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Introducción a los Sensores Distribuidos en Fibra Óptica: Fundamentos y Aplicaciones

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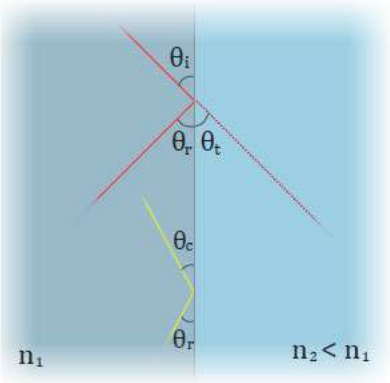
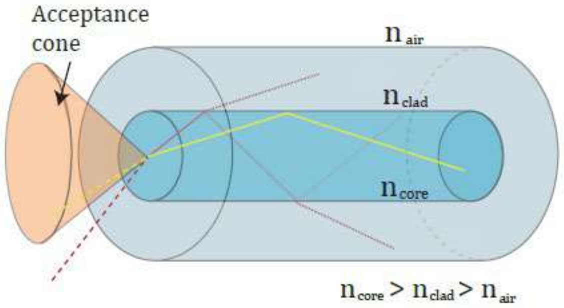
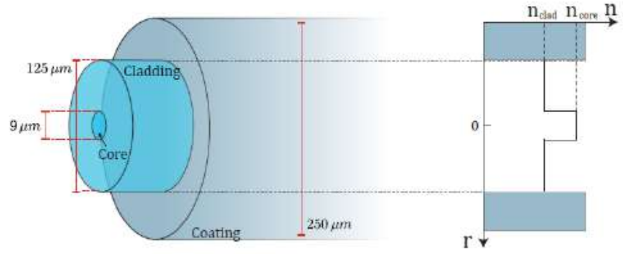
1. Fundamentals of optical fibers

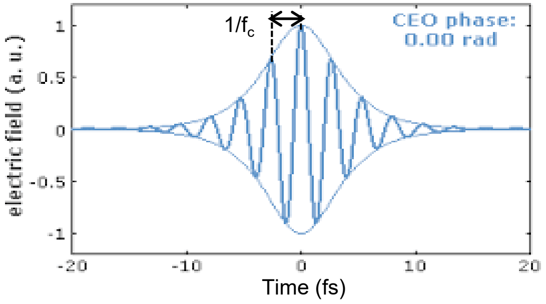
- Optical fiber: long, thin strand of carefully drawn glass (SiO_2) about the diameter of a human hair that transmits light signals. Those signals carry data (i.e., information), which is transmitted at very high speed over very long distances.

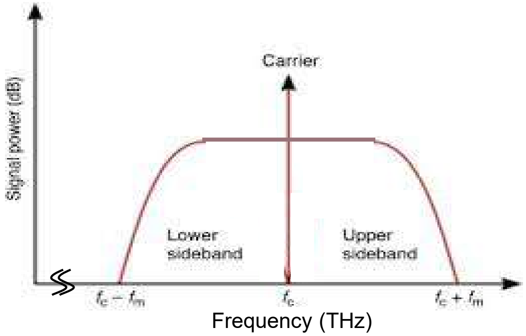






- An optical carrier wave is modulated to carry the information.





1. Fundamentals of optical fibers

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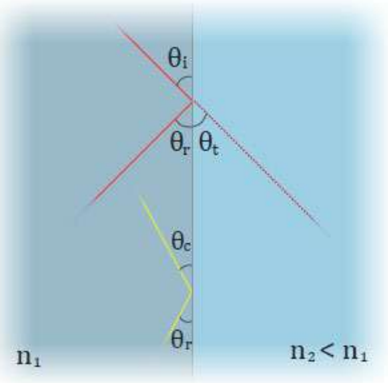
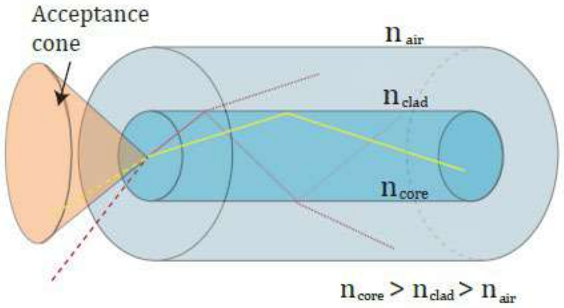
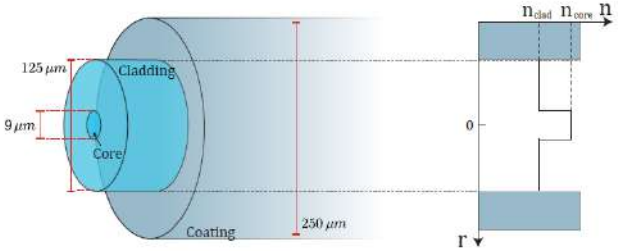


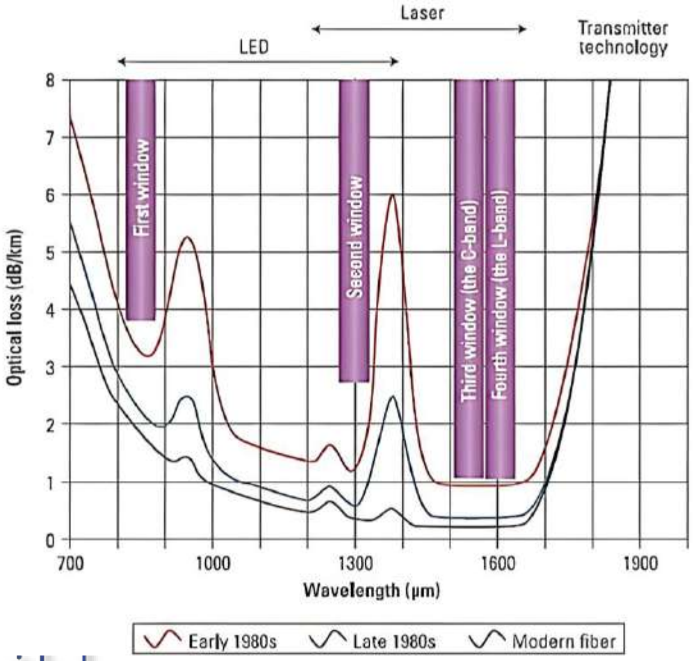


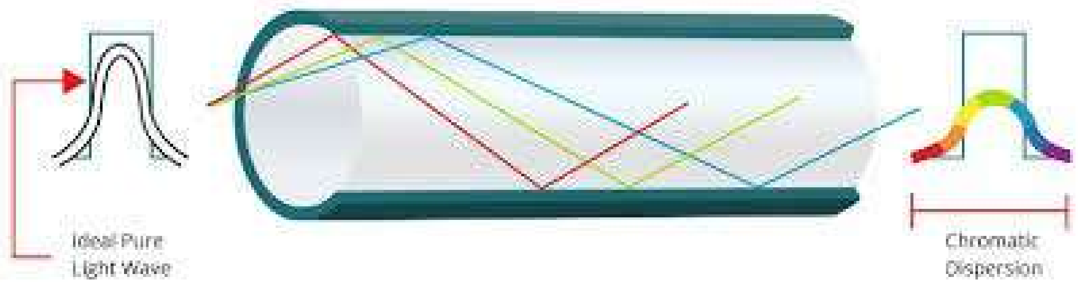


- An optical carrier wave is modulated to carry the information.
- Core of current telecommunication networks.

1. Fundamentals of optical fibers

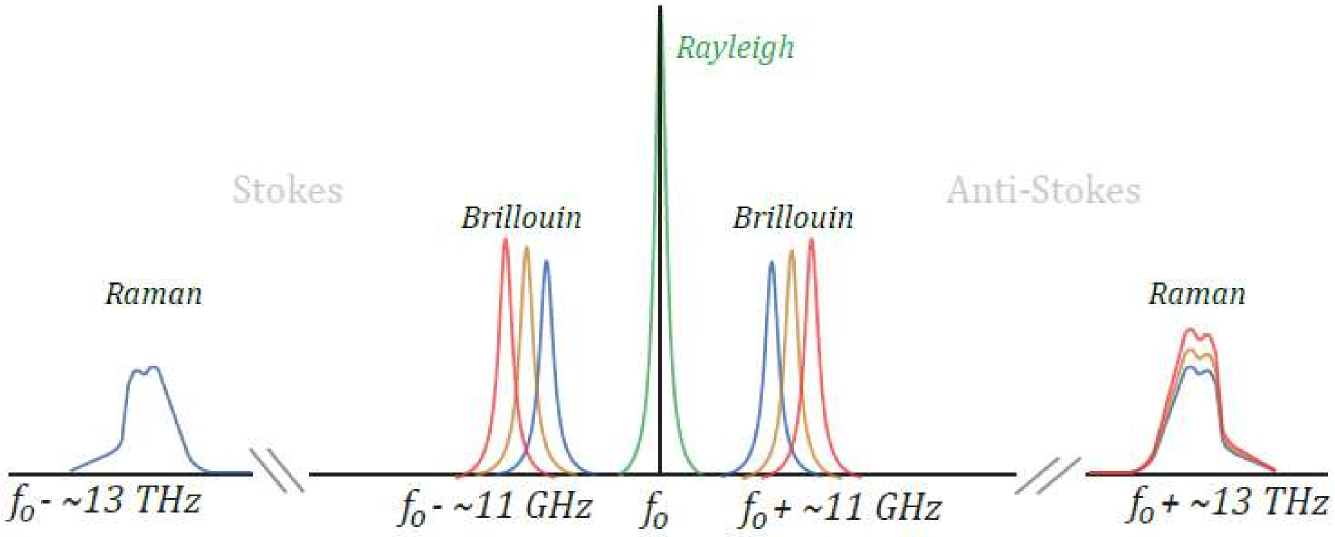
- Limitations of ligth propagation in optical fibers:
  - Attenuation → Loss of intensity with propagation (<0.2dB/km at C band ~1550nm)
  - Dispersion → Pulse broadening due to different velocity of different spectral components
  - Non-linear effects → Signal distortion caused by propagation of high power





