Distributed Acoustic Sensing
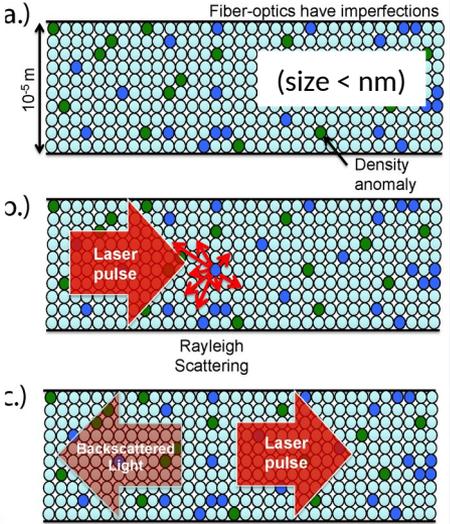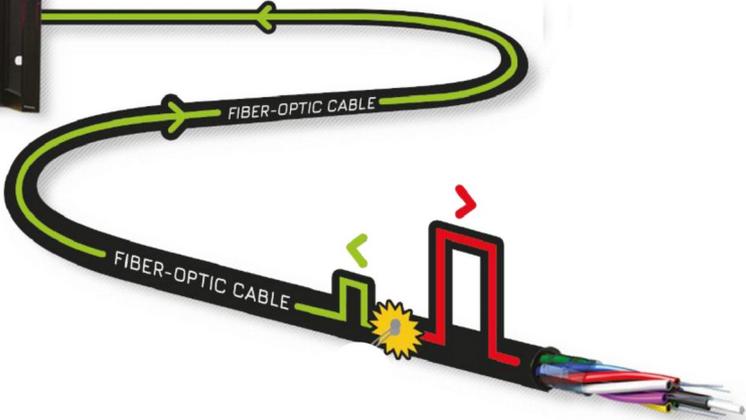
Olivier Coutant, ISTerre , UGA

DAS – DTS – DSS ???

Optical fiber as "distributed sensors" has several acronyms or declination

- Distributed measurements for temperature (**DTS,** Raman, Brillouin scattering)

- quasi-static strain (**DSS** Brillouin scattering)

- **dynamic strain or acoustic sensing (DAS,** Rayleigh scattering**)**
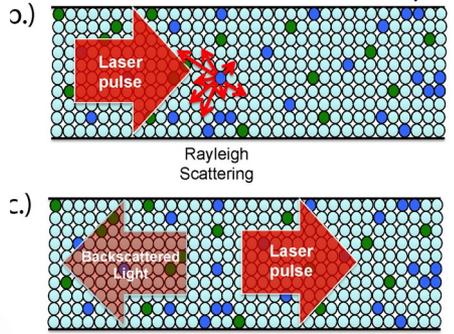
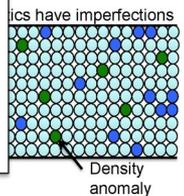Not speaking about discrete optical fiber sensors or deported sensors
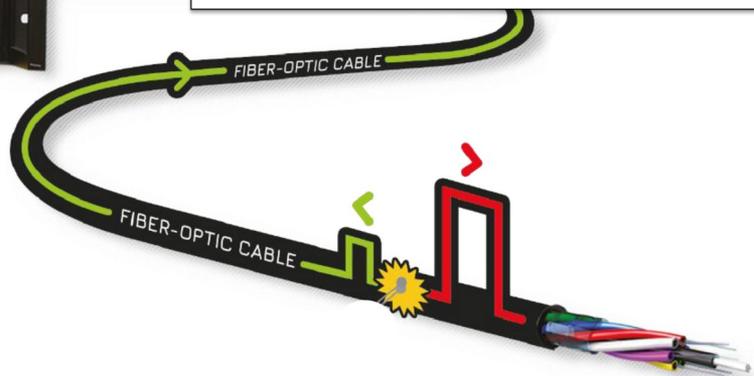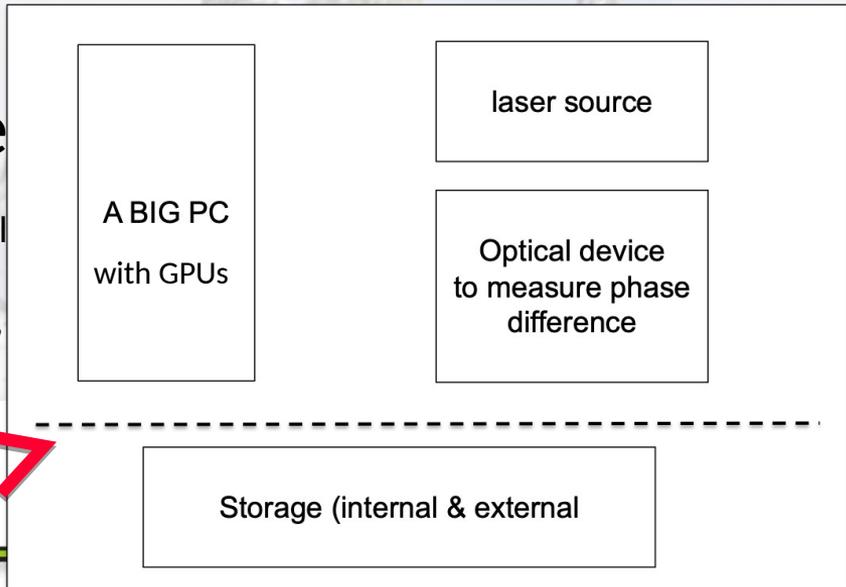
The DAS setup

- The DAS interrogator comes out of the shelve (oil industry)

- Connection on one end of the optical fiber, no need for a terminator device

(size < nm)

Density anomaly

Rayleigh Scattering

Laser pulse

Backscattered Light

Laser pulse

Fiber-optics have imperfections

Credit: FebusOptics, Silixa, Lindsey, N.J., Rademacher, H. and Ajo-Franklin, J.B., 2020

The

- The DAS interrogator comes out of the shel
- Connection on one end of the optical fiber,

| A BIG PC with GPUs | laser source |
| | Optical device to measure phase difference |

Storage (internal & external

ics have imperfections

Density anomaly

c.) Laser pulse

Rayleigh Scattering

c.) Backscattered Light — Laser pulse

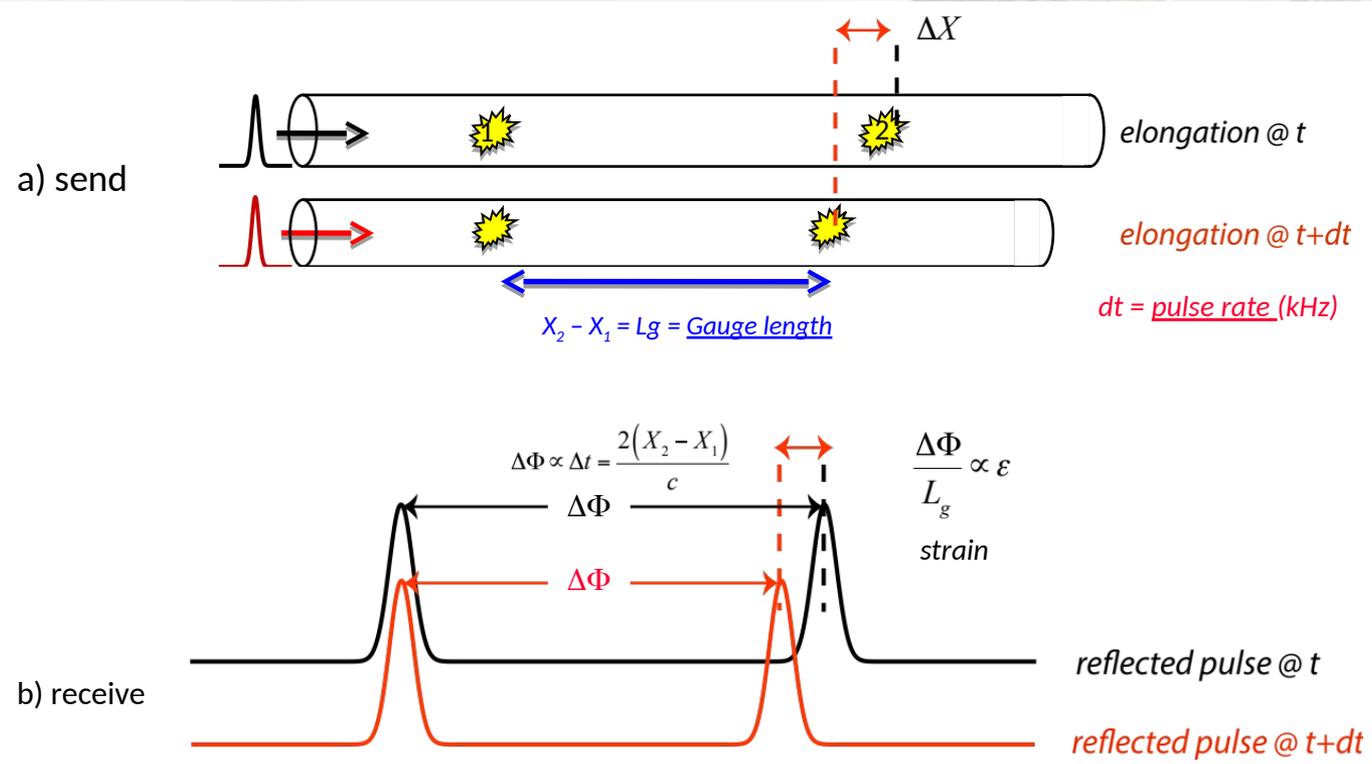**Credit:** FebusOptics, Silixa, Lindsey, N.J., Rademacher, H. and Ajo-Franklin, J.B., 2020

