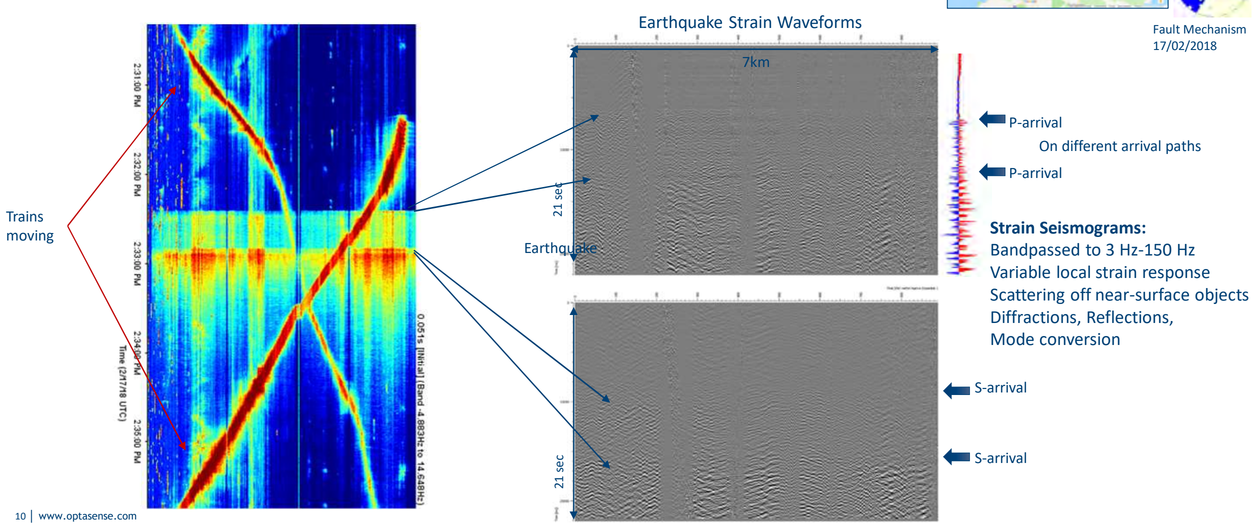
Transport Infrastructure Monitoring

Primary goal: monitor trains

Opportunity: monitor earthquake waves and local soil response



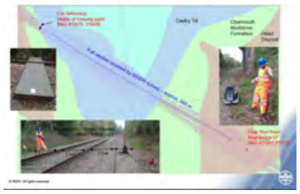
Fault Mechanism
17/02/2018



Strain Seismograms:
Bandpassed to 3 Hz-150 Hz
Variable local strain response
Scattering off near-surface objects
Diffractions, Reflections,
Mode conversion

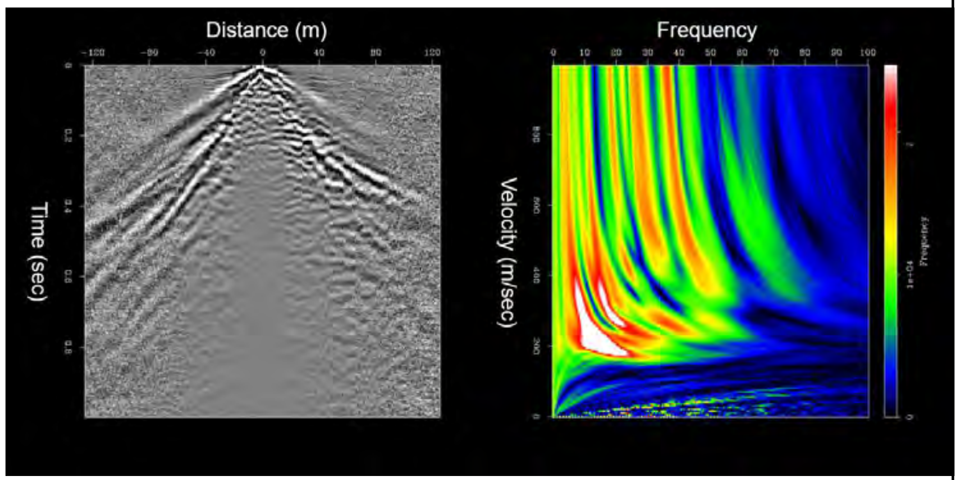
Active DAS Source Gather and MASW Dispersion Plot

DAS recording of small active sources along a 340m stretch of train tracks



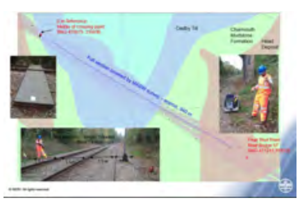
Acquisition and data analysis in cooperation with British Geological Survey and Network Rail.