1. Fundamentals of optical fibers

- Scattering effects: process by which ligth, interacting with a material medium, is radiated in an arbitrary direction.
  - Rayleigh → One of the main actors in attenuation. Elastic process (no change in the scattering wavelength, electronic excitation or de-excitation). Wavelength dependent, following a $\propto 1/\lambda^4$ dependency,
  - Brillouin and Raman → Inelastic processes: the energy of the incident and scattered photons is different, an interchange with the propagation medium is produced. They can be spontaneous or stimulated. Stimulated scattering is used to develop temperature and/or strain sensors.



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2. Distributed sensing in optical fibers: definition and types

- Optical sensor: system composed of a transducer, a communication channel and a subsystem to generate and/or detect, process and condition the signal, such that light is used in one of the subsystems.
- Optical fiber sensor (OFS): optical sensor in which any of the processes or parts use fiber optic technology.
- OFS can be classified as a function of several factors:

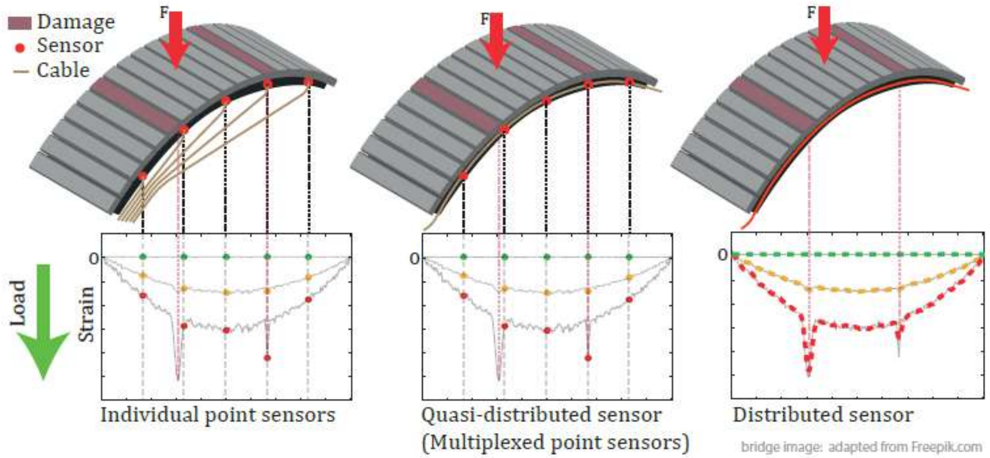
Nature of the magnitude to be measured	Spatial distribution	Nature of the transducer	Modification of ligth property
Mechanical Thermal Chemical composition Electromagnetic Flow and turbulence fluids Magnitudes in the biochemical field	Point Quasi-distributed Distributed	Intrinsic Extrinsic	Amplitude-modulated Intensity-modulated Interferometric Polarimetric Spectroscopic

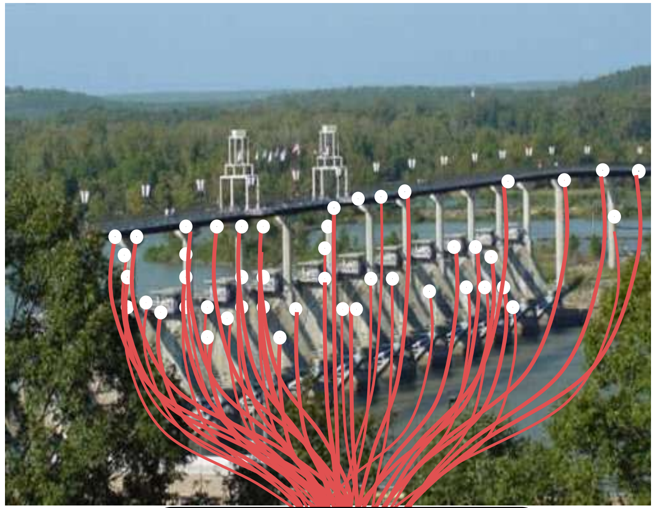
2. Distributed sensing in optical fibers: definition and types

- Advantages of optical fiber sensors with respect to competing (e.g., electrical) sensors:
  - They are not affected by electromagnetic radiation.
  - Do not emit electromagnetic radiation
  - Remote sensing over long distances
  - Safety against deflagration
  - Ease of multiplexing using a single optical fiber
  - Small size and weight
  - Ability to monitor in real time
  - High temperature tolerance
  - Stable and durable
- Disadvantages
  - Little selectivity in some cases
  - Cost

2. Distributed sensing in optical fibers: definition and types

- Classification by spatial distribution:





N sensors, N wires,

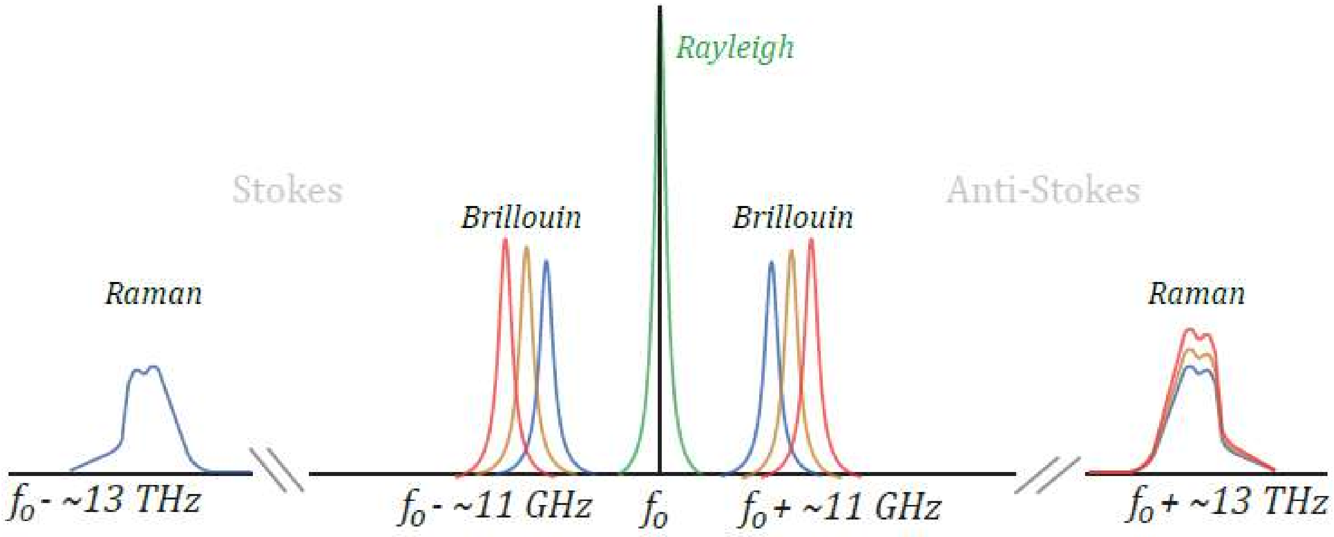
N calibrations

2. Distributed sensing in optical fibers: definition and types

- Characteristics:
  - Less spatial resolution that point or quasi-distributed sensors
  - Much more sensing points, in the tens of thousand range
  - Each section of fiber is a sensor
  - Reduced cost per monitored point
- Types of distributed optical fiber sensors (DOFS):
  - Raman scattering
  - Brillouin scattering
  - Rayleigh scattering

2. Distributed sensing in optical fibers: definition and types

- Distributed optical fiber sensing based on Raman Scattering:
  - There is a pump signal whose photons are annihilated to create lower energy photons and optical phonos (vibrational states of the silica molecule)
  - Only sensitive to temperature variations: Distributed temperature sensing (DTS):



