Coherent Fiber Interferometry for Environmental Monitoring

Geant Infoshare: Advanced Fibre Sensing Techniques and Monitoring Systems

30/04/2026

Simone Donadello
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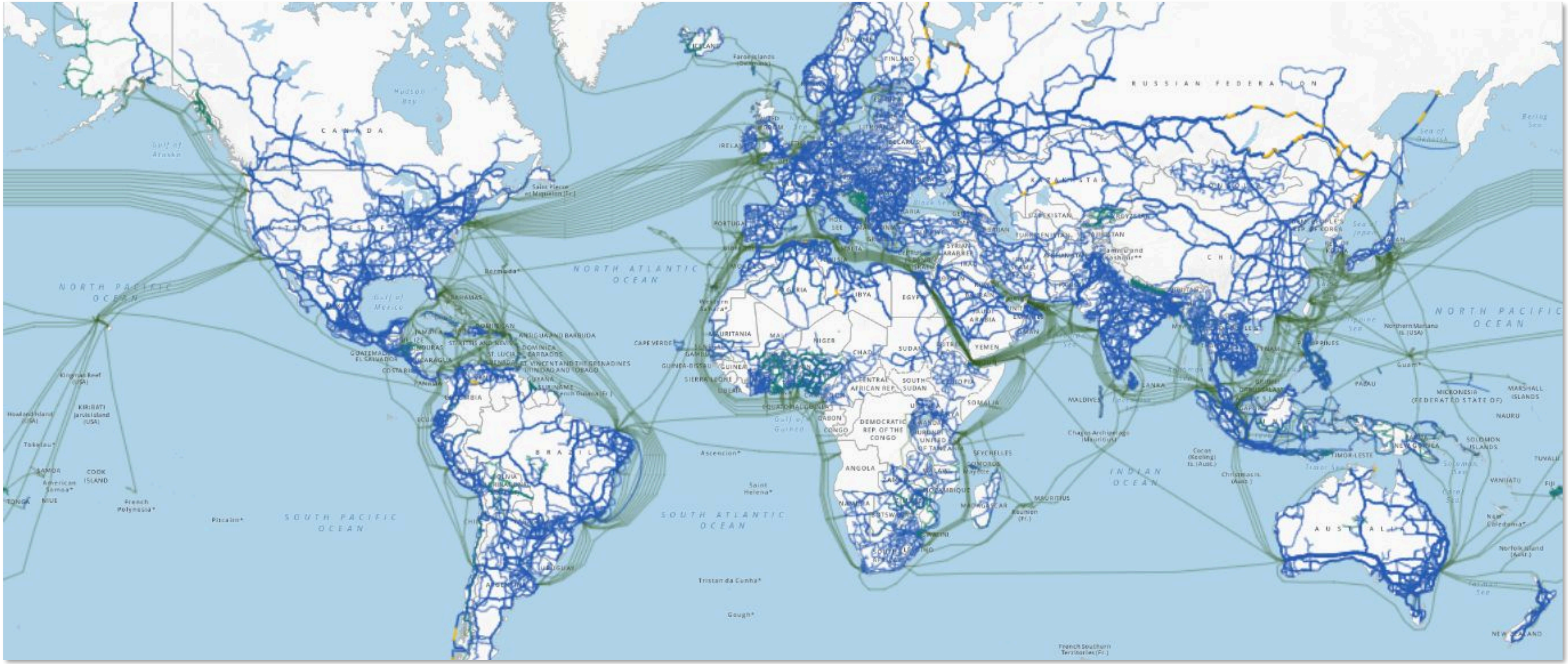
ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Optical fibers as sensors

Telecom networks for global sensing



ITU connectivity map, https://bbmaps.itu.int/bbmaps/

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Fibers: from networks to ubiquitous sensing tools

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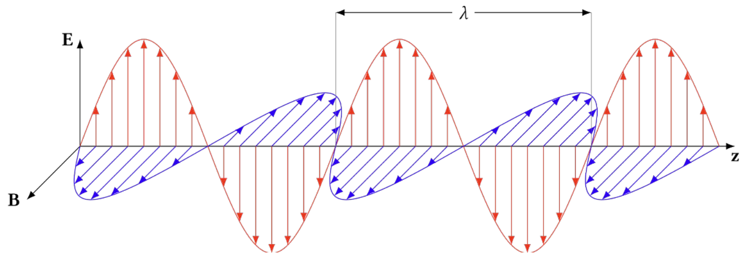
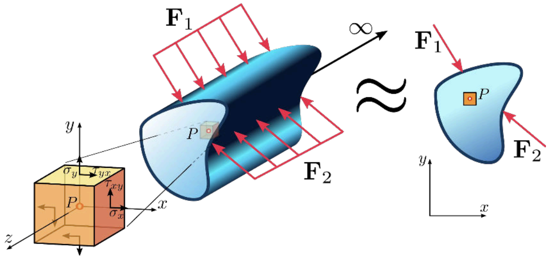
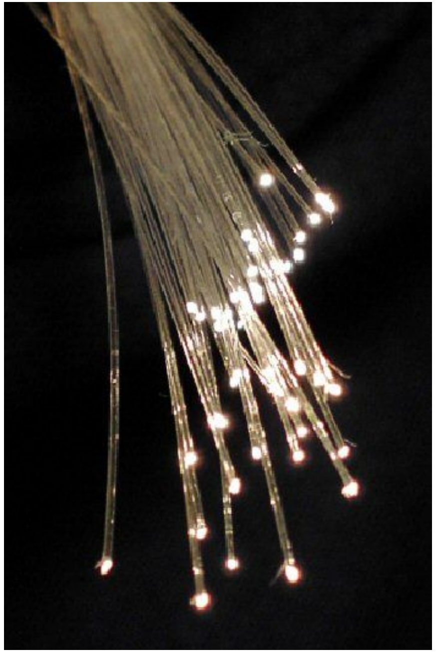
Optical fiber as a sensor







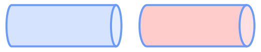
Pressure, **Temperature**, **Strain**

- **optical path** variation
- physical **deformation**
- **refractive index** change
- **polarization** rotation

Strain

Pressure

Temperature



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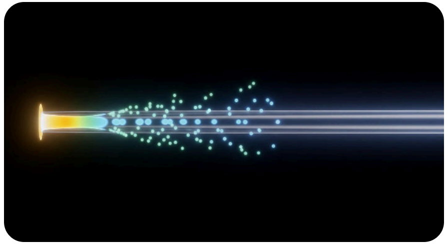
Integrated Fiber Sensing: Techniques & Comparison

Distributed (DAS)



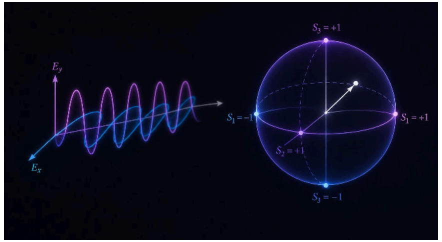
Principle: Phase of Rayleigh backscattering from light pulses.

Pros: High spatial resolution (meter-scale), distributed mapping.

Cons: High data rate (>100 GB/day), bulky equipment, network incompatibility (partial), limited reach.

Pulsed / Backscatter

Polarization (SOP)



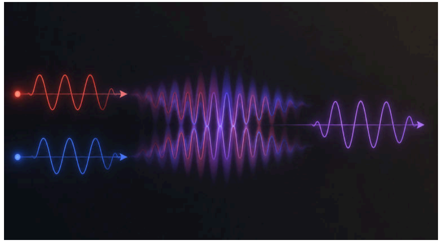
Principle: Changes in State of Polarization of transmitted light.

Pros: Very little hardware overhead, can use standard transceivers.

Cons: Lower sensitivity than phase-sensing, poor localization.

Transceiver Based

Coherent Interferometry



Principle: Phase/frequency shift of a CW laser carrier.

Pros: Extreme sensitivity, coexists with data traffic, low data rate (~1 GB/day), very long reach (up to ~ 1000 km).

Cons: Requires low-phase-noise lasers, limited localization resolution.

CW / Integrated

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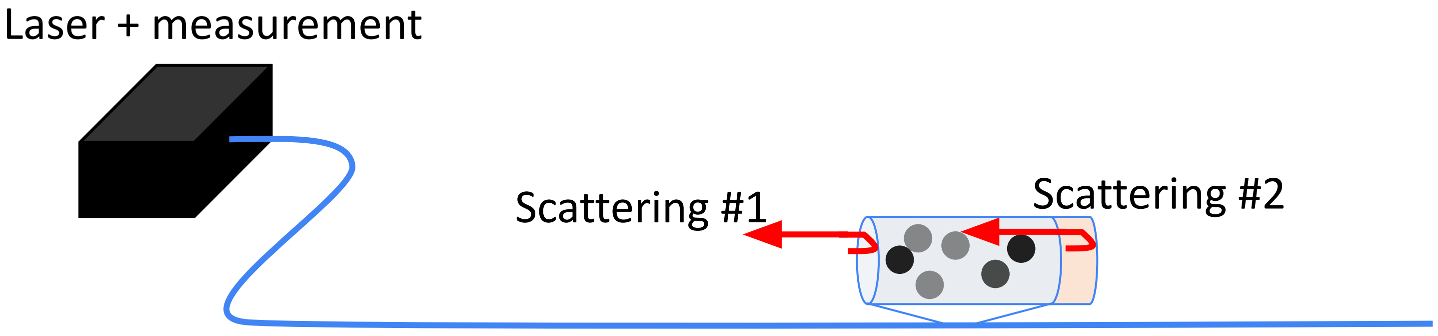
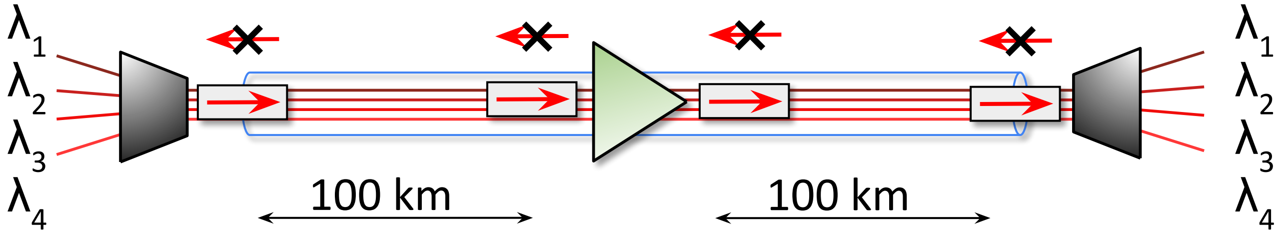
Conventional sensing (Distributed Acoustic Sensing)



1) Dense **Wavelength-division multiplexing**: requires constant launch power
2) Data links are protected by **isolators** that block backscattered light



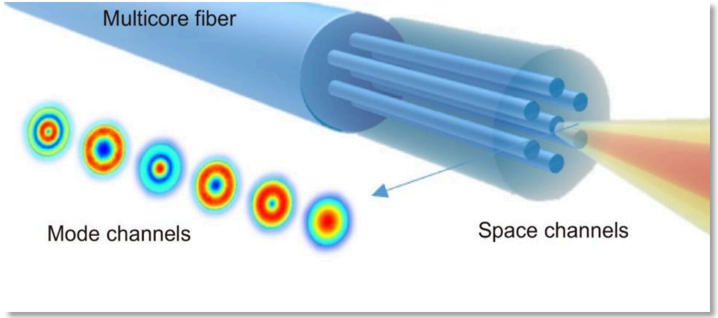
Dedicated fibers for sensing?