Dense DAS recording allows multi-channel analysis of surface waves (MASW) for energy traveling in line with the fiber.



Ambient Noise Interferometric DAS Gathers and Dispersion

DAS recording of 30 minutes of ambient noise along a 340m stretch of train tracks

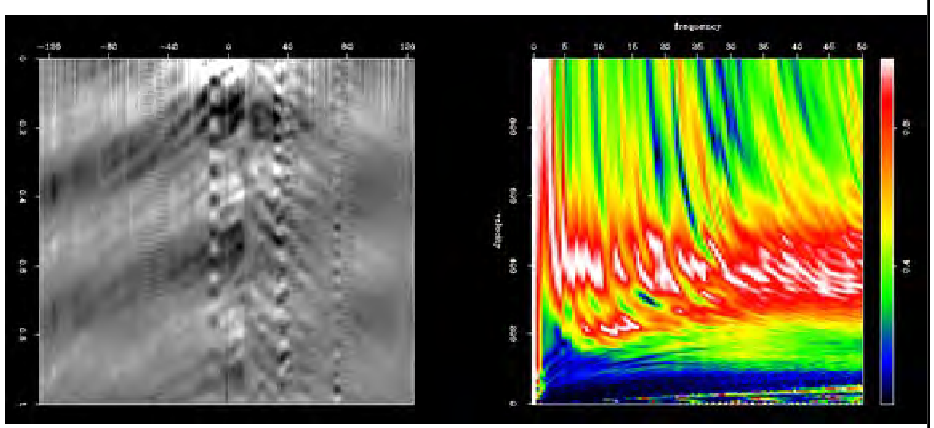


Passive recordings operationally very efficient and safe.

Interferometry shows similar features as active source gather

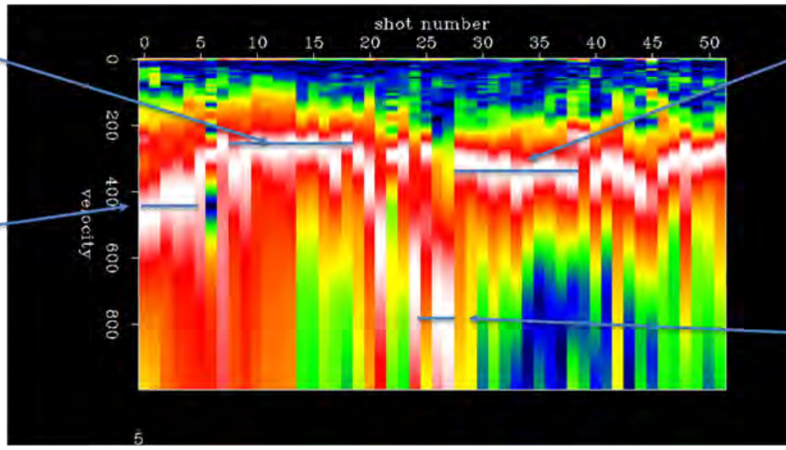
SNR can be built up by stacking over hours/days.

Dense DAS recording allows multi-channel analysis of surface waves (MASW) for energy traveling in line with the fiber.



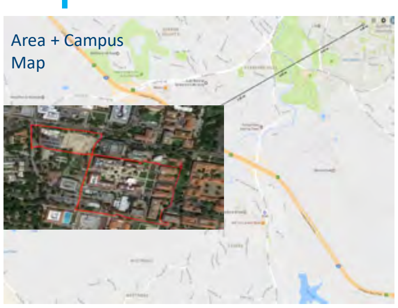
Lateral Velocity Variation Estimation from MASW

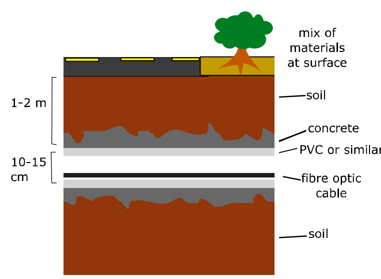
5 Hz dispersion curves vs shot



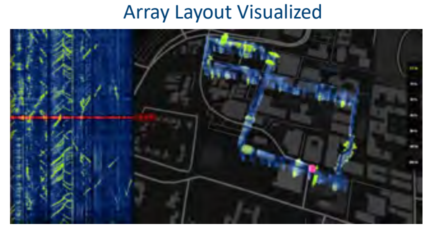
The Stanford Fiber-optic Seismic Observatory

