Universidad de Alcalá

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MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD

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WHAT CAN WE LEARN ABOUT OUR PLANET USING SUBMARINE OPTICAL CABLES

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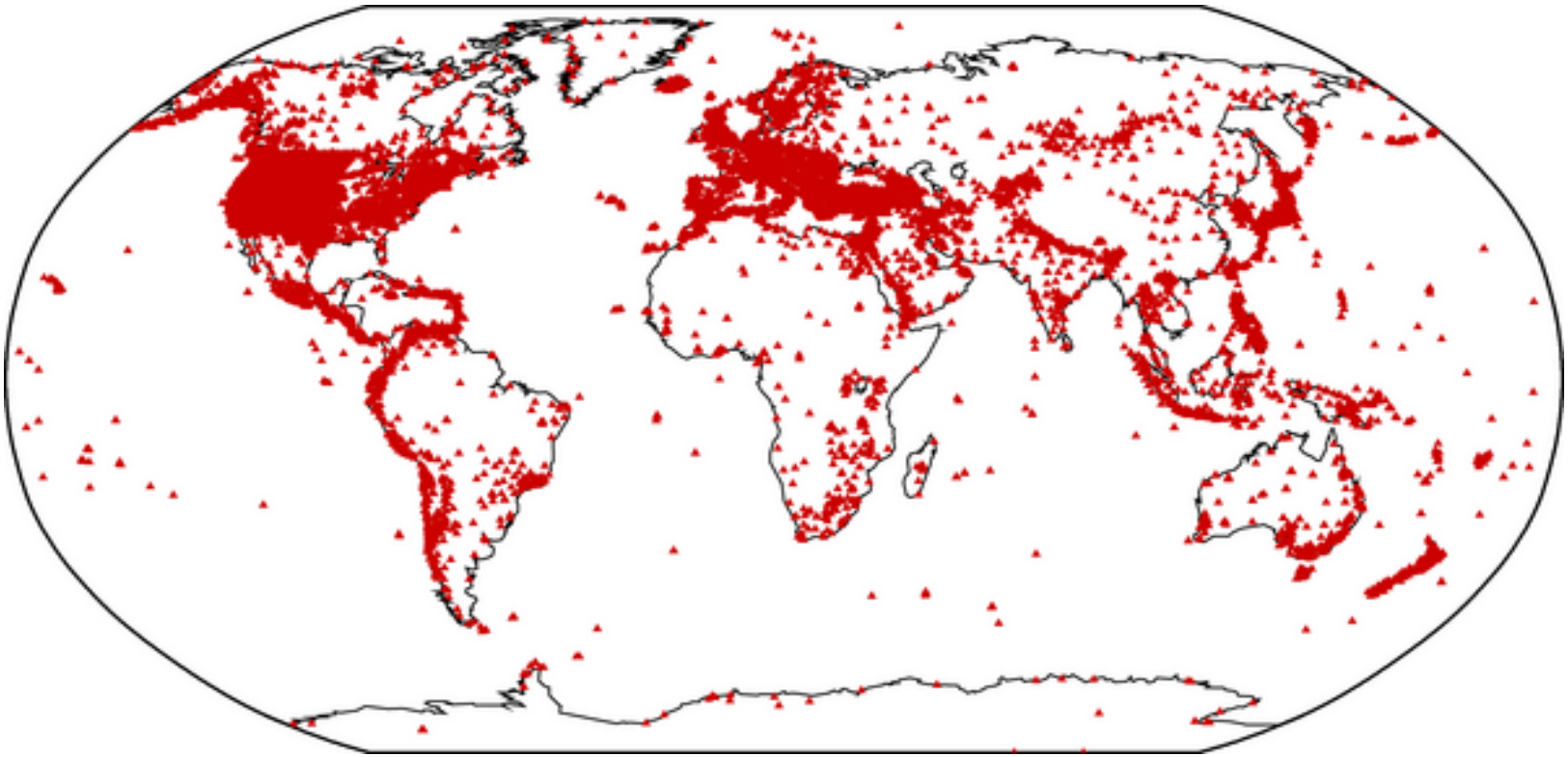
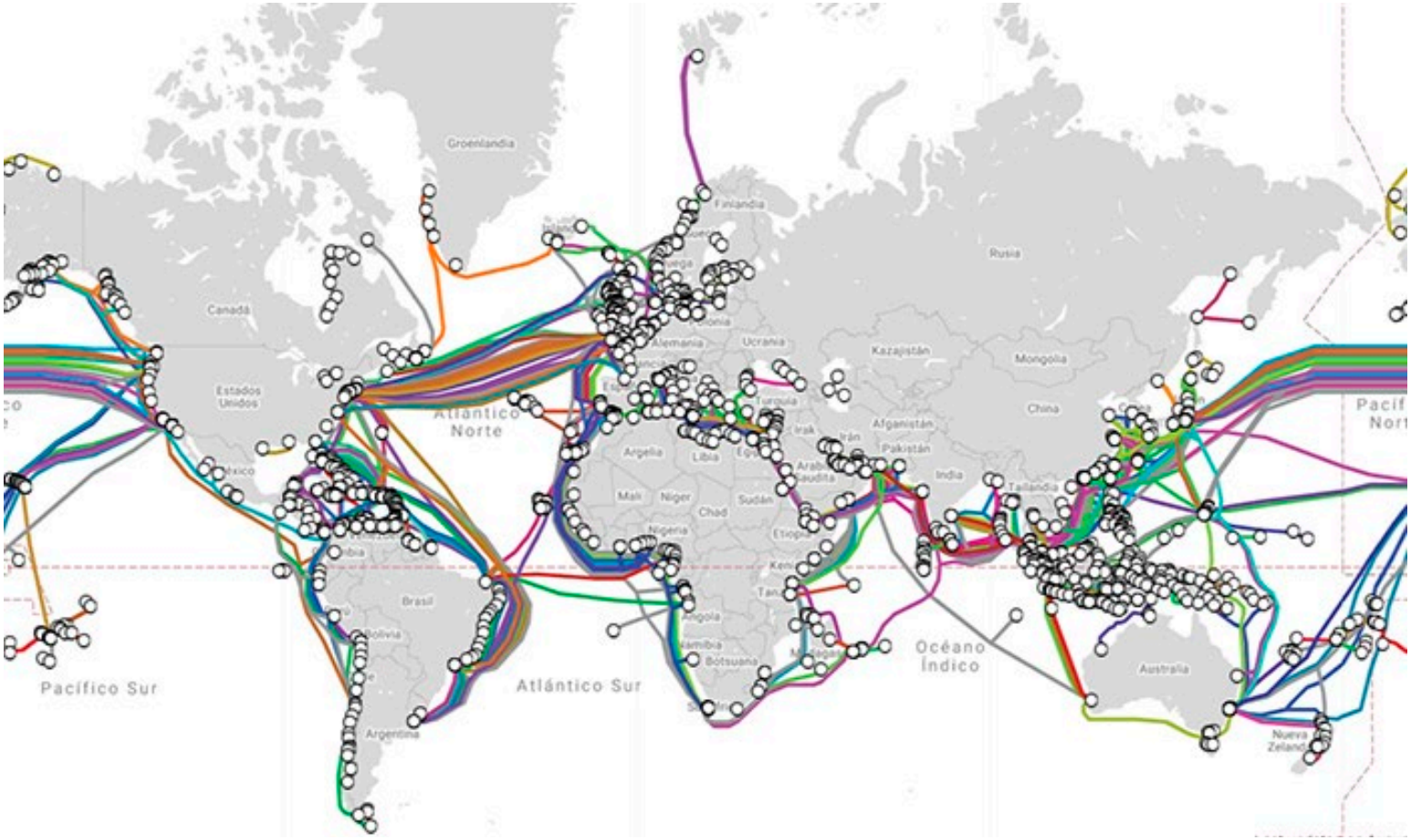
Lack of permanent geophysical observation of the ocean



