Fibre-optics sensing for the exploration of geophysical effects

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Greek Network Operators' Group

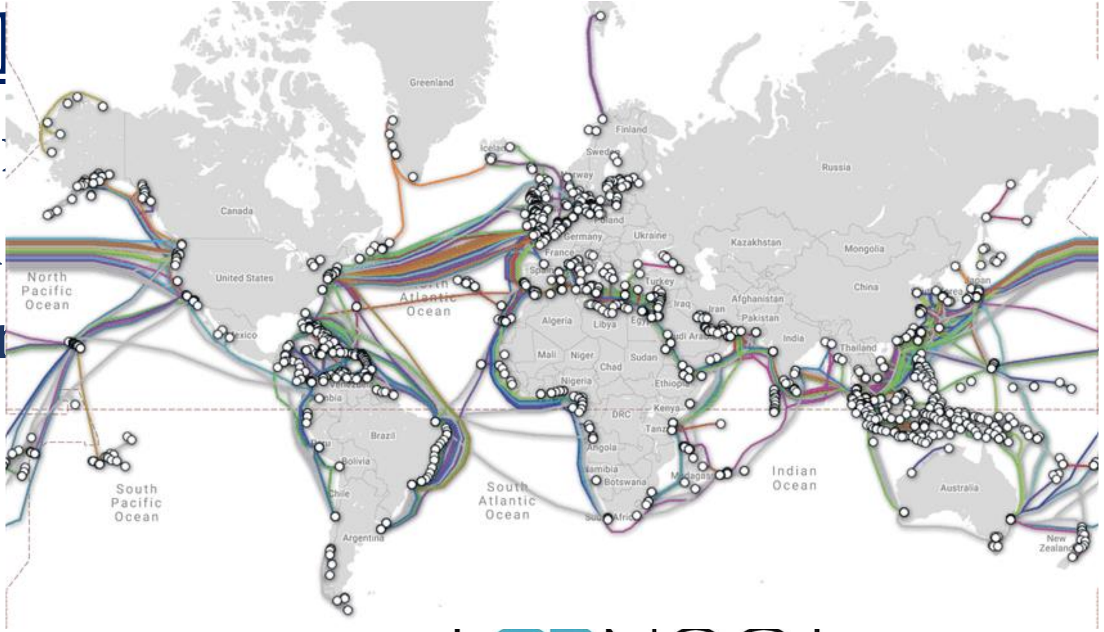
Fiber Infrastructures for Environmental Sensing

Why Fibers ?

- Low cost and easily accessible platforms exhibiting large terrestrial deployments
- Fibers provide coverage in the largely unexplored submarine areas - **detailed structure of the earth especially on seismogenic submarine faults becomes possible**

Various approac

- Distributed Acoust
- Ultrastable laser in
- Optical polarizatio ing



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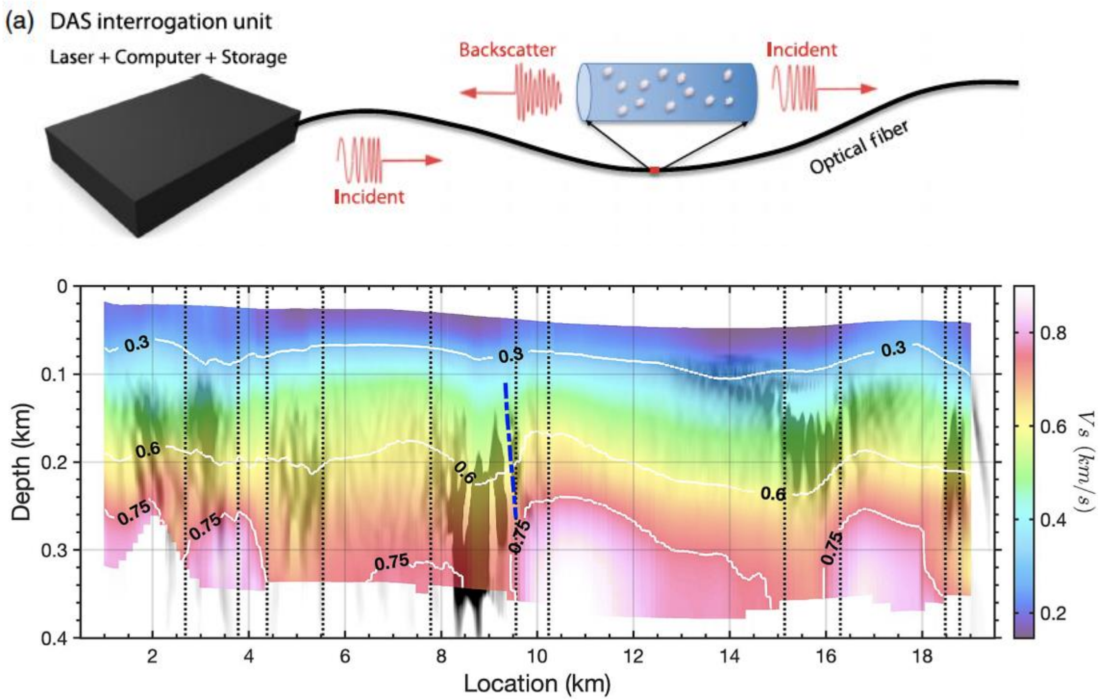
Distributed Acoustic Sensing (DAS)