A few words about the method

The method is know as Optical Time Domain Reflectometry (OTDR)

- DAS uses **intensity** and light **phase**
- DAS technological solutions varies among constructors (e.g. some records two polarizations to manage fading effect)
- DAS uses mostly Single Mode Fiber (SMF), but MMF are ok on short distances
- DAS uses standard telecom SMF but dedicated fibers with enhanced diffracting capabilities are sometime used

a) send

elongation @ t

elongation @ t+dt

ΔX

$X_2 - X_1 = Lg = \underline{Gauge\ length}$

dt = <u>pulse rate</u> (kHz)

b) receive

$\Delta\Phi \propto \Delta t = \dfrac{2(X_2 - X_1)}{c}$

$\dfrac{\Delta\Phi}{L_g} \propto \varepsilon$

strain

$\Delta\Phi$

$\Delta\Phi$

reflected pulse @ t

reflected pulse @ t+dt

- The strain is proportional to the phase difference as:

$$\epsilon_{xx}(t, x_j) = \frac{\lambda}{4\pi n L_G \zeta} \Delta\Phi = \frac{1550 \cdot 10^{-9} \text{ (m)}}{4\pi \cdot 1.445 \cdot 10 \text{ (m)} \cdot 0.735} \Delta\Phi = 11.6 \cdot 10^{-9} \cdot \Delta\Phi \text{ (rad)}$$

- The DAS is sensitive only, at first order, to longitudinal fiber extension/shortening

- We can neglect temperature variations, perpendicular strain, pressure effects

DAS measures difference of motion (strain) along the fiber, « almost » like seismometer
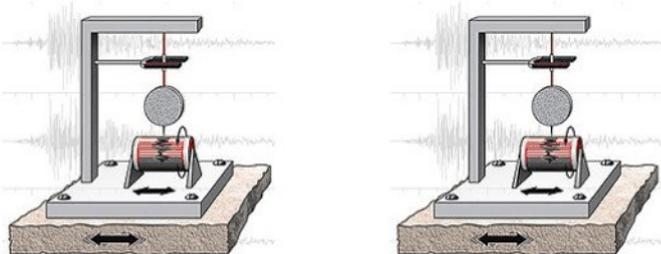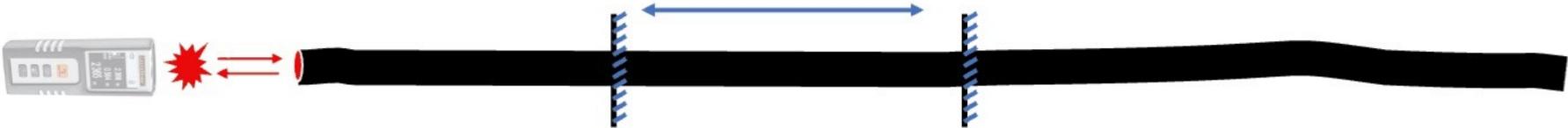
Two seismometers record the displacement

DAS does not measure difference of motion perpendicular to the fiber unlike seismometer
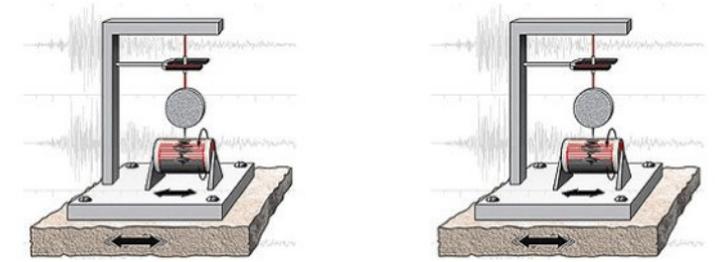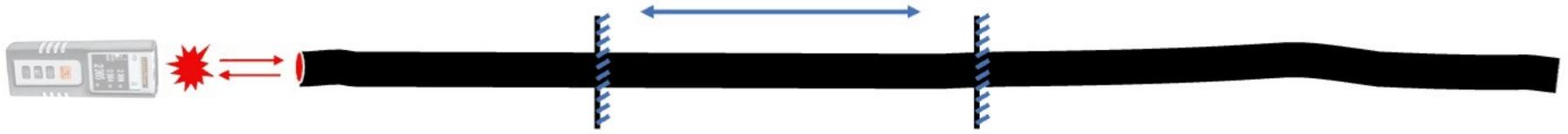
Two seismometers
record the displacement

Parameters to acquire data are:

- **Pulse Rate Frequency** (PRF), the frequency at which the laser pulse is sent
    The higher, the better but fiber length gives the upper limit (1/PRF < 2L/C)

- Laser pulse **power** (typically <30db)

- **Laser pulse width**, converted in distance (typically <GL/2)

- **Phase sampling-rate**, time converted into distance (typically 10-30cm)
- **Gauge length** (1m < GL <100m)
The longer the better for SNR, but record only wavelength > GL

- A **time derivation** is applied to eliminate effect of spurious cycle skip

- **Decimations** are then applied for both spatial and temporal sampling

- *Typical values: PRF 1KHz, GL 5m, derivation 5ms, output @ 250Hz every 2m*

Processing issues

- Gauge length, fading
- Cable coupling to the ground
- calibration of gain
- Localization of the fiber location
- Unidirectional sensitivity complicates local wave discrimination