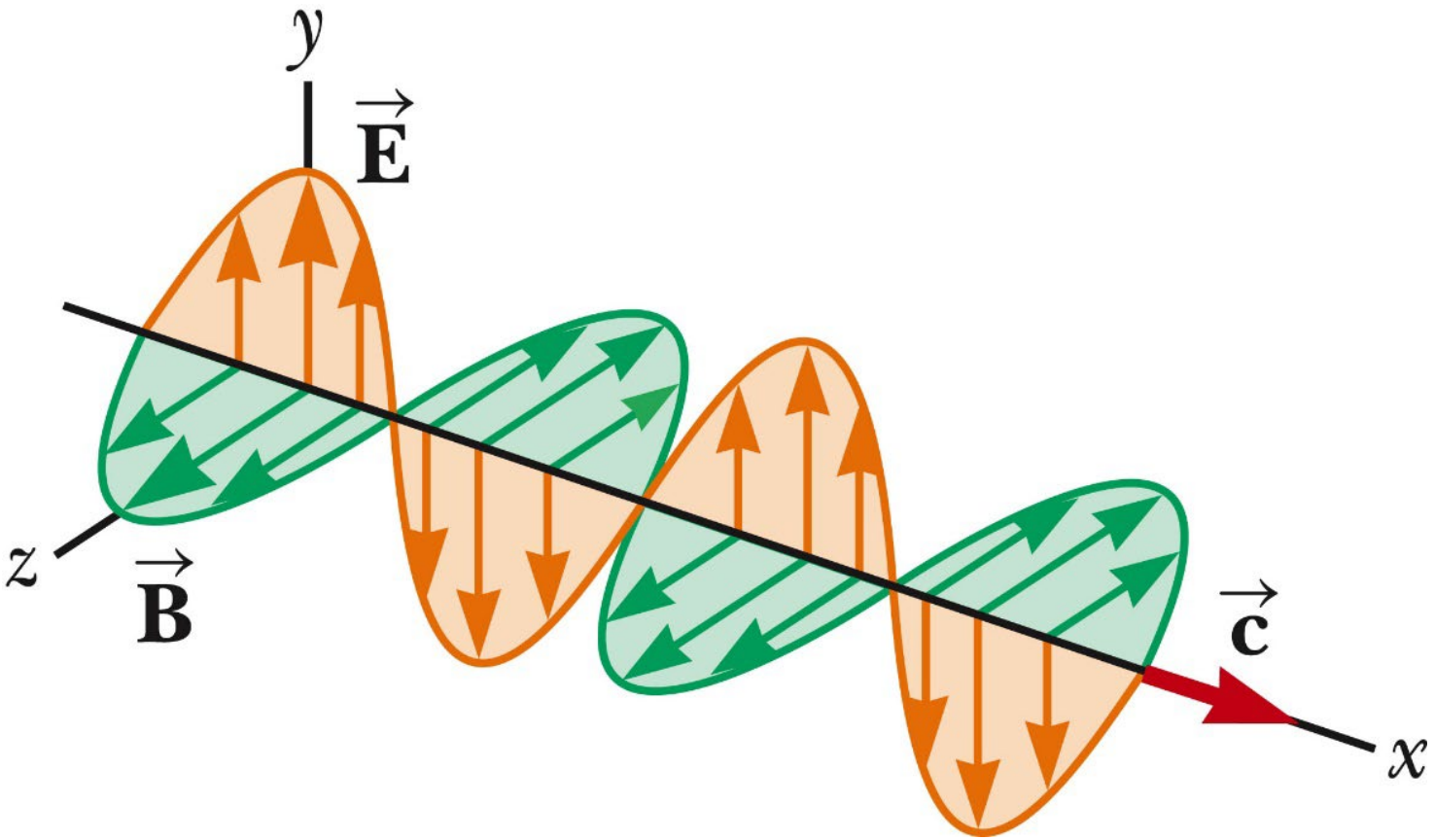
Can optical fibers help?



Foreword

- While poorly known among the telecom community, Optical Fibre Sensing (OFS) has been steadily developed for over more than 4 decades now.
- There are several examples of very successful OFS systems like the fibre-optic gyroscope. Most of these sensors require specific constructions to be developed on the fibre.
- With the advent of coherent communications, the optical fibre communication infrastructure itself with little or no modification has also proven to be a very good sensor of environmental variables.

Information carried by a lightwave



Environmental changes affect the lightwave

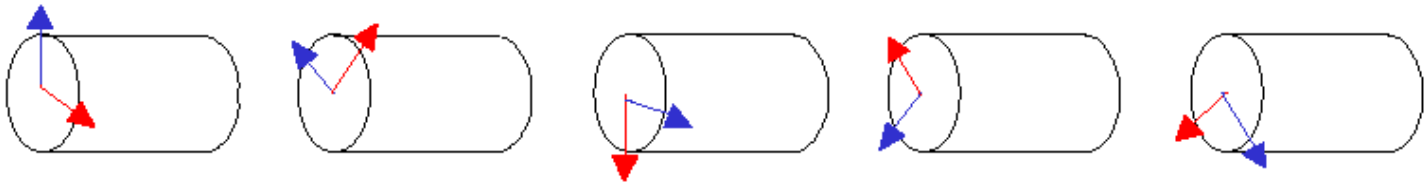
- Old, non-coherent communication systems (pre-2010) only measured intensity/amplitude. The amplitude of the light field is generaly not affected by small thermal/mechanic disturbances in the fiber:
  - Fibers are designed to confine light tightly in the core and fibers are cabled and deployed to avoid power losses caused by environmental variables,
- However, phase and polarization are indeed affected by thermal/mechanical disturbances, particularly when integrating over long lengths of fiber. **Both phase and polarization are routinely measured by coherent communication systems !!**

