An introduction to

Fibre optic sensing

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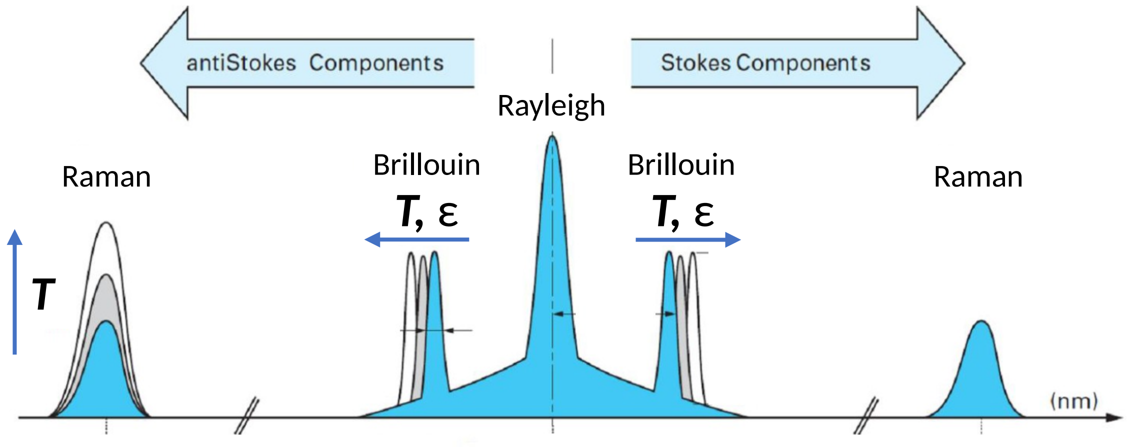
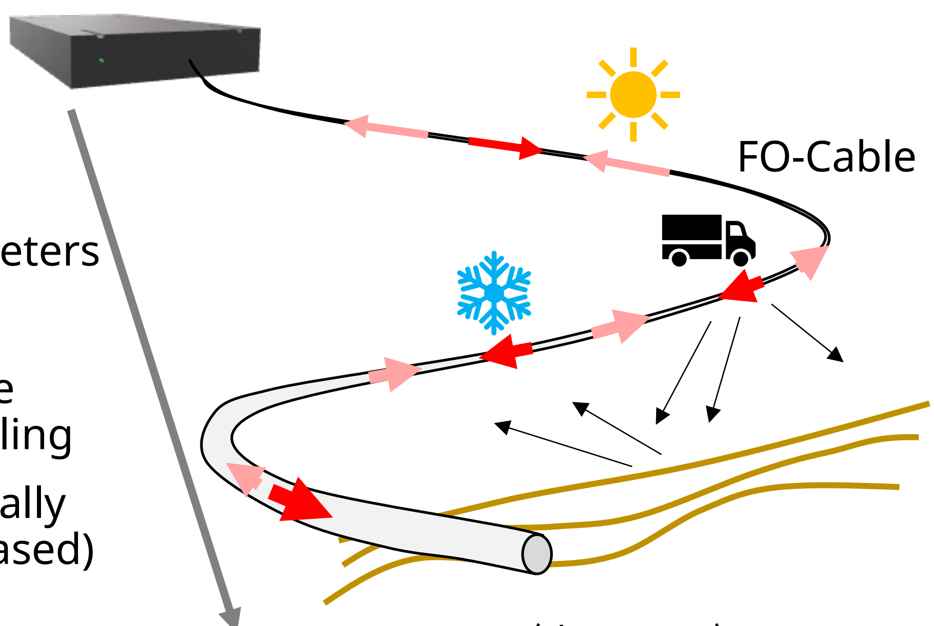
Measurement Principle

General setup



(modified from Bergman et al., 2016)

Unit (Source + Detection)



Many kilometers

With

Dense sampling

(spatially unaliased)

(Lipus, 2022)

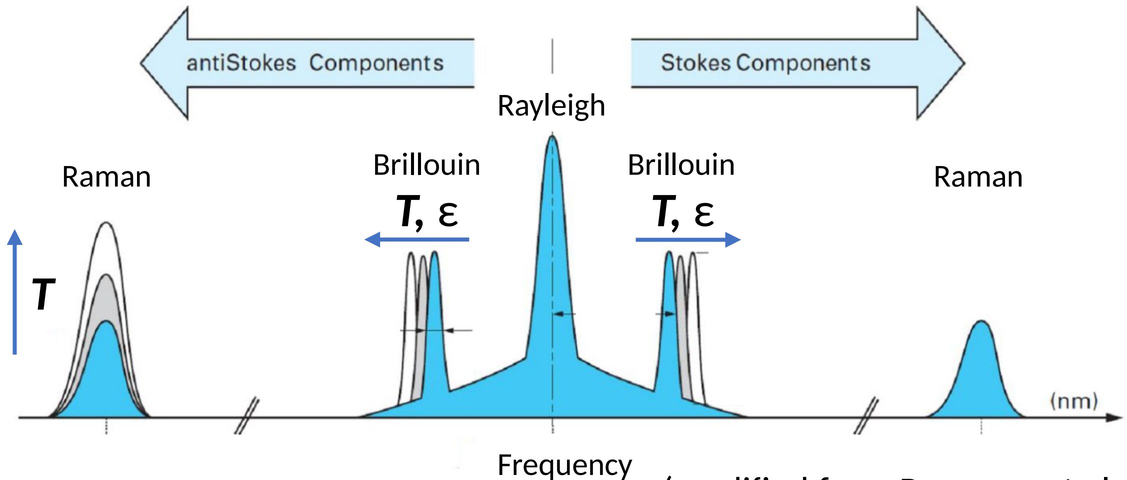
Distributed

- **S**train (DSS)
- **T**emperatur (DTS)
- **A**coustic (DAS)

Sensing

Measurement Principle

General setup



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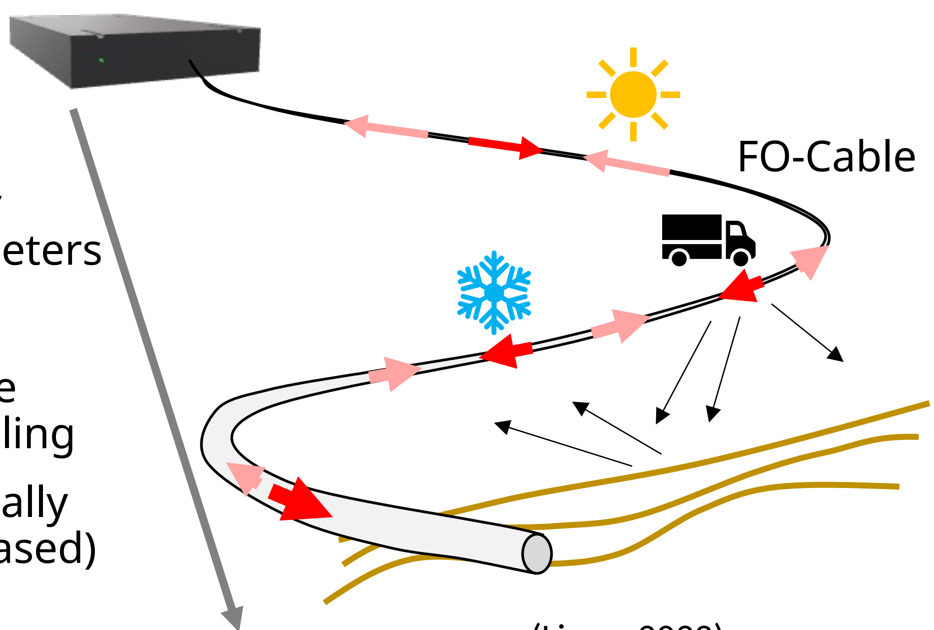

Many kilometers

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(spatially unaliased)

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absolute **S**train	(DSS)

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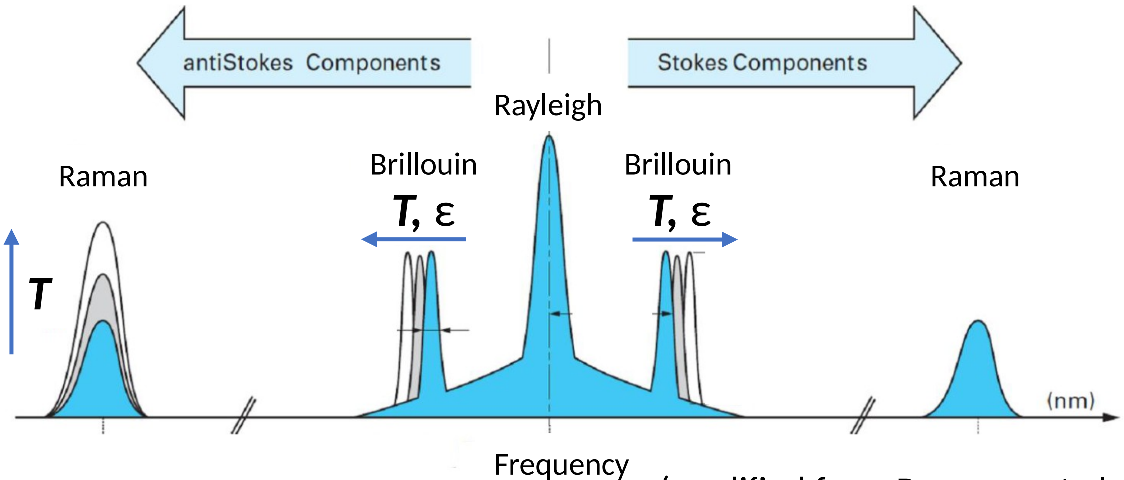
Sensing

Measurement Principle

General setup



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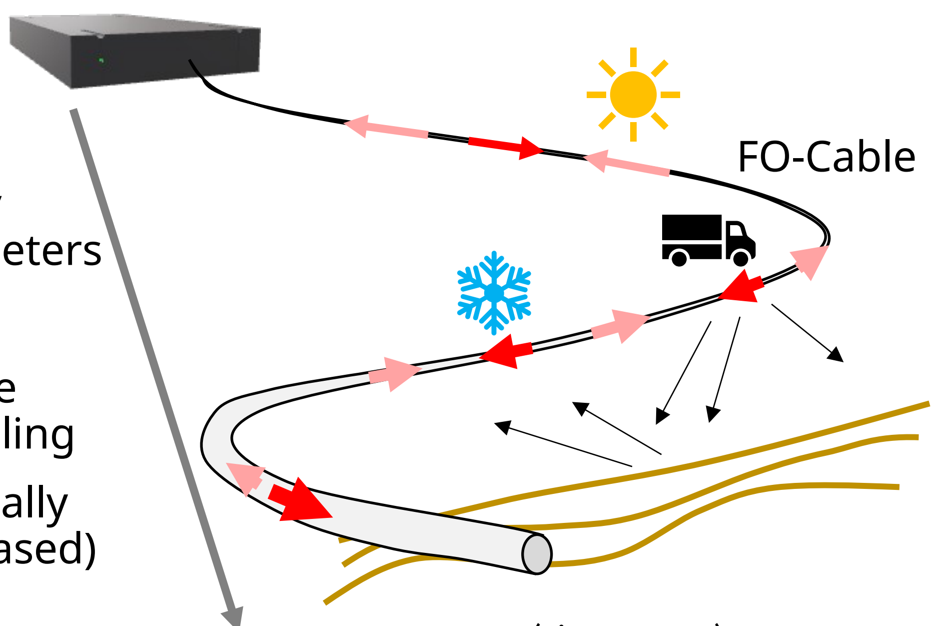


Many kilometers

With

Dense sampling

(spatially unaliased)

(Lipus, 2022)