2. Distributed sensing in optical fibers: definition and types

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  - There is a pump signal whose photons are annihilated to create lower energy photons and optical phonos (vibrational states of the silica molecule)
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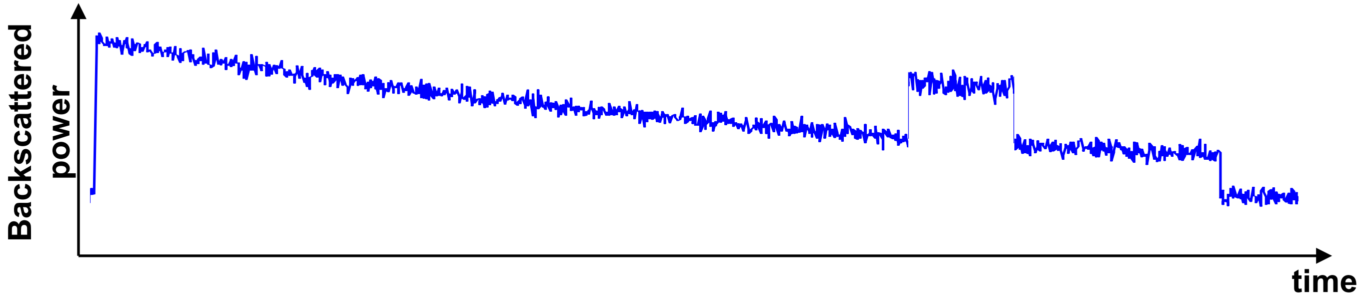
- Typical performance:
  - Range: 20 km
  - Spatial resolution: 1 meter
  - Sampling rate: Hz
  - Temperature accuracy: 1ºC



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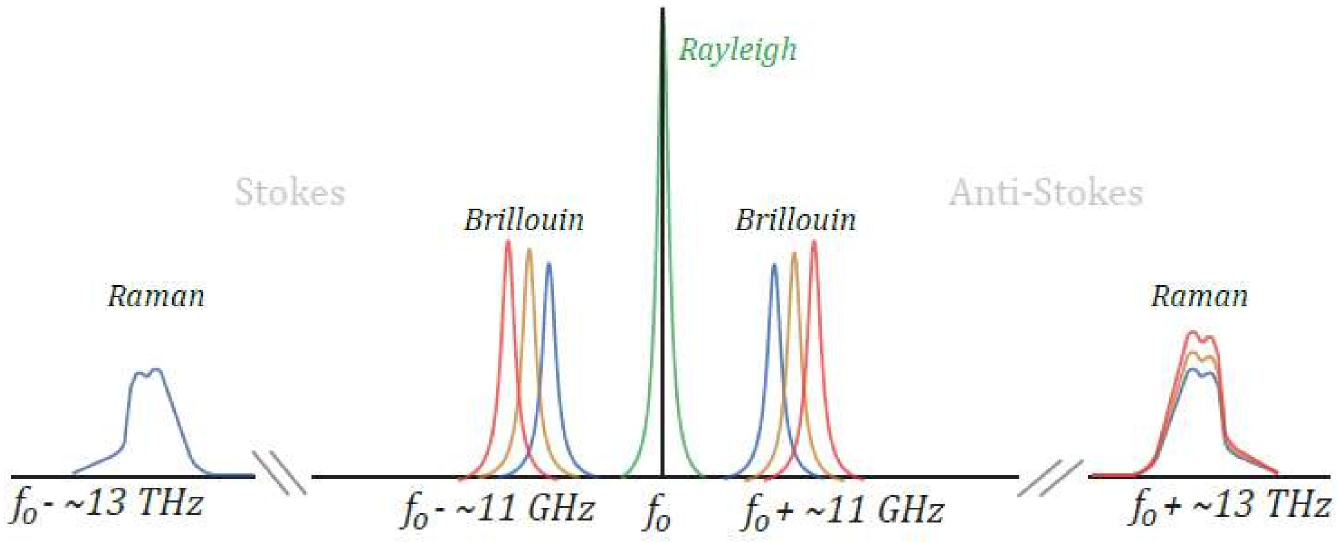
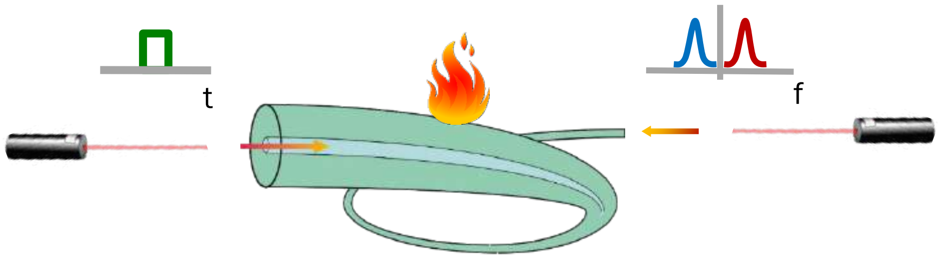
2. Distributed sensing in optical fibers: definition and types

- Distributed optical fiber sensing based on Brillouin Scattering:
  - There is a pump signal whose photons are annihilated to create lower energy photons and acoustic phonos (acoustic vibration, pressure waves)
  - Sensitive to temperature and strain variations



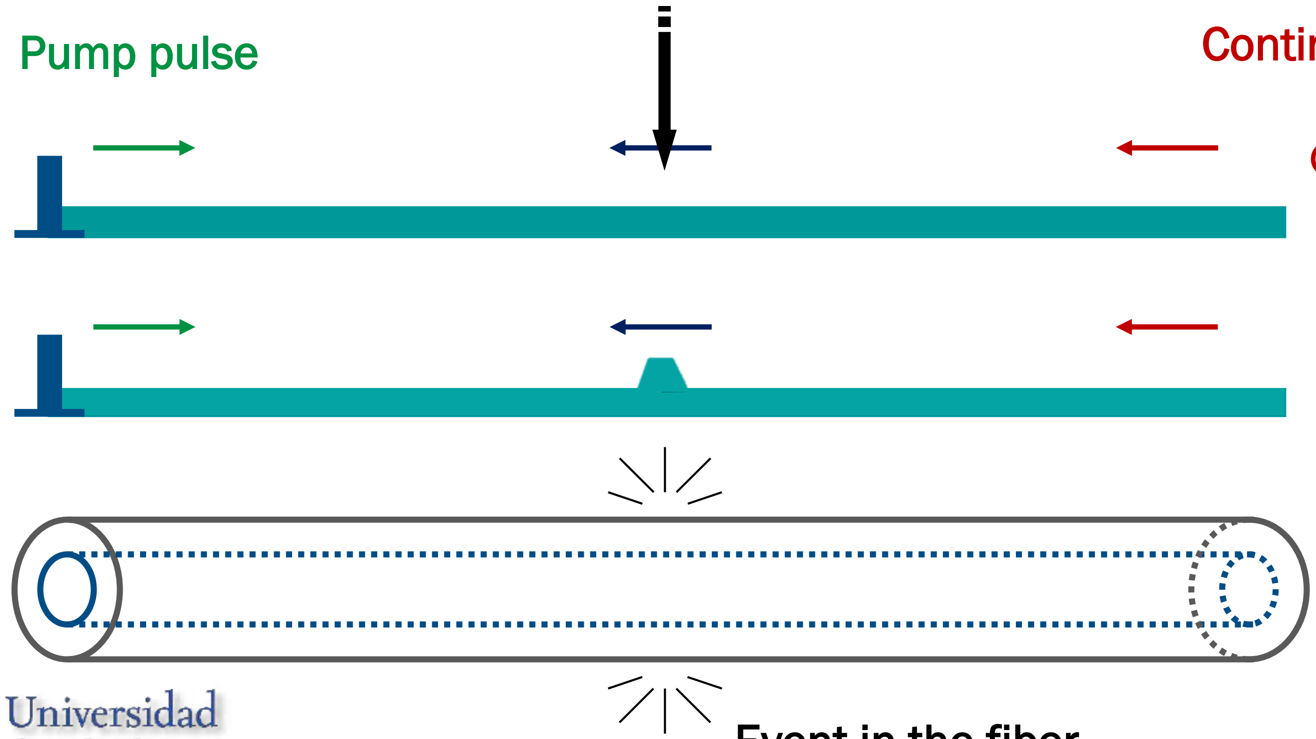
2. Distributed sensing in optical fibers: definition and types