DAS Advantages:
- Spatial resolution of 1-2 m – thousands of scatterers (strain meters) are provided along the fiber link offering high resolution tomography
- Impressive sensitivity (down to nanostrain)
- High dynamic range

DAS disadvantages:
- Not compatible with WDM transmission
- Limited reach (~ 50 km) – can be extended with Raman amplification
- Expensive tool (> 100 k$) – it prohibits massive deployment



Feng Cheng et al., Scientific reports, (2021) 11:5613
Z. Zhan et al., Zhan, Z. (2019). Seismol. Res. Lett. 91, 1–15

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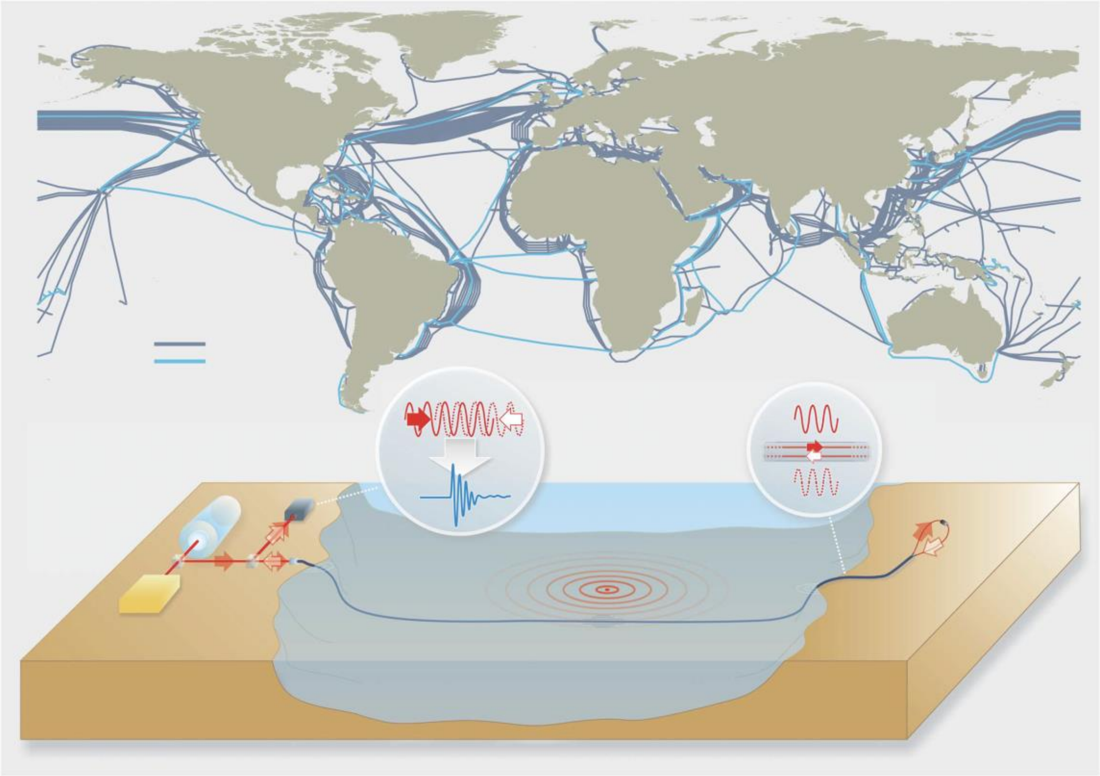
Ultrastable laser interferometry (ULI)

ULI Advantages:
- It can provide unparalleled reach (> 500 km)
- The most sensitive technique (fiber deformation can be detected at nm resolution)