- Deployment & maintenance costs (surveys, digging, repairs...)
- Regulations and permits (government, ecosystem...)
- Revenue uncertainty (geophysical hotspots, borders, subsea...)
- Space occupation (conduits and endpoints)
- Power consumption (amplifiers & terminal equipment)

More fibers per cable...

Diam: 32 mm, 3456 fibers (thefoa.org)

...more cores per fiber



M. V.d. Hout, Nat. Comm. 16, 3833 (2025)

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Coherent interferometry

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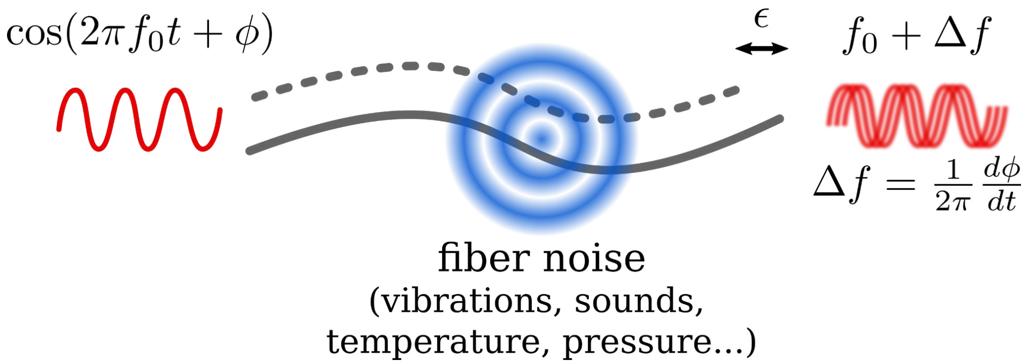
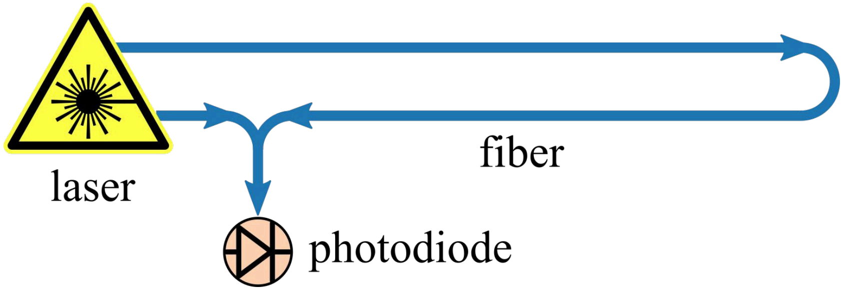
Coherent interferometry



$$\Delta\phi = \frac{2\pi n}{\lambda}\Delta L$$

$$\phi \propto \epsilon$$



- **compatible with telecom infrastructure**
- coexists with **data traffic**
- high **sensitivity & linearity**
- **long range** – can be **amplified**
- ultrastable lasers – **long coherence**

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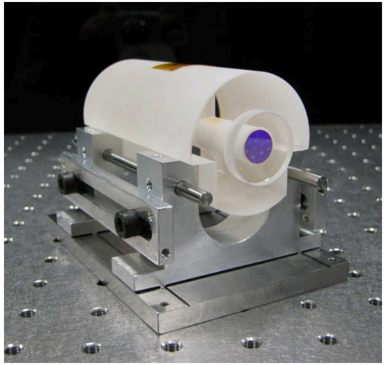
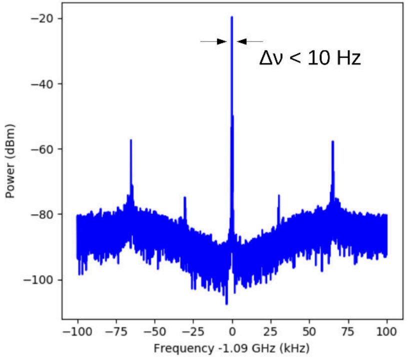
Frequency metrology meets seismology

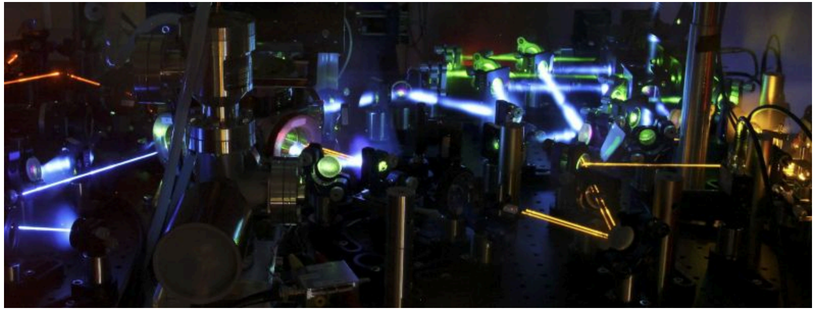
Optical clocks techniques:

- frequency distribution over **optical links**
- **ultra-low-noise narrow-linewidth lasers**
- high coherence
- very **long range** (> 1000 km)

laser noise < fiber noise < earthquake







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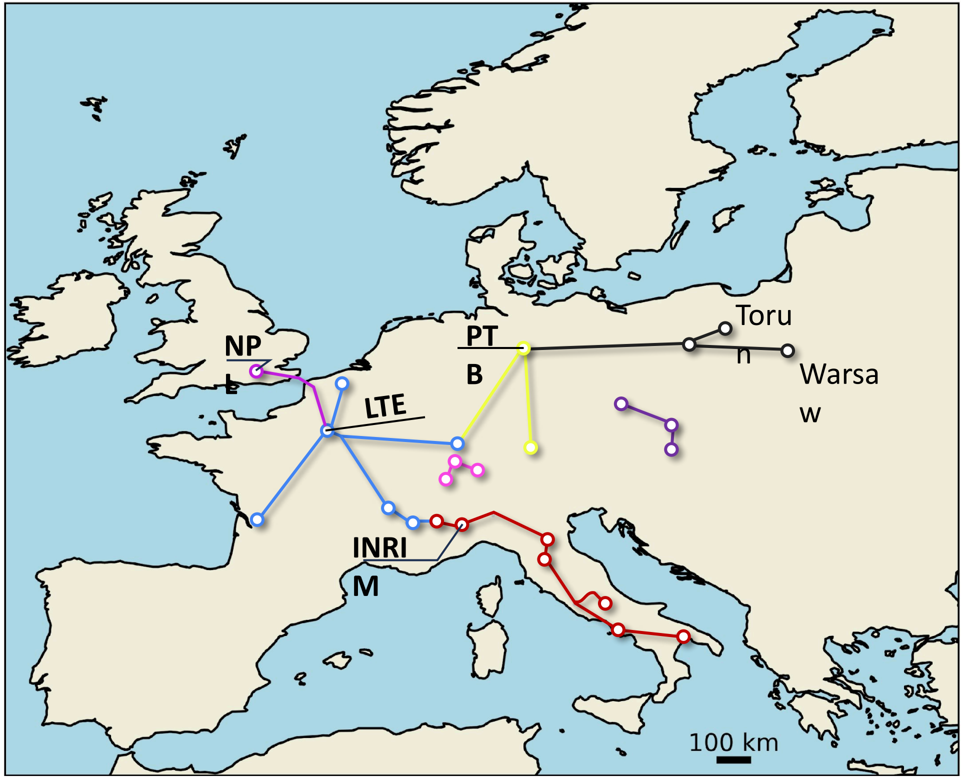
International Comparison of Optical Clocks

- 11 optical clocks in Italy, UK, France, Germany, Poland compared across 3000+ km of fiber
- Optical clock comparisons needs optical fiber links with **phase noise cancellation**



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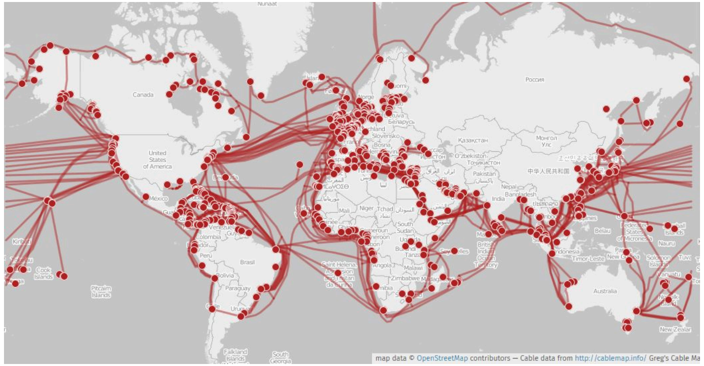
Sensing underwater

Earthquake monitoring & fiber sensing

Sub-sea cables:

- **seafloors are unmonitored**
- base for **early warning**
- deep seas are **quiet** – high SNR
- **ideal sensing environments**
- cable is mostly **inaccessible – difficult calibration**



GEOPHYSICS

Optical polarization–based seismic and water wave sensing on transoceanic cables

Zhongwen Zhan[1]*, Mattia Cantono[2], Valey Kamalov[2], Antonio Mecozzi[3], Rafael Müller[2], Shuang Yin[2], Jorge C. Castellanos[1]

GEOPHYSICS

Optical interferometry–based array of seafloor environmental sensors using a transoceanic submarine cable

G. Marra[1]*, D. M. Fairweather[2], V. Kamalov[3], P. Gaynor[1], M. Cantono[3], S. Mulholland[1], B. Baptie[4], J. C. Castellanos[3], G. Vagenas[1], J.-O. Gaudron[1], J. Kronjäger[1], I. R. Hill[1], M. Schioppo[1], I. Barbeito Edreira[1], K. A. Burrows[1], C. Clivati[5], D. Calonico[5], A. Curtis[2]

OPTICAL SEISMOLOGY

Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables

Giuseppe Marra[1]*, Cecilia Clivati[2], Richard Luckett[3], Anna Tampellini[2,4], Jochen Kronjäger[1], Louise Wright[1], Alberto Mura[2], Filippo Levi[2], Stephen Robinson[1], André Xuereb[5], Brian Baptie[3], Davide Calonico[2]