What is the fiber sensitive to? The case of phase

$$\varphi(L) = \int_0^L \frac{\omega n(z)}{c} dz$$

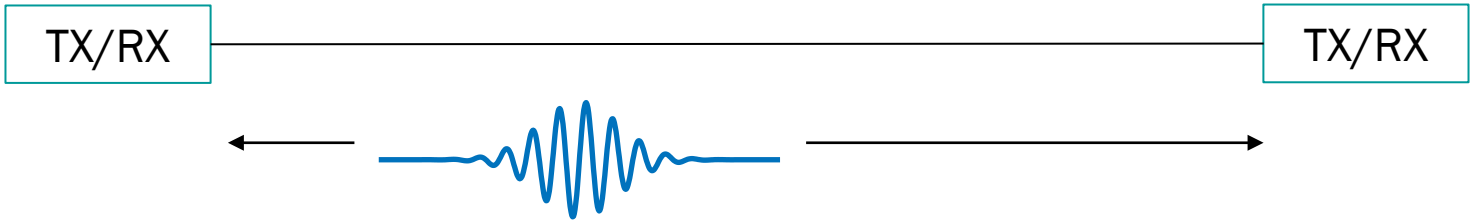
- Phase is affected by any physical change affecting the optical path, namely **strain and temperature.** Pressure sensitivity of the fibre is generally small but can be registered in the seafloor using seabed compliance (i.e. strain).
- Note that the laser frequency also impacts the phase. The laser frequency fluctuation in normal telecom lasers will completely screen environmental changes. **Special ultra-stable frequency lasers are needed.**

Polarization



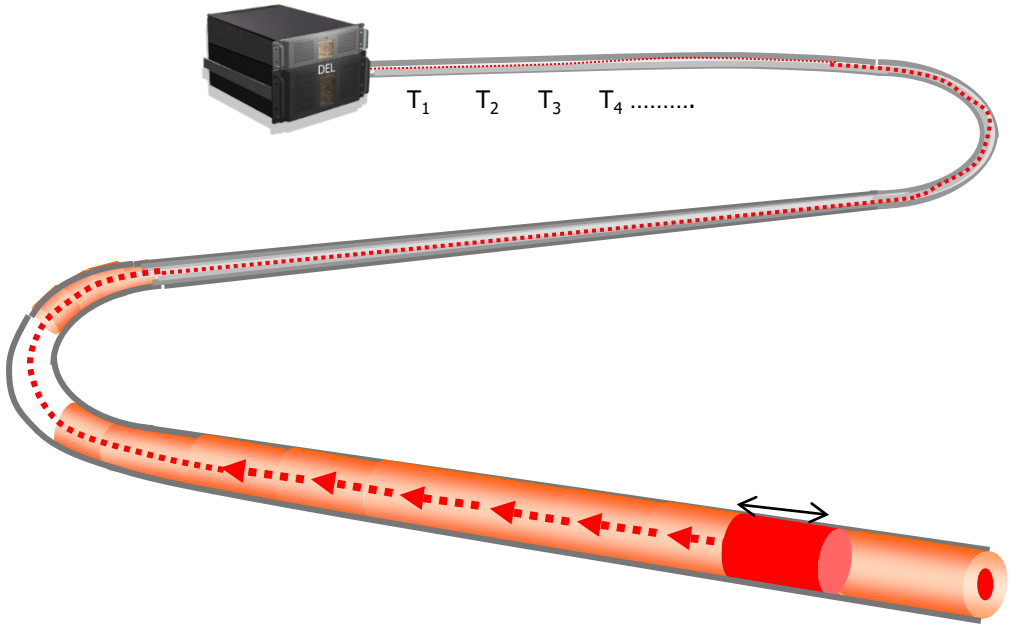
- Polarization will be affected by the same variables but will only change under a change in fibre **birefringence** (differential refractive index between the two polarization axis). Ideally fibres have no birefringence. Normal telecom fibres exhibit a very small residual birefringence whose orientation varies randomly across the length. The amount of polarization change will thus depend a lot from fibre to fibre.
- In other words, the evolution is rather unpredictable.

Localization of disturbances with phase (/polarization?)



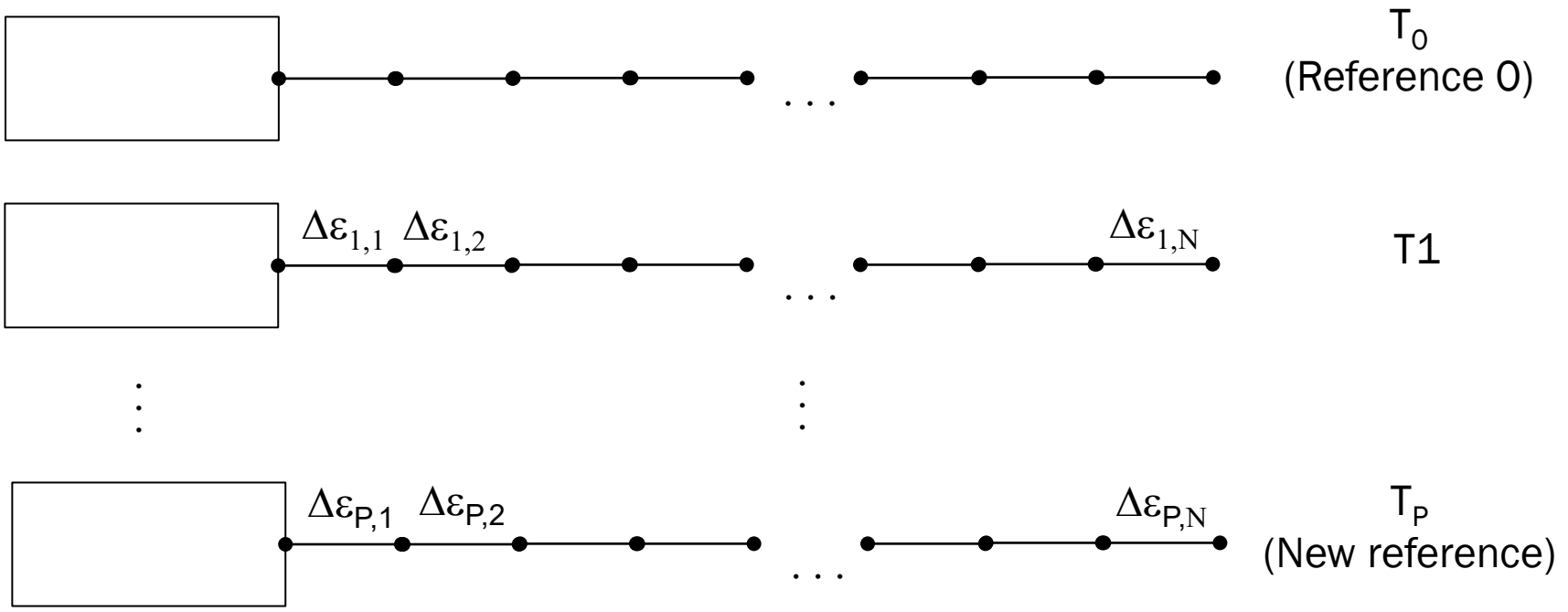
- The perturbation reaches each receiver at a different time delay. The differential delay provides an estimate of the position. TX/RX require GPS synchronization.
- **The accuracy in the localization is limited by a number of things, but ultimately can not be much better than the wavelength of the perturbation (~1 km for seismic signals)**