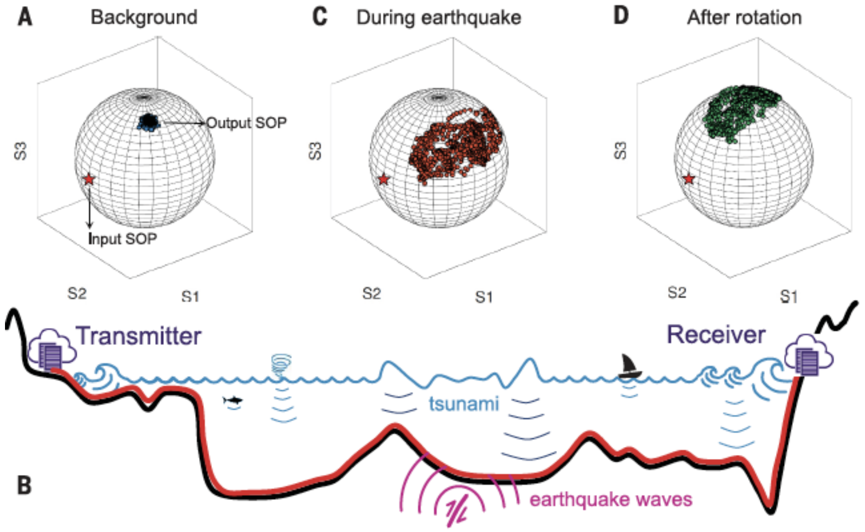
ULI disadvantages:
- It requires spectrally pure (sub-Hz linewidth) laser sources which are extremely expensive
- The system is vulnerable to laser’s phase noise



Marra, G. et al. Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables. Science 361, 486-490 (2018).

Optical polarization–based seismic sensing (OPS)

OPS Advantages:
- It can provide unparalleled reach (> 500 km)
- It relies on already deployed digital coherent transceivers in transoceanic links



OPS disadvantages-open issues:
- Its sensitivity is less than that of systems relying on phase measurements

Zhan, Z. et al. Optical polarization–based seismic and water wave sensing on transoceanic cables. Science, 37, 931-936 (2021).

Microwave Frequency Fiber Interferometers (MFFI)

What we propose

- Transmission of microwave, spectrally pure carriers in a closed-loop configuration – comparison in the electronic domain

Basic advantages

- They are much cheaper than their optical carriers counterpart (sub-Hz linewidth)
- They are compatible to WDM transmission – only a single wavelength is needed
- They are capable of supporting long distances (> 500 km)
- They rely on the off-the-shelf components of extremely low cost (< 5 k$)

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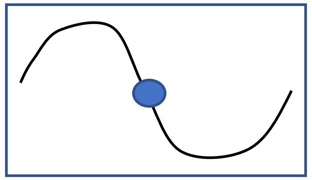
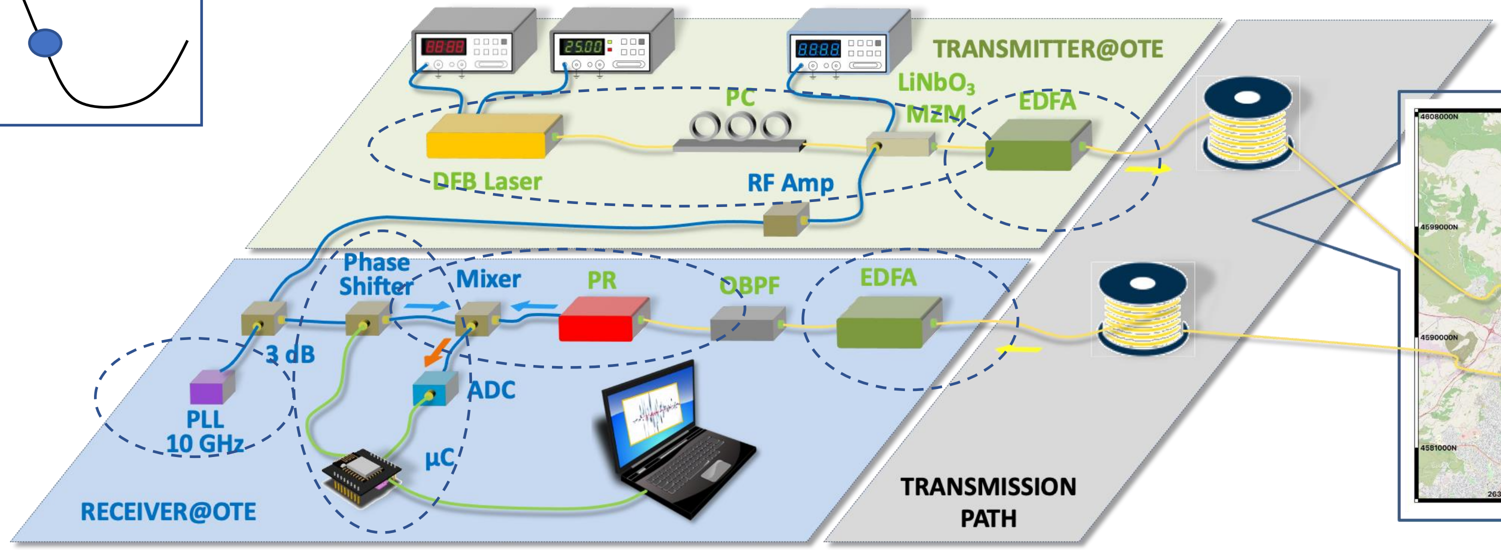
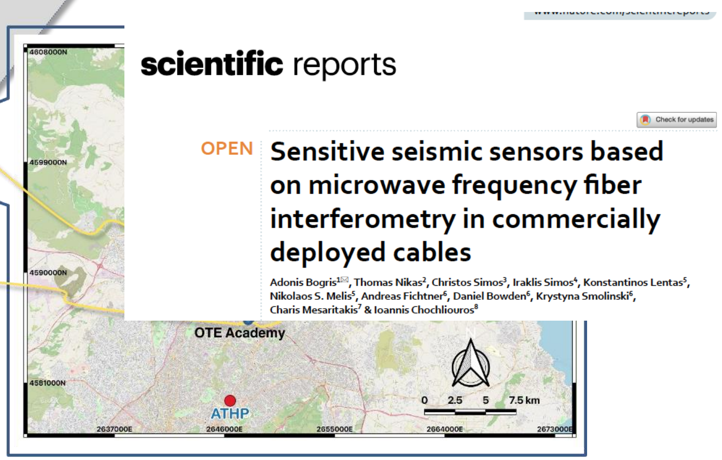
Experimental Field Trial of MFFI in Attika (@ OTE Academy)