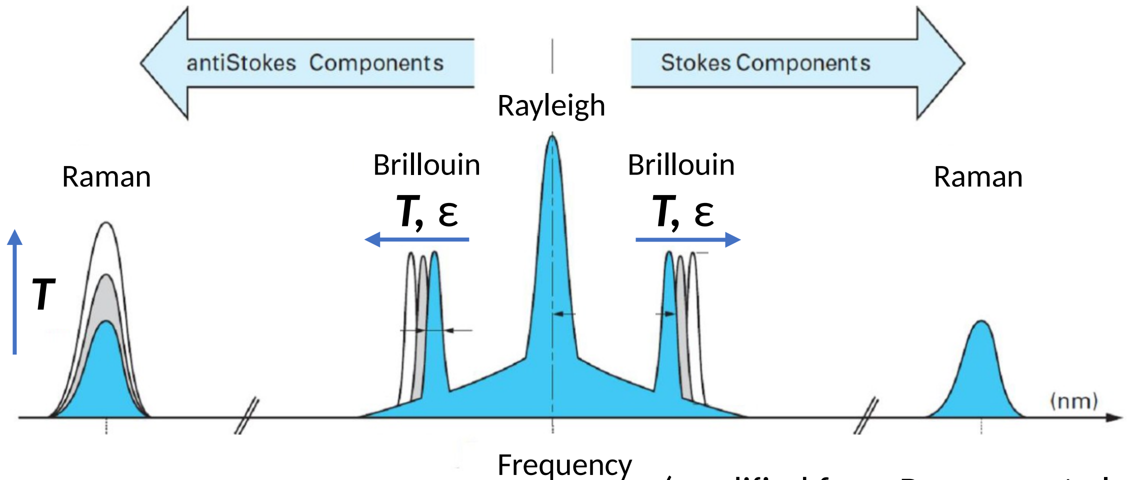
Distributed

absolute **S**train	(DSS)
• **T**emperatur	(DTS)
Dynamic Strain	(DDSS)

Sensing

Measurement Principle

General setup



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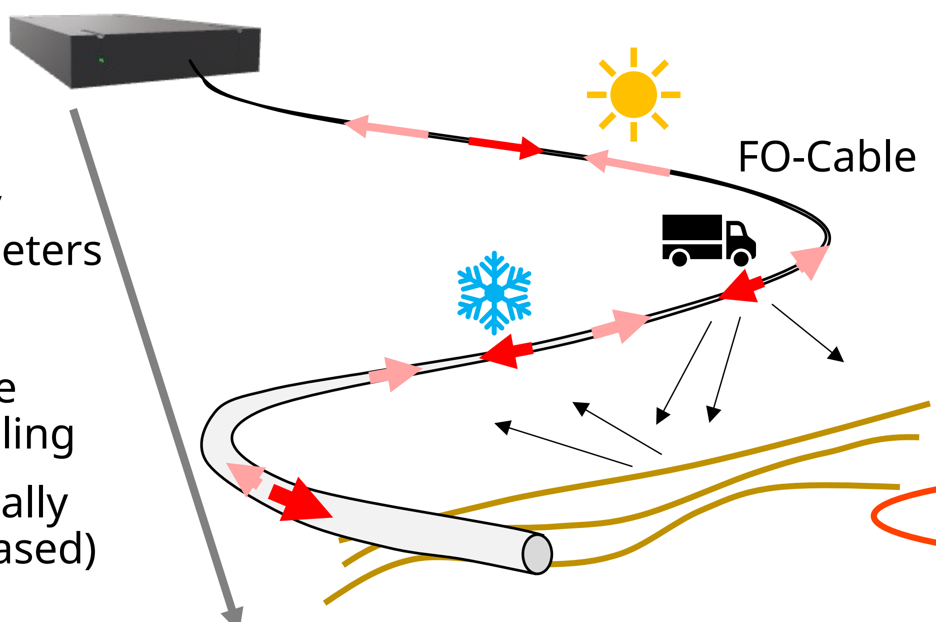


(Lipus, 2022)

Many kilometers

With

Dense sampling

(spatially unaliased)

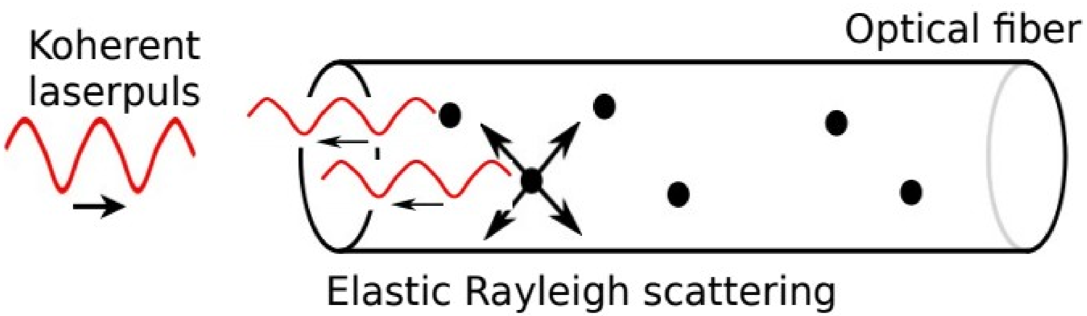
Distributed

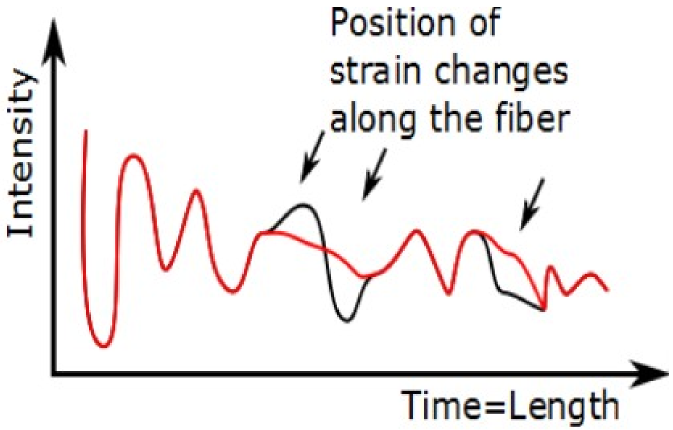
absolute **S**train	(DSS)
• **T**emperatur	(DTS)
Dynamic Strain	(DDSS)

Sensing

Distributed Acoustic Sensing

Measurement Principle



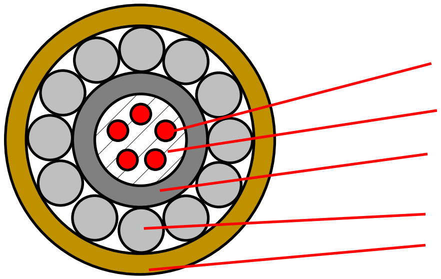


- Change of intensity = strain-rate
- Integration in time = local strain

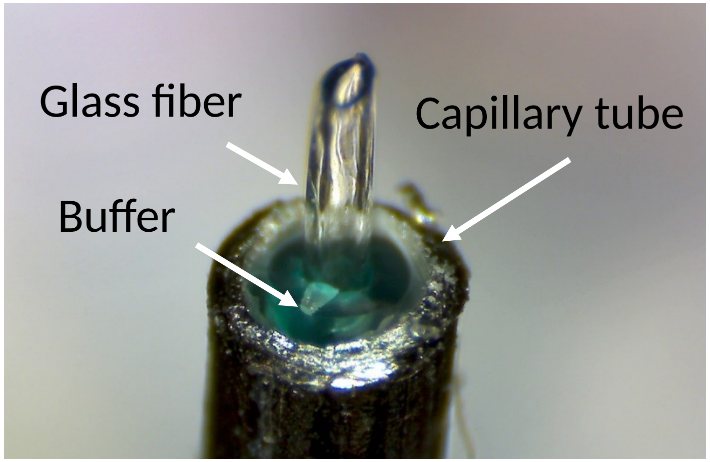
Cable Design

Objective → fiber type → fiber design → cable design

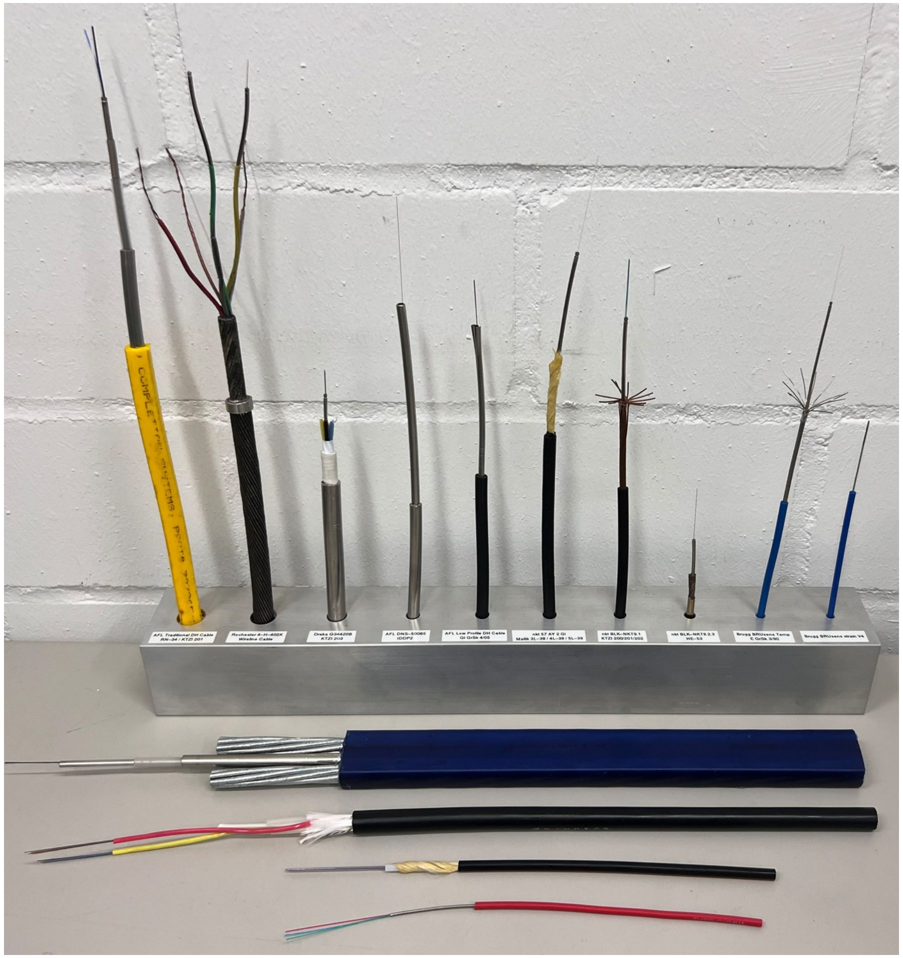
Fiber In Metal Tube (“FIMT”)



D = 5.5 mm



(Cunow, 2021)



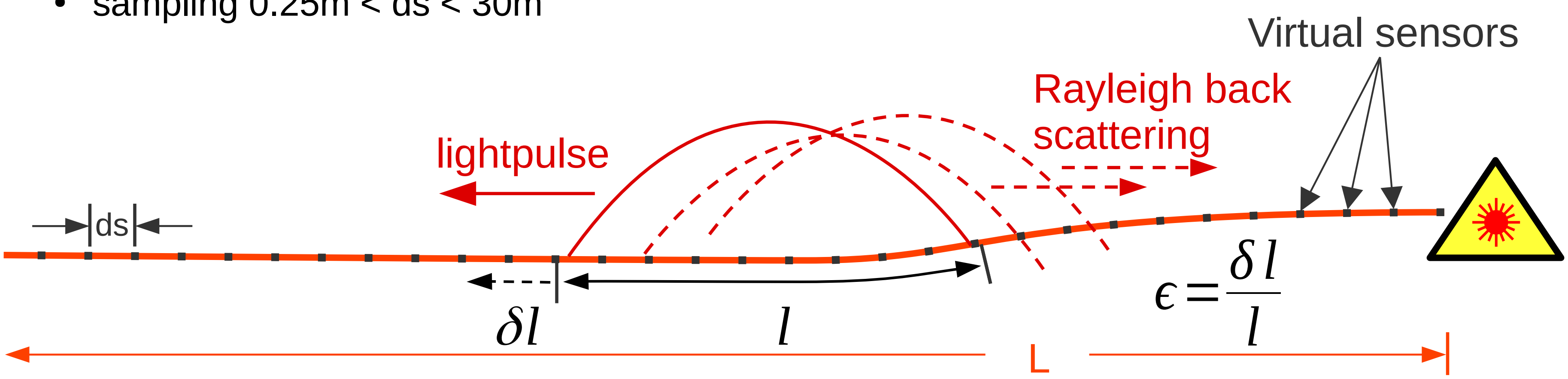
Distributed Acoustic Sensing

Important measurement parameters

- Measureing one component of the strain tensor
  - Strain is a relative quantity