Different ν'_B

Pump pulse

Continuous & Modulated Probe Wave @ ν_B = 11GHz



Probe Wave now tuned @ ν'_B = 11 GHz + $\Delta\nu$

Event in the fiber

2. Distributed sensing in optical fibers: definition and types

- Distributed optical fiber sensing based on Brillouin Scattering:
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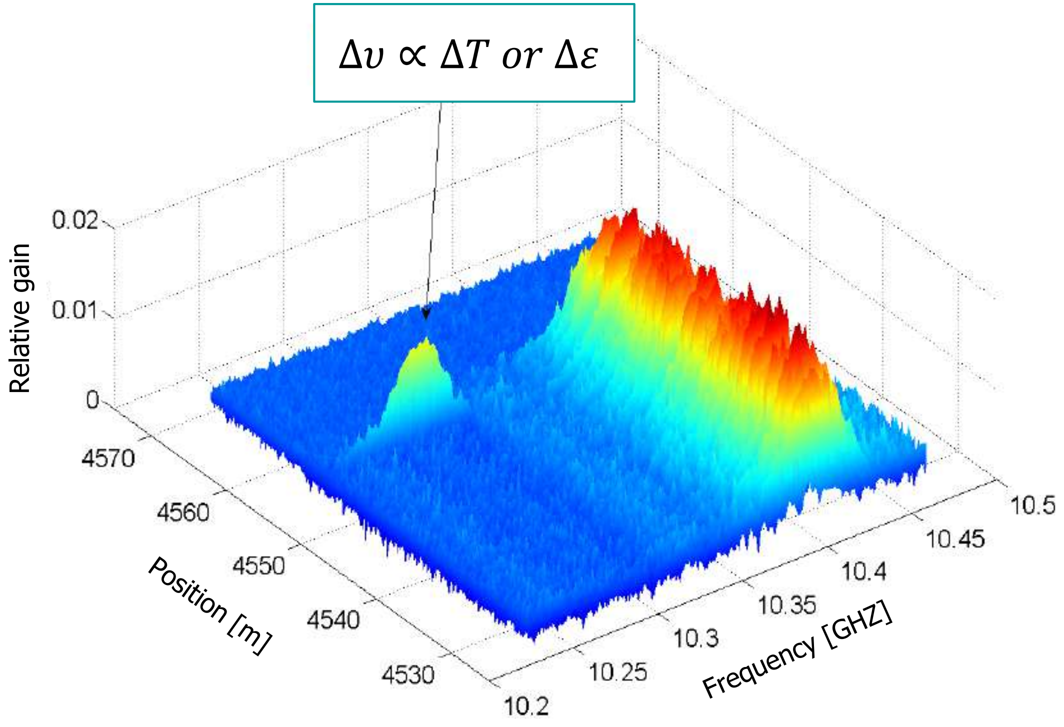
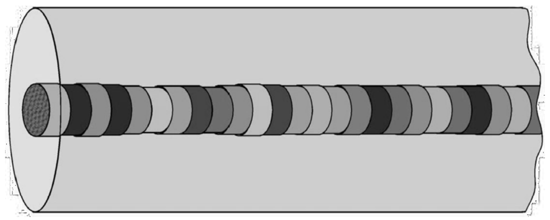
  - Sensitive to temperature and strain variations



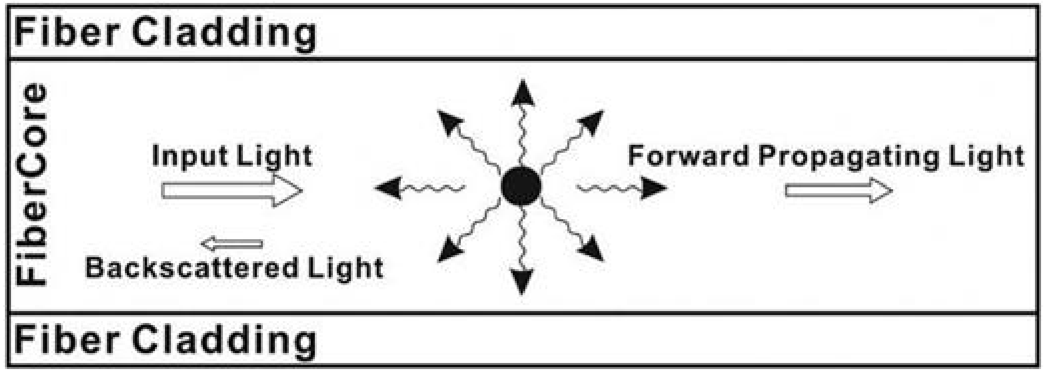
- Typical performance:
  - Range: 50 km
  - Spatial resolution: 1 meter
  - Sampling rate: mHz
  - Temperature/Strain accuracy: 1ºC/ 10 με

2. Distributed sensing in optical fibers: definition and types

- Distributed optical fiber sensing based on Rayleigh Scattering:
  - Elastic (linear process)
  - Sensitive to temperature and strain variations
  - Main **current research line** in the Photonics Engineering Group of the UAH



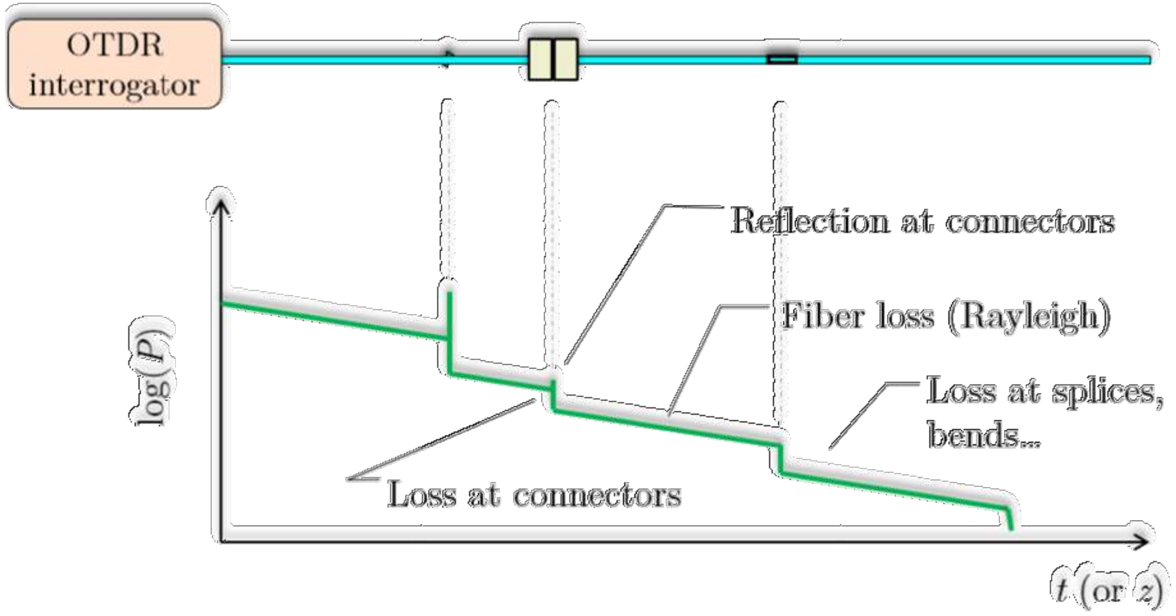
The fiber can be seen as a series of closely-packed refractive index discontinuities, each one causing a tiny amount of reflection.



Reference: P. Lu et al., Applied Physics Reviews, **6** (4) (2019)

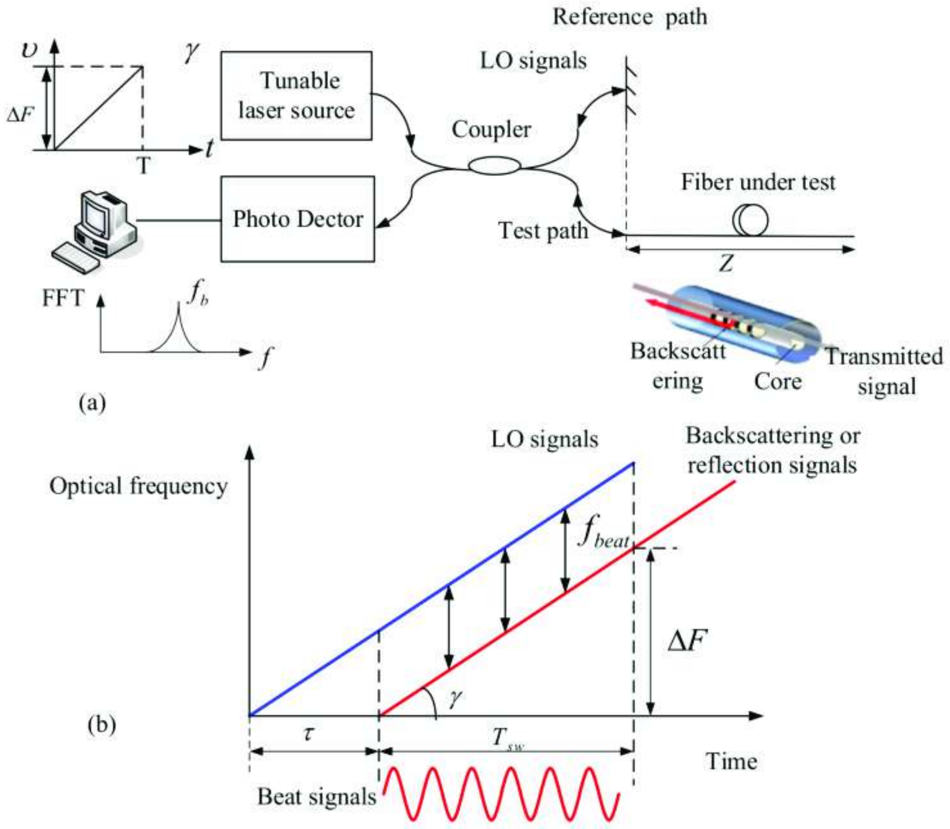
2. Distributed sensing in optical fibers: definition and types

- Types of Rayleigh scattering-based DOFS:
  - Incoherent optical time-domain reflectometry (OTDR)
    - OTDR finds the cut when it has already occurred



2. Distributed sensing in optical fibers: definition and types

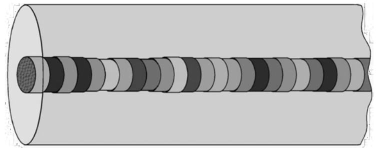
- Types of Rayleigh scattering-based DOFS:
  - Coherent optical frequency-domain reflectometry (OFDR)
- Typical performance:
  - Range: Few meters
  - Spatial resolution: 10 μm-cm's
  - Sampling rate: Hz
  - Temperature/Strain accuracy: 0.1ºC/ 1 με