Phase Shifter - ideal point







The transmission path (Marousi - Afidnes – Marousi, 50 km round trip)

- DFB Laser externally modulated as the optical carrier modulated by a 10 GHz PLL - the microwave carrier
- 10 GHz Photodetector followed by a mixer – comparison of local and transmitted microwave carriers
- Phase shifter – assures that phase comparison takes place in the linear regime - compensates for thermal drifts (very intense in terrestrial cables!) and a μC that dynamically tunes the phase shifter based on the digitized ADC data.
- EDFAs in order to compensate for link losses (overall loss is intentionally increased to 25 dB ~ 125 km of transmission)

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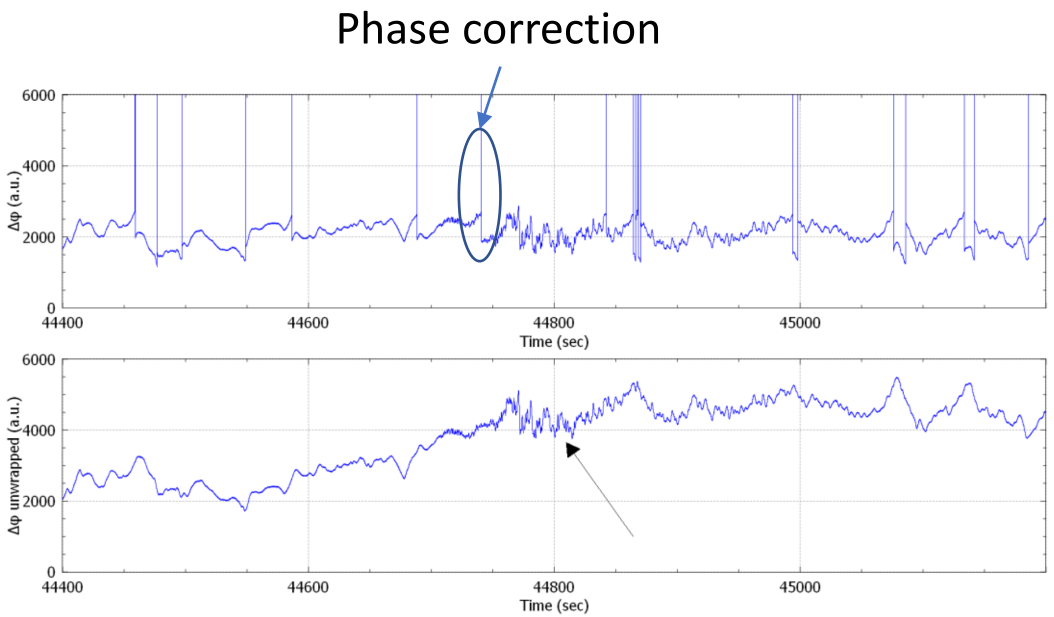
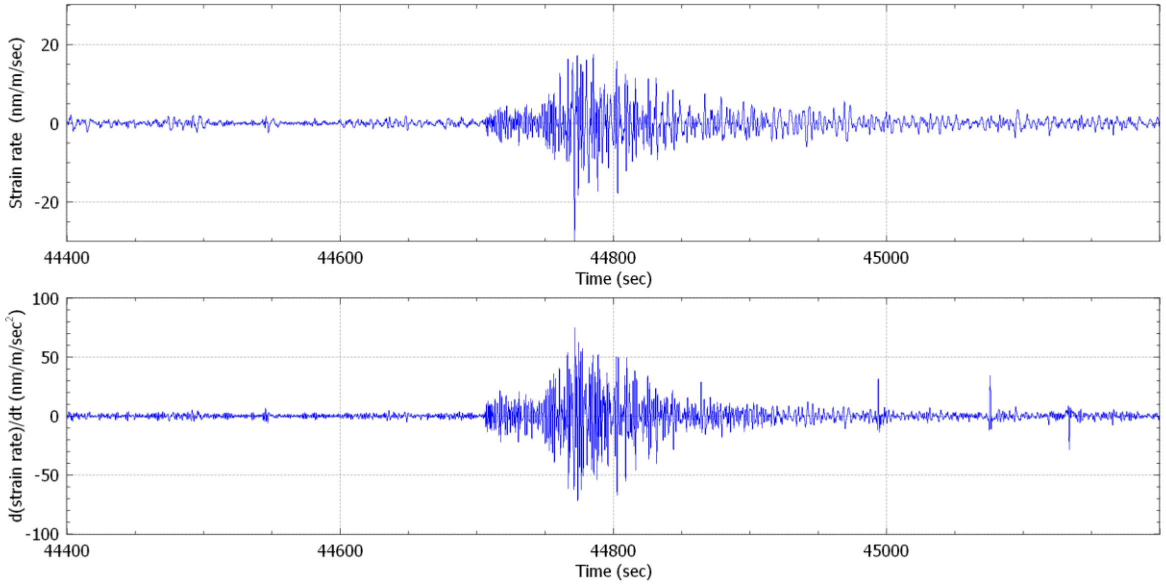
Data processing