Long-range fiber-optic earthquake sensing by active phase noise cancellation

Sebastian Noe[1], Dominik Husmann[2], Nils Müller[1], Jacques Morel[2] & Andreas Fichtner[1]

Polarization sensing using submarine optical cables

Antonio Mecozzi,[1,*] Mattia Cantono,[2] Jorge C. Castellanos,[3] Valey Kamalov,[2] Rafael Muller,[2] and Zhongwen Zhan[3]

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Coherent laser interferometry & earthquake detection

OPTICAL SEISMOLOGY

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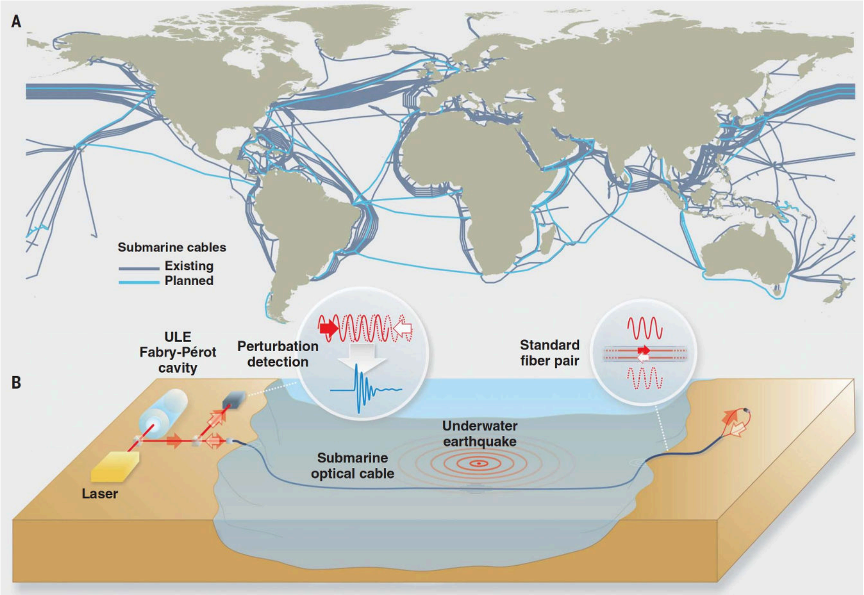
Giuseppe Marra[1*], Cecilia Clivati[2], Richard Luckett[3], Anna Tampellini[2,4], Jochen Kronjäger[1], Louise Wright[1], Alberto Mura[2], Filippo Levi[2], Stephen Robinson[1], André Xuereb[5], Brian Baptie[3], Davide Calonico[2]

Earthquake detection:

- fiber links for **metrology**
- **phase noise** measurement
- first technique **demonstration**



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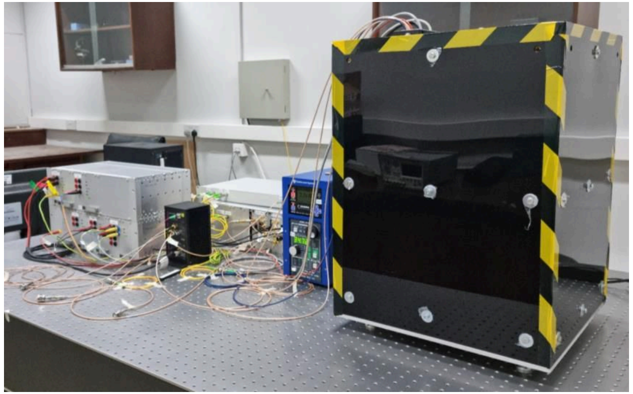
The underwater cable from Malta to Sicily

Environmental sensing in the Mediterranean sea:

- Malta to Catania (Italy)
- **260 km telecom fiber**
- earthquakes, tides, waves…



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L-Università ta' Malta

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S. Donadello
C.Clivati
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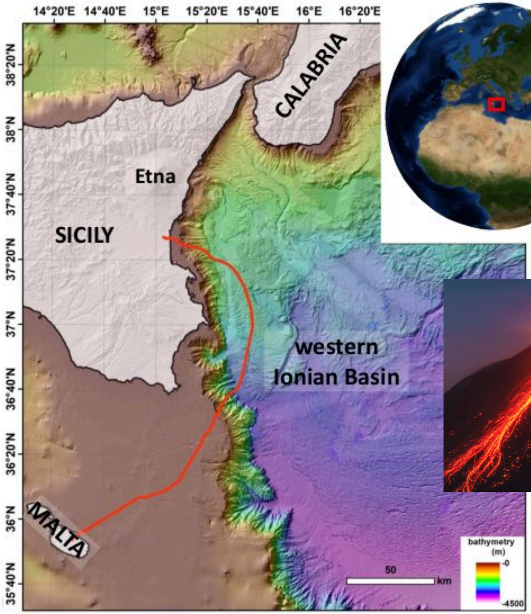
A. Micallef
M. Agius
A. Xuereb
G. Marra



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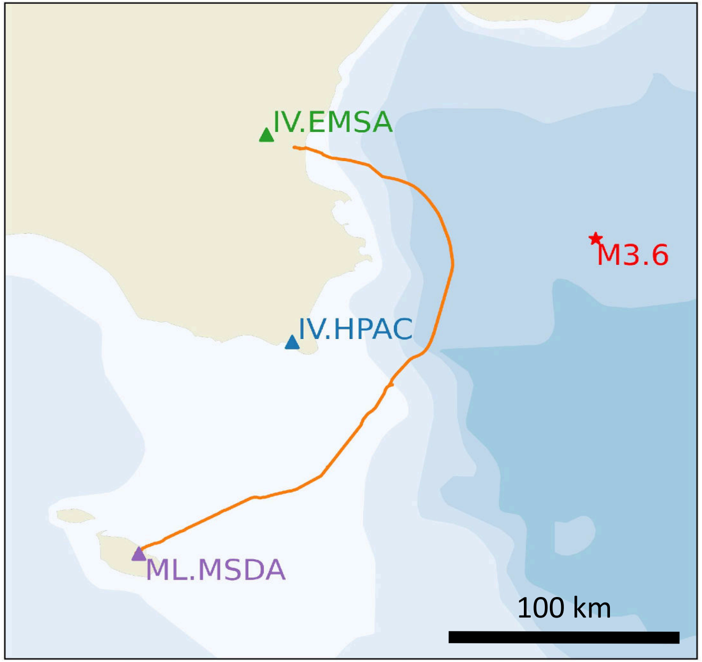
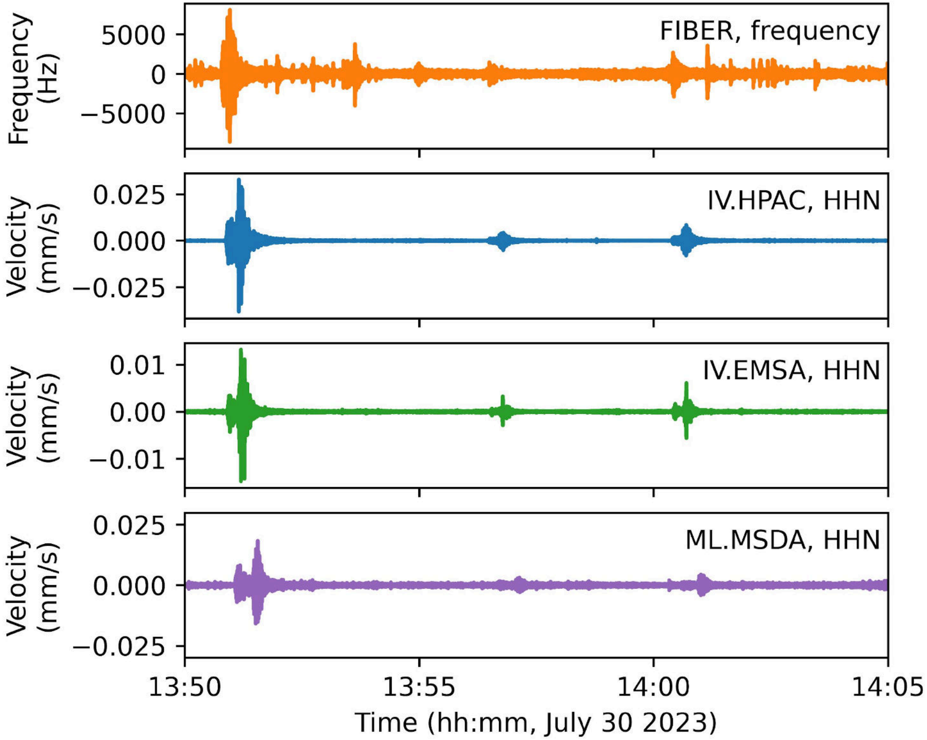
Detection of an earthquake under the sea





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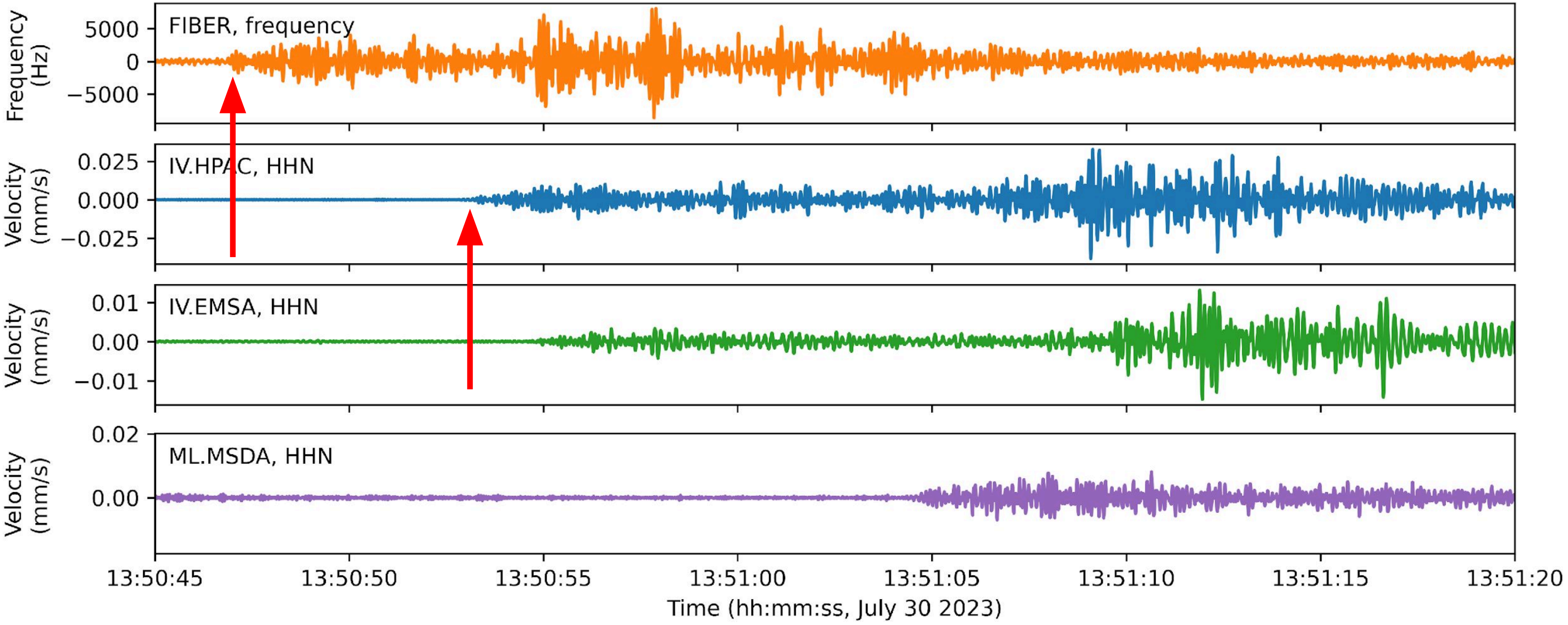
Fibers and early detection