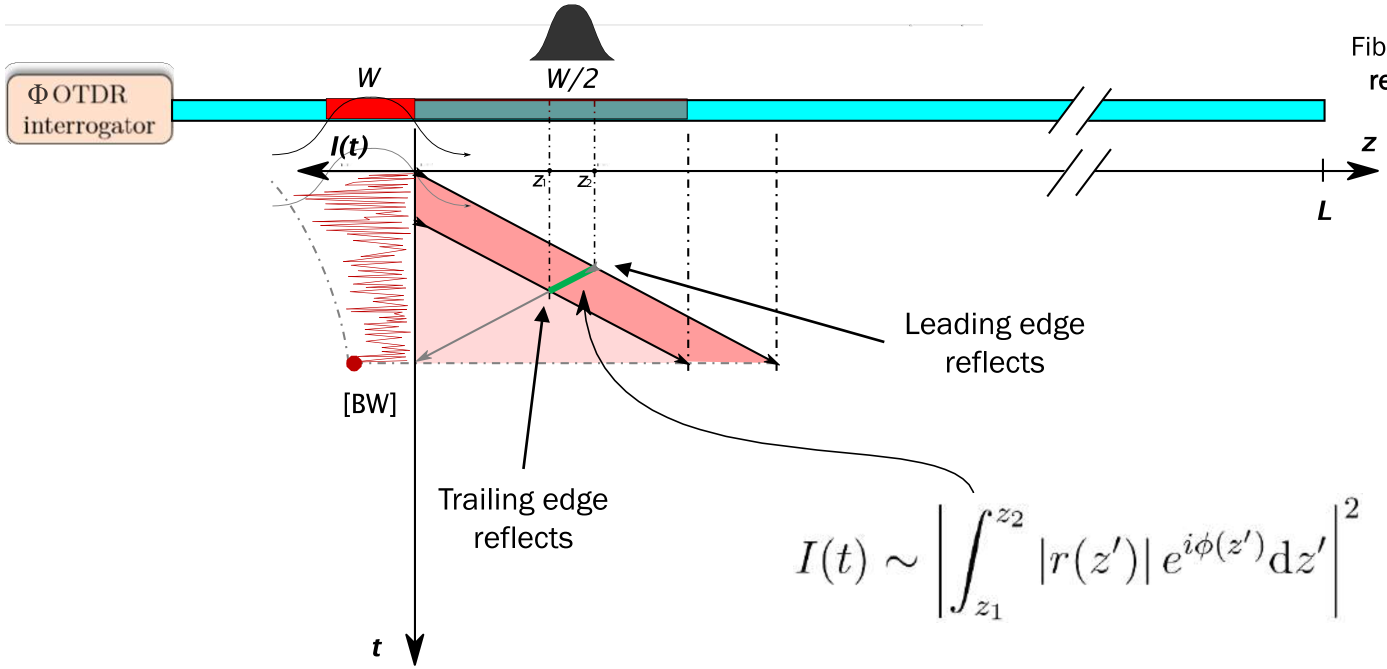


Reference: Ding, Z.; Wang, et al. Distributed Optical Fiber Sensors Based on Optical Frequency Domain Reflectometry: A review. *Sensors* **2018**, *18*, 1072.

2. Distributed sensing in optical fibers: definition and types

- Types of Rayleigh scattering-based DOFS:
  - Coherent (phase-sensitive) OTDR: ΦOTDR





$$I(t) \sim \left| \int_{z_1}^{z_2} |r(z')| \, e^{i\phi(z')} \mathrm{d}z' \right|^2$$

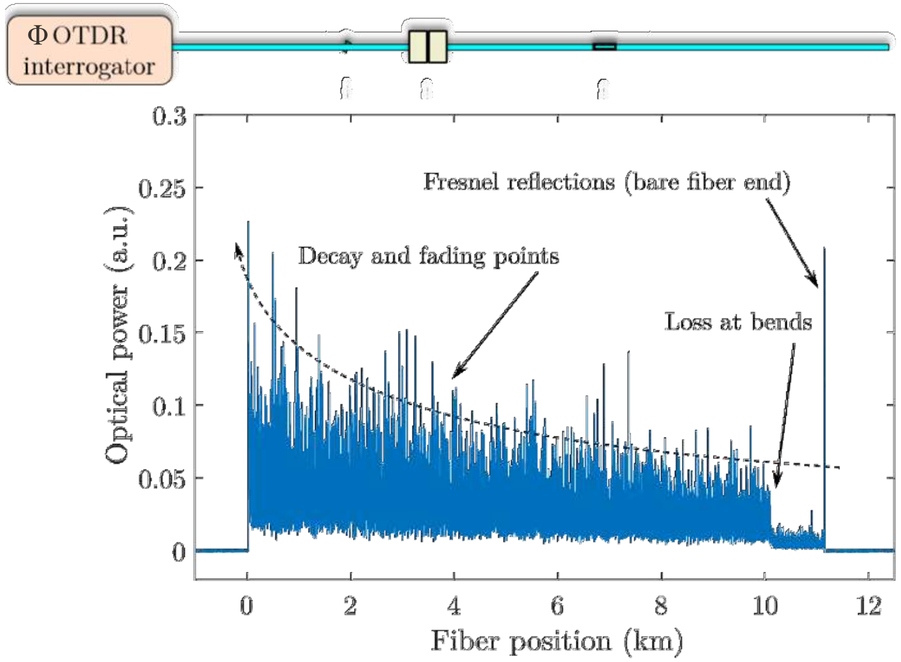
$$\phi(z') = \int_0^{z'} \frac{2\omega n(\xi)}{c} d\xi$$

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

Trace = physical state   Consecutive traces → *Continuous* monitoring

2. Distributed sensing in optical fibers: definition and types

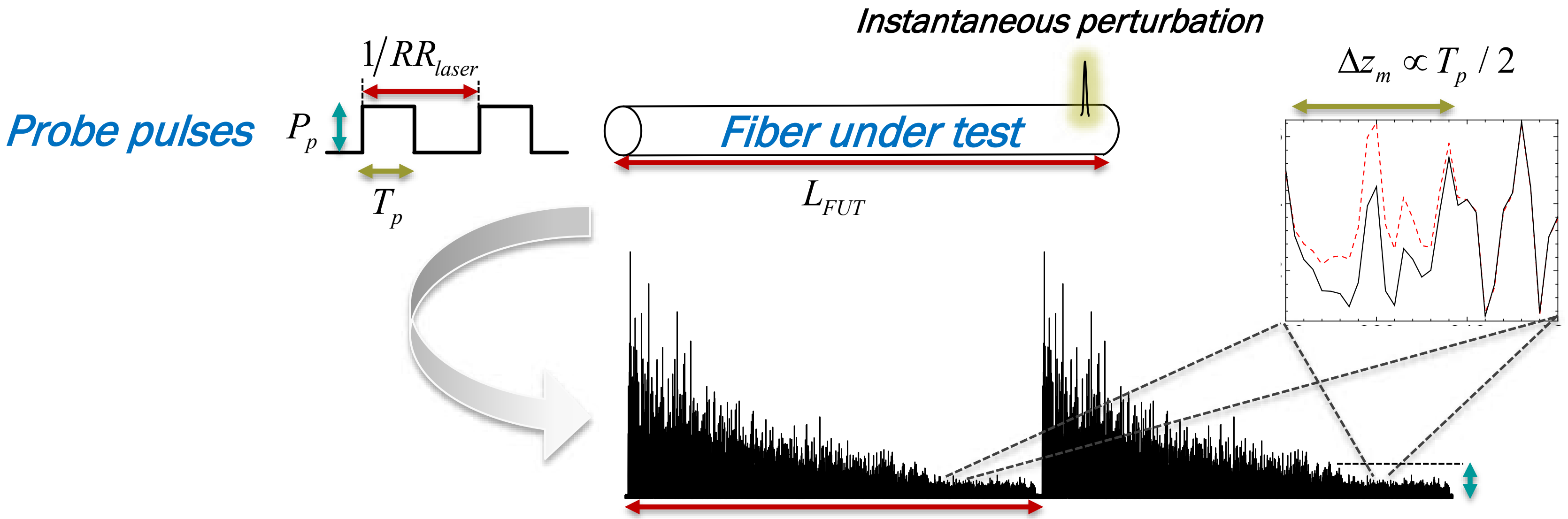
- Types of Rayleigh scattering-based DOFS:
  - Coherent (phase-sensitive) OTDR: ΦOTDR



- Coherence length > pulse length → illuminated region → becomes an interferometer!
- Fingerprint evolution from shot to shot under local fiber perturbations
- Signal from some regions **will sum-up zero → fading random points** of the final trace
- Provides relative measurements with respect to an initial state: ΔT or Δε !!