DAS Array has been continuously operating since Sept 1, 2016 as part of Prof Biondi's Research Group





Array Layout Visualized



DAS Array Parameters

- 2 x 2.45 km fiber-optic cable
- 2 x 305 channels
- 8 m sensor spacing
- 7 m gauge length
- Continuous recording
- 0-25 (50) Hz recording (SEGY)
- DAS (ODH 3.1)

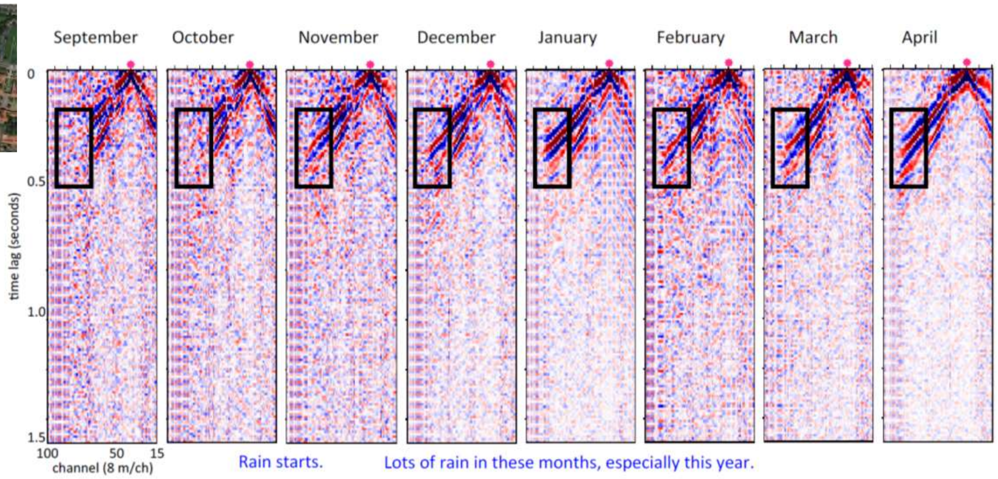
Cable + Conduits in Manhole
(fiber coupled by gravity only)

courtesy Prof Biondi, Stanford

Ambient Noise Time-Lapse Monitoring Rayleigh Waves

Virtual source gathers: interferometry turns “noise” into signal – analyze changes over time

Stanford Fiber-optic Array recording continuously allows for long-term time-lapse monitoring.



From Eileen Martin, Ph.D. Thesis, 2018.

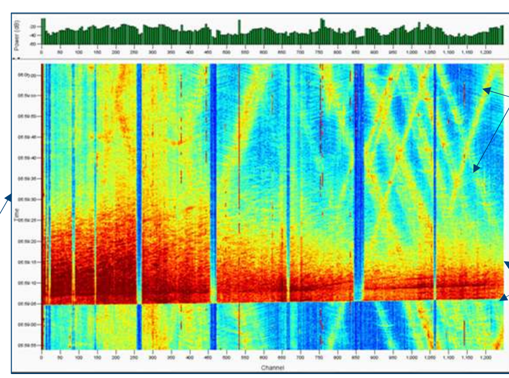
Southern California Earthquake Monitoring

Infrastructure fiber-optic cables along Highways turned into seismic sensor arrays