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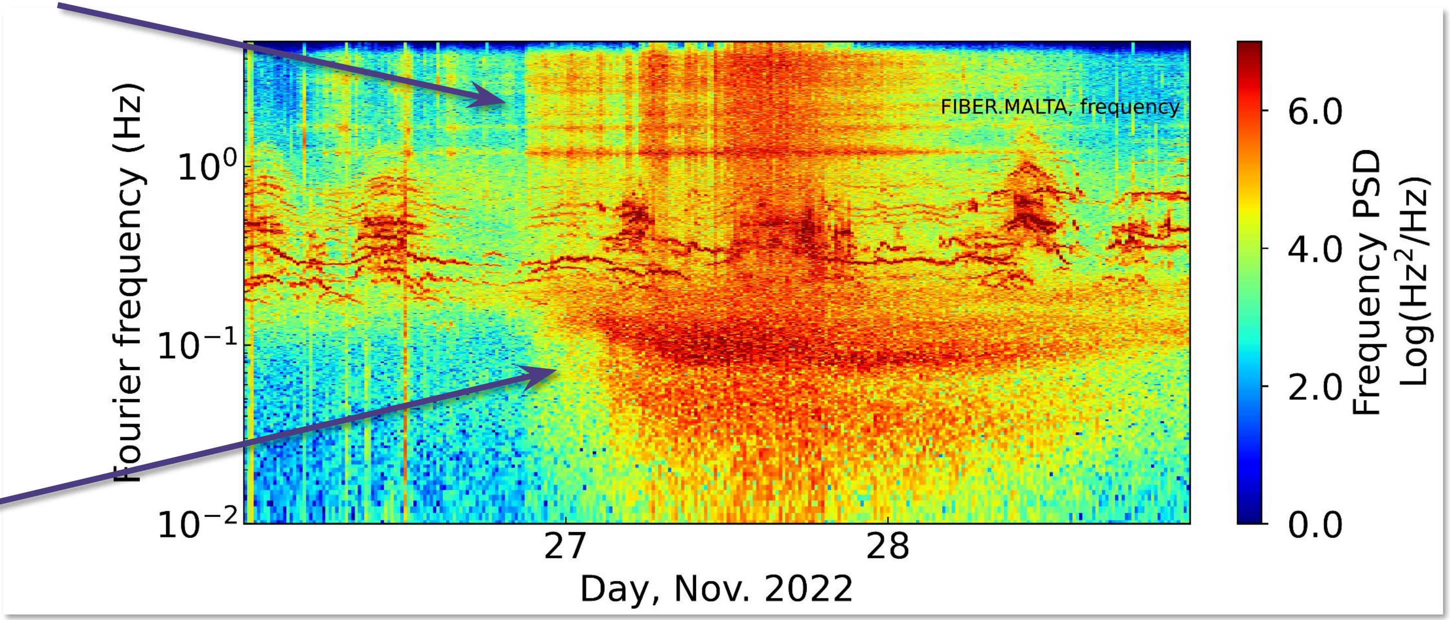
Oceanographic events (tides, storm, microseism...)

Wind shaking aerial cable



Sea waves on seafloor

Phase on submarine fiber (Italy-Malta, 260 km)

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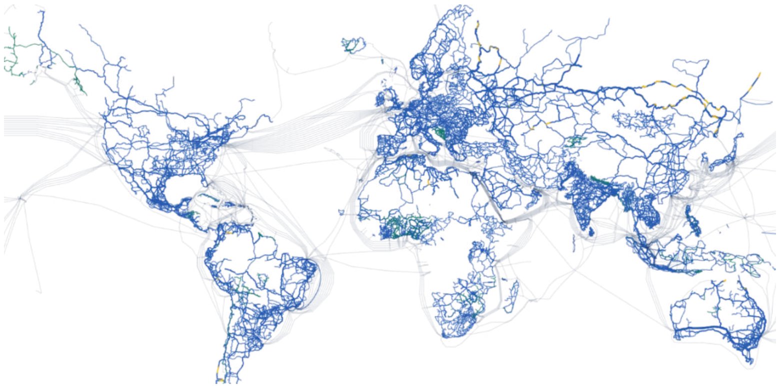
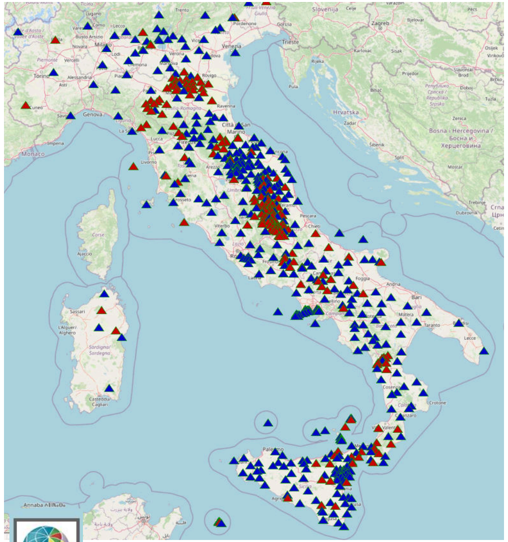
Sensing on land

Sensing with terrestrial fibers: challenges and opportunities

Land cables:

- **comparison with seismometers**
- **technique validation** and calibration
- integration with **seismic networks**
- reach **inaccessible and urban areas**
- **higher noise**





INGV

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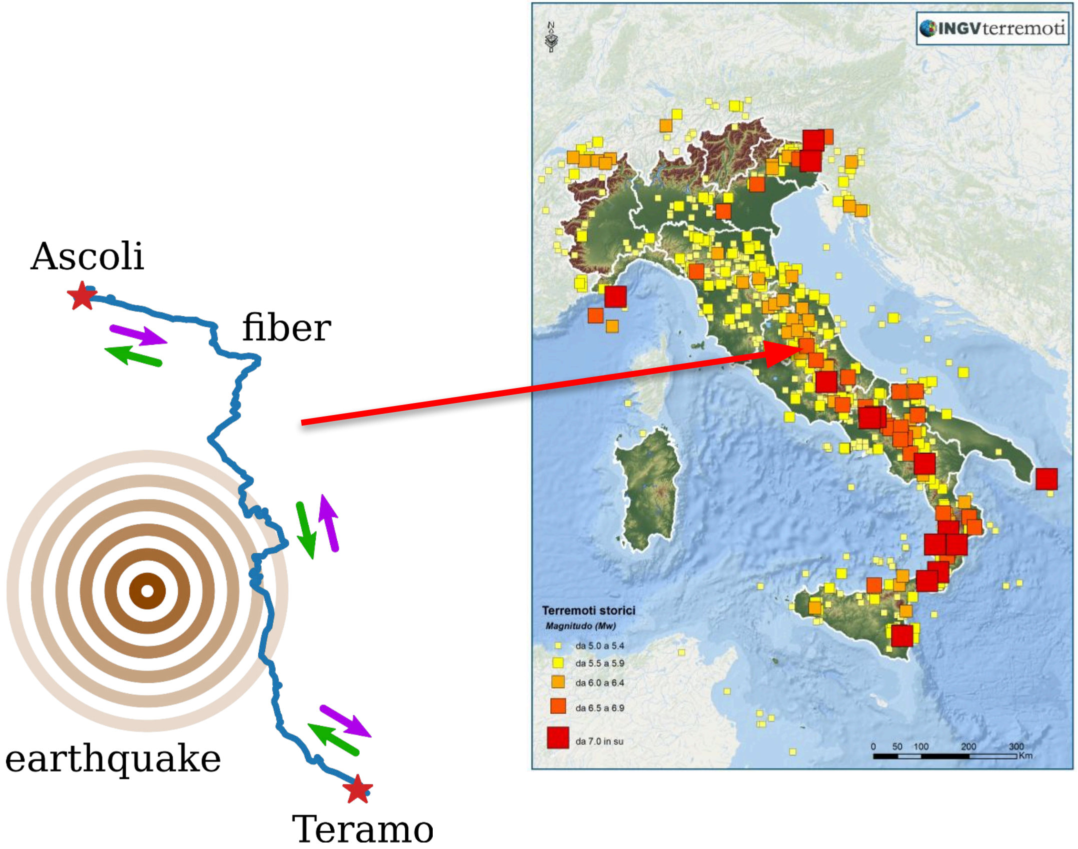
Laser interferometry… on land



The MEGLIO project on the optical data network in Italy:

- highly seismic area
- permanent fiber observatory
- field deployed
- data coexistence

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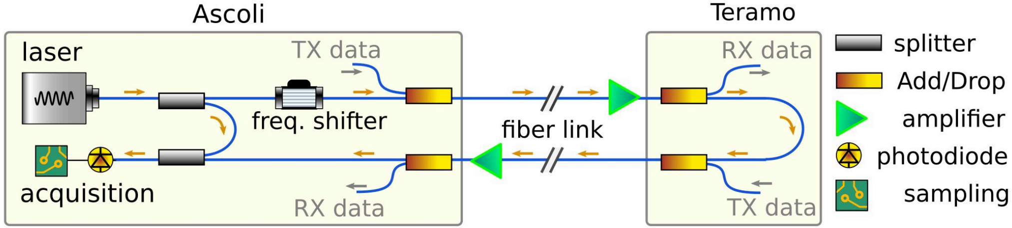
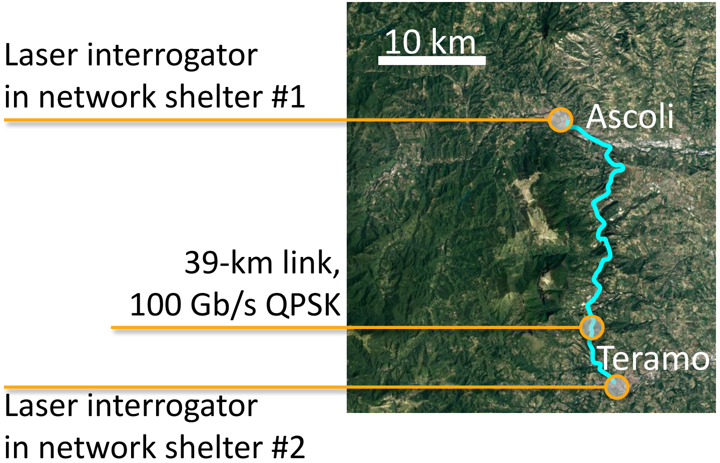
Field observatory