DAS sensing in the sea bottom



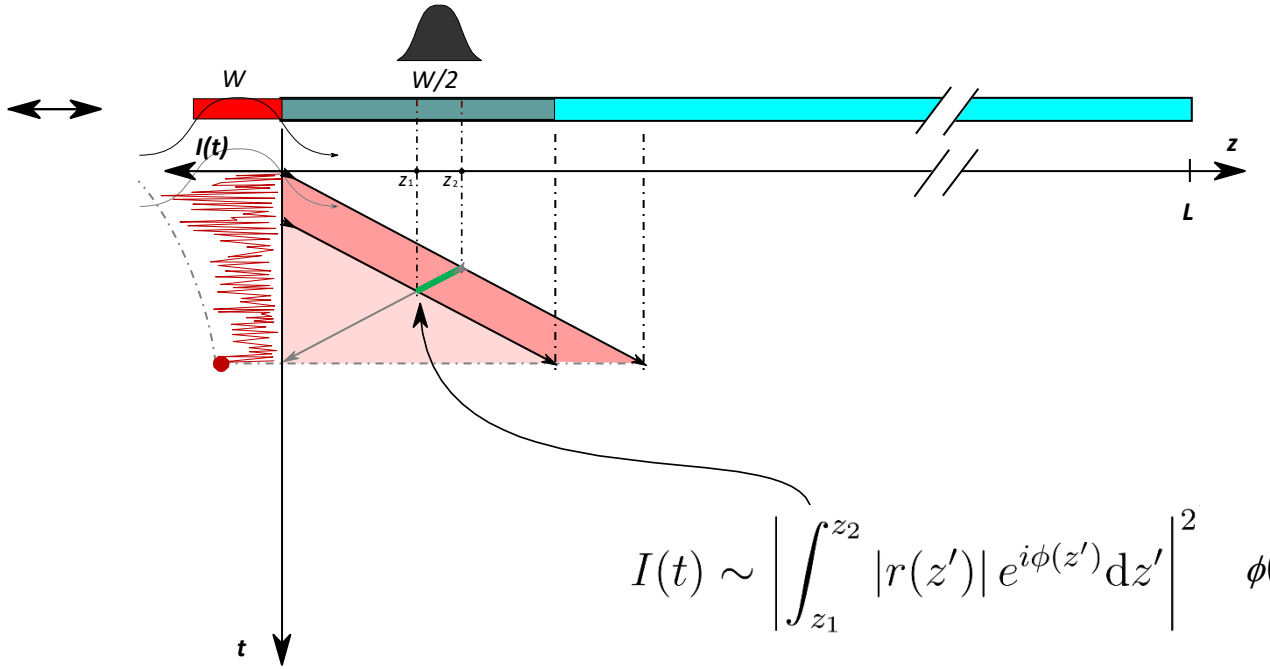
- Single DAS interrogator transforms an optical cable into a dense array of ***synchronized*** strain seismometers/short-term thermometers (measurements are **relative**)
  - Typ. 10s km to >100km, with metric spatial resolutions
  - Sampling frequency = pulse repetition rate < c/2nL

DAS performs *relative* measurements



Total strain accumulated in position 1 at instant P+1 will be $\Delta\varepsilon_{P+1,1} + \Delta\varepsilon_{P,1}$
Strain will grow with the sqrt(Nref updates)!!!

Phase-measuring DAS



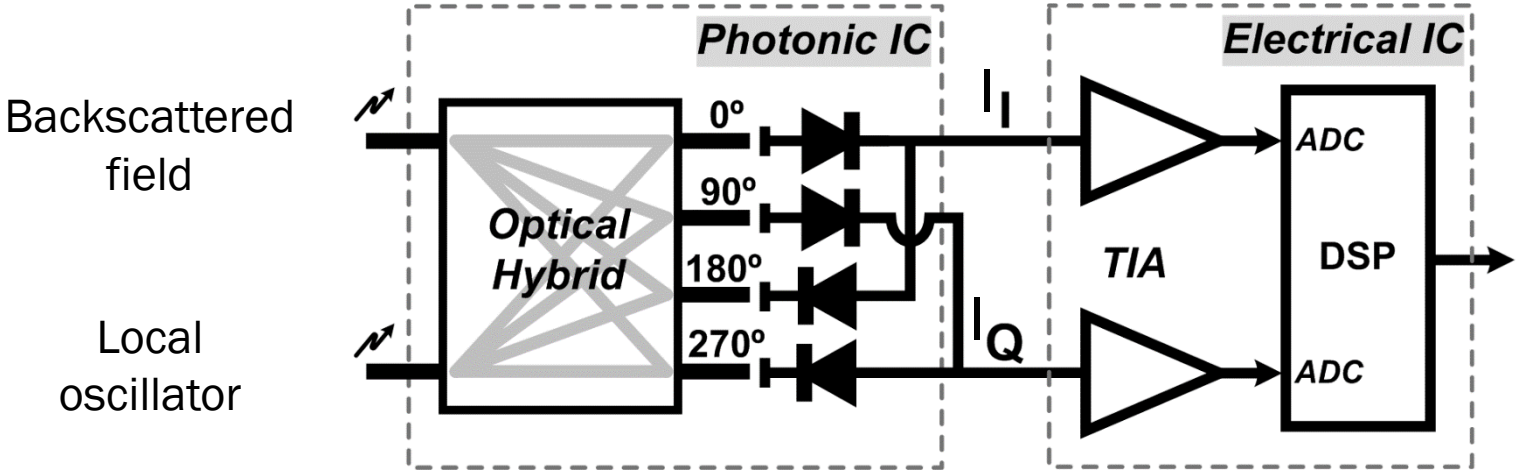
$$I(t) \sim \left| \int_{z_1}^{z_2} |r(z')|\, e^{i\phi(z')} \mathrm{d}z' \right|^2 \qquad \phi(z') = \int_0^{z'} \frac{2\omega n(z'')}{c} dz''$$

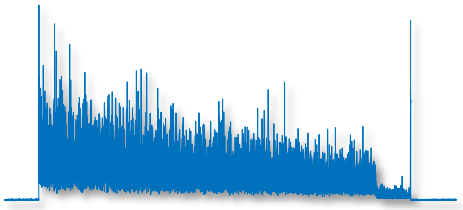
$$n = c_\varepsilon \Delta\varepsilon + c_T \Delta T$$