Highlights

- DAS Interrogates fiber as long as 80km/150km
- Very dense sensor distribution BUT unidirectional
- Poor SNR
- Poor dynamic range
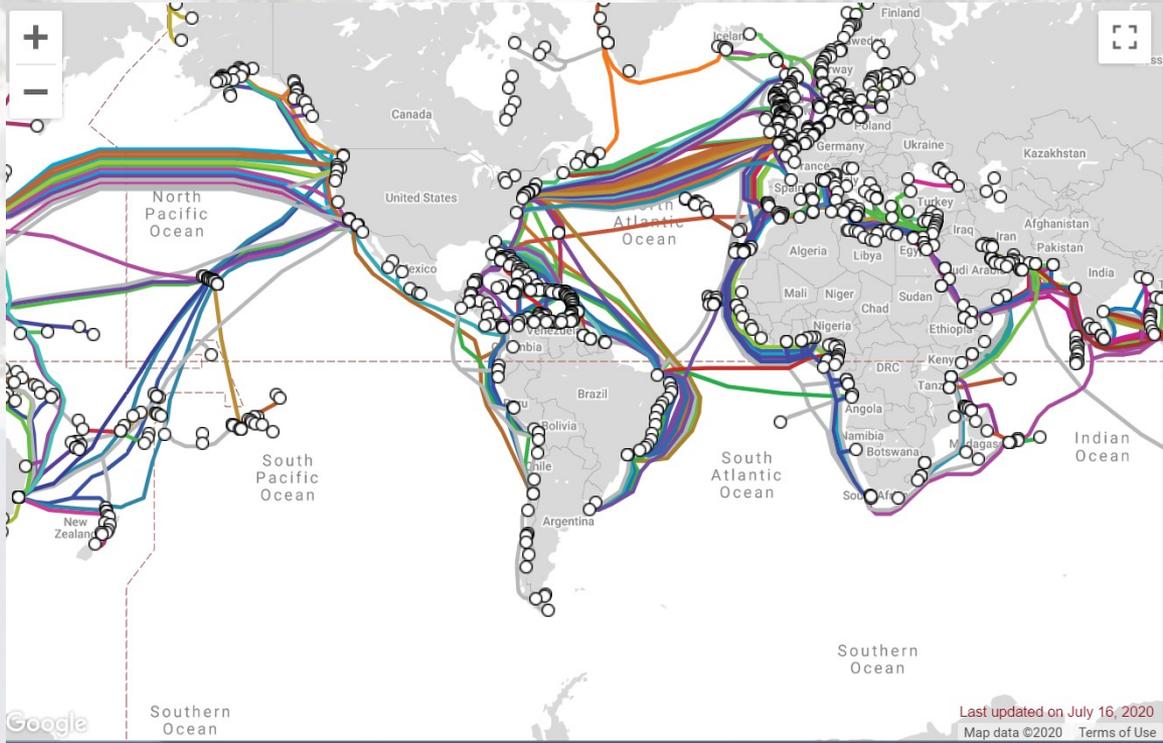
A DAS: for what purposes?

The DAS IRIS Research Coordination Network (RCN) has created several working groups:

- Energy technology and CO_2 monitoring
- **Earthquake and array seismology**
- **Urban seismology**
- Engineering infrastructure
- Hydrology
- Geomorphology
- **Cryosphere**   *+ intrusion detection*
- **Volcanic and Seismic Hazard monitoring**   *+ pipeline monitoring*
- Geotechnical
- **Marine geophysics**

In geophysics, the DAS take advantage of existing Telecommunication fibers

Marine geophysics: cable distribution over oceans

https://www.submarinecablemap.com/

The ABYSS project (D. Rivet Geoazur, Nice)
Early Warning along the Chilean subduction zone

Figure 1 Experimental setting, and examples of DAS data saturation. (a) Overview of the ABYSS experiment, located along the Central Chilean margin. The route of each of the three DAS cables (CCN.N, SER.S, and SER.N) are indicated in black. The epicentre of the M_{ww} 6.6 Huasco earthquake is marked by the orange star; (b) Time-series of the Huasco event recorded by a poorly-coupled DAS channel, which are not saturated; (c) Time-series of the Huasco event recorded by a well-coupled DAS channel. The data are strongly saturated, approaching the limit of uniform (white) noise; (d) Time-series of ocean gravity waves (swell) recorded close to shore. The data are mildly saturated, and could potentially be recovered by unwrapping; (e) Time-series of a vibrating segment, driven by ocean-bottom currents. Data saturation starts after 4 s. In panels (b)-(e), the dynamic range is indicated by the dotted lines.

Van den Ende, M., Trabattoni, A., Baillet, M., & Rivet, D. (2024). An analysis of the dynamic range of distributed acoustic sensing for earthquake early warning.

The ABYSS project (D. Rivet Geoazur, Nice)
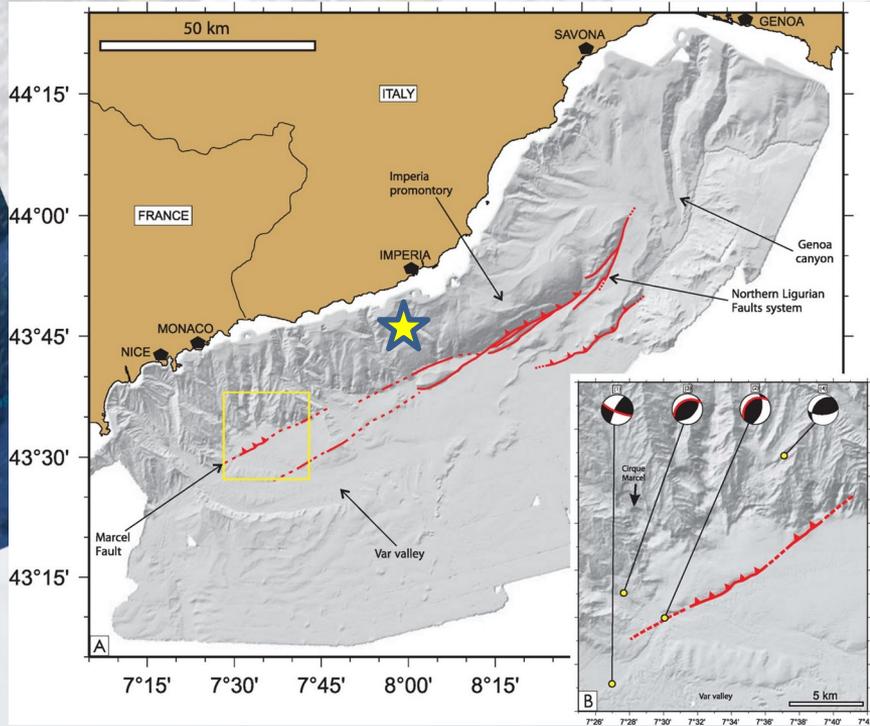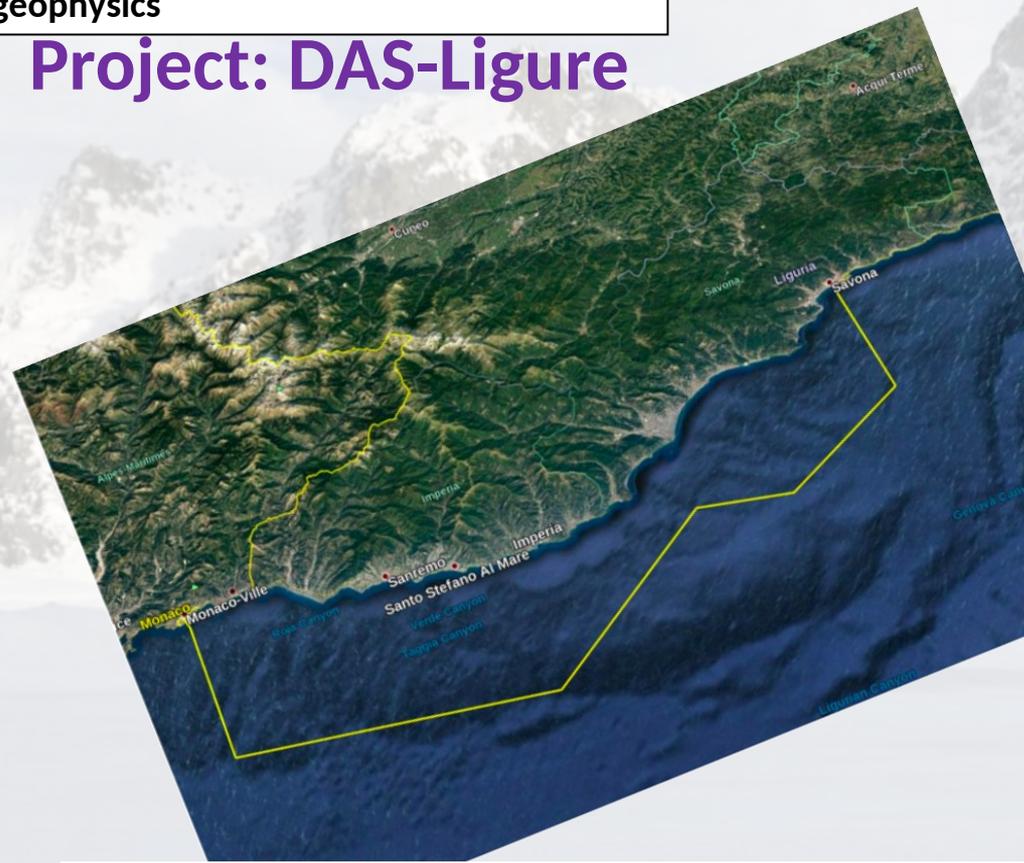Early Warning along the Chilean subduction zone