- Phase detection close to maximum sensitivity - phase corrections every 2 sec (π/2)
- Phase unwrap
- Strain rate
- 1st derivative of strain rate

Principle of Operation of MFFI

What we can measure

- MFFI estimates the accumulated phase experienced by the microwave carrier

$$\varphi = \frac{2\pi f_{RF} n_g L}{c}$$

- Fiber deformations affect both fiber length L and refractive index n_g
- Phase measurements can be easily transformed to strain $\varepsilon = \frac{d\varphi}{\varphi}$ (ξ=0.78 is the strain coefficient of the optical fiber due to the photoelastic effect)

$$\varepsilon = \frac{c d\varphi}{2\pi n_g \xi f_{RF} L}$$

- Strain rate (equivalent to ground velocity) and rate of strain rate (equivalent to ground acceleration) can be easily estimated

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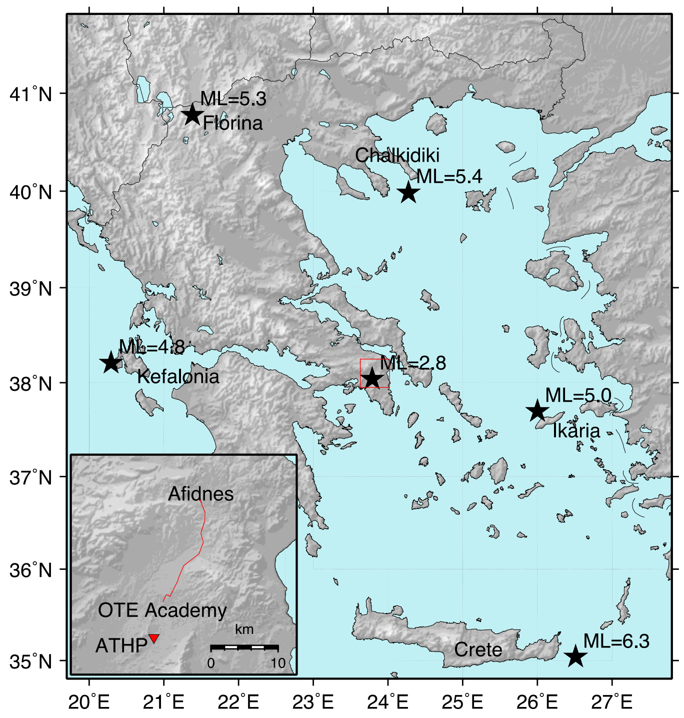
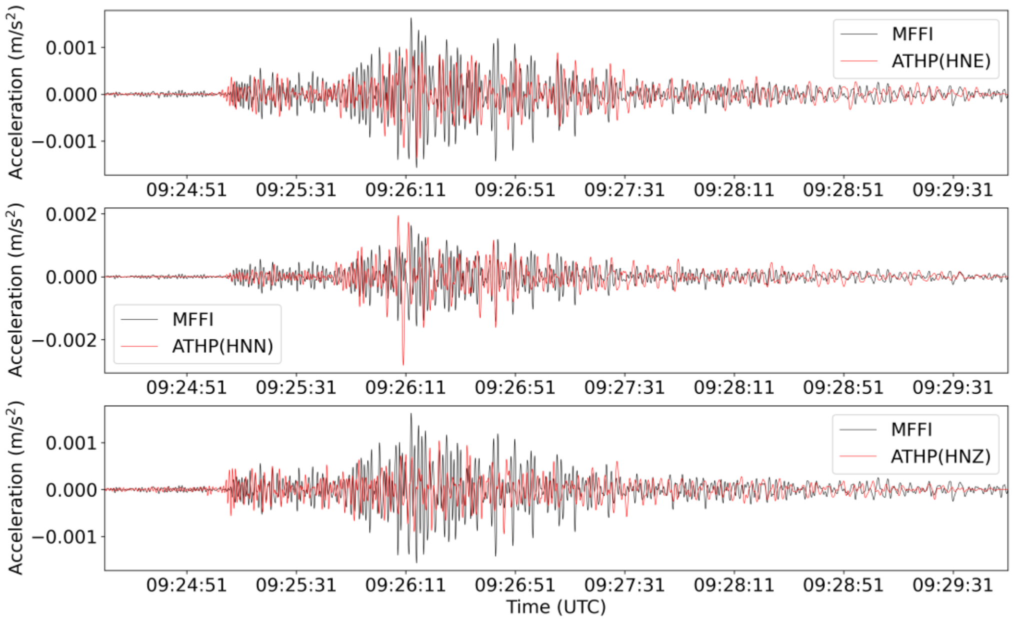
Evaluation of MFFI in a terrestrial infrastructure