- **self-heterodyne** detection
- transportable **ultrastable lasers:**
  - installed at data centers:
  - linewidth < 10 Hz
  - laser diode + optical cavity
- **multiplexed with internet traffic**
- **comparison with local seismometers**
- urban environment

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open fiber

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Systematic earthquake detection

- **quantitative** comparison
- **P- and S-waves**
- like a "**distributed seismometer**"
- **from 2021** to present

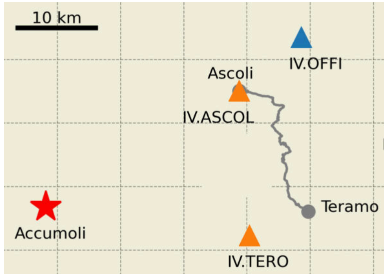
ground velocity

$$v \propto \dot{\epsilon}$$

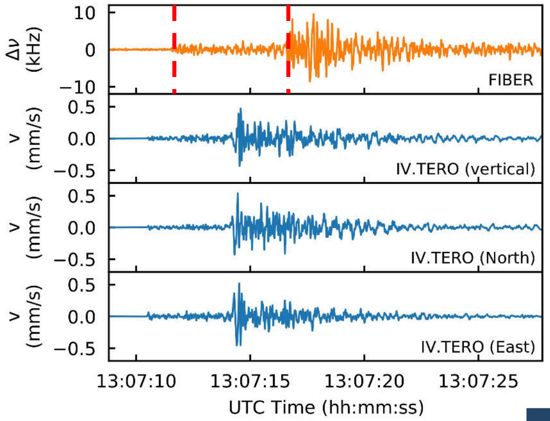
$\longleftrightarrow$

optical frequency deviation

$$\Delta\nu = \frac{1}{2\pi}\dot{\varphi}$$



Accumoli (Italy), Feb. 27th, 2022
M=3.4, distance 30 km



communications earth & environment **Article**

https://doi.org/10.1038/s43247-024-01338-2

Seismic monitoring using the telecom fiber network

Check for updates

Simone Donadello[1], Cecilia Clivati[1], Aladino Govoni[2], Lucia Margheriti[2], Maurizio Vassallo[3], Daniele Brenda[4], Marianna Hovsepyan[4], Elio K. Bertacco[1], Roberto Concas[1], Filippo Levi[1], Alberto Mura[1], André Herrero[5], Francesco Carpentieri[4] & Davide Calonico[1]

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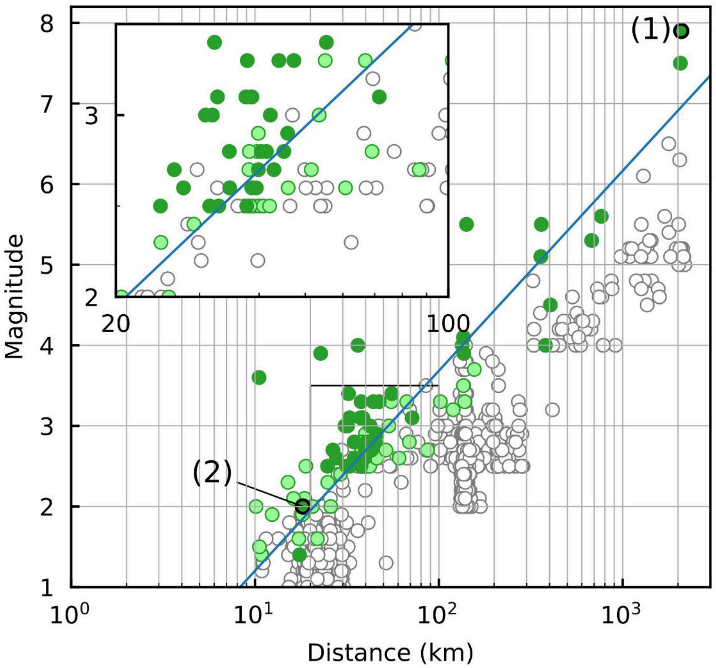
Sensitivity curve

Analysis over ~ 570 events
(June 2021 to September 2022)

- detection of ~ **70 events**
- down to **M ~ 1**
- **detection probability**: distance – magnitude
- good seismic sensitivity

$$P = A_2 \frac{10^{A_1 M}}{d}$$



Donadello et al. (**2024**), **Commun. Earth Environ. 5, 178**

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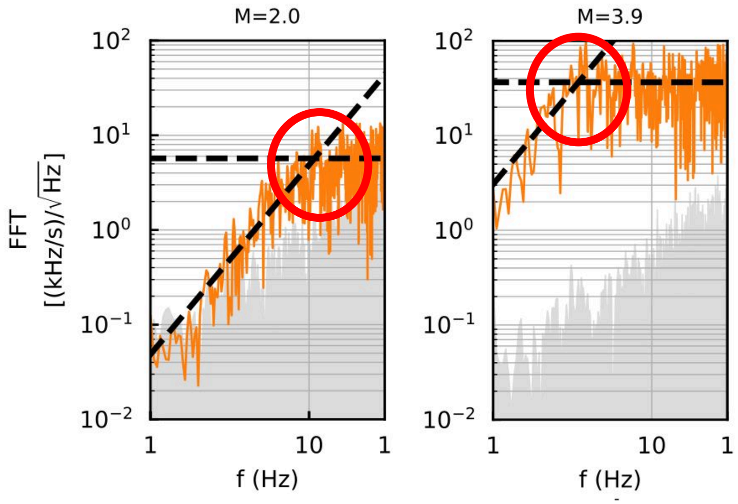
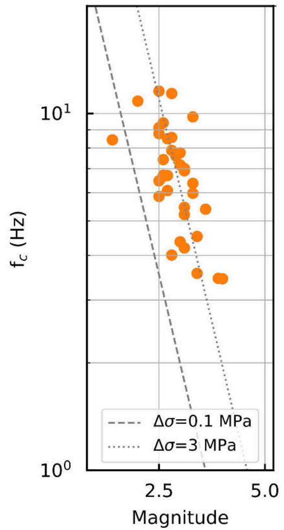
Earthquake magnitude estimation

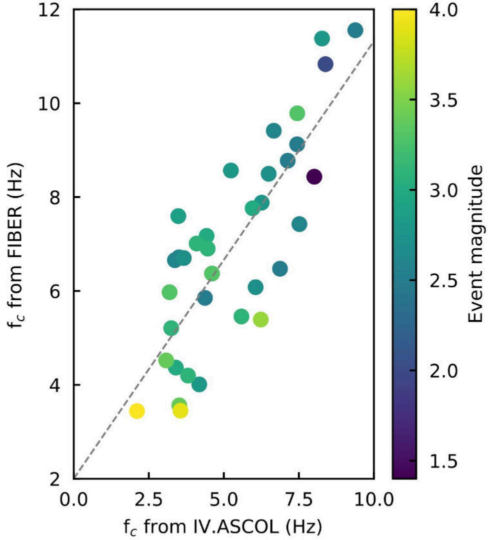
Fourier analysis and Brune's model:

- ground acceleration **spectrum**
- **corner-frequency – magnitude**

$$f_c = kC_d\beta\left(\frac{16}{7}\frac{\Delta\sigma}{M_o}\right)^{1/3}$$







Donadello et al. (**2024**), **Commun. Earth Environ. 5, 178**

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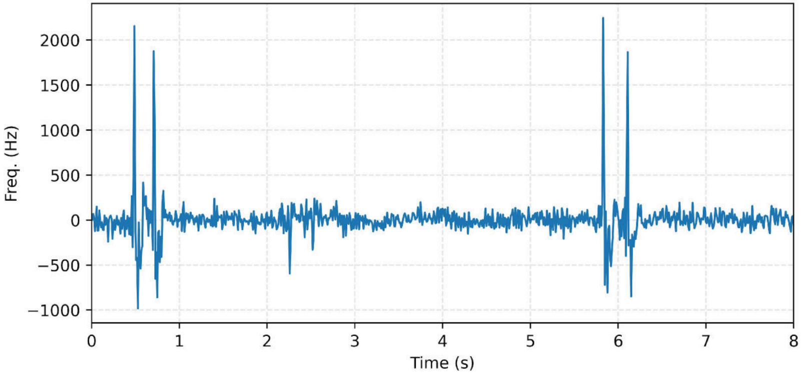
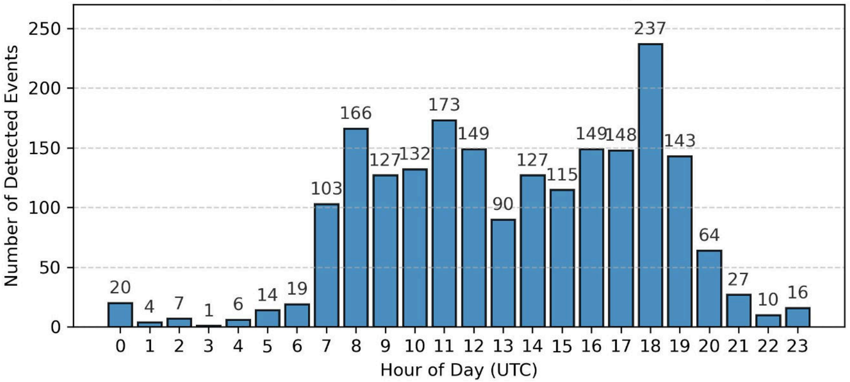
Human activity