Figure 1. Map of central Chile and DAS deployment. (a) The fiber-optic cable between Concón and La Serena is shown in black and the 150 km section sensed during the POST experiment is indicated in red. Colored solid circles correspond to the 20 earthquakes that were used in this study. The three main geomorphological features are the Juan Fernandez Ridge (JFR), the Punta Salinas Ridge (PSR) and the Valparaíso Forearc Basin (VFB). (b) Bathymetry profile along the fiber-optic cable that crosses the edges of the VFB between 30 and 80 km and the PSR around 90 km.
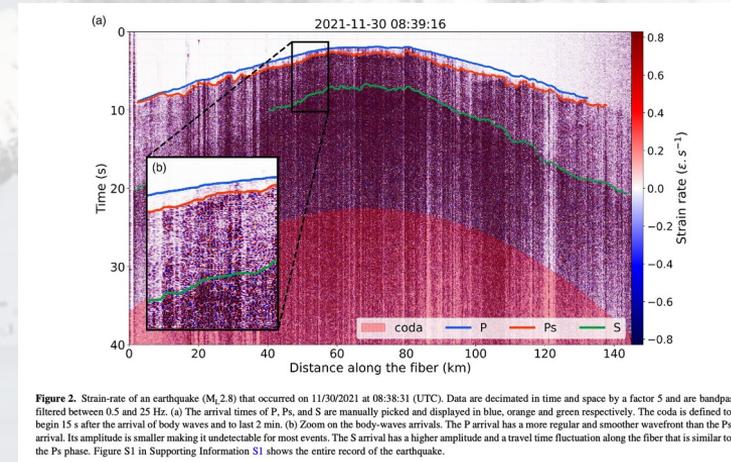
Figure 2. Strain-rate of an earthquake (M_L 2.8) that occurred on 11/30/2021 at 08:38:31 (UTC). Data are decimated in time and space by a factor 5 and are bandpass filtered between 0.5 and 25 Hz. (a) The arrival times of P, Ps, and S are manually picked and displayed in blue, orange and green respectively. The coda is defined to begin 15 s after the arrival of body waves and to last 2 min. (b) Zoom on the body-waves arrivals. The P arrival has a more regular and smoother wavefront than the Ps arrival. Its amplitude is smaller making it undetectable for most events. The S arrival has a higher amplitude and a travel time fluctuation along the fiber that is similar to the Ps phase. Figure S1 in Supporting Information S1 shows the entire record of the earthquake.

Vernet, C., Trabattoni, A., Baillet, M., van den Ende, M., & Rivet, D. (2025). Imaging the sediment cover offshore central Chile with surface-wave dispersion and P-Wave conversion using distributed acoustic sensing. *Journal of Geophysical Research: Solid Earth, 130*(7), e2024JB030507.

Project: DAS-Ligure

Out of use Câble telecom cable from Monaco to Savone.
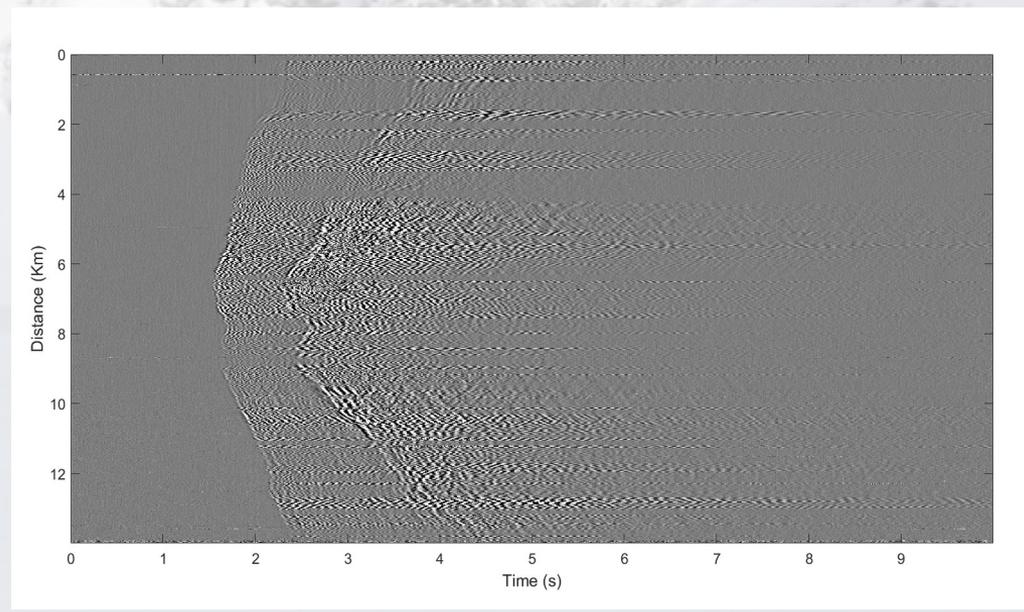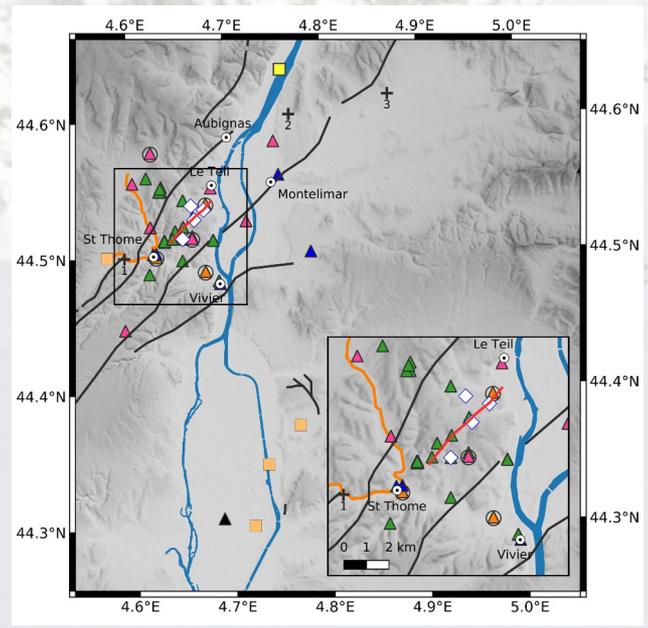140 km + DAS = 14 000 seismo-acoustics sensors

Ligurian fault system
Star = 1887 earthquake epicenter
(Larroque et al, 2012)