- MFFI has been evaluated from Jul. 2021 to Feb. 2022
- It has managed to capture many local and regional earthquakes in a cable vastly affected by thermal effects and city noise





October 12, 2021, 09:24:03 UTC, Crete (ML=6.3)

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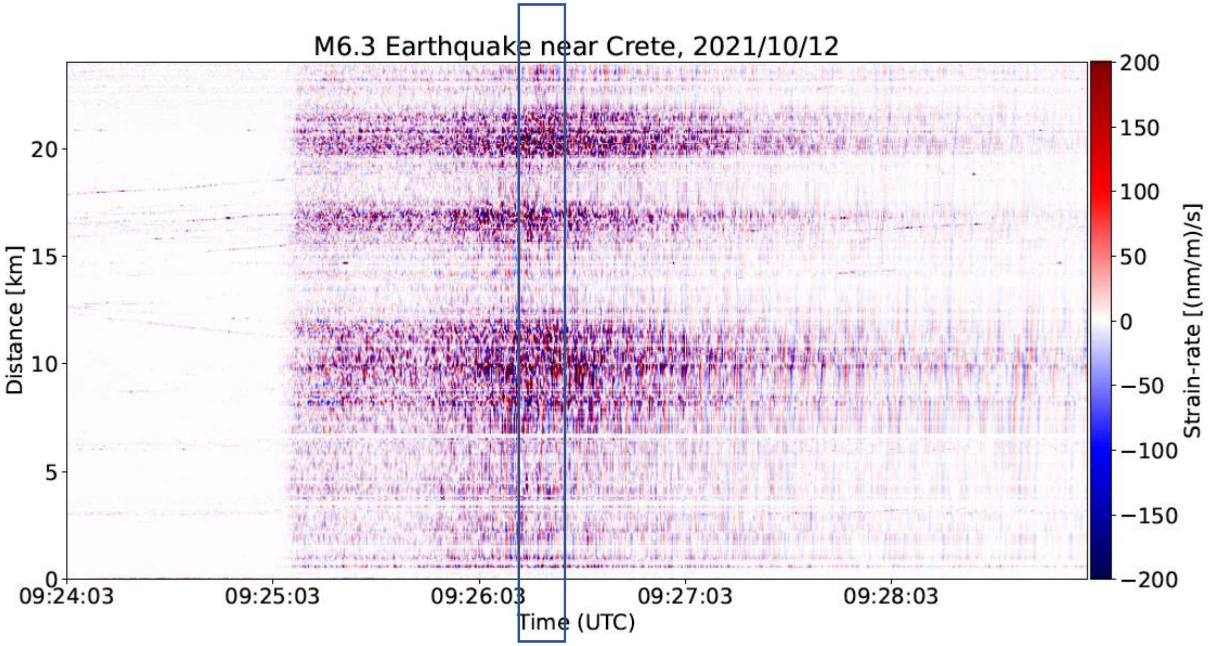
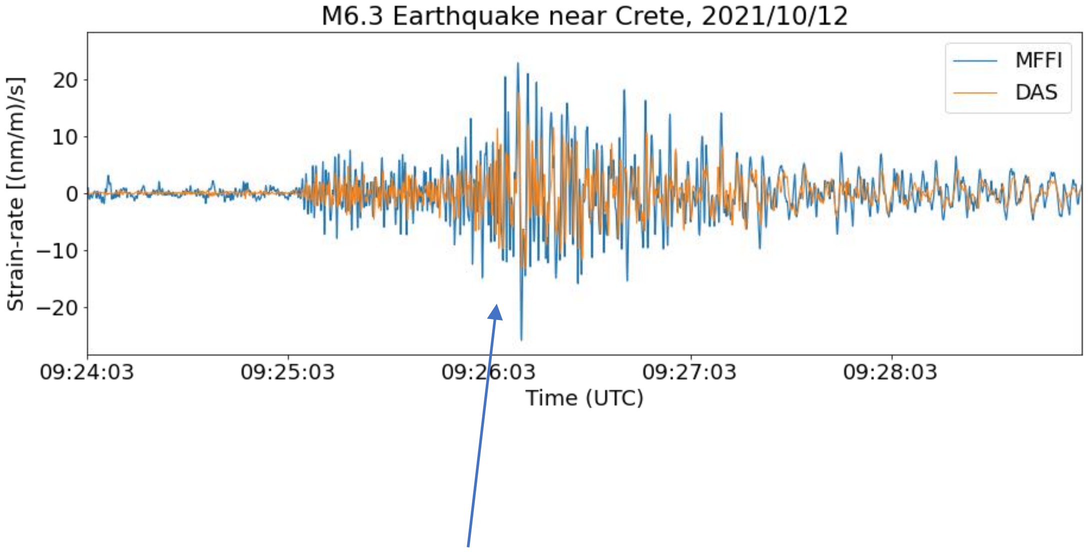
Comparison of MFFI to DAS