Trace = physical state

Consecutive traces → *Continuous* monitoring

Phase-measuring DAS using coherent detection



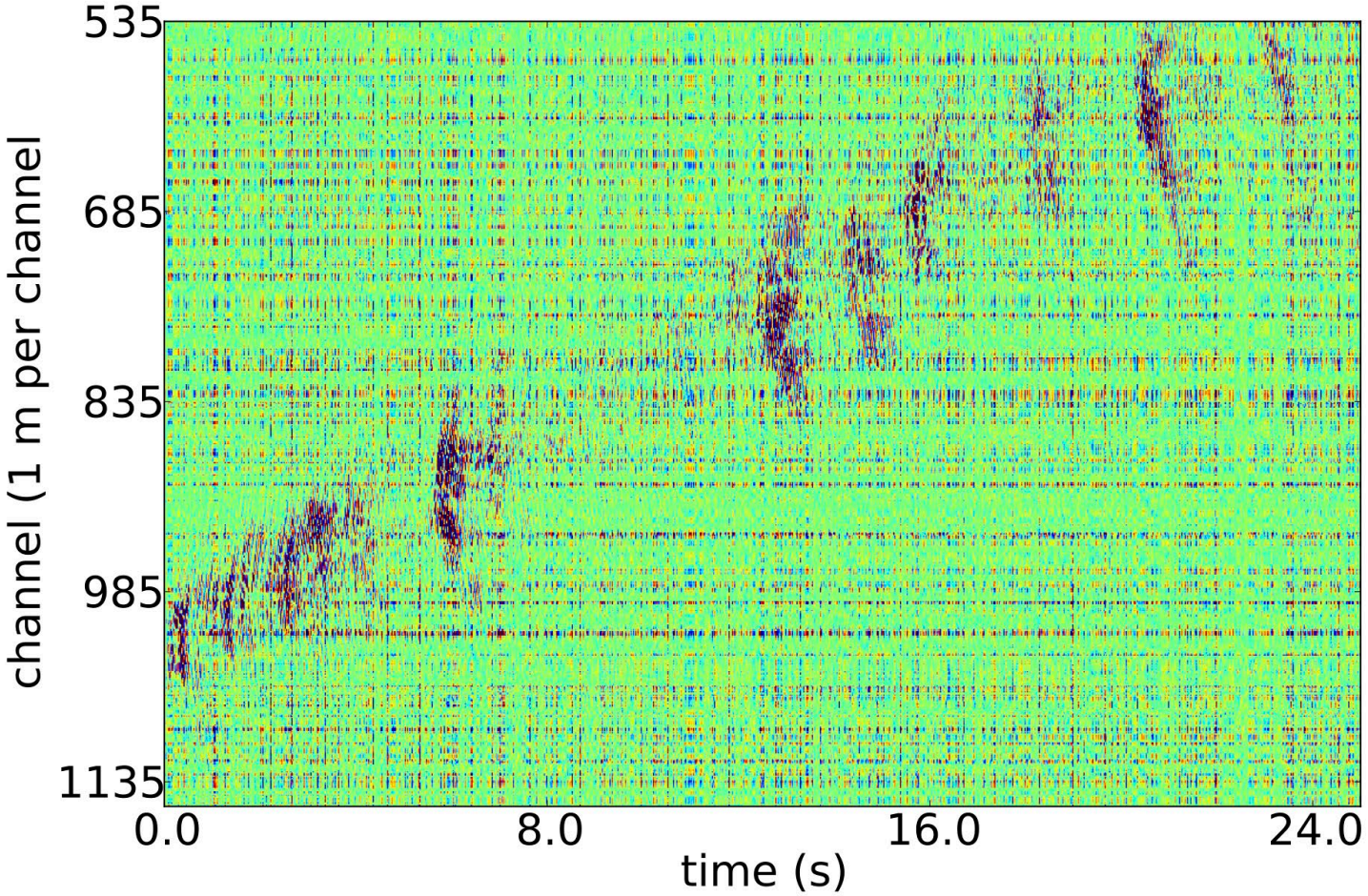


$$\phi(z) = \arctan\left(\frac{I_Q(z)}{I_I(z)}\right)$$

What happens in fading points??

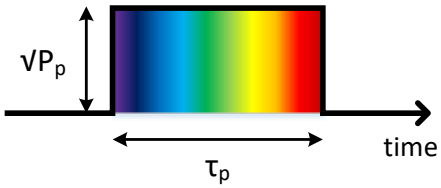
H. F. Martins et al., Opt. Express, **24** (19), 22303, (2016)

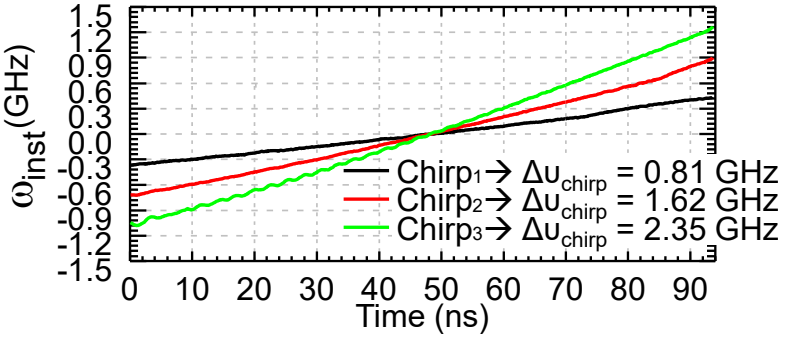
Raw data in conventional phase-measuring DAS



Single-shot sensing with chirped pulses

Probe signal: *Chirped* pulse ($\omega_{inst} \neq$ const.)



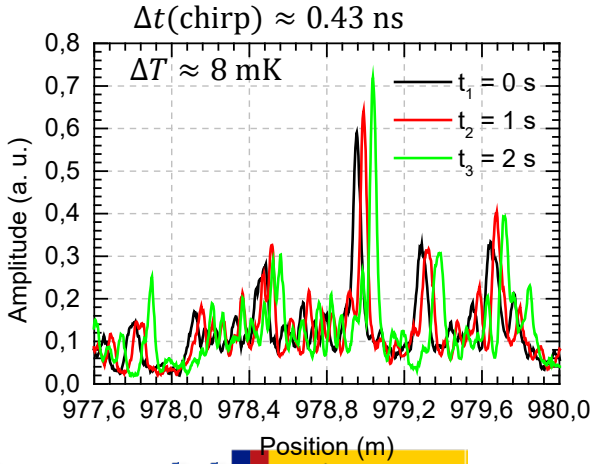


- **Trace Recovery Principle:**

Local perturbation in the fiber: $\Delta n \Rightarrow \Delta\omega$

If $\Delta\upsilon_{chirp} >> 1/\tau_p$ Time-to-frequency mapping → $\Delta\omega \Rightarrow \Delta t$ Locally shifted trace

Δt shift ← Detected via local correlation in time (~trace-to-trace)



Linear & dynamic measurement of temperature/strain gradients without *frequency sweeping strategies or phase detection*!