- The „gauge-length“
  - lies in the order of meters
  - is inverse to the spatial resolution and
  - proportional to the Signal-to-Noise Ratio

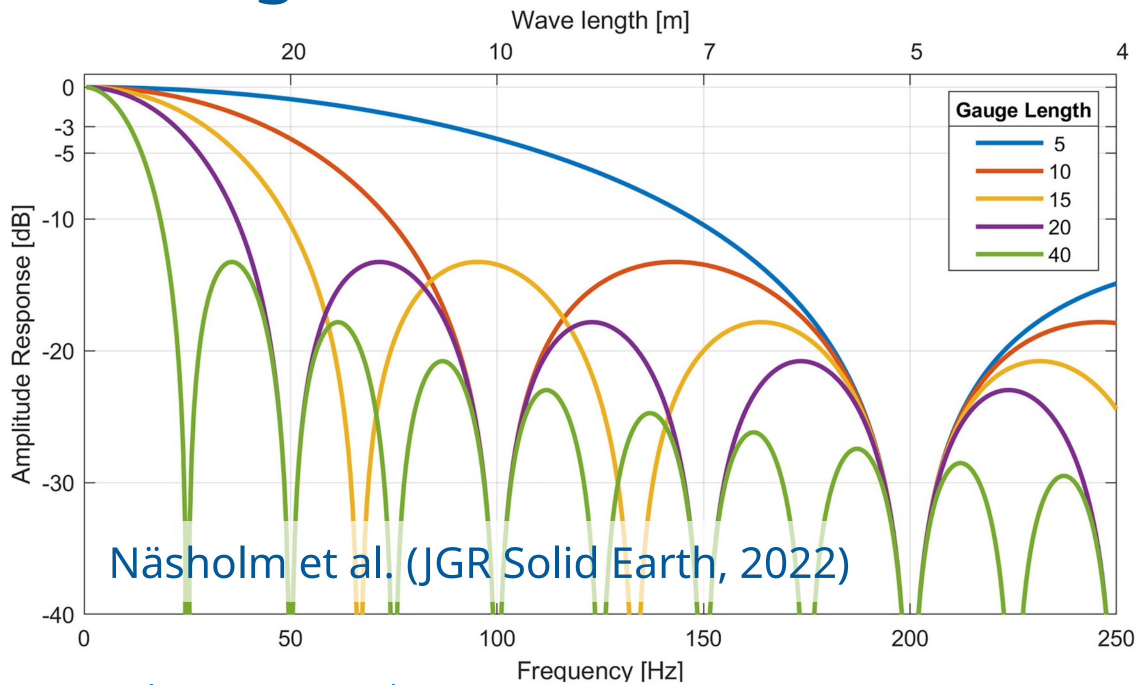
- Order of magnitude of spatial dimensions
  - fiber 100m < L < 30km
  - gauge 2m < l < 20m
  - sampling 0.25m < ds < 30m

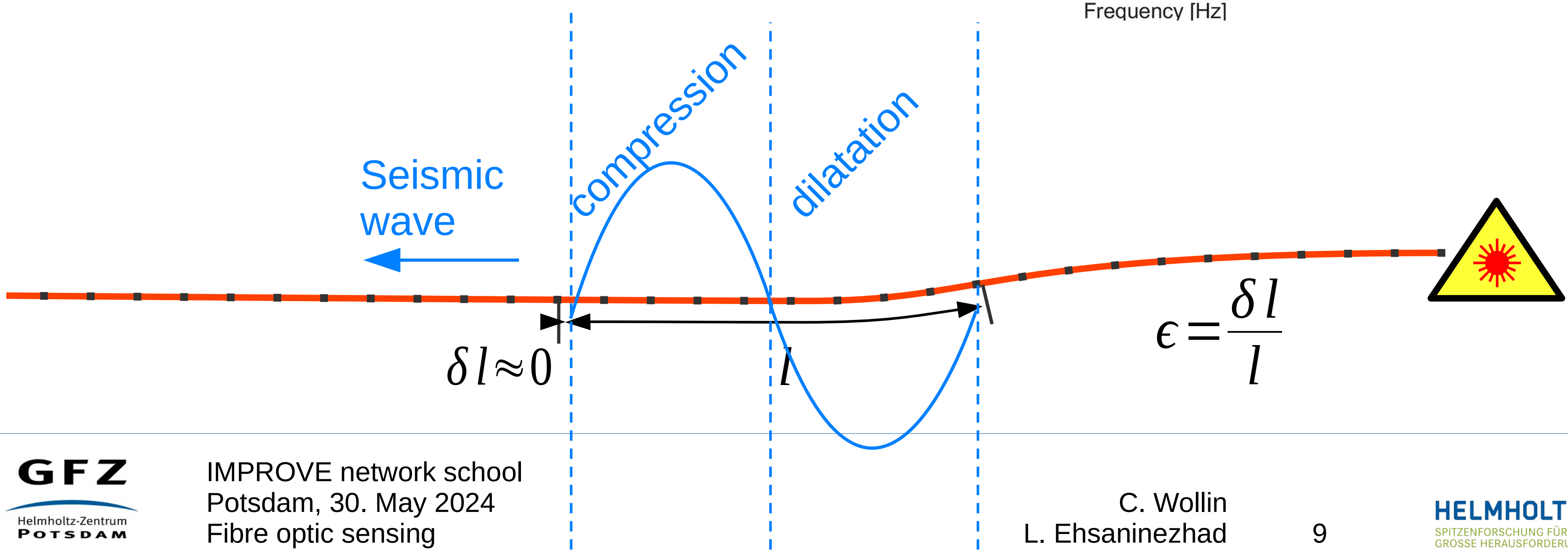


Distributed Acoustic Sensing

Response to seismic waves

- Depends on the impinging wave’s
  - **wavelength**
  - incidence angle
- „Gauge-length effect“ for wavelengths in the order of the gauge length

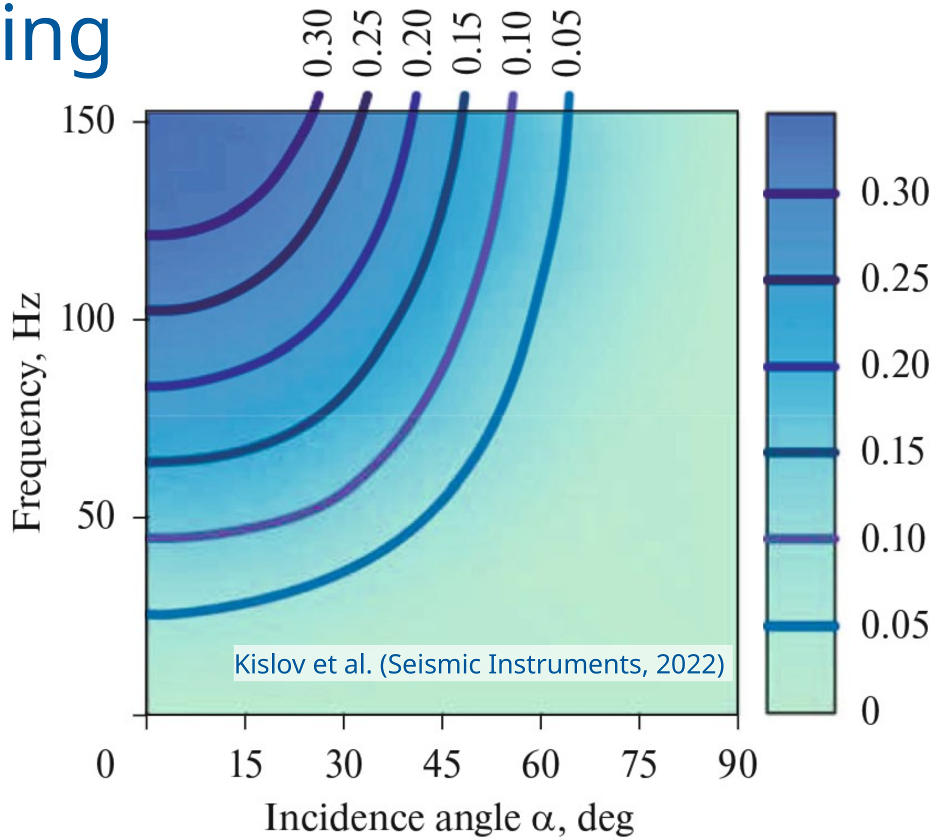




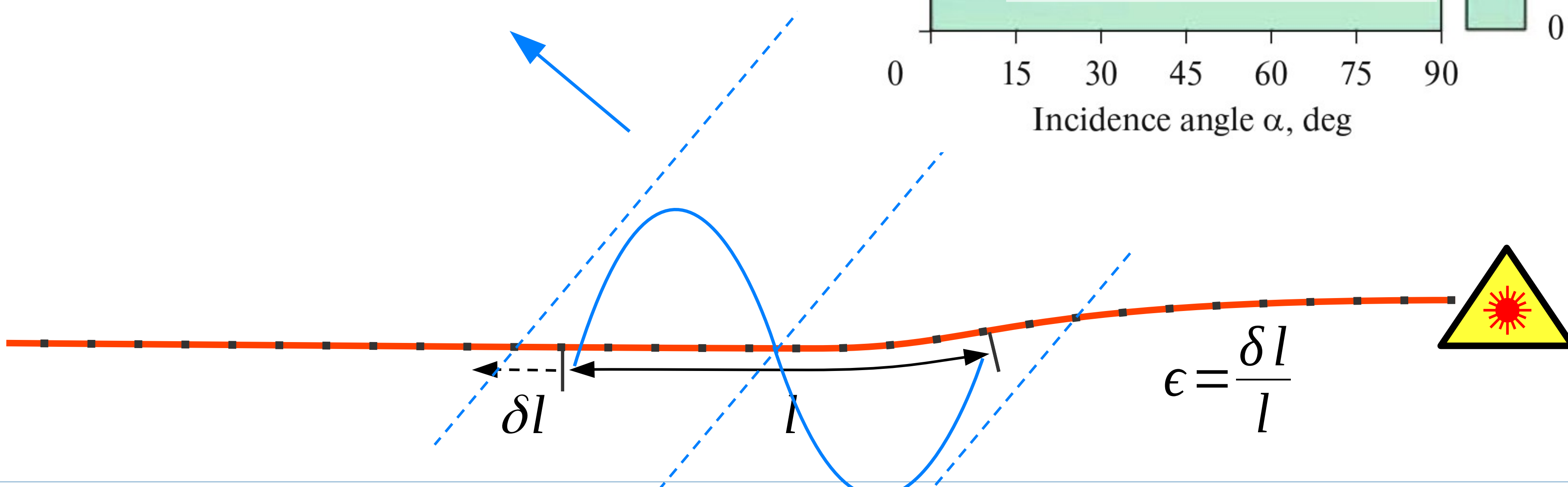
Distributed Acoustic Sensing

Response to seismic waves

- Depends on the impinging wave's
  - wavelength
  - **incidence angle**
- No response for orthogonal incidence