- MFFI was compared to a DAS instrument produced of Silixa (mid. September – late October)
- We compared strain rate measured by MFFI to average strain of DAS in the spatial domain





Confirmation that MFFI measures accurately the average strain

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MFFI prototype – limitations and actions for improvement

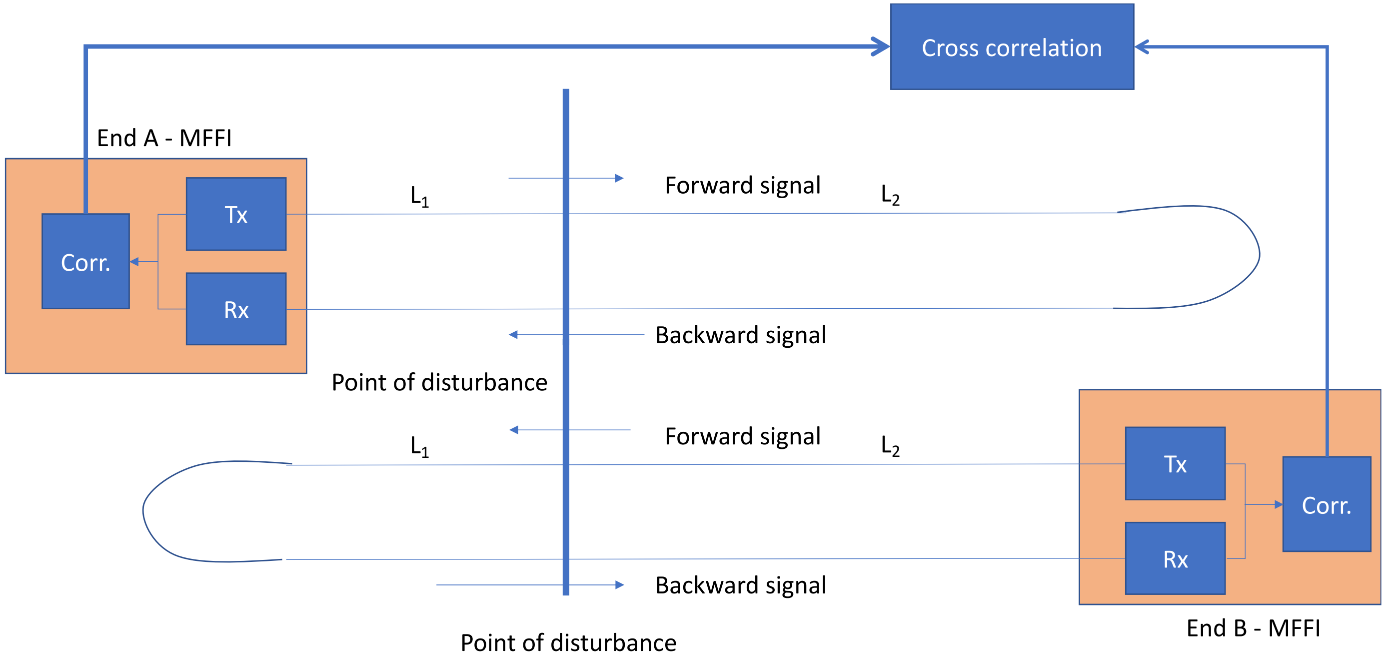
- Our prototype was limited by ADC performance (10 bit resolution) – 0.62 mrad the minimum detectable phase change
- 24 bit resolution ADCs would improve by a factor of 10 our sensitivity – **pending task, first impression is that we achieve a four-fold improvement in sensitivity**
- Higher RF frequency can further improve sensitivity