2. Distributed sensing in optical fibers: definition and types

- Typical performance of ΦOTDR:
  - Range: 40 km
  - Spatial resolution: few meters
  - Sampling rate: kHz
  - Temperature/Strain accuracy: 0,01ºC / 0,1 με



$$1/RR_{laser} = \frac{2nL_{FUT}}{c}$$

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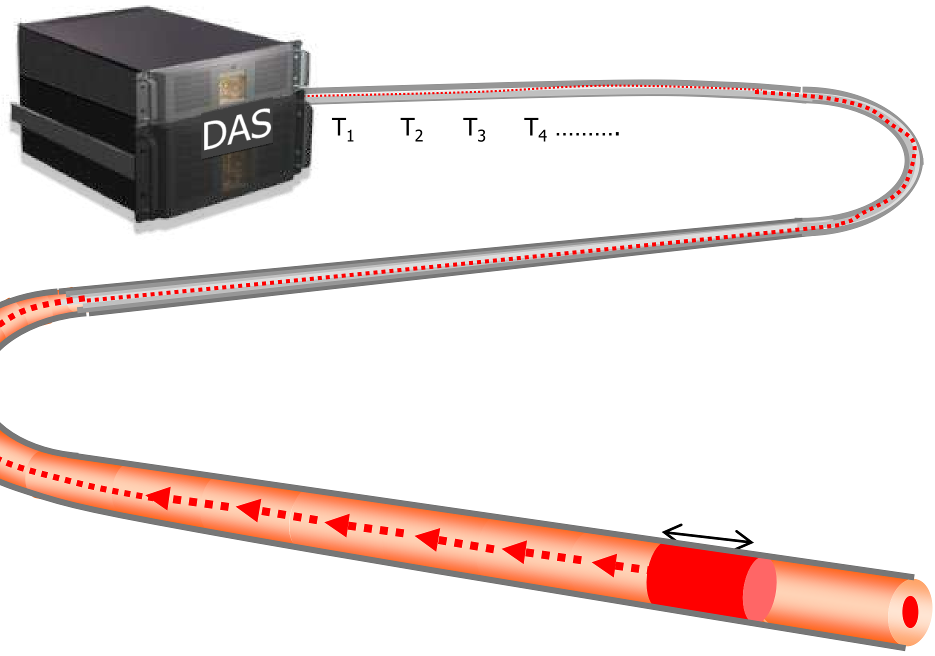
3. Distributed acoustic sensing (DAS)

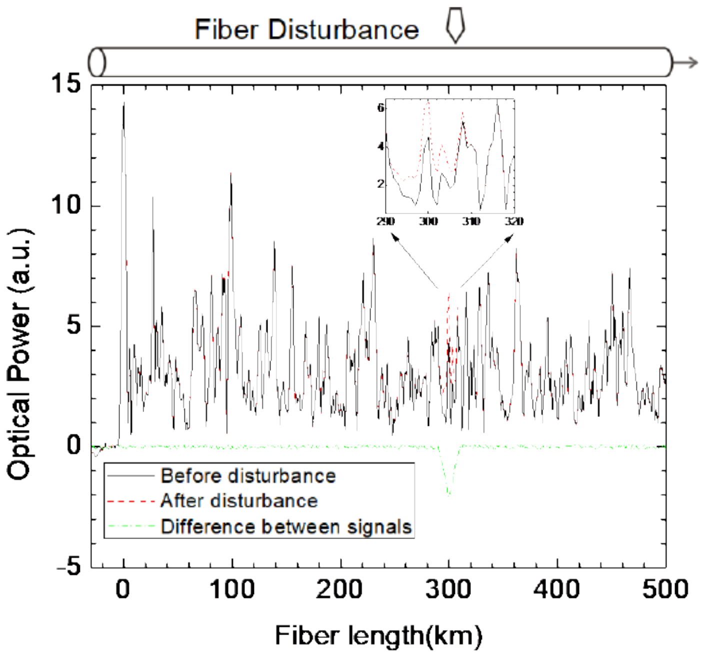
- What is a distributed acoustic sensor?

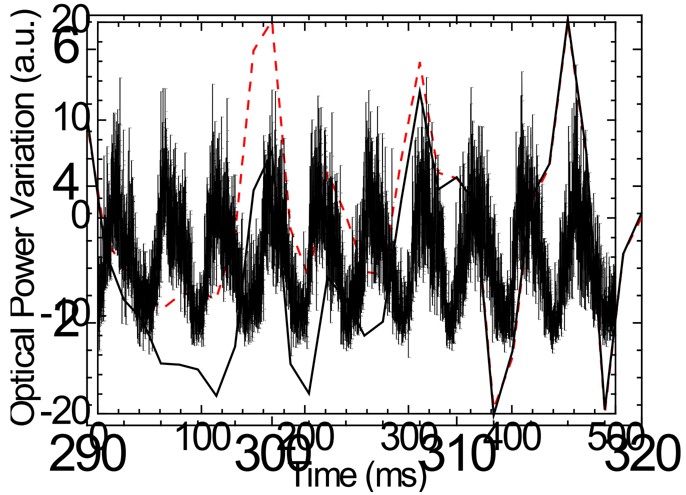


- Distributed optical fiber sensor where the interrogated fiber acts simultaneously as sensing element and transmission channel.
- DAS interrogator typically sends coherent light into the fiber and acquires and processes Rayleigh backscattering light.
  - Sampling frequency = pulse repetition rate < c/2nL (acoustic range, in the kHz regime)
  - **Dense network of distributed microphones**

3. Distributed acoustic sensing (DAS)

- Random pattern changes if perturbation occurs
- Localized **vibrations:** → Variations over time at that location synchronized with applied vibrations (but <u>the detected response is nonlinear</u>, and even <u>non-monotonic</u>!!)

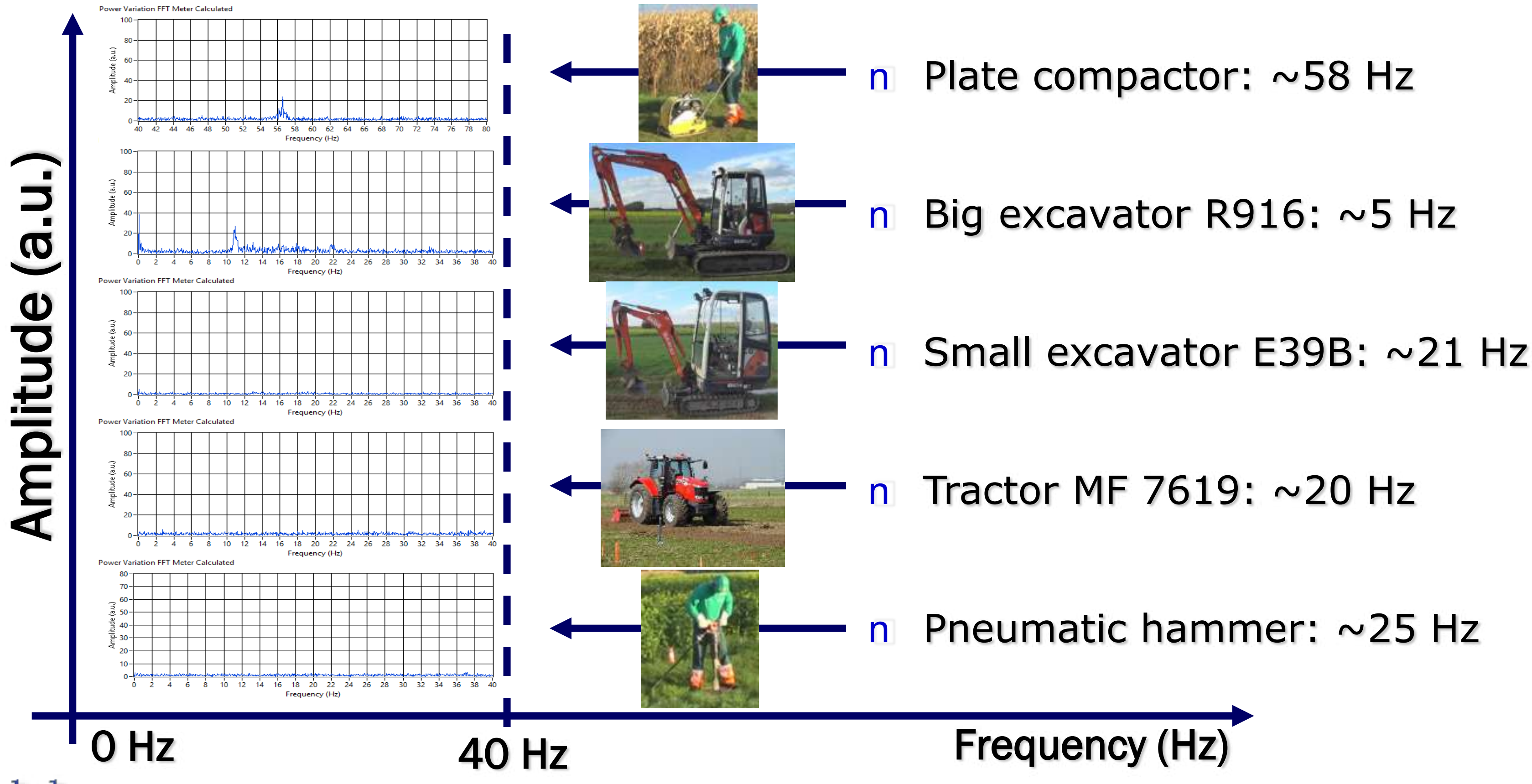




3. Distributed acoustic sensing (DAS)

- Development of AI to obtain RELIABLE threat/non-threat classification of the acoustic events