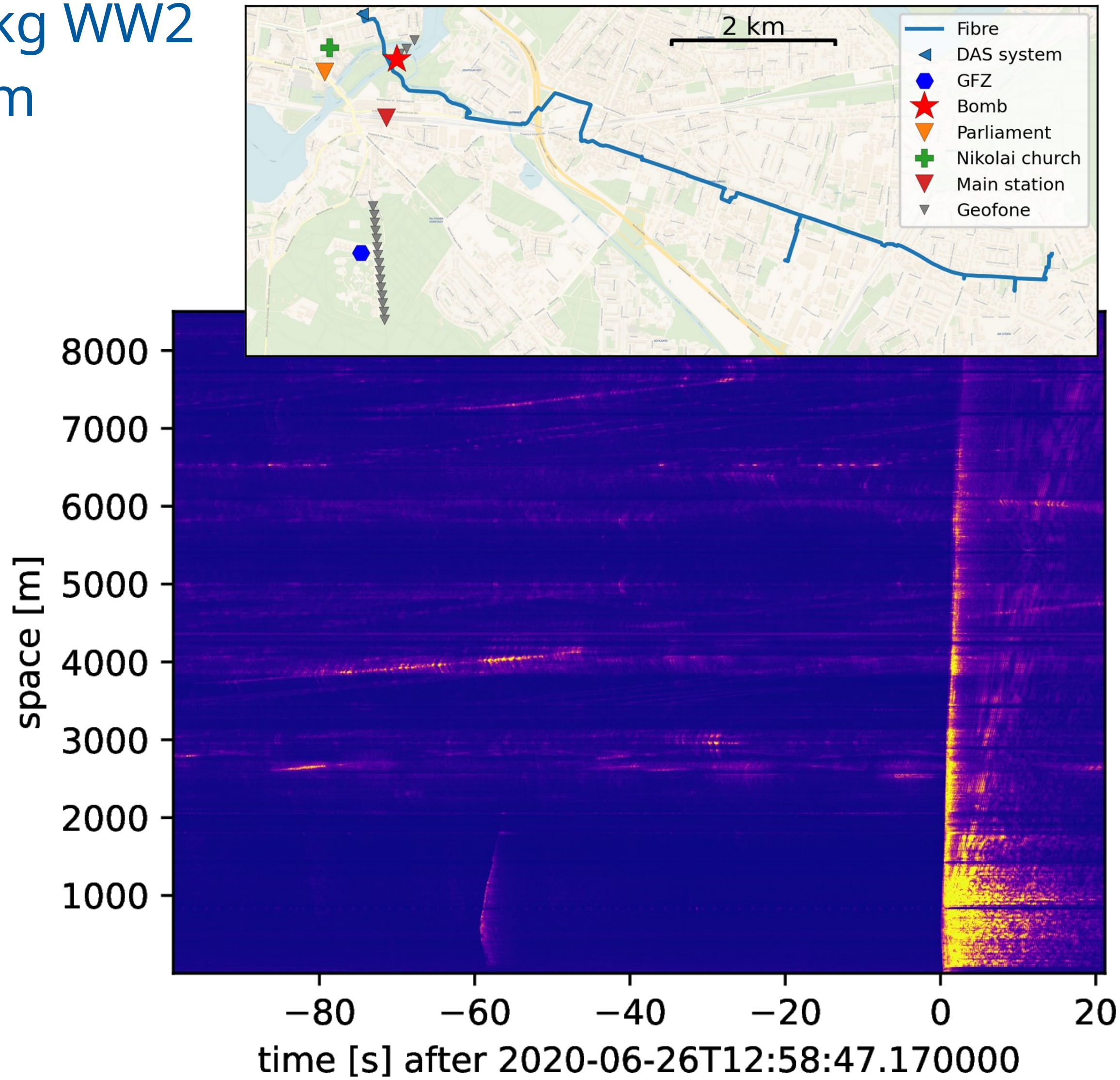


Kislov et al. (Seismic Instruments, 2022)



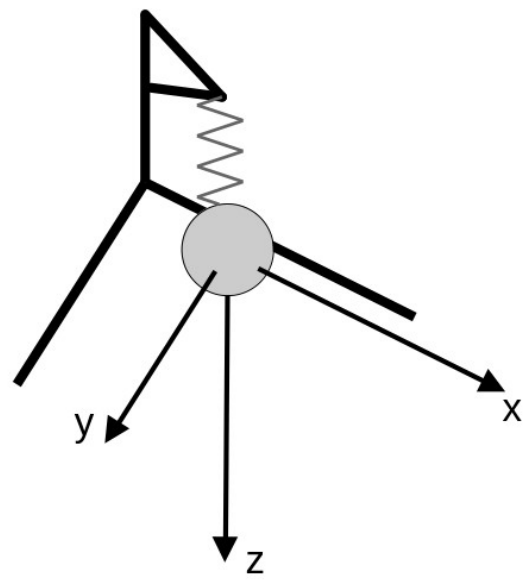
Distributed Acoustic Sensing

Explosive defusion of a 250kg WW2 bomb in Downtown Potsdam



Distributed Acoustic Sensing

vs. traditional seismometers



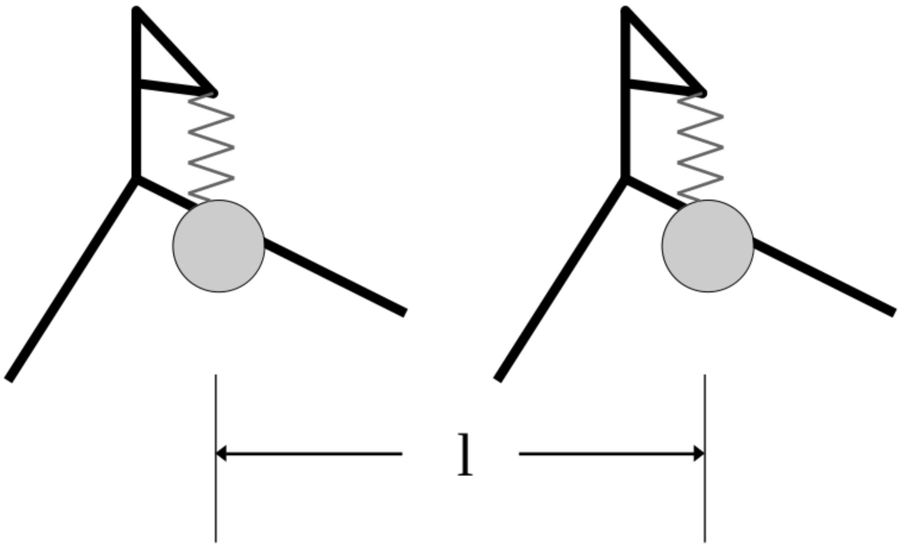
- A seismometers measures the 3D (particle)
  - movement,
  - velocity or
  - acceleration

  of an inertial mass.

- Response depends on the specifications of the oscillatory system (mass, spring constant, damping).

Distributed Acoustic Sensing

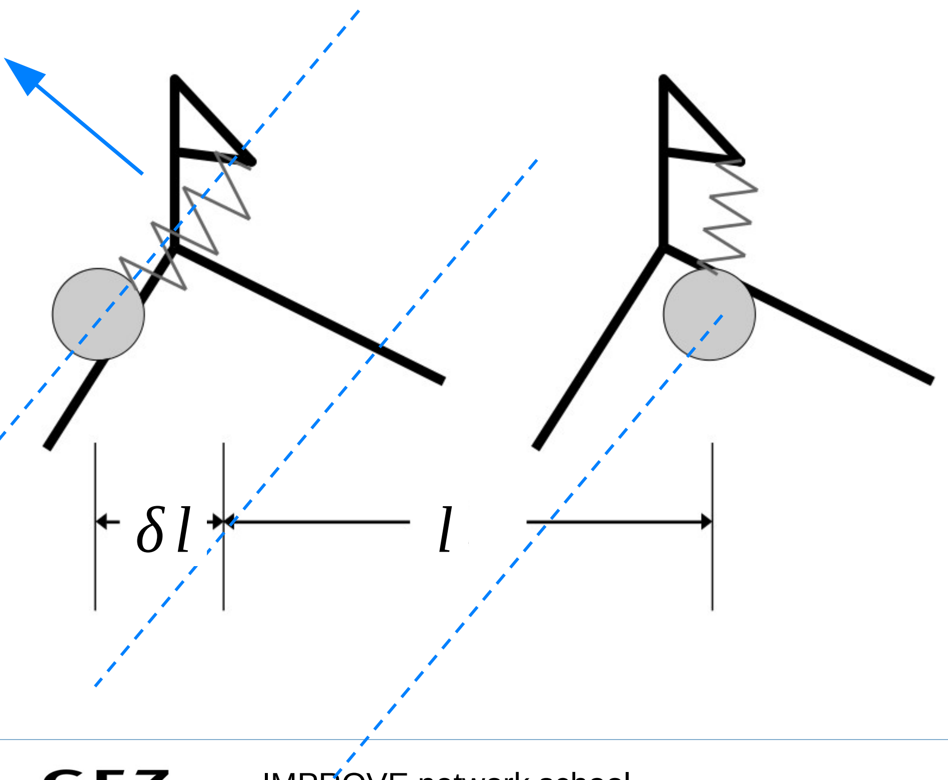
vs. traditional seismometers



Strain is the relative distance change of two seismometers at a certain distance l ...

Distributed Acoustic Sensing

vs. traditional seismometers

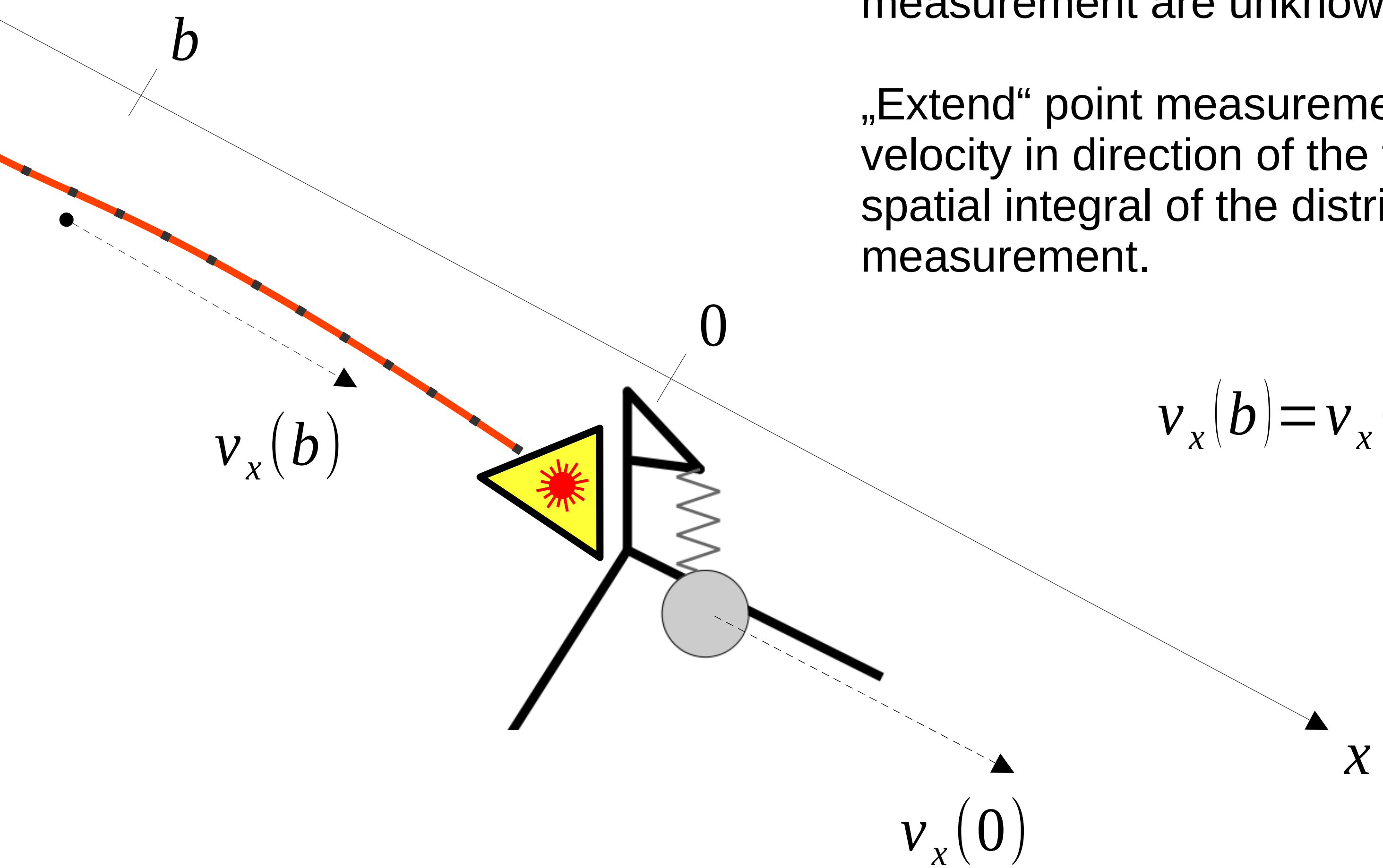


Strain is the relative distance change of two seismometers at a certain distance l when dislocated by some external forcing

$$strain = \frac{\delta l}{l}$$

Distributed Acoustic Sensing

„Distributed seismometer“



Absolute kinematic parameters (particle movment or velocity) of the DAS measurement are unknown.