Vehicles passage on a 40 km fiber





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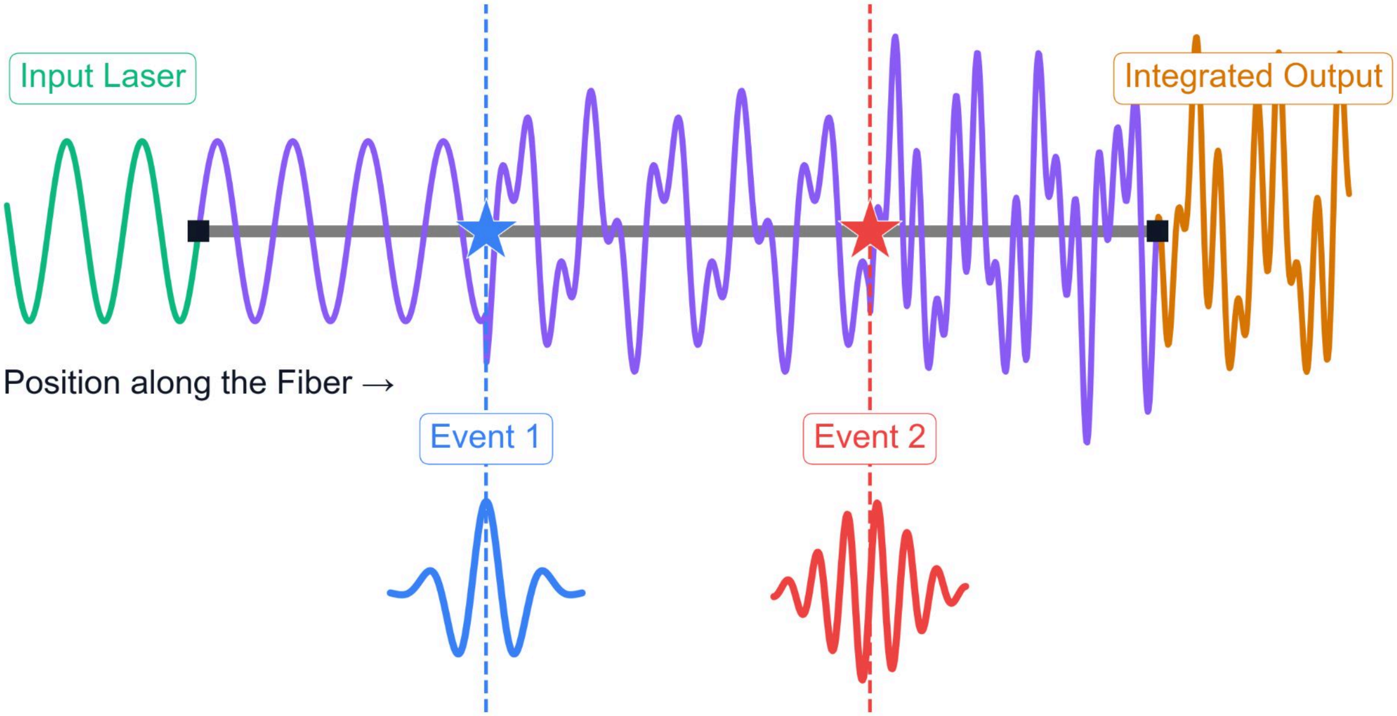
Localization

Interferometry & spatial integration



Fiber noise accumulates from different sources → localization?

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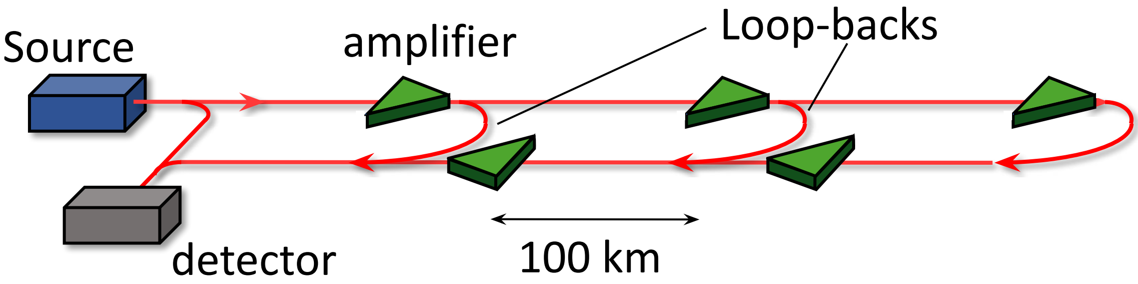
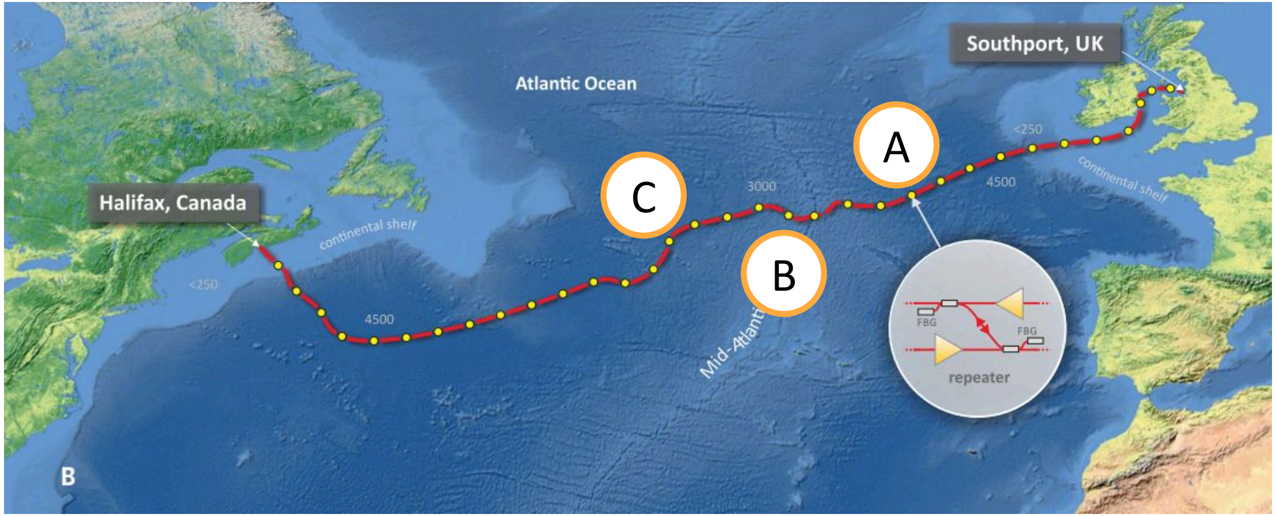
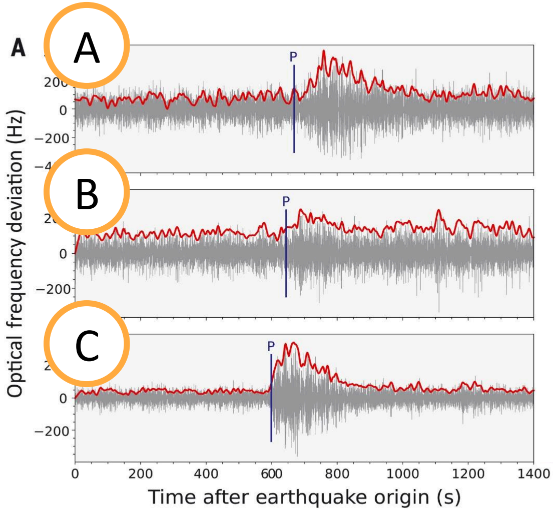
Span-wise localization



resolution ~ 100 km





G. Marra et al., Science 376, 874 (2022)

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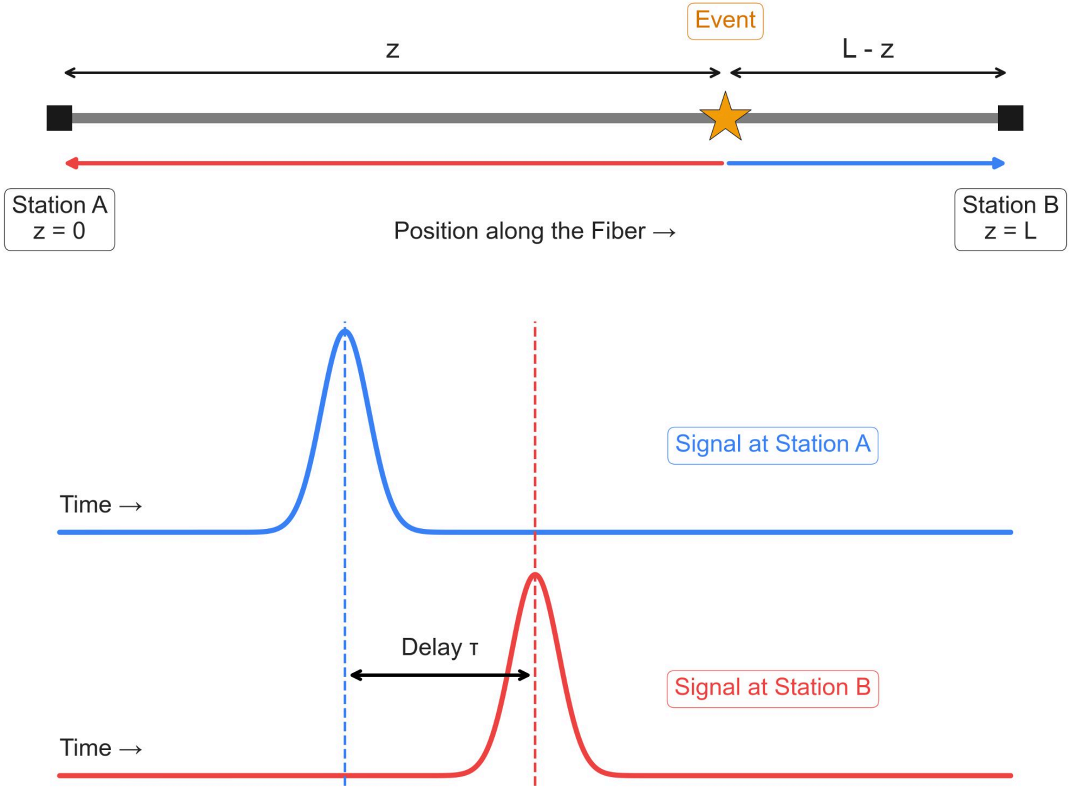
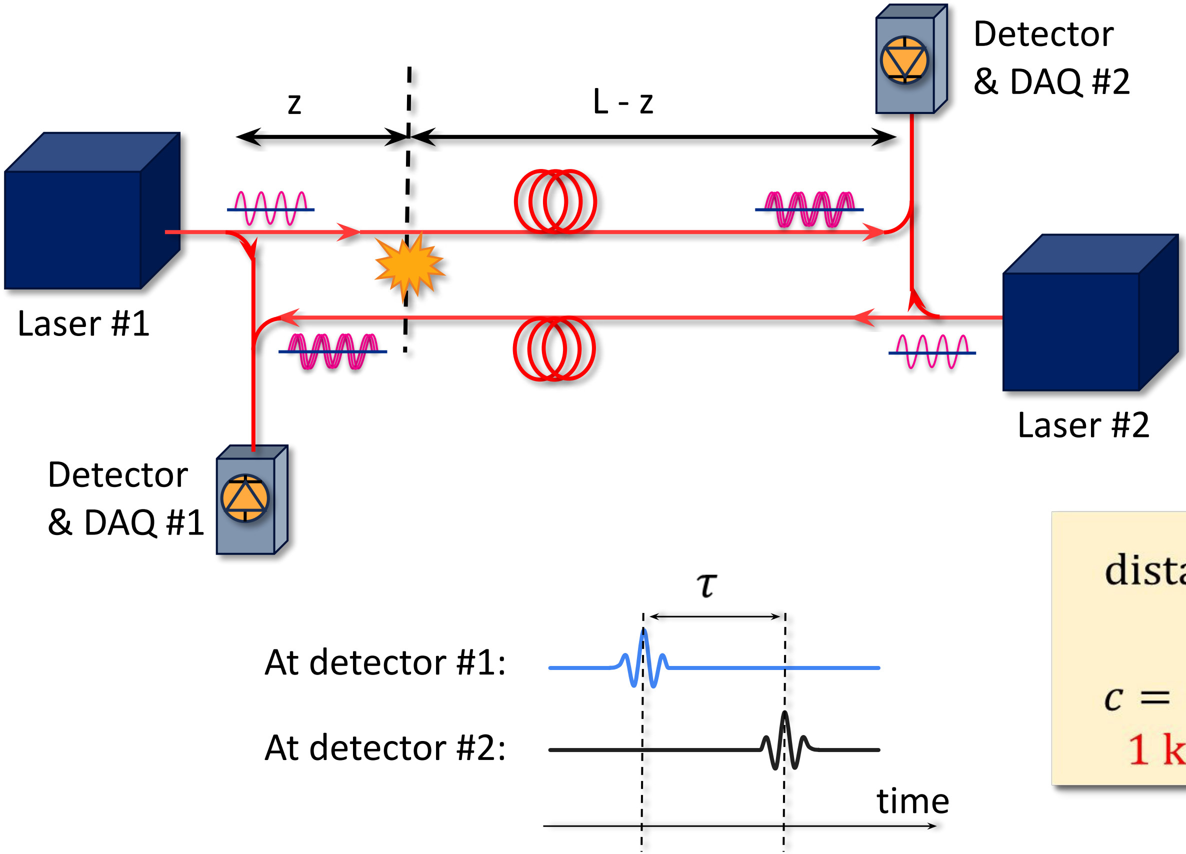
Better localization with Time-Delay Estimation