Different Machines/Activities = Different patterns → Distinction is possible

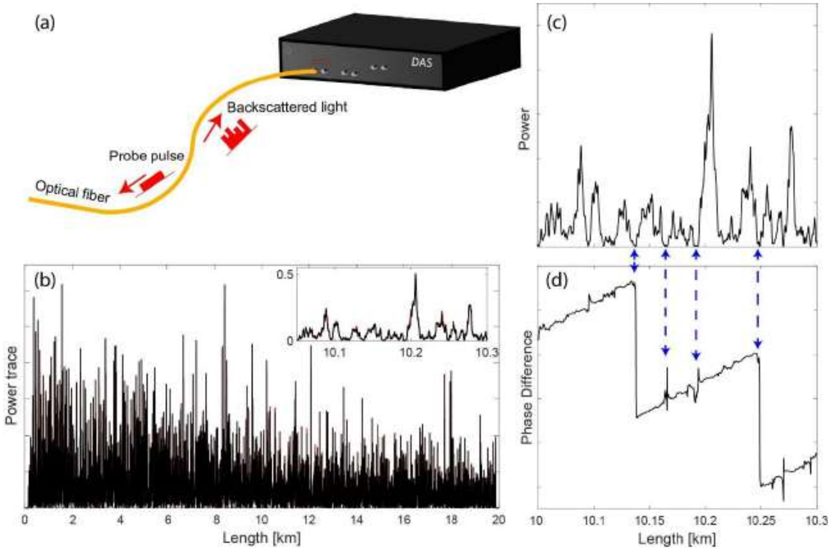


3. Distributed acoustic sensing (DAS)

- Linear strain/temperature determination suitable for **acoustic sensing**:
  - Phase-demodulation using coherent detection of traces $\phi(z') = \int_0^{z'} \frac{2\omega n(\xi)}{c} d\xi$ $\quad n = c_\varepsilon \Delta\varepsilon + c_T \Delta T$

But….

  - Shot-to-shot phase changes between consecutive points have to be **<2π**: trade-off between resolution and strain range.
  - **Phase unwrapping** is unstable with noise
  - High sensitivity to **fading** → Non stable SNR in all sensing points.



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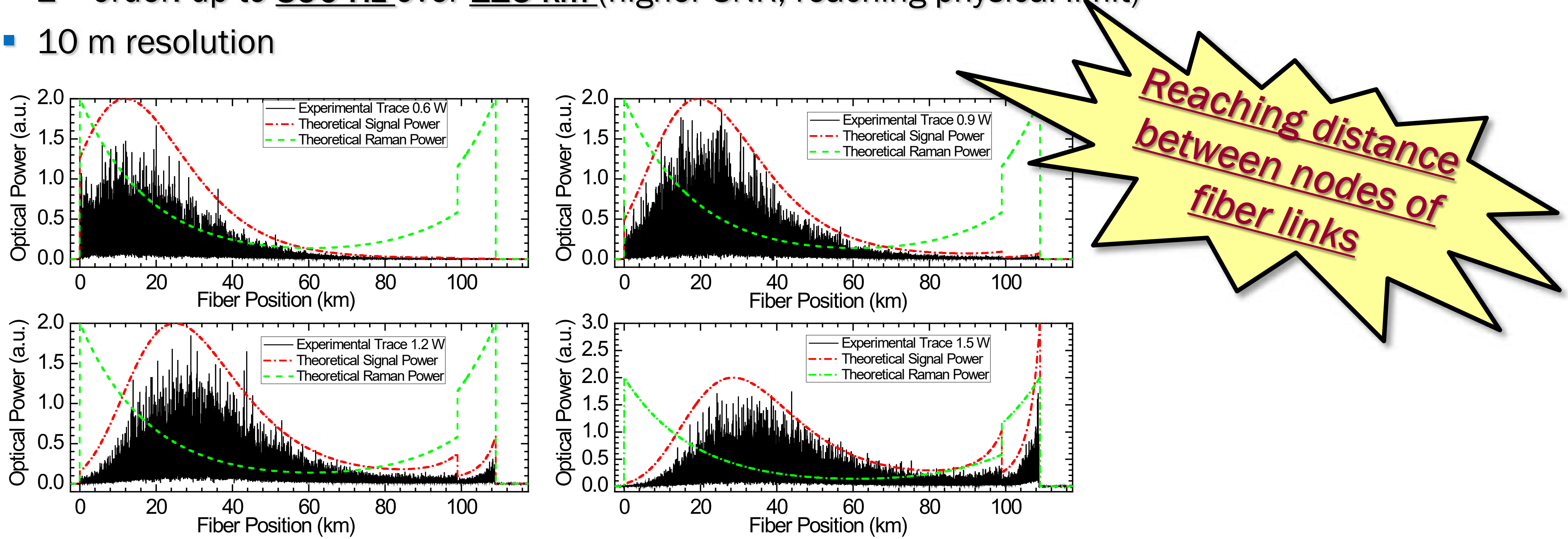
4. DAS in the University of Alcalá

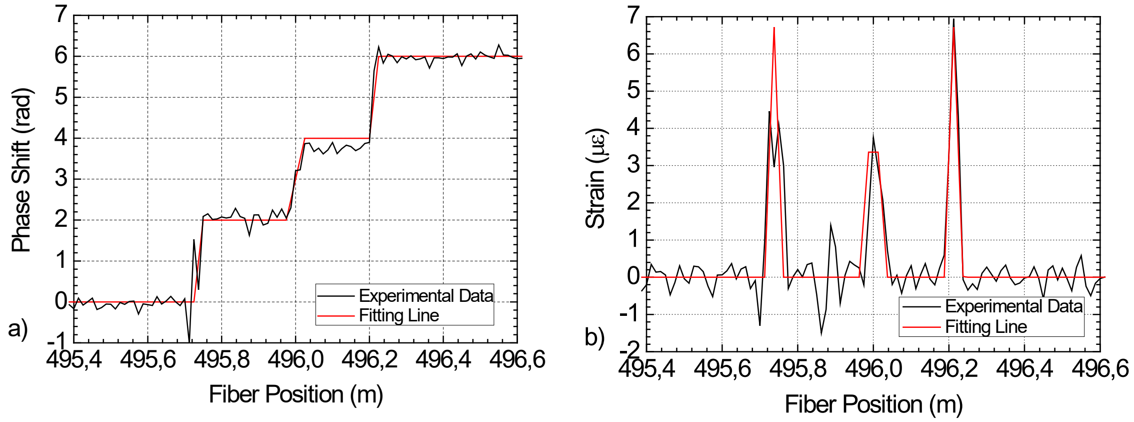
- Improvements with respect to typical performance:
  - Ranges of > 100 km reached using distributed Raman amplification
    - 1st order: up to 250 Hz over 125 km
    - 2nd order: up to 390 Hz over 125 km (higher SNR, reaching physical limit)
    - 10 m resolution

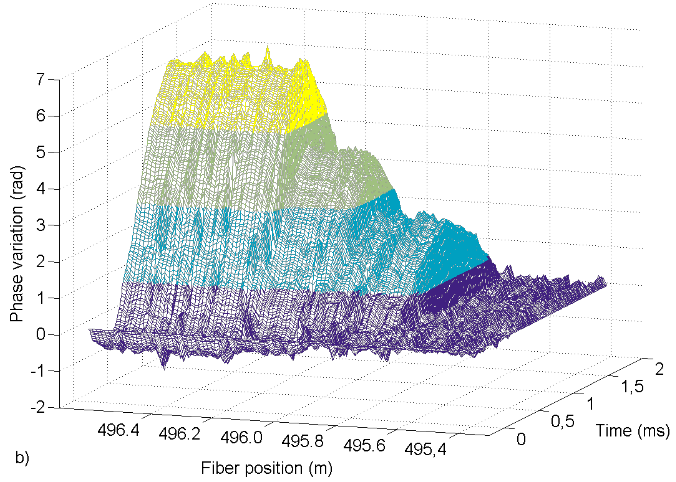


H. Martins et al., J. Lightw. Technol., **33** (12) 2628, (2014)

4. DAS in the University of Alcalá

- Improvements with respect to typical performance:
  - Spatial resolutions of < 1 m **have been reached using** pulse coding → live data of an operating optical communication channel (Binary PSK at 4 Gbaud).
    - 125 kHz over 500 m
    - 21 dB increase in SNR
    - 2.5 cm spatial resolution
    - Broad detection bandwidth (GHz) → Higher cost and noise

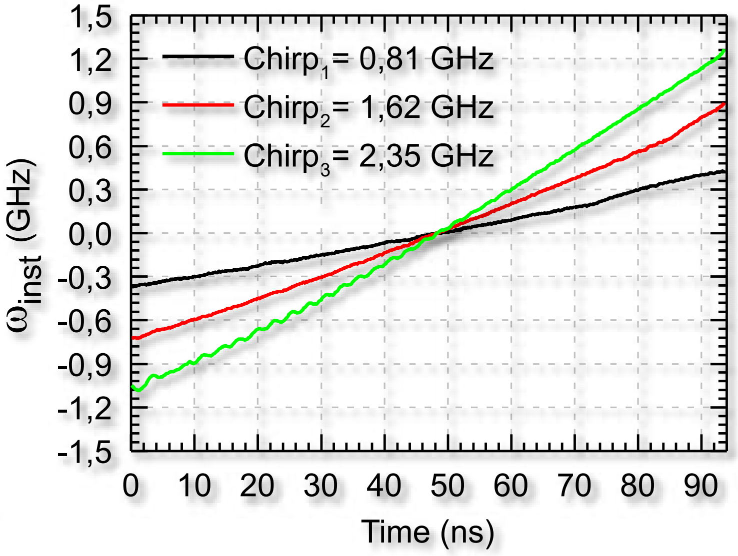




H. F. Martins et al.,
Opt. Express, **24** (19), 22303, (2016)

4. DAS in the University of Alcalá

- Improvements with respect to typical performance:
  - **Linear** temperature/strain determination using **direct detection** → **Chirped pulse DAS**
    - Insensitive to polarization/phase fading → Steady sensitivity
    - Phase noise compensation methods → Lower requirements in laser source
    - Broader detection bandwdith