„Extend“ point measurement of the particle velocity in direction of the fiber by adding spatial integral of the distributed strain-rate measurement.

$$v_x(b) = v_x(0) + \int_0^b \dot{\epsilon}(x)\,dx$$

Use cases / application examples

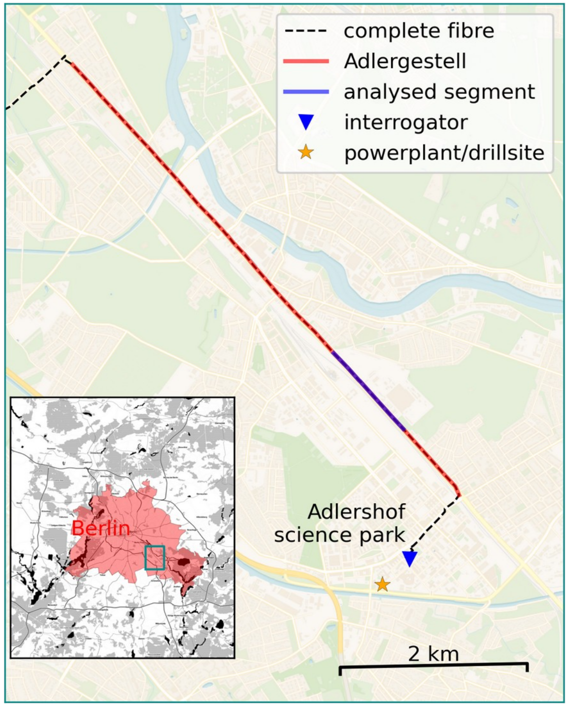
Exploration

Exploration

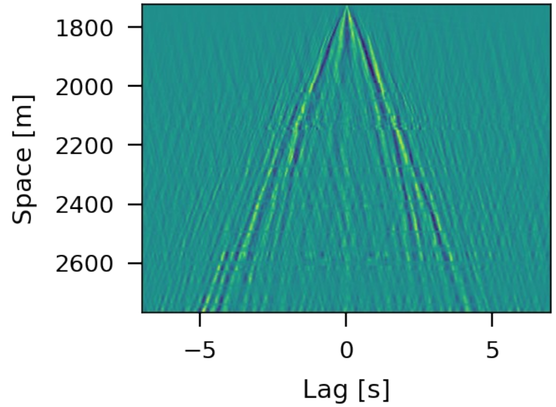
Urban ambient-Noise-Tomography, Berlin (MASW)

Dark fiber

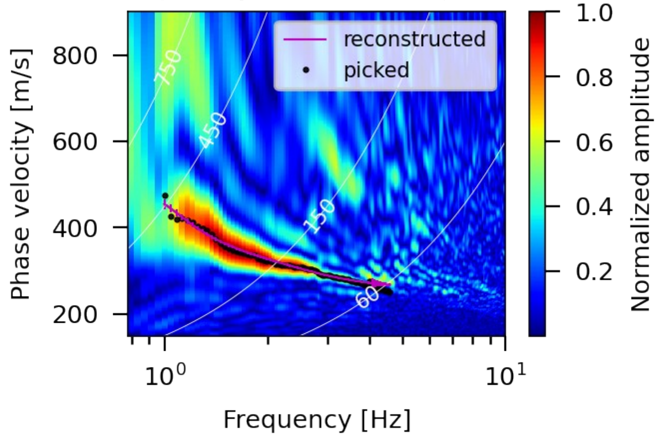
1) Ambient noise in the city



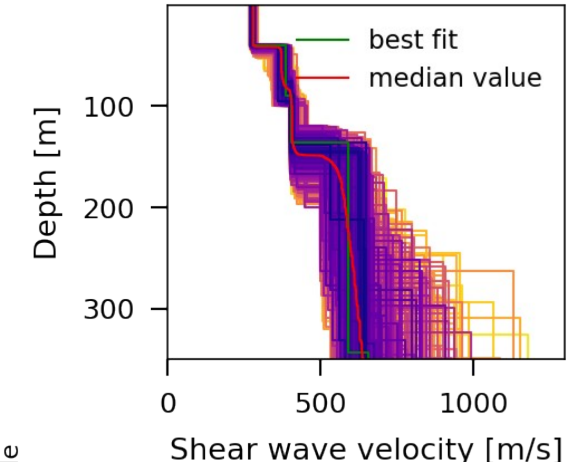
2) Surface wave



3) Dispersion analysis



2) 1D Shear-wave Velocity model



Ehsaniezhad et al. (2024)

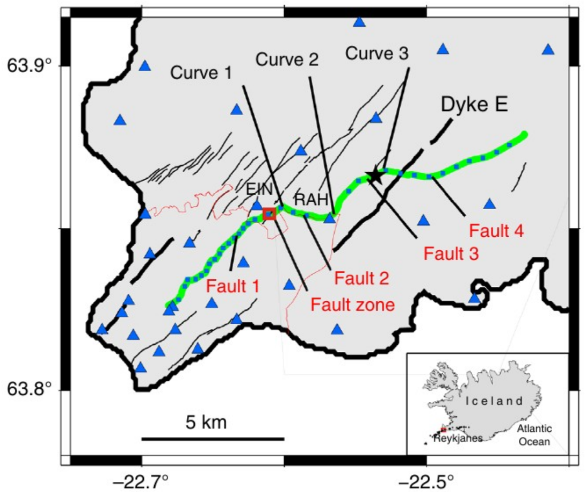
Use cases / application examples

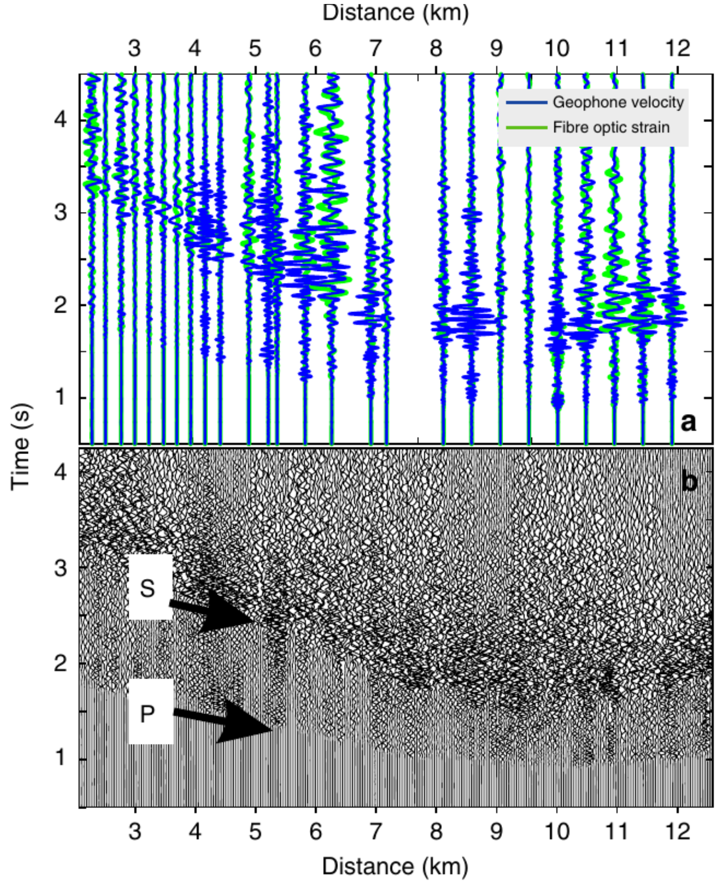
Seismological monitoring

Local seismicity

Recording with a horizontal telecommunication fiber

- M1.5
- 3.5 km depth
- P- and S-wave recorded along the entire fiber (approx. 12 km)
- Prolonged coda indicates location of faults

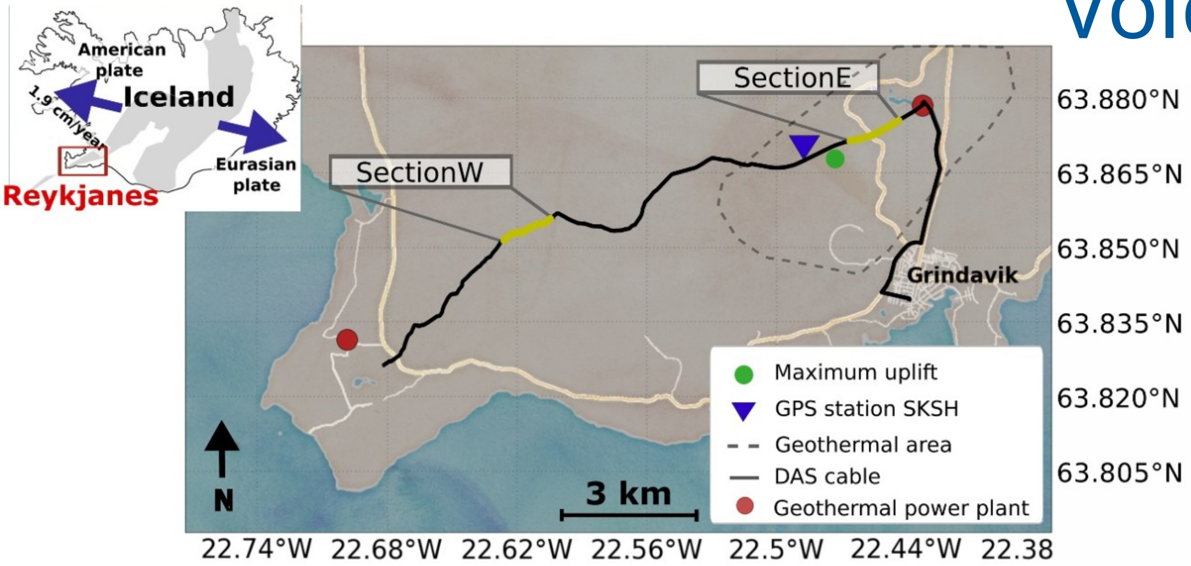




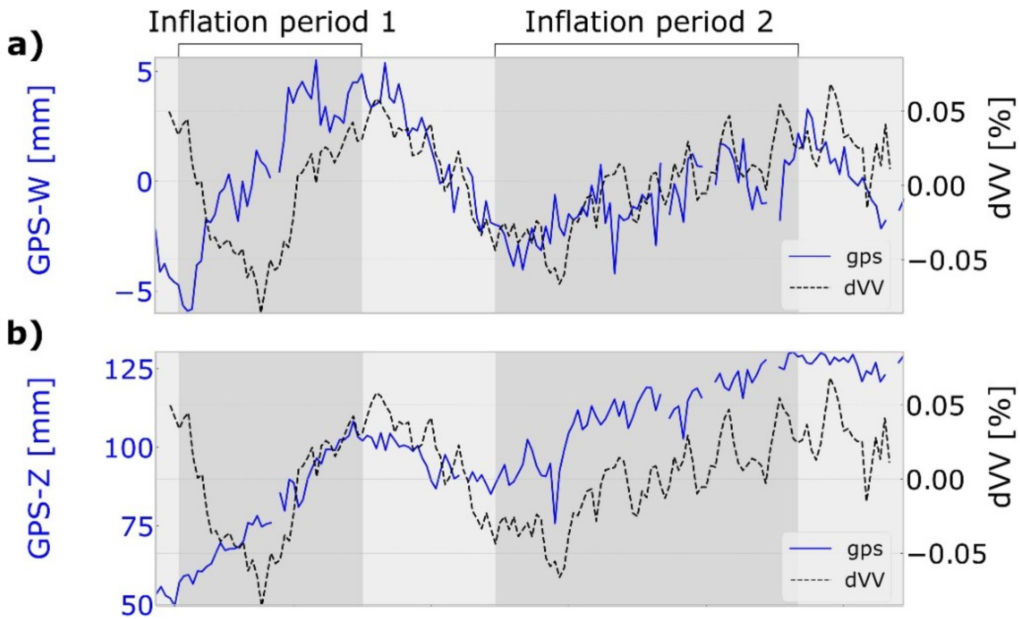
Jousset et al. (2018)