Synchronous interrogation from both ends:
delay measurement

$$\text{distance} = \frac{\text{delay} \times \text{speed}}{2}$$

Localizing events by correlation



- Counterpropagating signals
- Coherent detection against local laser
- Synchronized acquisition for time-delay extraction

$$\text{distance} = \frac{\tau \times c}{2}$$

$$c = 2 \times 10^8 \text{ m/s}$$

$$1 \text{ km} \Leftrightarrow 10\ \mu\text{s}$$

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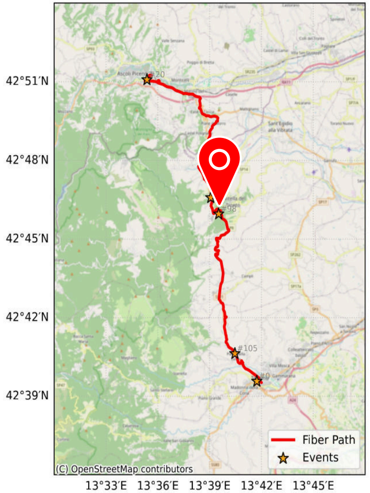
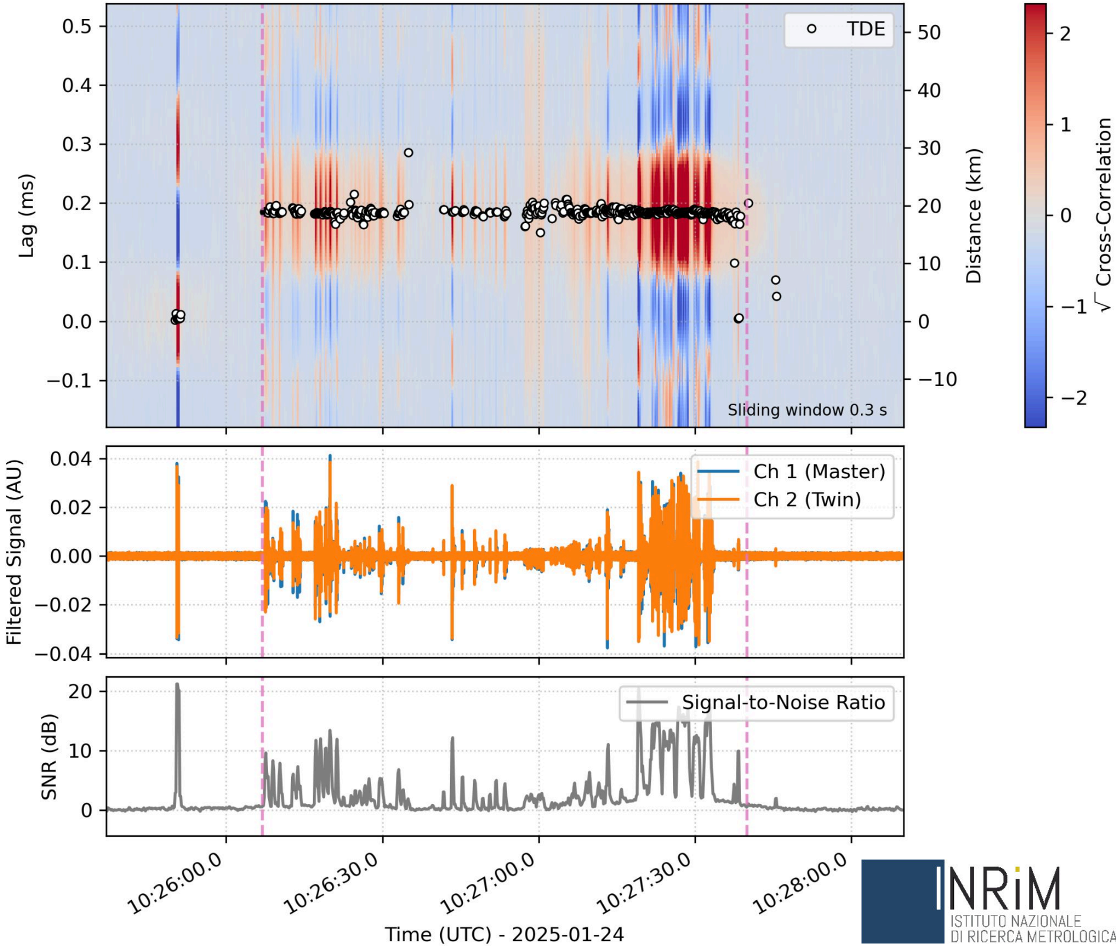
Tapping: fiber joint (km 19)





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Scalability

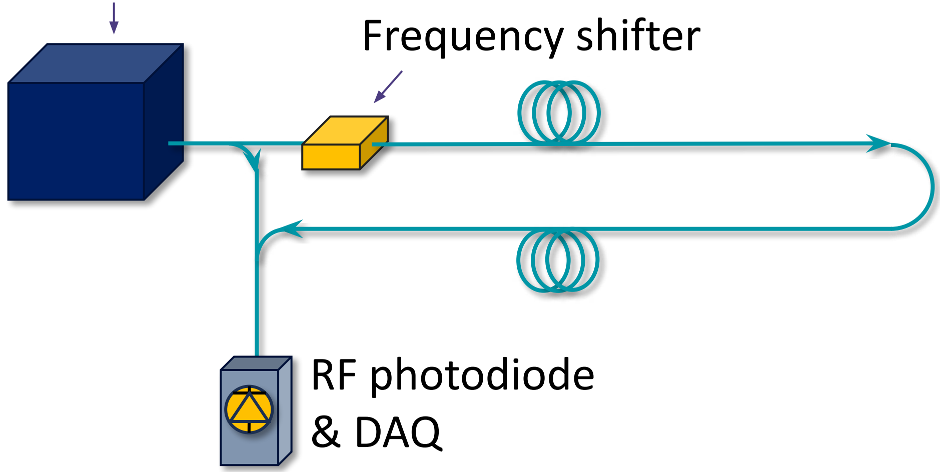
How to make it scalable

Performance-driven design:

- High-coherence laser (Fabry-Perot cavity + vacuum + temp. + vibration ctrl)
- Frequency shifters (heterodyne detection)

Drawbacks:

- Cost (Laser)
- Size, Weight and Power (Laser + RF detection)
- Limit to photonic integration (RF)



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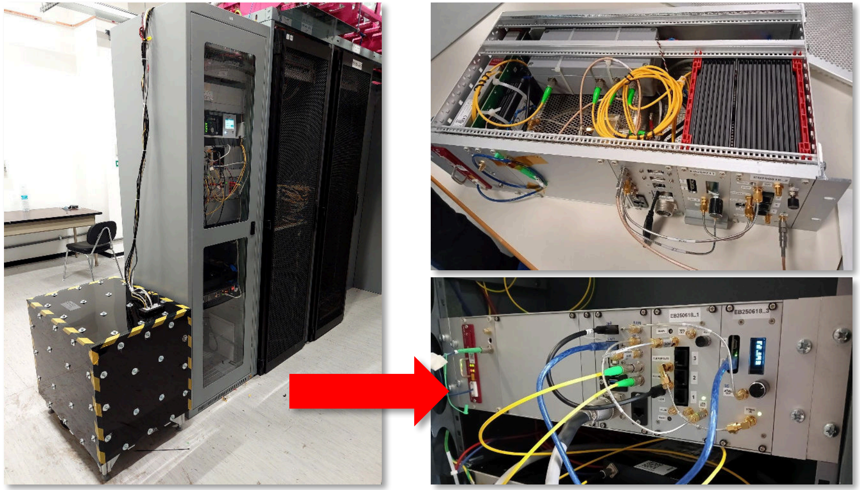
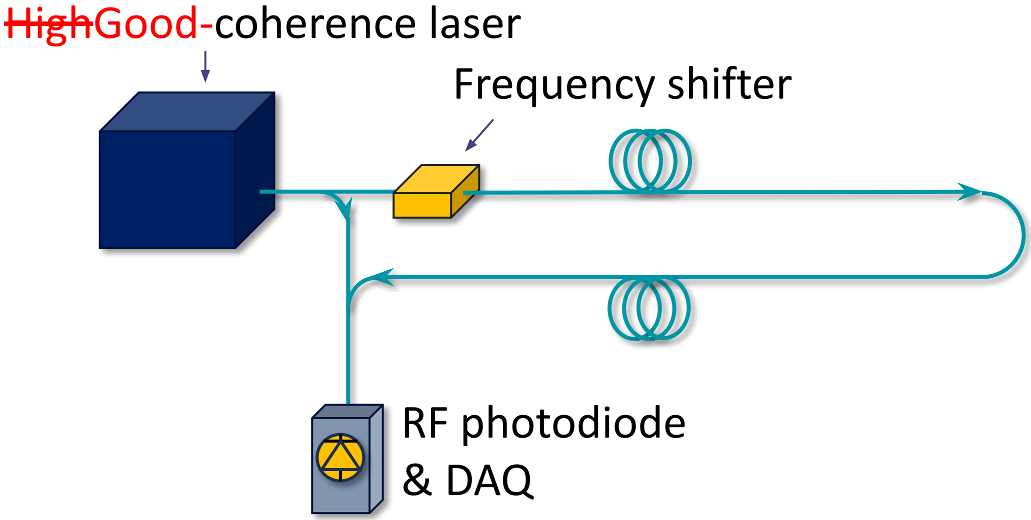
How to make it scalable