$$\varphi = \frac{2\pi f_{RF} n_g L}{c}$$

- Latest achievements in 100 GHz optoelectronic components pave the way for significant improvement of phase resolution.

Localization techniques –towards a distributed sensor

- Localization of events is very important in seismology
- First solution: Bidirectional MFFI (spatial resolution in the order of 100 m is possible)



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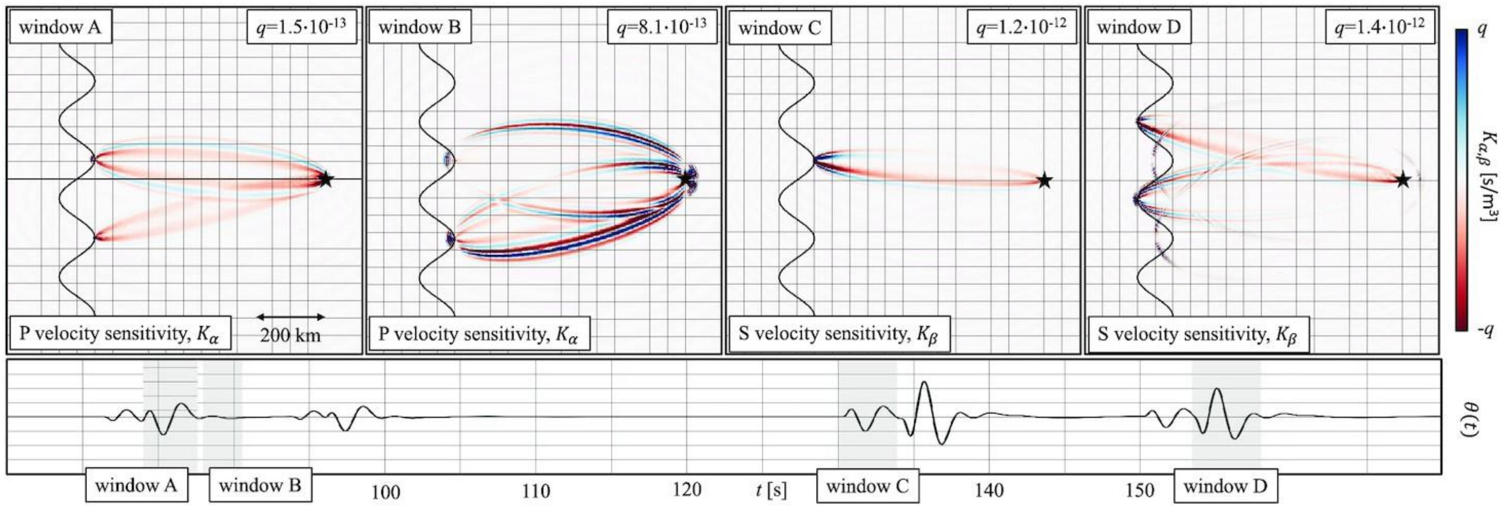
Localization techniques –towards a distributed sensor

- Based on adjoint methods, it is proved that transmission-based sensing can effectively provide distributed measurements when the phase delay time series is dissected into different windows
- The fibre must contain curved segments that behave similar to localized sensors because the sensitivity of a fibre segment to deformation is proportional to its local curvature



A. Fichtner, A. Bogriis et al., Geophys J Int, Volume 231, Issue 2, November 2022, Pages 1040–1044, https://doi.org/10.1093/gji/ggac238

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Conclusions

- We presented a novel seismic wave detection technique based on microwave frequency fiber interferometry
- The technique is simple and cost efficient – it estimates the phase variations in microwave frequency resolution as a result of fiber deformations
- The technique has been evaluated in a terrestrial cable (50 km long) and provided efficient detection of local and regional earthquakes.
- The sensitivity can be vastly improved if the microwave frequency is increased based on the latest achievements in 100 GHz optoelectronic components (We are in the process of upgrading the system to 20 GHz)
- The technique can be transformed to a distributed sensor with either bi-directional schemes or being aided by adjoint methods
- Other applications:
  - Technique for monitoring long-haul transmission networks
  - Technique for monitoring the resilience of the installed network – intrusion detection!

Thanks to ....

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