7.1 Earthquake with 80,00 aftershocks

Self-contained DAS Systems

Network cables turned into DAS Sensors

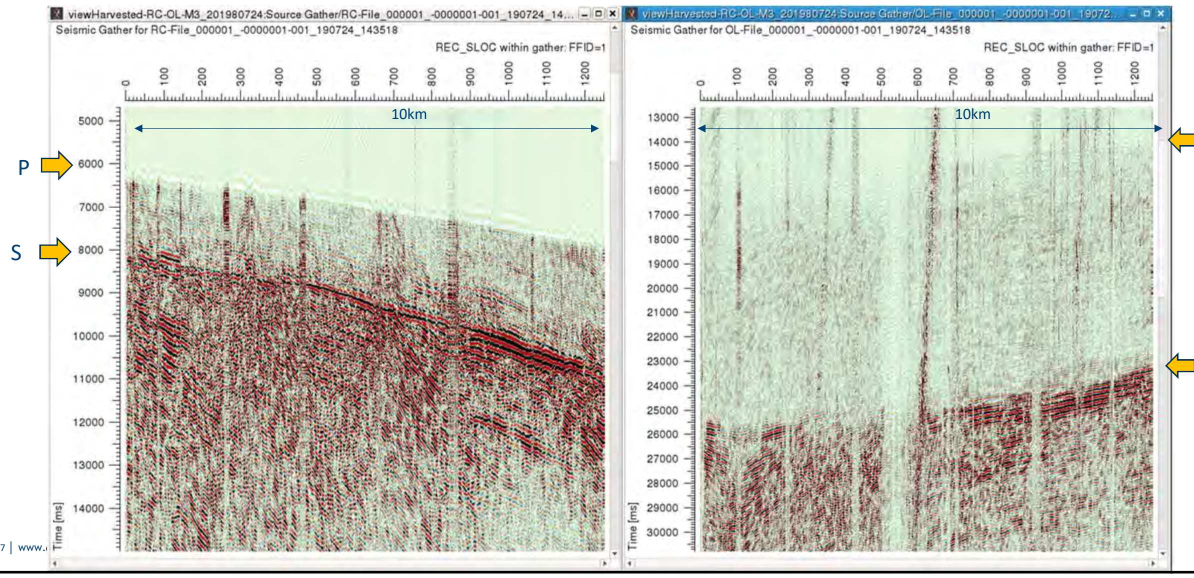


Rapidly Deployment of DAS systems
On-demand seismic arrays
(Currently 3 months continuous recording)

Permanent Infrastructure Monitoring
Early-Warning Systems

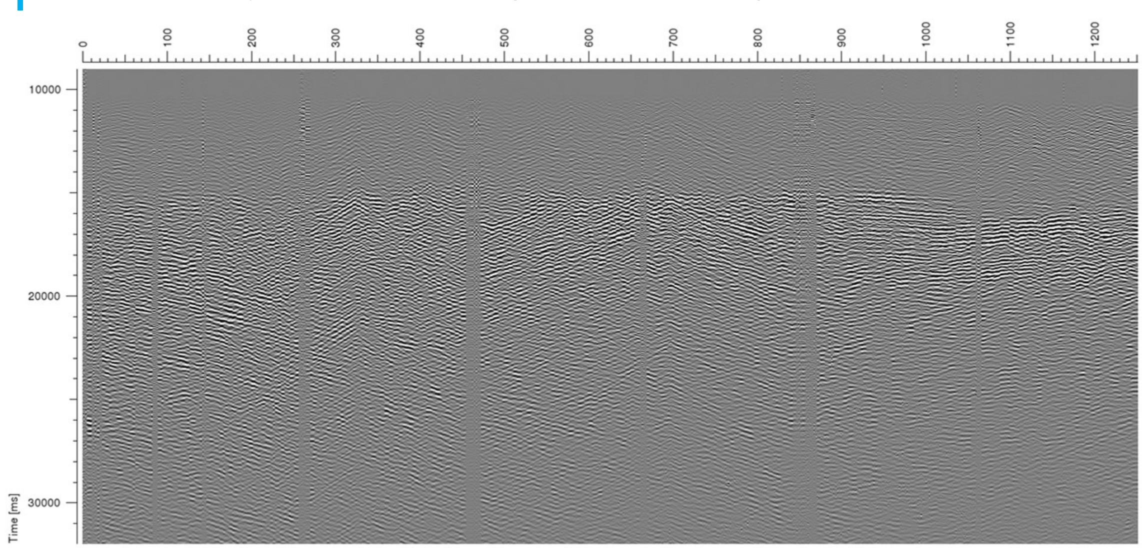
Earthquake Recording on Network Cables Along Highway 395

Excellent data quality, even with on-going traffic



Aftershocks provide near-surface and soil condition information

Derive Vs30 velocity and other models; improve seismic risk maps

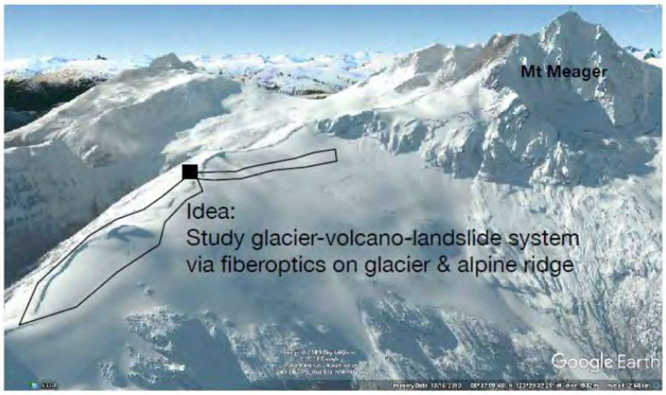


DAS monitoring of landslide-hazard and slope stability, micro-seismicity, tremors