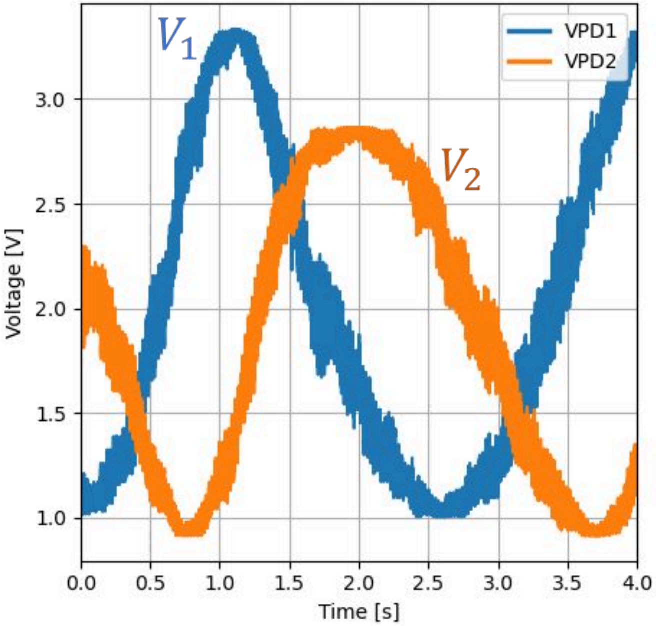


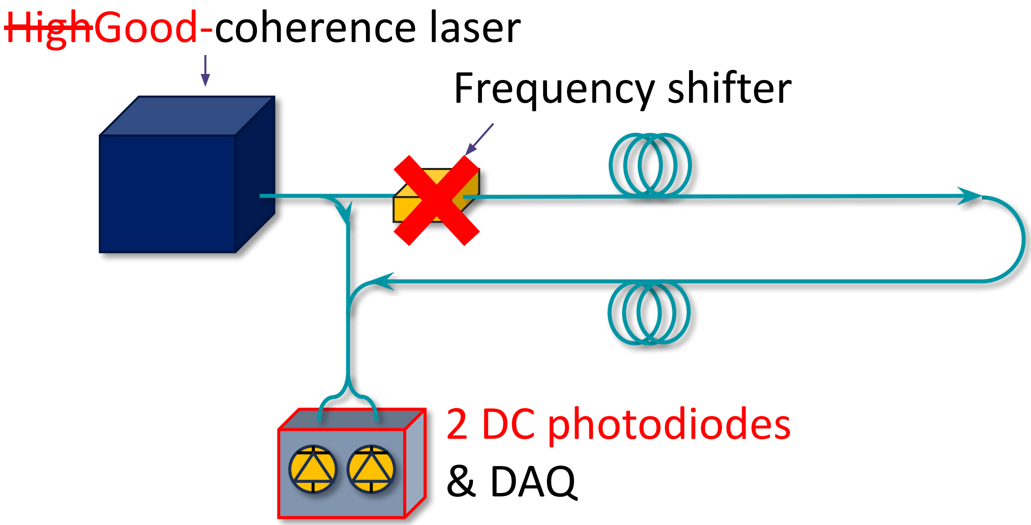


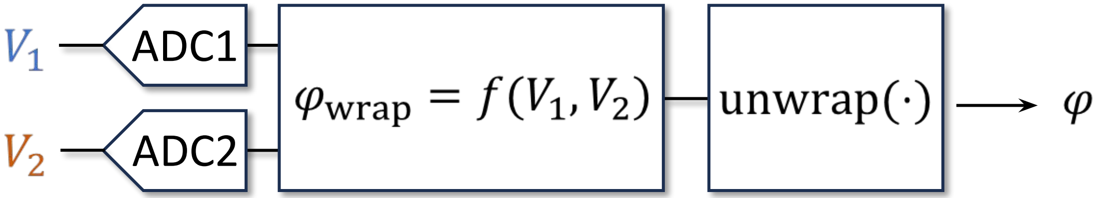
High coherence,
High SWaP,
Deployment: 1 day
Unlimited range

Good coherence,
Good SWaP,
Deployment: 1 h
Range 150 km

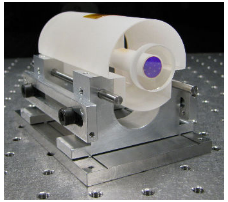
How to make it scalable







Photonics integration for sensing



(<600 L)

Lab equipment brought to the field

(< 1 L)

Commercial devices, partly suitable

(< 0.001 L)

Photonic integrated stable lasers

Low(er) cost
Quick deployability
Scalability

Mazur, arXiv:2303.06528 (2023); Fontaine, ECOC2025 (2025);
Zhirnov, *Opt. Spec.* **127**, 656 (2019); Gorshkov, *Appl. Opt*. **61**, 8308 (2022)

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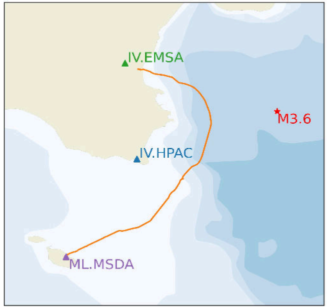
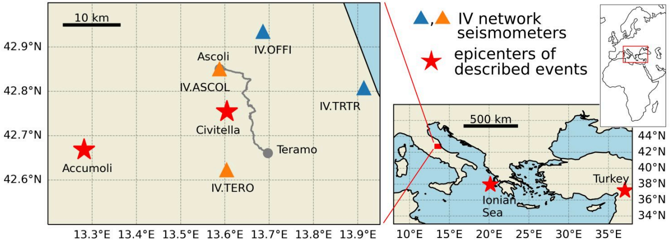
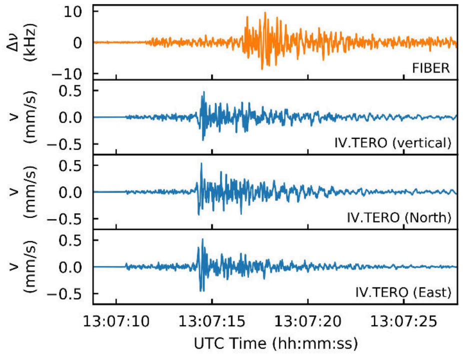
Conclusions

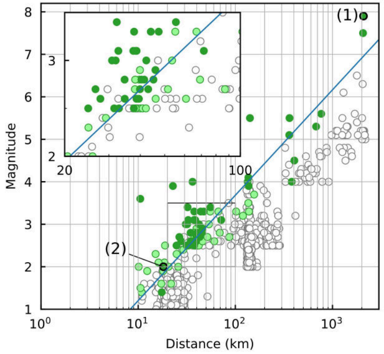
Coherent interferometry & sensing

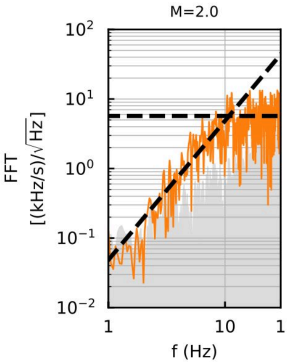
- **anthropogenic & seismic** sensing
- **sea & land field** demonstrations
- coexistence with **internet data**
- **permanent observatory**
- **24h/24h** acquisition
- **quantitative** seismological analysis
- **sensitivity curve**
- **earthquake magnitude**
- **localization capability**











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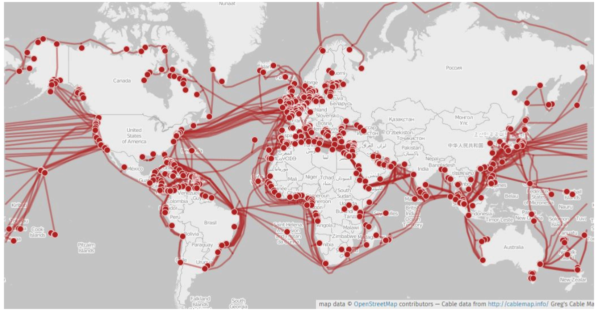
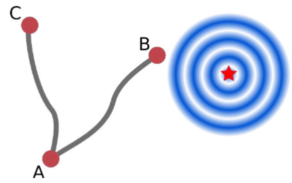
Outlooks

- scalable **early warning** infrastructure
- **tsunamis**
- **worldwide coverage**
- integration of **seismometer-fiber networks**
- **infrastructure** monitoring (**SHM**)
- **smart city** & traffic
- simplified setup & **integration**
- **seismic wave** modeling
- detection **directionality**
- **AI detection tools**

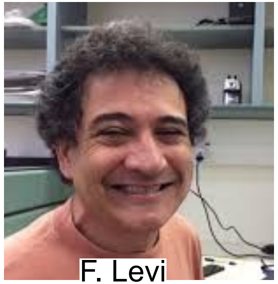


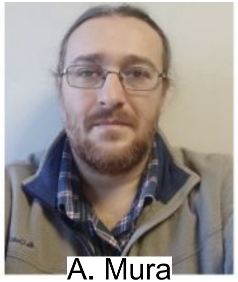


POSITIONS AVAILABLE!

Thank you!

s.donadello@inrim.it





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Acknowledgments

Funded by the European Union

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SENSEI
Smart European Networks for Sensing the Environment and Internet quality

This research was funded by:
the European Metrology Partnership (EMP) project **22IEM01 (TOCK)** which has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.
SENSEI, funded by the European Union in the Digital Europe Programme under the grant agreements 101091408 and 101189545.

Thank you for your attention!

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