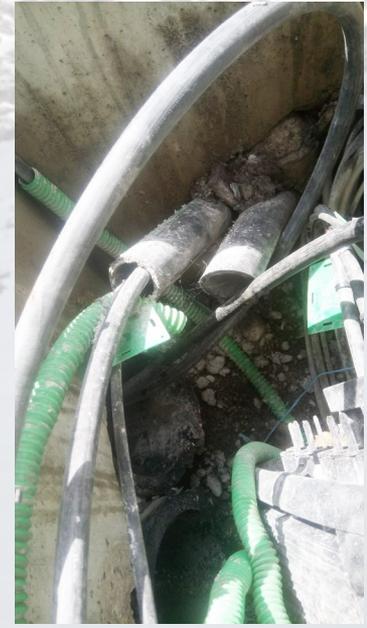**Earthquake and array seismology:** aftershock of "Le Teil" 2019 M.5.3 earthquake
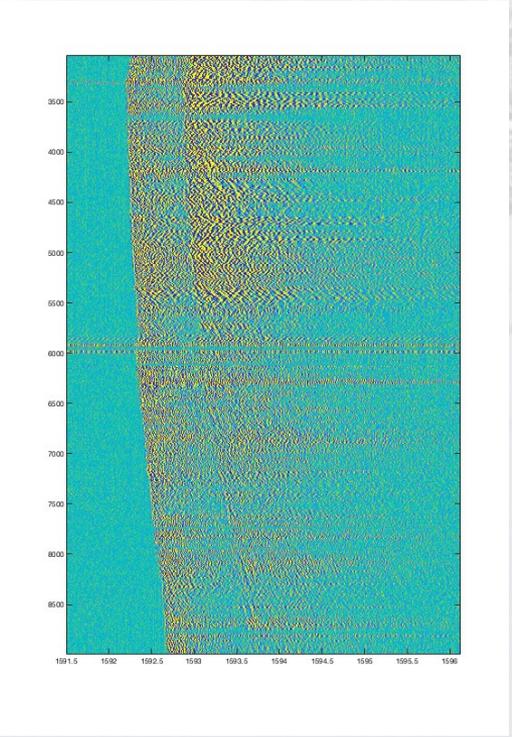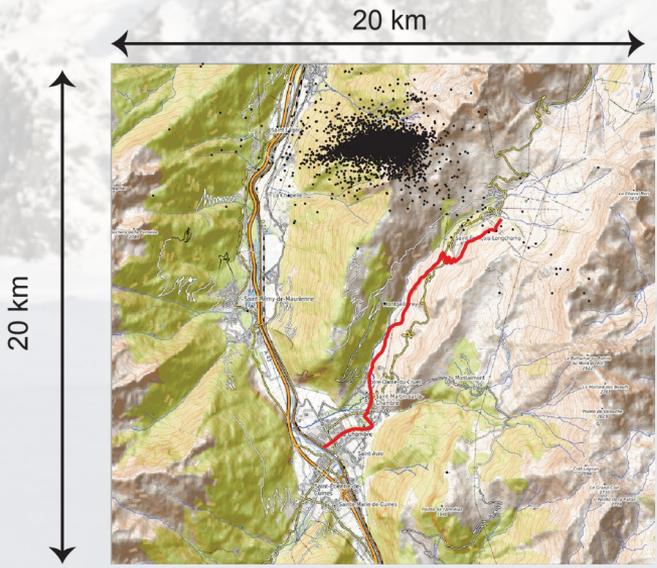
Close to a M5 earthquake

THD commercial telecom fiber network
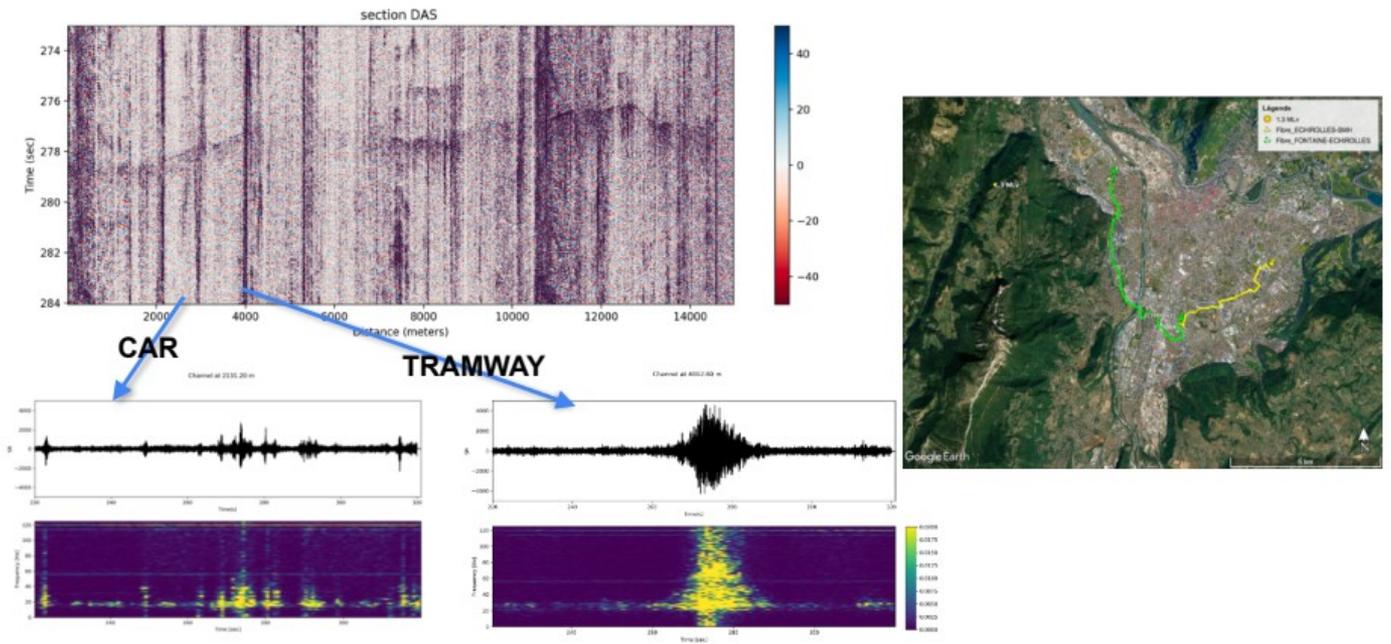
https://www.ardechedromenumerique.fr/

Earthquake and array seismology: La Chapelle (Savoie) Maurienne 2017-2018 seismic swarm

A 9km long fiber from the Maurienne valley to St François Longchamp ski resort
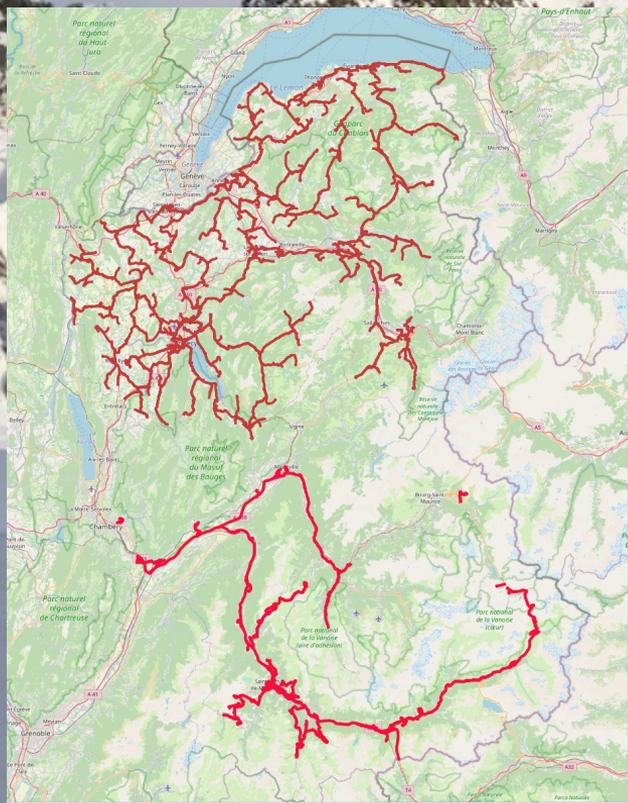
Urban seismology: risk assessment, structure monitoring, mobility monitoring
recording along a 7km long fiber in Grenoble city

Commercial telecom fibers in Savoie & Haute-savoie

Carte Fibrea 2019

**Notice that I do not show the map for our departement…**

There are hundreds of kilometers of fiber that could be interrogated, to monitor

- Landslides
- Earthquakes
- Rock fall

When the fiber is operated by « collectivités locales », we have access to the fibers (e.g. Grenoble, Annecy urban areas)

However, the big commercial operators are not yet prepared, nor interested, in working with scientific institutions, although a non negligible part of the fiber funding is public