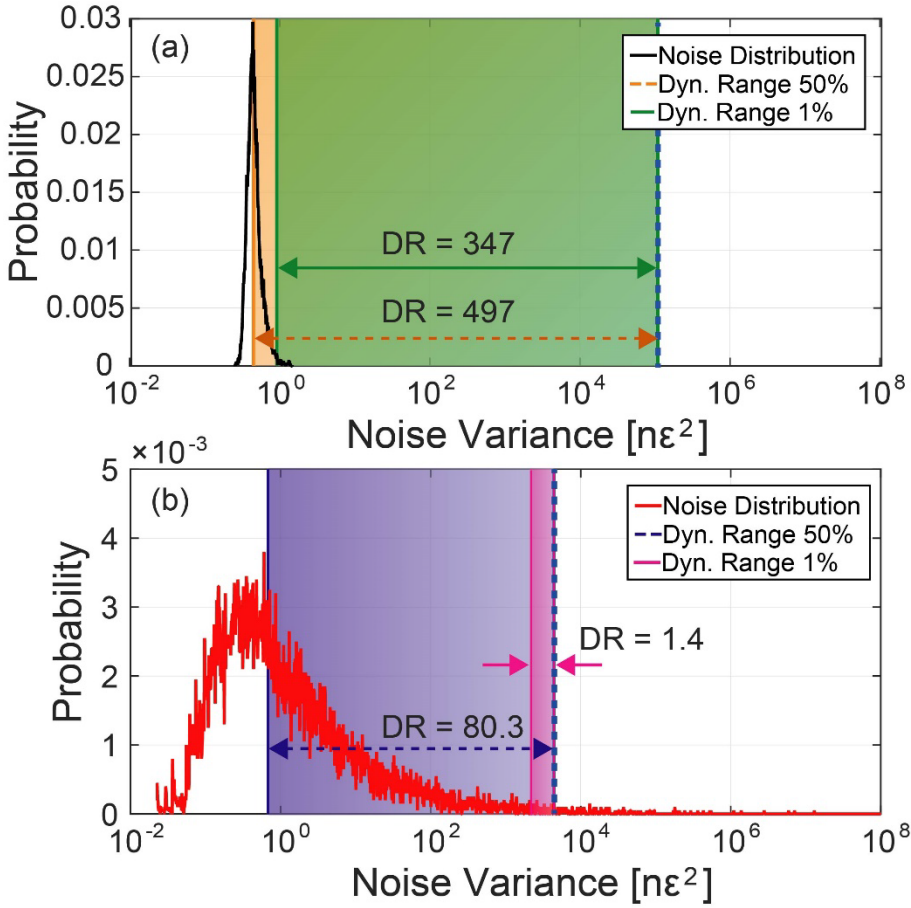
Single–shot and mK/nε resolution!

J. Pastor-Graells et al., *Opt. Express*, **24**, 13121 (2016)

A totally different measurement procedure...

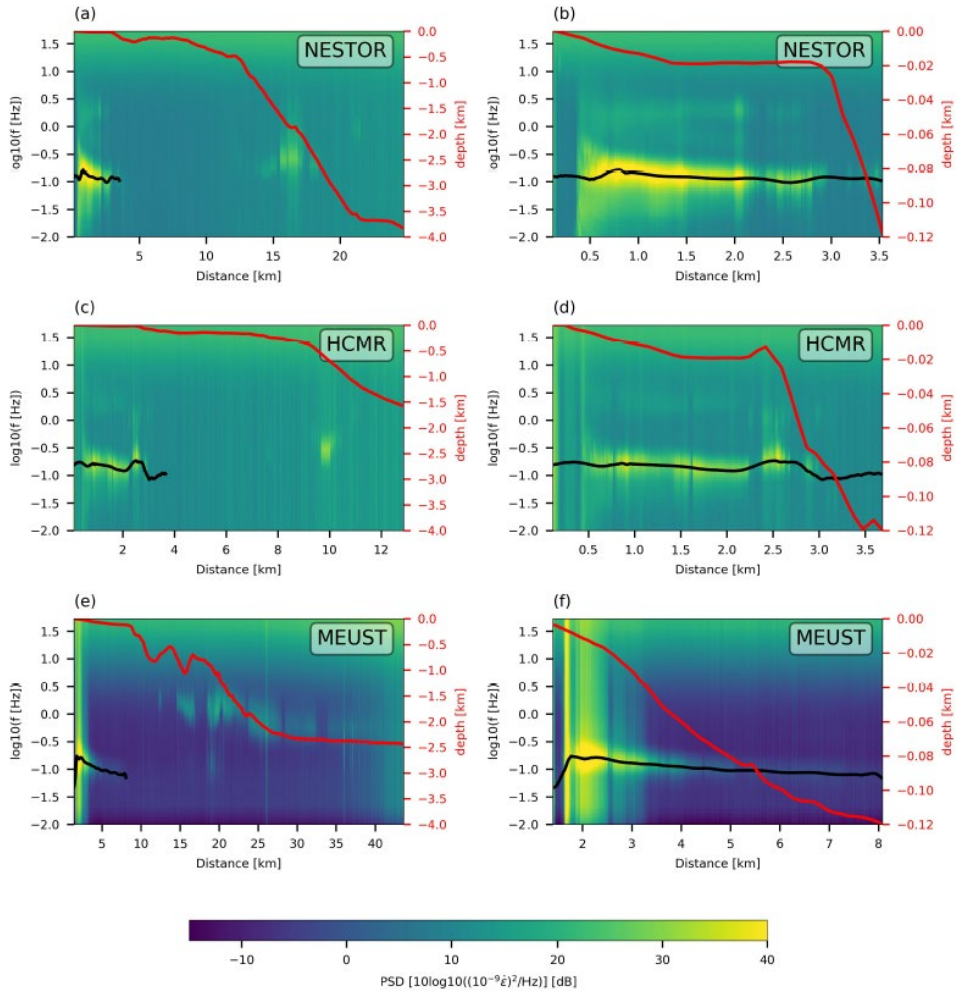
- **Chirped-Pulse DAS**
  - Time shift of Zero-Intensity Point can be measured
  - Almost Constant SNR along fiber

- **Phase-Measuring DAS**
  - Phase of Zero-Intensity Point cannot be measured
  - High SNR variability & Fading ("Dead Zone")