Volcanic monitoring

Using ambient noise



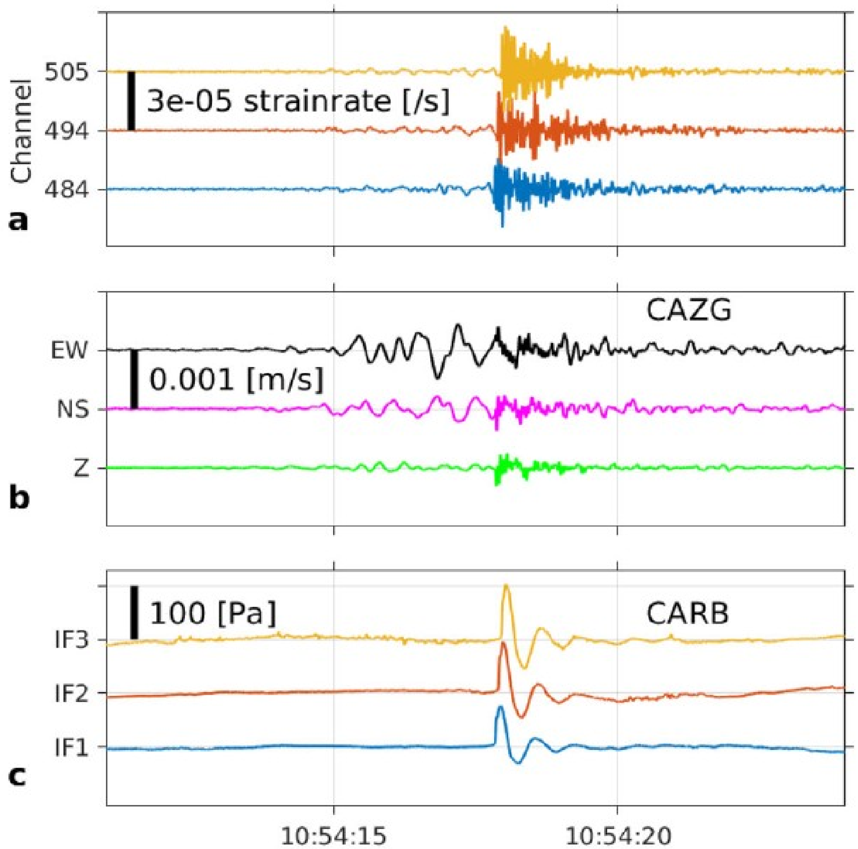
Maass et al. (JGR Solid Earth, 2024)

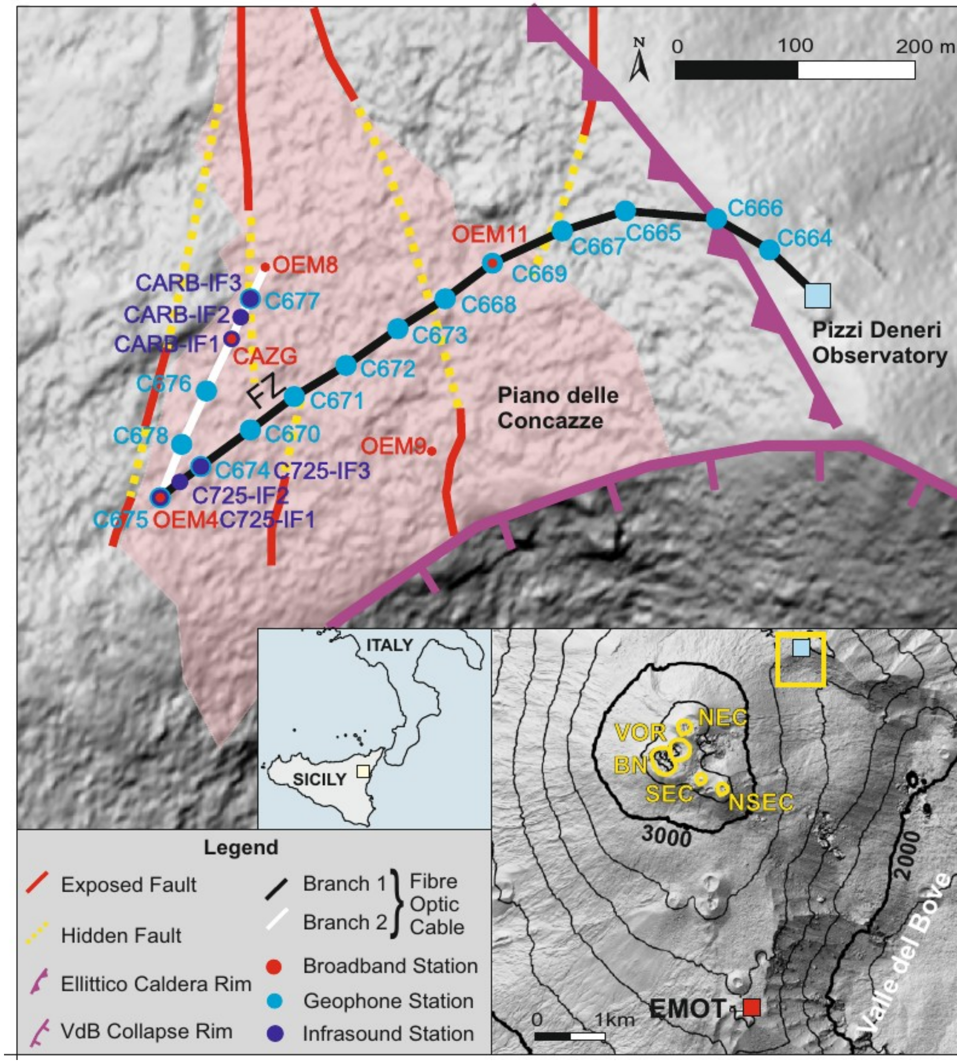


- Two cycles of crustal inflation
- Analysis of ambient noise traveling between two fiber segments
- Relative velocity changes correlate with the uplift documented by GPS timeseries

Volcanic monitoring
with multiparametric measurements

Jousset et al. (Nature Communications, 2022)





a) DAS
b) Broadband seismometer
c) Infrasound pressure sensors

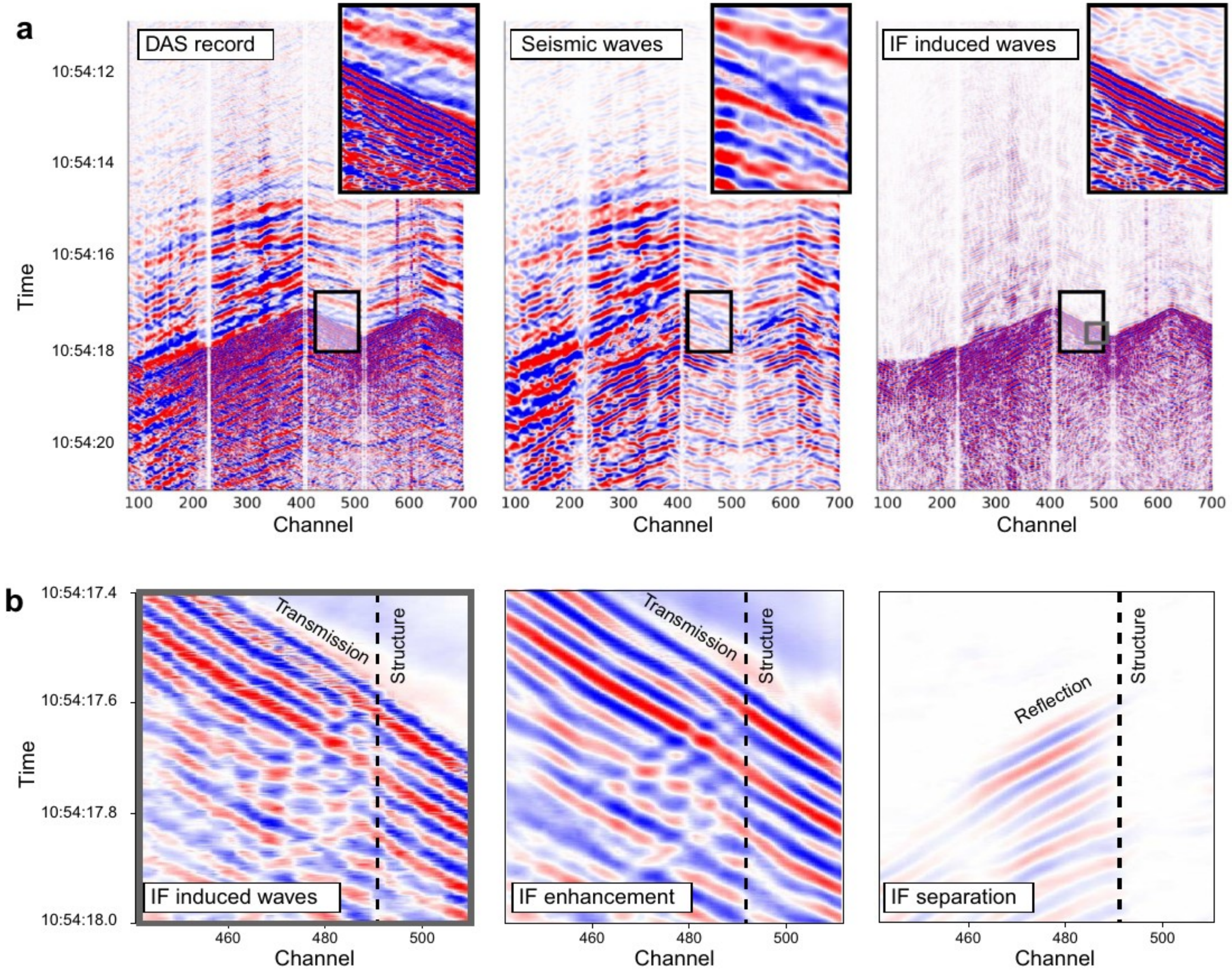
Volcanic monitoring

Jousset et al. (Nature Communications, 2022)

Wavefield coherency and separation

a) DAS record is separated into seismic and the infrasound wavefield

b) Wavefield enhancement and separation into components transmitted and reflected at a vertical structure crossing the fiber.