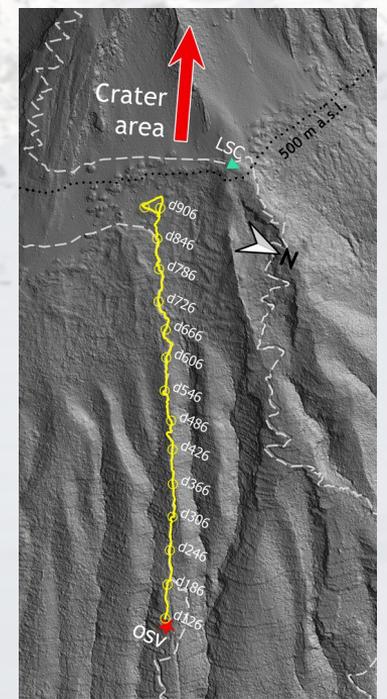# Volcanic and Seismic Hazard monitoring: Stromboli monitoring
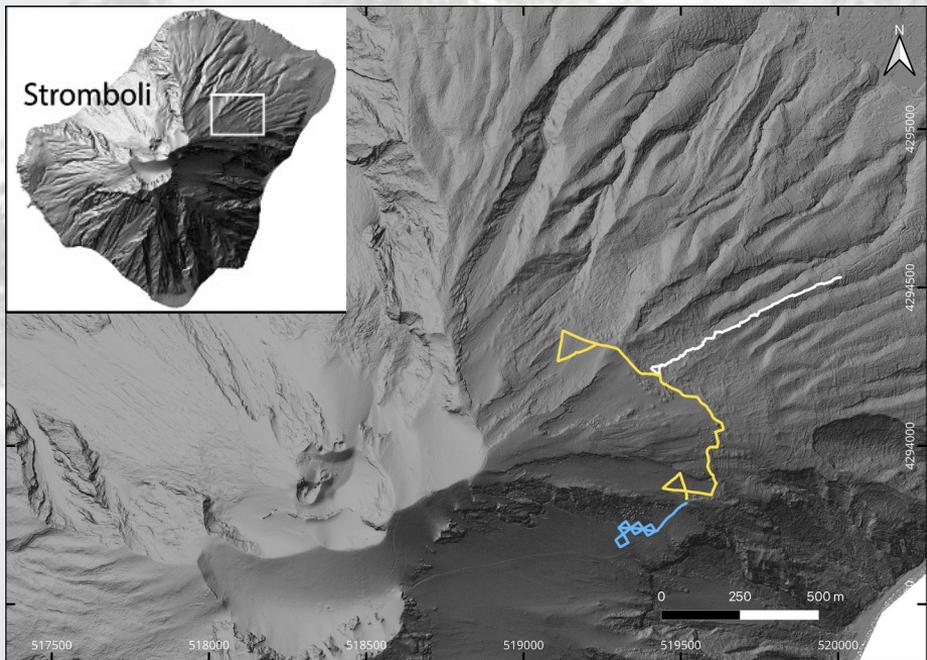
Biagioli, F., et al. , M. P. (2024). Array analysis of seismo-volcanic activity with distributed acoustic sensing. *Geophysical Journal International*, *236*(1), 607-620.
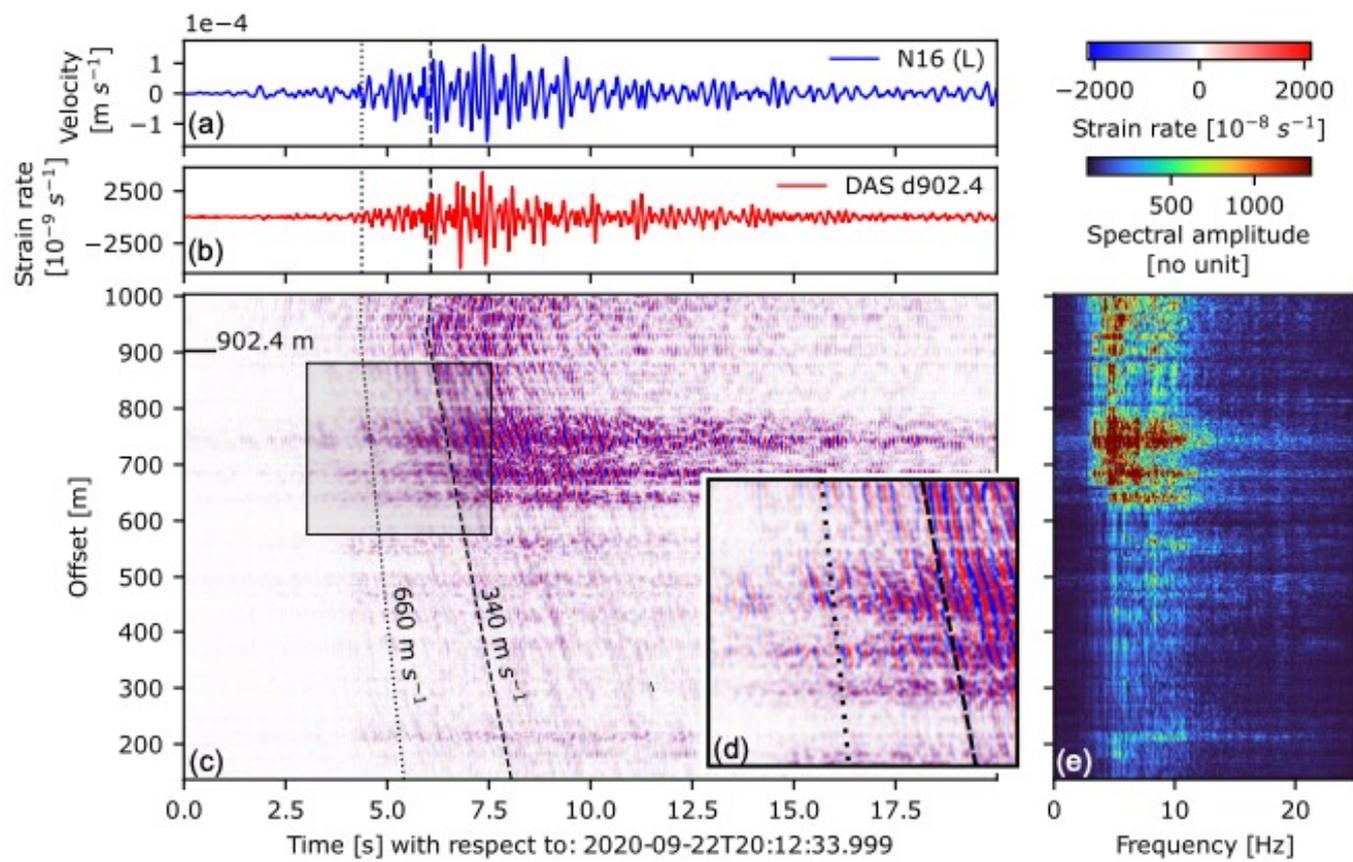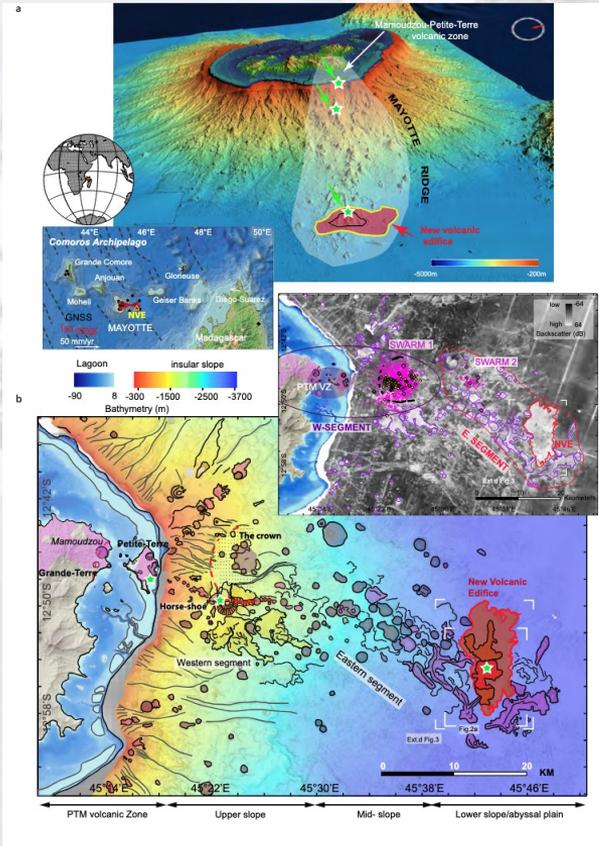
Origin time: onset of the acoustic wave recorded at the crater