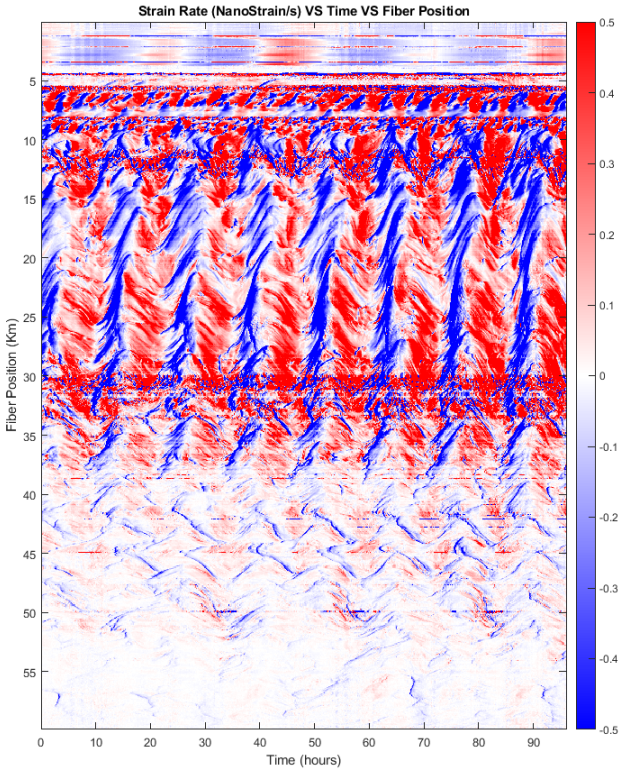
M. R. Fernández-Ruiz, et al. "Steady-Sensitivity Distributed Acoustic Sensors," IEEE J. Lightwave Technol. 36, 5690-5696 (2018)

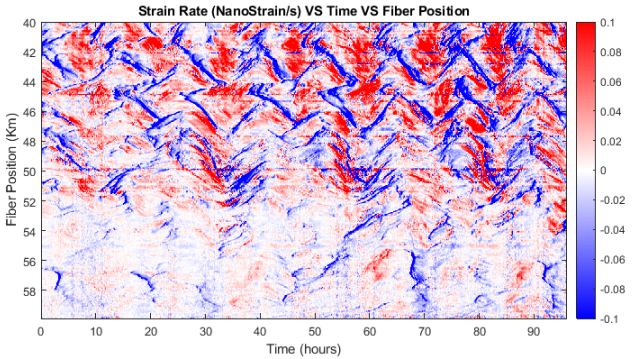
… with outstanding performance at low frequencies

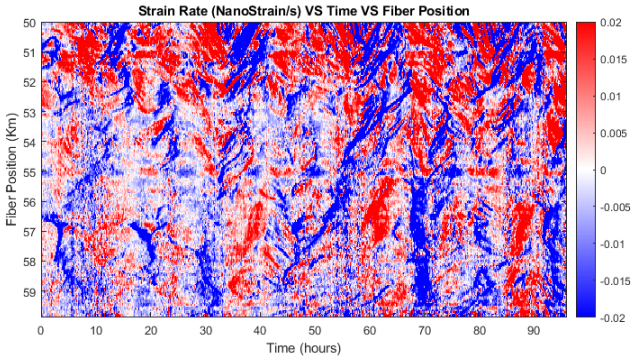


Lior et al. J Geophys. Res (2021)

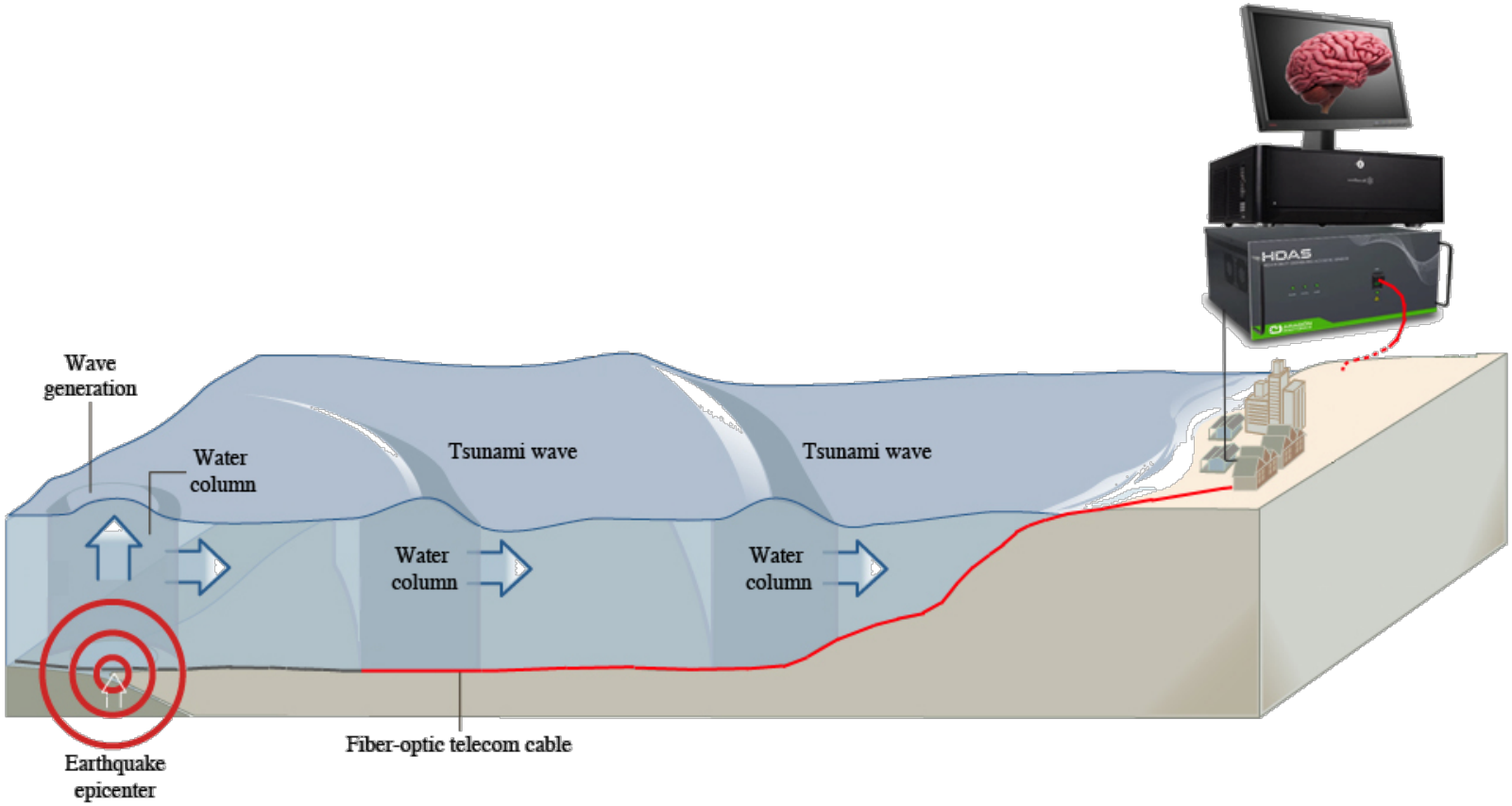
Tracking internal waves with chirped-pulse DAS