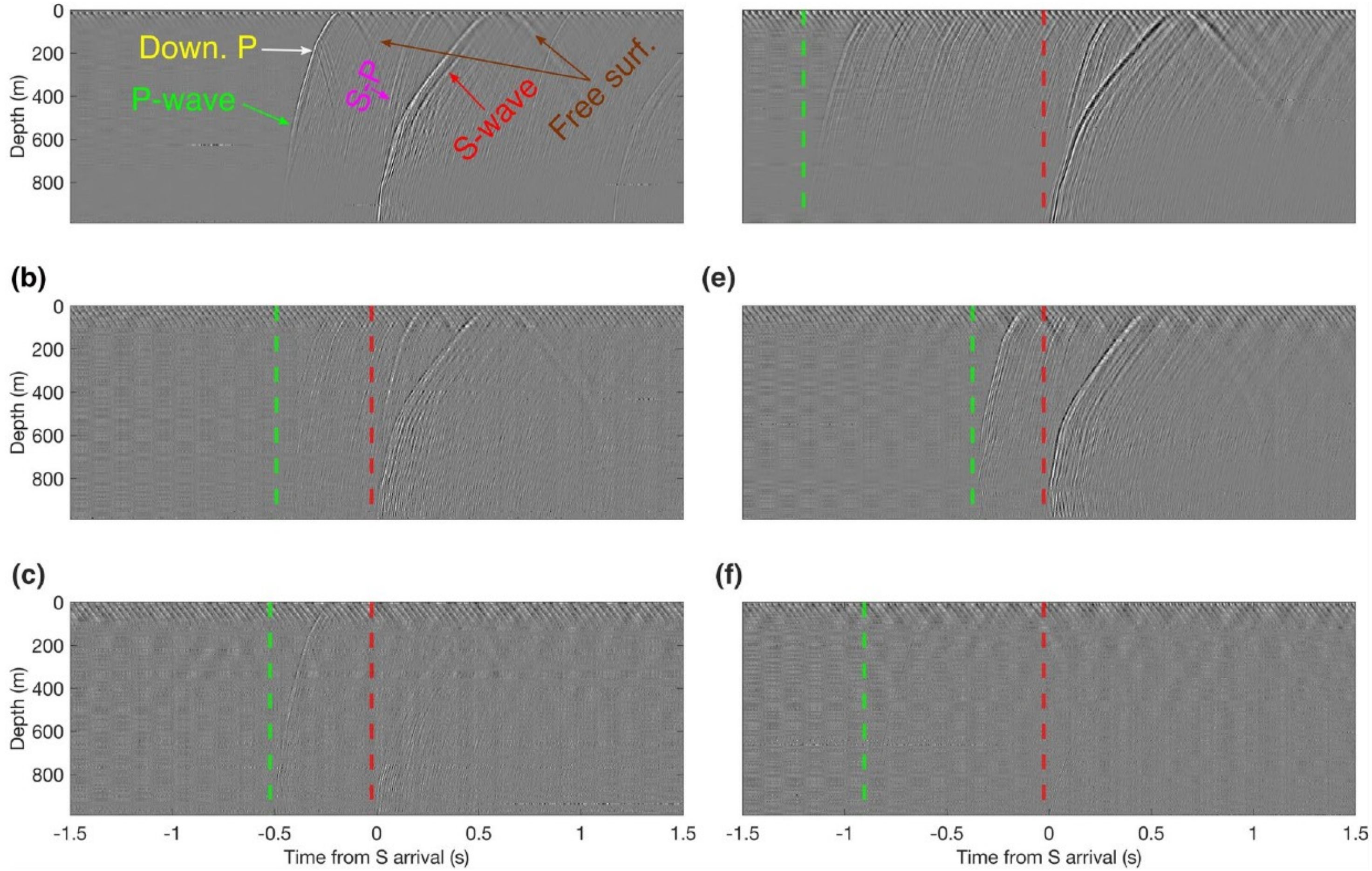


Local seismicity

Recording with a vertically cemented borehole fiber (approx. 1 km depth)

- Induced seismicity in vicinity of an Enhanced Geothermal System (EGS), Utha, USA

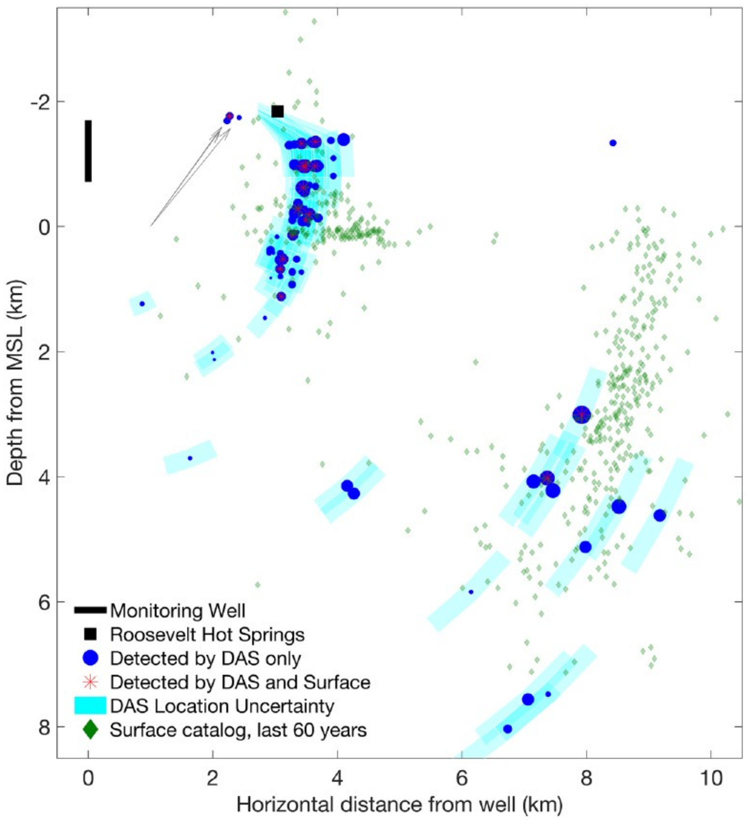
- Varying contrasts between amplitude values of different seismic phases, e.g. P- and S-wave could originate from different source mechanisms

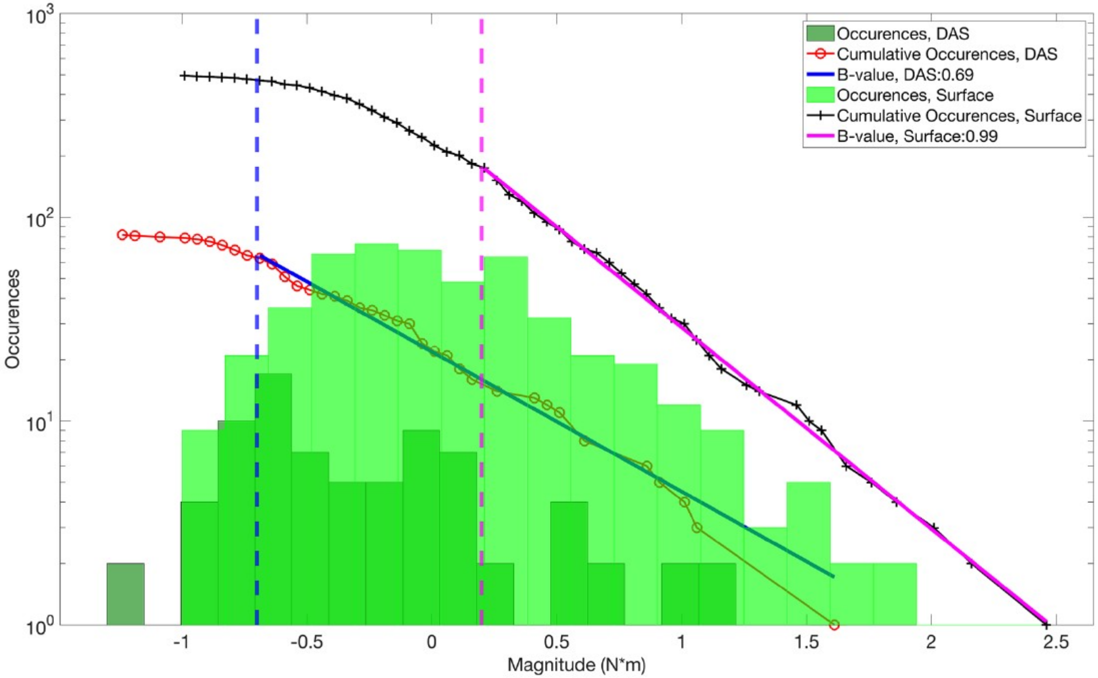


Lellouch et al. (2018)

Local seismicity

Recording with a vertically cemented borehole fiber



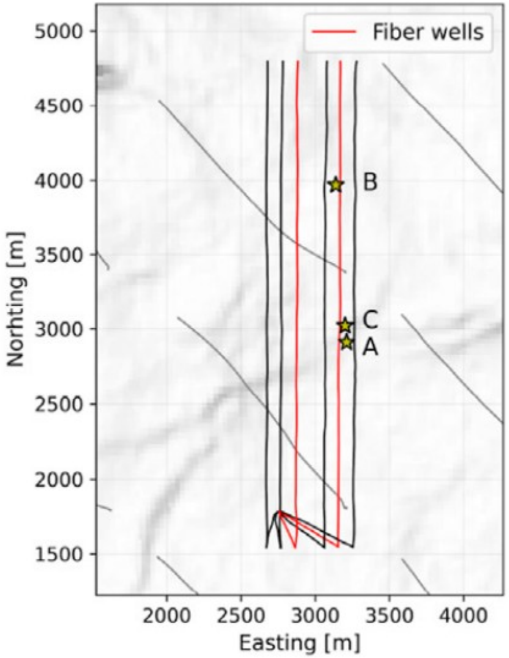


- Detection and localisation of earthquakes with DAS
- In a cross section of approx. 10 x 10 km
- A lower detection threshold (<M -1) than seismological network at the surface
- => Shift in the b-value

Lellouch et al. (2018)

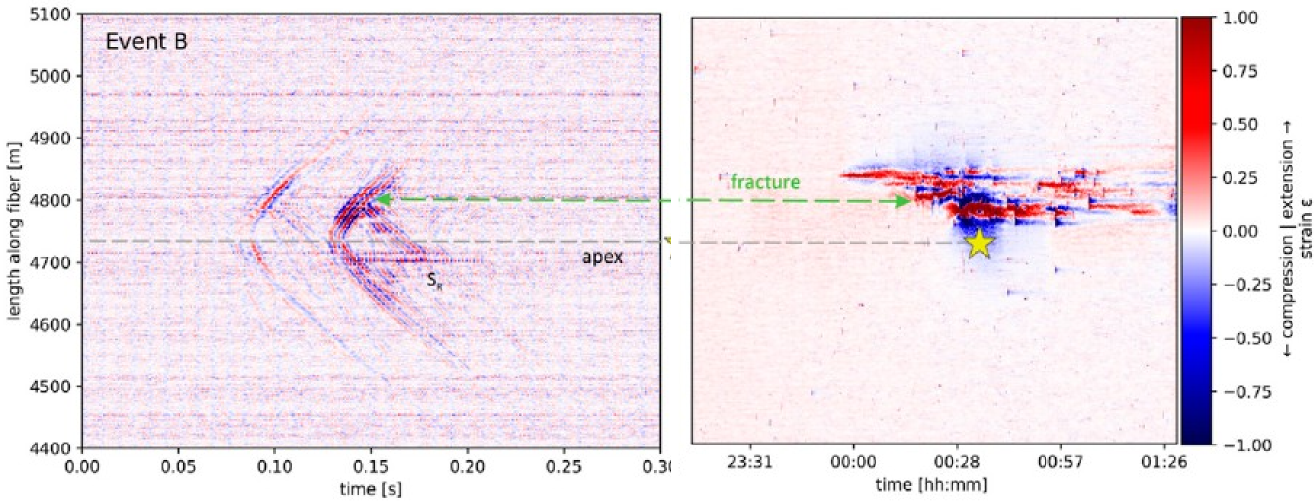
Induced seismicity

Micro seismicity resulting from hydraulic fracking, Denver (USA)