Prof J. Dettmer, U of Calgary, Research Collaboration

New Frontiers in Research Fund: Exploration

Towards next-generation geohazard monitoring: Distributed acoustic sensing and probabilistic machine learning for volcano- and landslide-hazard monitoring



Multi-disciplinary collaboration between academia and industry

Mt. Meager: Ideal study site (55 M m³ Mass Failure in 2010)

https://geoscience.ucalgary.ca/dettmer/

Courtesy Prof. Dettmer, U Calgary

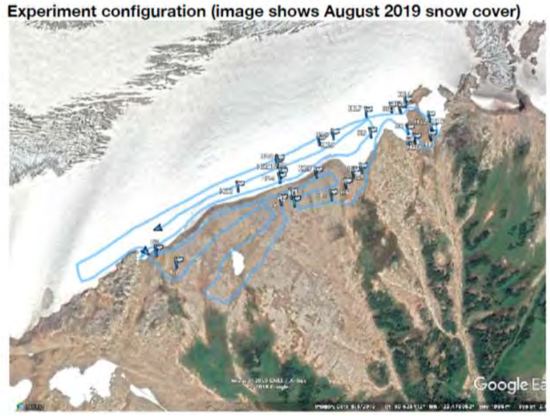
System installation and final fiber-cable layout

Fiber cable trenched both on glacier and on rock face

September: Install instrument (laser & computer)

Carson Laing & Jason France (OptaSense)
Pejman Shasavari (UofC)

Experiment configuration (image shows August 2019 snow cover)

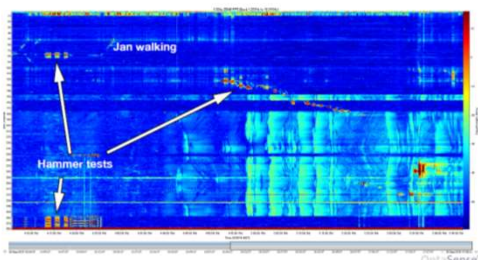


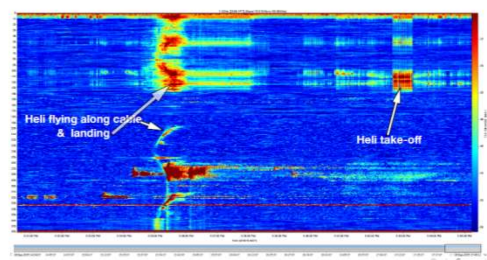
Courtesy Prof. Dettmer, U Calgary

Mt Meager DAS Monitoring

unattended, since September 18, continuous life signs transmitted

Initial Data promising





DAS Sensing for pre-cursory strain changes

before catastrophic failures occur in Land-slide Slope Stability and Geohazard applications

- For optimal transfer of strain from soil, rock, ice:
  - Utilize tight-buffered fiber-optic cable
  - Trench shallow fiber-optic cable
- Acquires densely sampled strain wave field to capture near static behavior up to high frequencies (kHz)
- Allows analysis of low-frequency strain evolution and microseismic activity, tremors, ambient noise time-lapse imaging
- Traditional near-surface imaging analyses or machine-learning algorithms
- Many practical applications …

Enabling Future Sensing Applications

- Near-surface investigations
- Geotechnical, Engineering
- Condition Monitoring

- **Smart Cities**
- **Smart Buildings**
- **Smart Infrastructure**

… add fiber as part of the design !

- Cities implementing fiber-optic master plans

Acknowledgements

- OptaSense Teams US, UK, CA
- Prof Biondi, Prof Ellsworth, Prof Martin, Stanford Exploration Project & sponsors
- B. Dashwood, R. Gunn, BGS
- Prof Z. Zhan, E. Williams, Caltech, GMG Consortium
- Prof J. Dettmer, and Prof. D. Eaton , University of Calgary
- Network Rail
- British Geological Survey

Thank You ! Questions ?

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