Tsunami warning using chirped-pulse DAS: Project SAFE



SMART and OFS

- OFS on the telecom infrastructure itself is an attractive option for rapid deployment.
  - Low cost
  - No/minor modifications needed in the infrastructure.
  - All 3 approaches can be made compatible with running telecoms

Z. Jia et al, "Experimental Coexistence Investigation of Distributed Acoustic Sensing and Coherent Communication Systems," in Optical Fiber Communication Conference (OFC) 2021

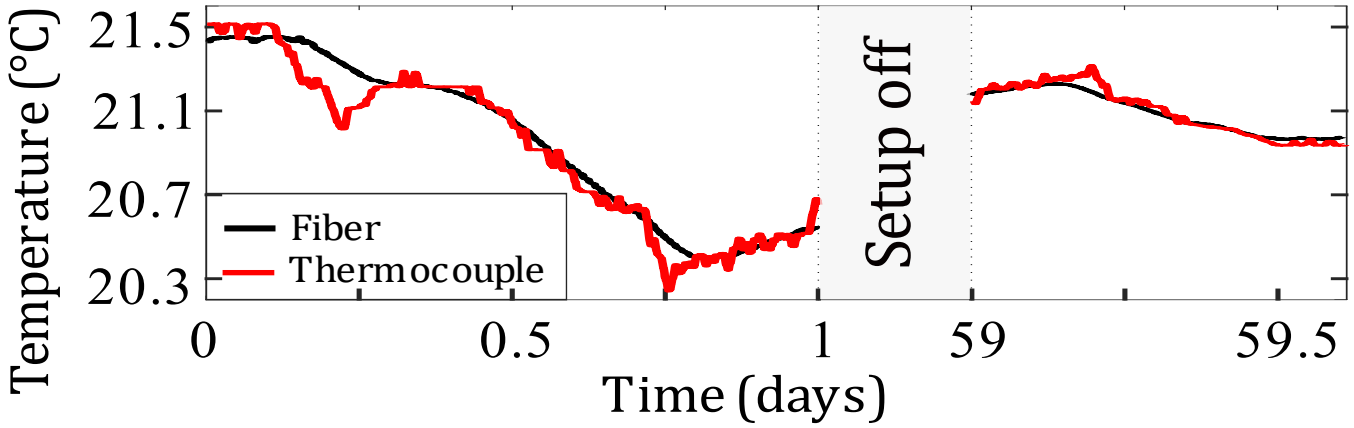
- OFS can also be used to retrofit obsolete cables!
- OFS offers an insufficient number of variables (only strain/relative temperature changes): it should be complementary with the SMART approach for a full picture of the sea bottom.

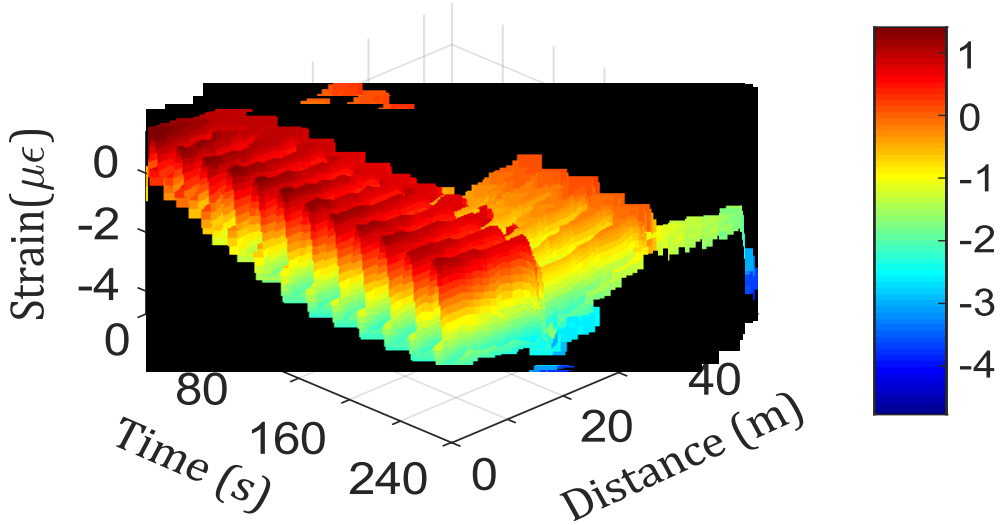
SMART and OFS

Contribution for discussion	DAS	SMART (wet sensors)	SoP & Phase Detection
Need to have dedicated fibre	No (?)	Yes (?)	No
Possible utilization in existing systems	Yes (?)	No	Yes
Range for detection	Short (?)	All the cable length if necessary	All the cable length if necessary
Seismic detection • **Acceleration** • **Vibration** • **EEWs** • **TEWs**	 • Yes • Yes • Yes • Yes	 • Yes • Yes • Yes • Yes	 • Yes • Yes • Yes (?) • Yes (?)
Environmental detection • **Pressure** • **Temperature** • **Others**	 • Yes • Yes • No (?)	 • Yes • Yes • Yes (?)	 • Yes (?) • No (?) • No (?)
Accuracy of measurement	++	+++	+ (?)
Trust, credibility	++	+++	+ (?)
Ease of interpretation and processing of data obtained in real-time and deferred	++ (?)	+++	+ (?)
Reliability	+++	+++	+++
Spatial resolution of the observation	Accurate	Accurate	?
Legal and permitting problems	No (?)	?	??
Cost	100k to 200k USD in each CLS	~10% to 15% of the total telecom system cost	?
Standardization	No	ITU-T, SG15/Q8 is trying to establish a common general approach	No (?)
Contribution to Security and Safety of the sub cable	Yes	Yes	Yes
Operation in already existing repeated systems	No (?)	No	Yes (?)
Operation in already existing non-repeated systems	Yes	No	Yes (?)

Courtesi of Jose Barros · Director of External Affairs at ANACOM

Towards a "calibrated" DAS





P.J. Vidal et al. Optics Letters 47 3588 (2022)

Conclusions

- DAS can turn a submarine optical fiber into an array of thousands of geophysical strain/temperature sensors, allowing the recovery of many processes so far poorly understood (including processes that are key in the understanding of climate change evolution)
- DAS Compatibility with pre-existing telecom infrastructures
  - Fast/Massive implementation & Minimal deployment costs
- Additional dimension of data (space):
  - Advantages of 2D signal processing
  - Isolating different features (wave propagation, etc.) not previously available
- …Already a reality: we only need to leverage this technology in existing infrastructure.

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omnisens
Securing asset integrity

ARAGÓN PHOTONICS

Acknowledgements

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