- Horizontal boreholes equipt with fibers
- in approx. 2.3 km depth
- Measurement with distributed dynamic (DAS) and static (DSS) strain sensing
- Wavefronts are reflected at the crack surfaces

Stanek et al. (2022)

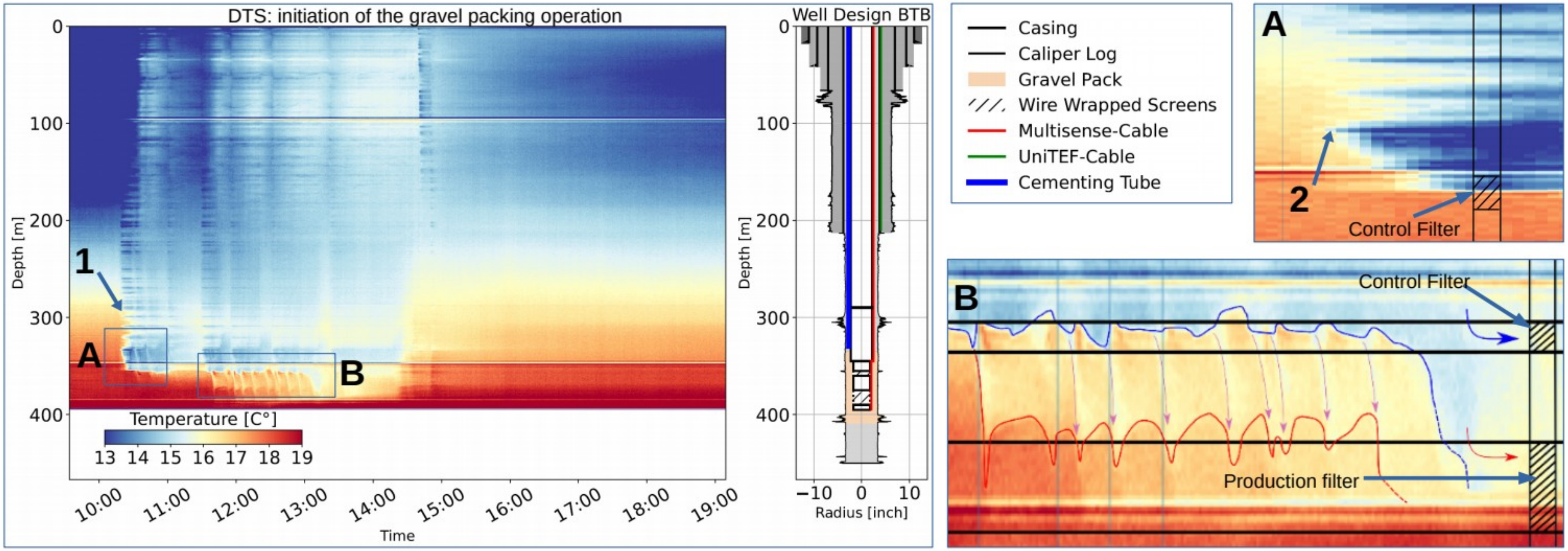


Use cases / application examples

Infrastructure monitoring

Monitoring of a well integrity
during completion: Distributed Temperature Sensing (DTS) monitoring of gravel-packing operation

Hart et al. (2022, in preparation)



A) cool flushing flow (1) arrives at the end of the flushing lance (2); circulation through the control filter.
B) periodic cooling below control filter due to the arrival of gravel

Summary

- DAS offers an efficient and powerful way to observe not only creep deformations (DSS) and temperature (DTS) but also elastic processes (DAS) with the same infrastructure.

- Several thousand (virtual) sensors along several dozen kilometers of fiber allow for spatially unaliased sampling of the strain-/wave- or temperature field.

  - In the case of the seismic wavefield, coherence analysis is a powerful tool for enhancing the recordings and exploring the underlying elastic medium.

  - Broadband spectral response.

- The specific measurement characteristics of the wavelength- and direction-dependent sensitivity as well as fiber properties and circumstance of deployment must be taken into account.

History of FO Sensing

- 1960: invention of the laser by Theodore H. Maiman at Hughes Research Laboratories (California, USA).
- 1970: Corning Glass Works (Company, New York, USA) develop the first optic fiber practical for telecommunication.
- 1977: Installation of the first commercial fiber optic communication system
- 1980s: Optical Time Domain Reflectometry (OTDR) allows for the distributed measurement of signal loss
- 1990s: Development of further intrinsic scattering techniques (Raman and Brillouin)
- 2000s: Distributed Temperature Sensing applied in the oil and gas industry borehole monitoring
- 2024: IMPROVE network school

History of FO Sensing

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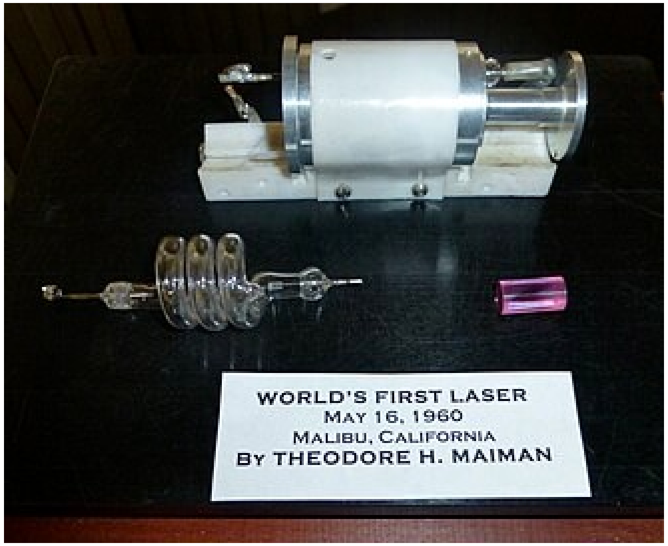

Scetch of Maiman's ruby laser from 1960. Approx. 6X4 cm size. [https://en.wikipedia.org/wiki/Ruby_laser]

Commercial semi-conductor laser component (14-Pin butterfly) for modern applications. Approx. 2X3cm size [www.beaq.com]

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-
-
-
-
-
-

Year	1977	2024
Optical attenuation	17 dB/km	0.25 dB/km

[FIBRASENS DSS 2f, Datasheet, sucess4u GmbH, Switzerland]

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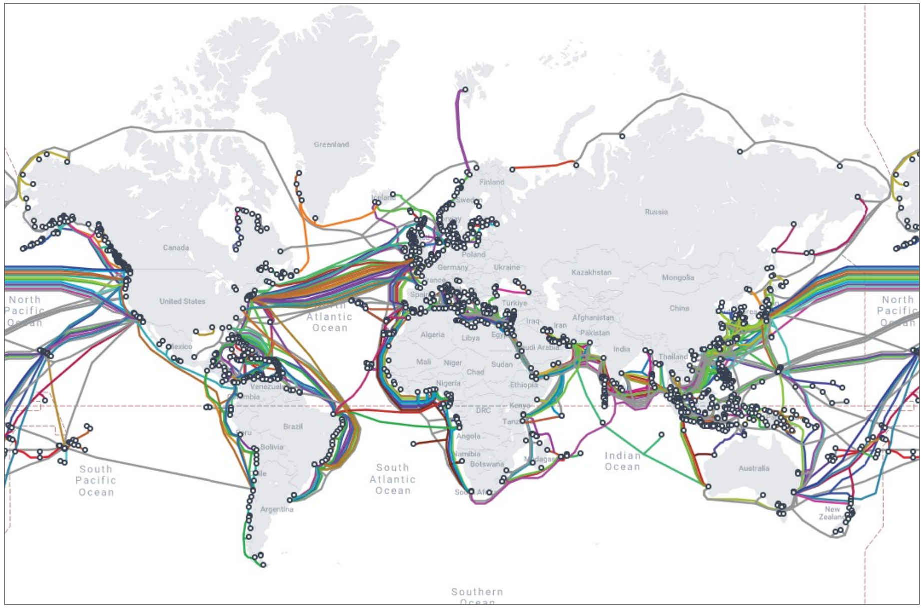
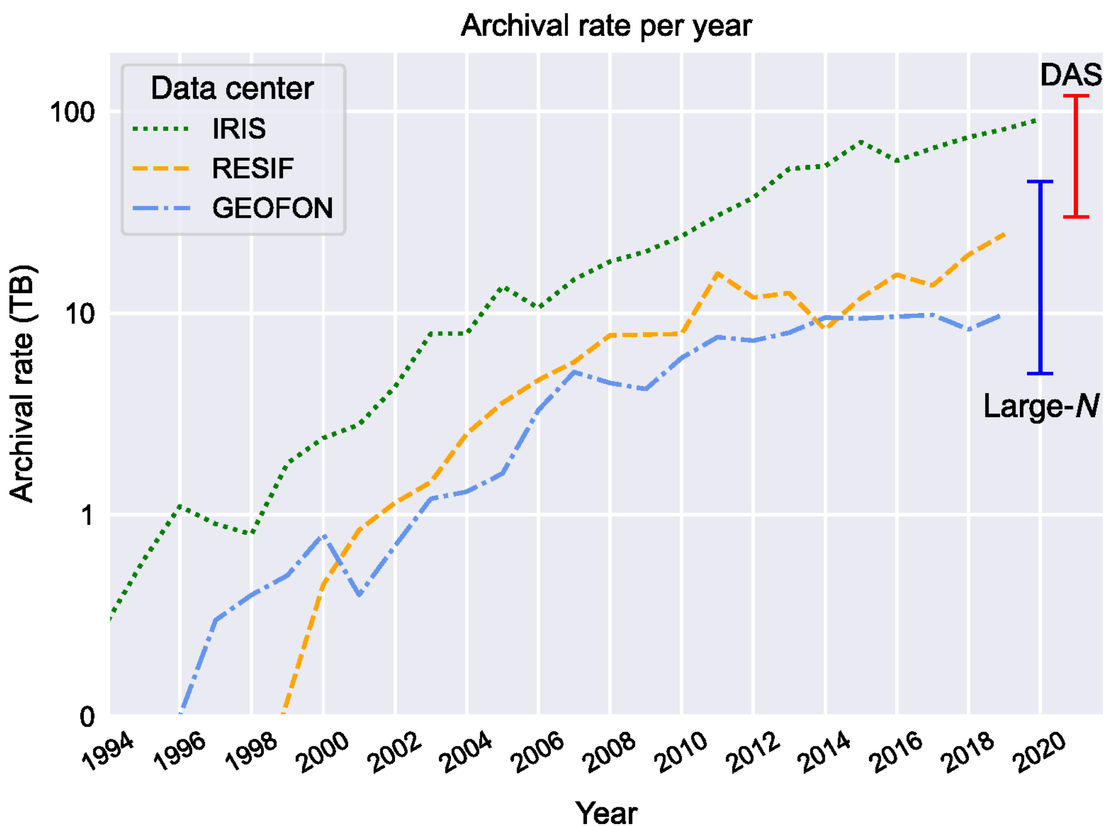
- First transatlantic fiber optic telecom. Cable (TAT 8) went into operation in 1988.



Contemporary submarine telecom. Cables.
[https://www.submarinecablemap.com]

History of FO Sensing

Evolution of the data archived yearly at different data centers vs. the size of single datasets of large-N and DAS experiments. [Quinteros et al., 2021]



- **2010s: Commercialization of Distributed Acoustic Sensing**
- **2018: Detection of seismicity with DAS using dark telecom. fibers (Jousset et al. 2018)**

History of FO Sensing

We now invite you to

- visit the GIPP,
- look at a live DAS recording,
- perform a small experiment and
- touch some some seismic data.

- **2024: IMPROVE network school**

History of FO Sensing

We now invite you to

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- perform a small experiment and
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- **2024: IMPROVE network school**

Thank you for your attention and …

… let's go