Biagioli et al., 2023
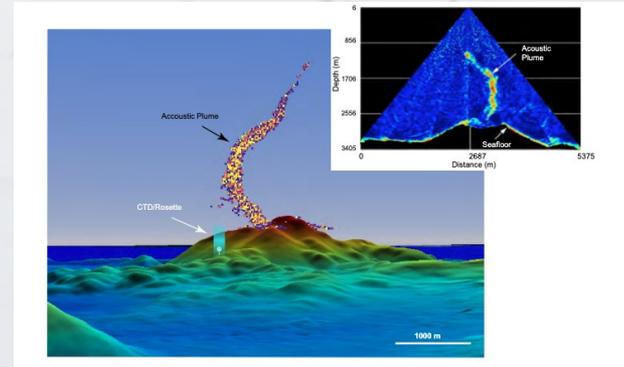
The new volcanoe that erupted in 2020 off coast of Mayotte at depth of 3400m is now monitored by a marine cable temporarely lended by ORANGE

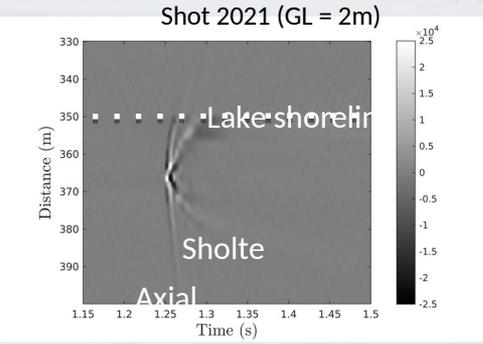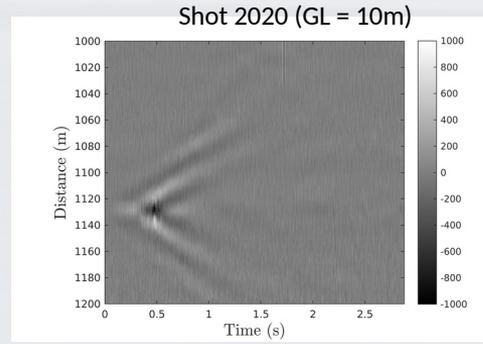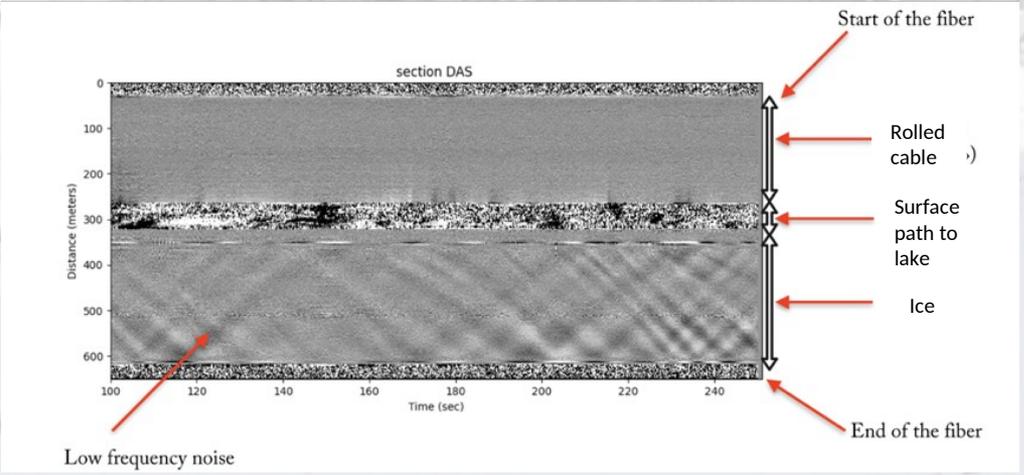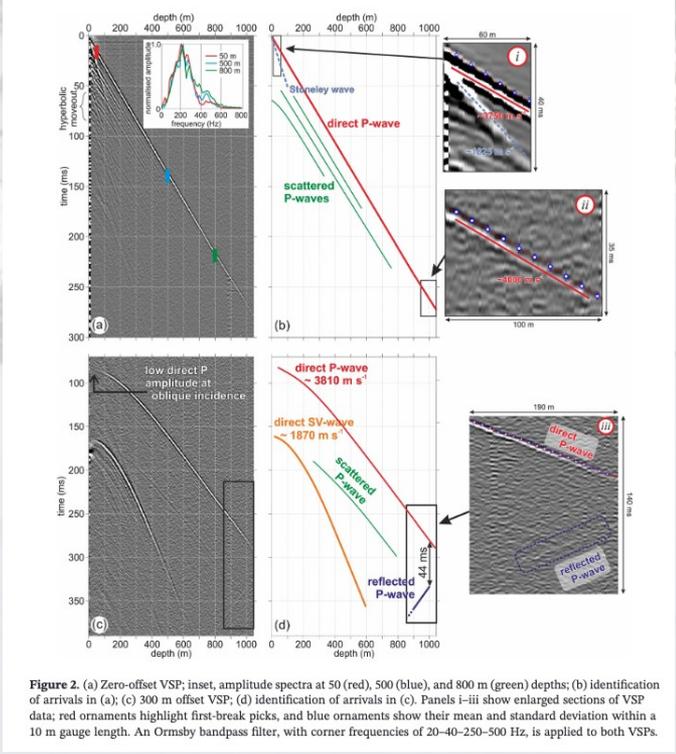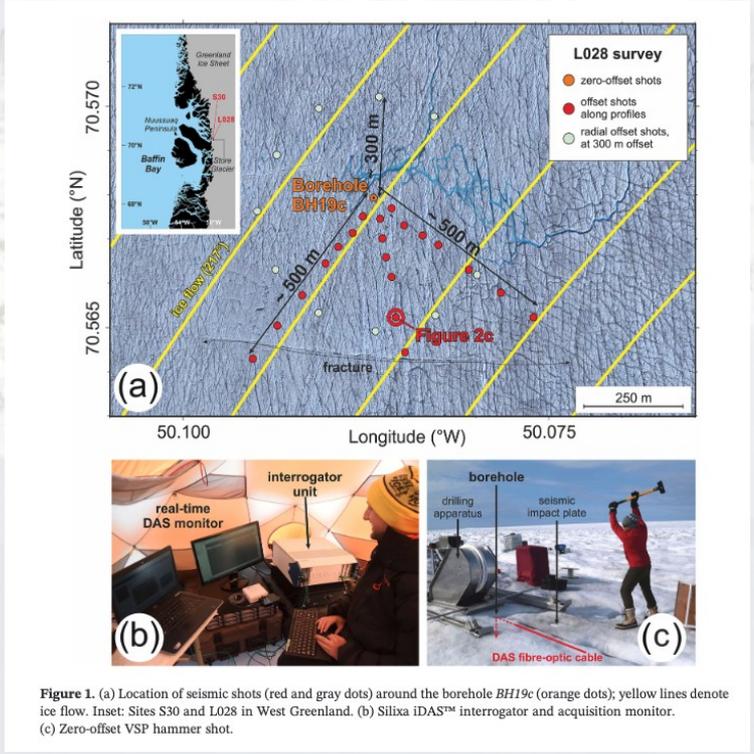Le câble Fly-Lion 3 va se rajouter au réseau actuel

Feuillet, N., Jorry, S., Crawford, W.C. et al. Birth of a large volcanic edifice offshore Mayotte via lithosphere-scale dyke intrusion. Nat. Geosci. (2021)

Cryosphère: geophysic for environmental studies, glacier and ice monitoring, river, …

Profile along a fiber deployed on a moutain lake above Grenoble

Shot 2020 (GL = 10m)

Shot 2021 (GL = 2m)

Monitoring of glacier movement and melting: groenland, antarctique, and Alps

Figure 1. (a) Location of seismic shots (red and gray dots) around the borehole *BH19c* (orange dots); yellow lines denote ice flow. Inset: Sites S30 and L028 in West Greenland. (b) Silixa iDAS™ interrogator and acquisition monitor. (c) Zero-offset VSP hammer shot.

Figure 2. (a) Zero-offset VSP; inset, amplitude spectra at 50 (red), 500 (blue), and 800 m (green) depths; (b) identification of arrivals in (a); (c) 300 m offset VSP; (d) identification of arrivals in (c). Panels i–iii show enlarged sections of VSP data; red ornaments highlight first-break picks, and blue ornaments show their mean and standard deviation within a 10 m gauge length. An Ormsby bandpass filter, with corner frequencies of 20–40–250–500 Hz, is applied to both VSPs.

Booth, A. D., et al., A. (2020). Distributed acoustic sensing of seismic properties in a borehole drilled on a fast-flowing Greenlandic outlet glacier. *Geophysical Research Letters*, *47*

# Data processing: what are the challenges?

1. Store temporarily the data (10 days, 57 km -> 15Tbytes)
   - Room available?
   - Storage is secure? Is fast ?
   - Academic versus private solution: data made available on the cloud by Febus/Silixa/optasens?

2. There is a larger gap between "raw data" and "used data" than before
   - Data reduction (redundancy, selection)
   - Dedicated local solution (server and local storage) versus datacenter and HPC center?

3. Development of large dataset analysis (IA, array analysis,…)
   - DAS is used for intrusion detection and pipeline monitoring using IA (PhD EOST+FebusOptics)

Data distribution, what are the challenges?

- Metadata ? Do we follow previous standards (IRIS-SEED) ?
  - Fiber location, multiple fibers, continuous location...

- What data do we make available?
  - Full dataset / selected dataset / published dataset?
  - Derived products?
  - How to proceed with continuous monitoring fiber?

- These questions are addressed by a several working group in US (IRIS-DAS working group) and in Europe (EPOS infrastructure)

We need public DAS data, but it is hard to host.

Reference point:
Incorporated Research
Institutions for
Seismology (IRIS) Data
Management Center
(DMC) Archive in USA
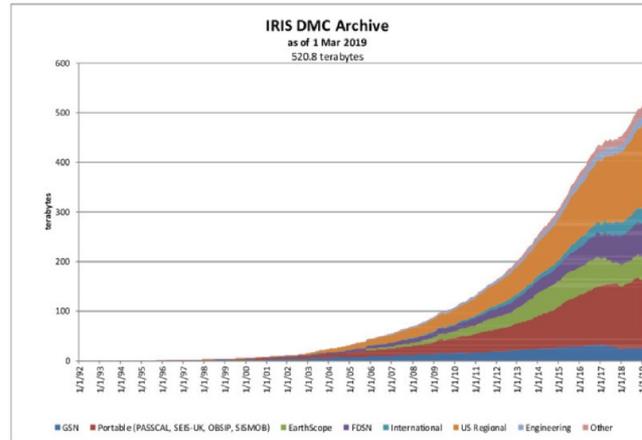
Amount that would
be added by FORESEE
if it were included.

Penn State Data Commons has agreed to host our entire +100 TB
data set publicly upon release (2-3 years from now).

Slide from: Fiber Optics foR Environmental SEnsE-ing (FORESEE) at Pennsylvania State University T. Zhu et al., EGU 2020

Conclusions: DAS is a new complementary tool for many fields in geophysics

- Can be deployed in harsh (volcanoes) or inaccessible (marine cable) environment
- Unprecedented coverage (distance >50km and density)
- Strain is more sensitive than displacement to local heterogeneities
- Optical fiber is cheap (1€ to 5€ / meter)
- Simple maintenance: interrogator at one end

- Lower signal-noise ratio than geophones (5-10 db)
- Single component
- Strain is more sensitive than displacement to local heterogeneities
- Requires strong power supply (1.5kW)
- But where is the fiber?

Important issues that remains :

- Get access to commercial fibers (e.g. Orange-IPGP for Mayotte volcano monitoring)
- Find smart solutions for data management

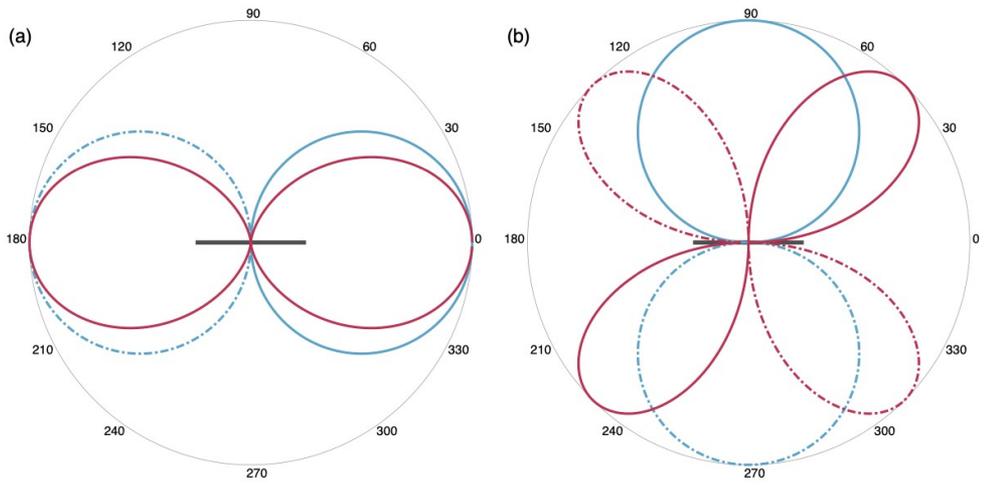# Azimuthal sensitivity to various wave polarization (P, S, Love, Rayleigh)

Figure 3.4 Comparison of seismometer and DAS strain-rate directional sensitivity in the horizontal plane. The seismometer results for the central point are shown in light blue and the DAS in red. The wavelength is assumed to be long compared to the gauge length marked in black. Dashed lines indicate negative zones. (a) *P* waves and Rayleigh waves; (b) *S* waves. [After Zhan (2020)].

These technologies are based on the analysis of the back scattered light generated by a laser pulse
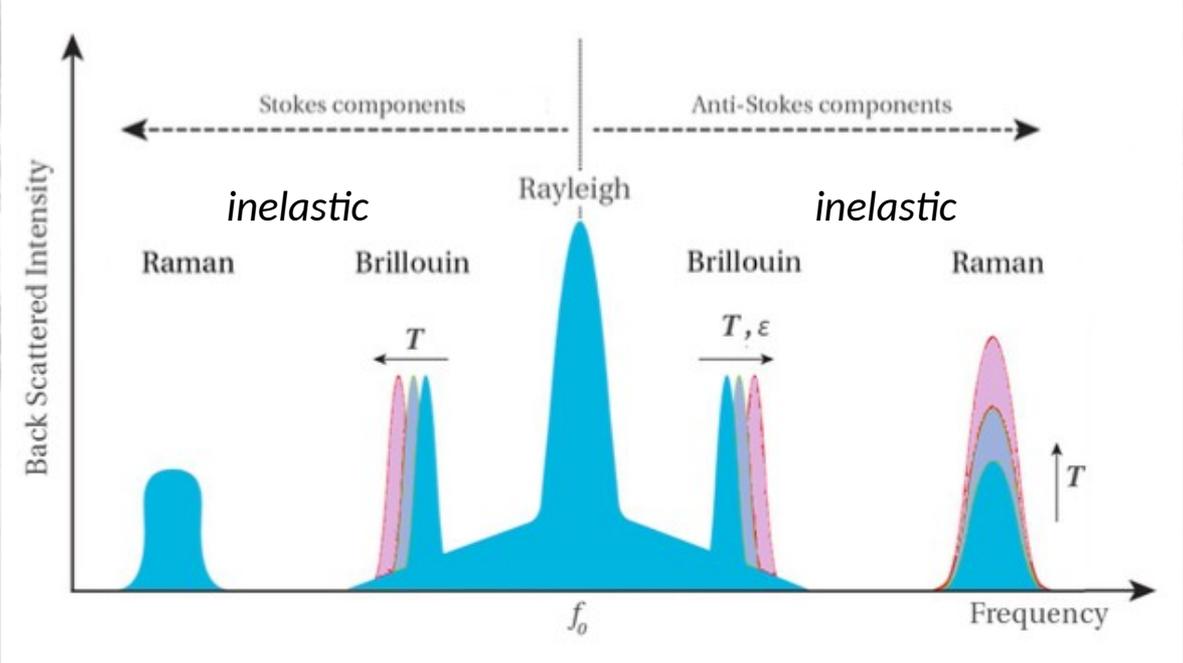
Schematic of the character of the Rayleigh, Raman, and Brillouin peaks in the back-scattered light spectrum. T is temperature, ε is strain (Kennet, 2024)