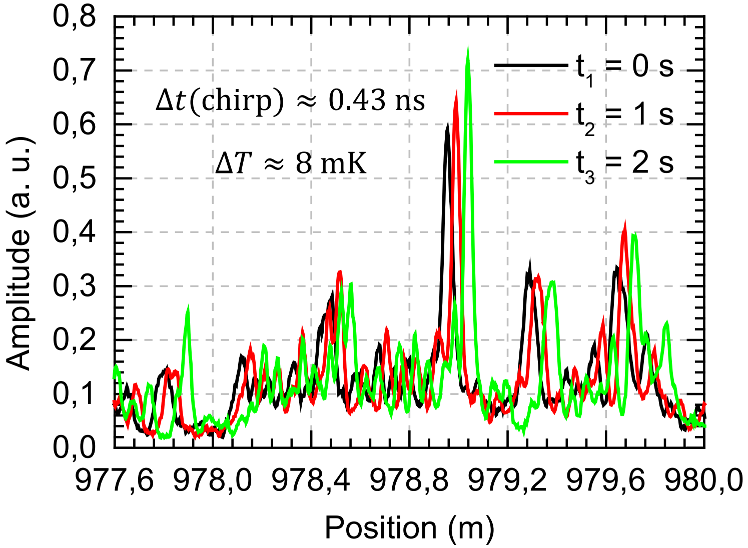
J. Pastor-Graells et al.,
Opt. Express, **24** (12) 13121, (2016)

4. DAS in the University of Alcalá

- ## Chirped pulse DAS
  - Trace recovery principle at each point:

$$\Delta n / n = -\left(1 / \nu_0\right) \cdot \left(\Delta \nu_p / \tau_p\right) \cdot \Delta t$$

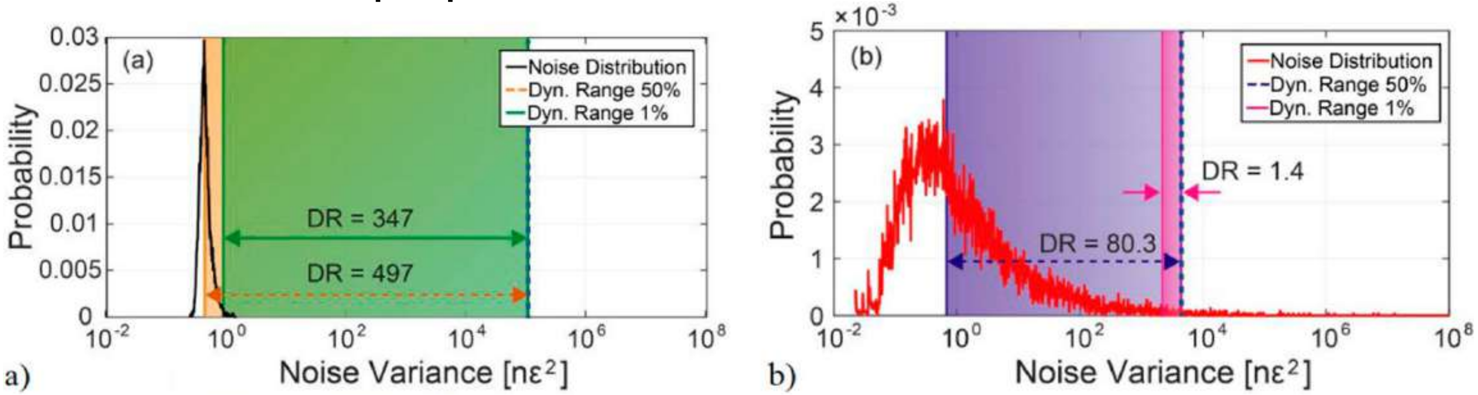
$$\Delta n / n = \Delta \nu / \nu_0 \approx -0.78 \cdot \Delta \varepsilon$$



J. Pastor-Graells et al., Opt. Express, **24** (12), 2016

Linear
Every shot ! → Dynamic!
Every point ! → Steady SNR
mK/nε resolution !

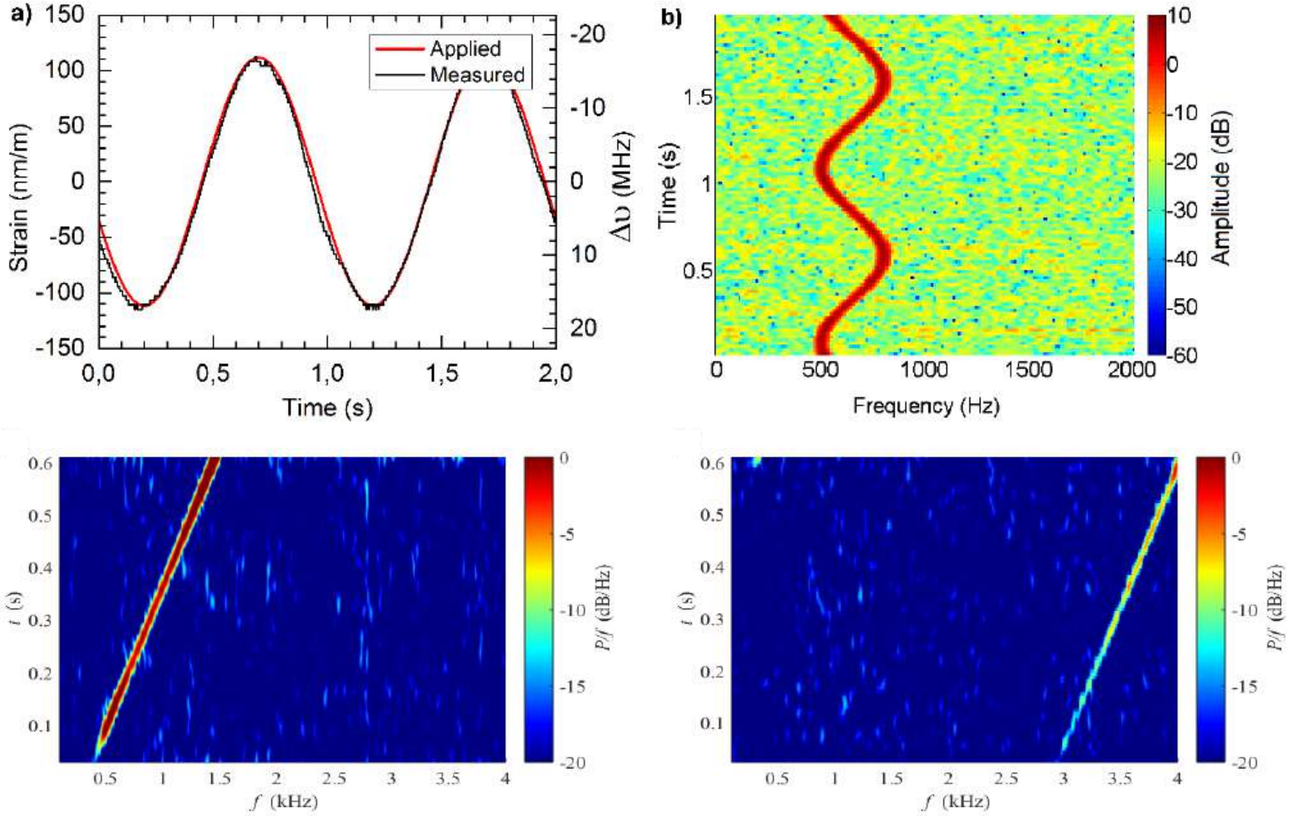
Chirped-pulse DAS vs. Phase demodulation DAS



M. R. Fernández-Ruiz et al., J. Lightw. Technol, **36** (23), 2018

4. DAS in the University of Alcalá

- **Chirped pulse DAS**
  - Good linearity and **extremelly high sensitivity (pε/√Hz)**:
  - **Excellent dynamics**: Tens of km range preserving the performance



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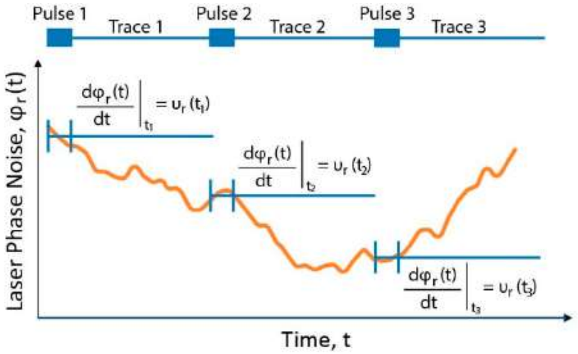
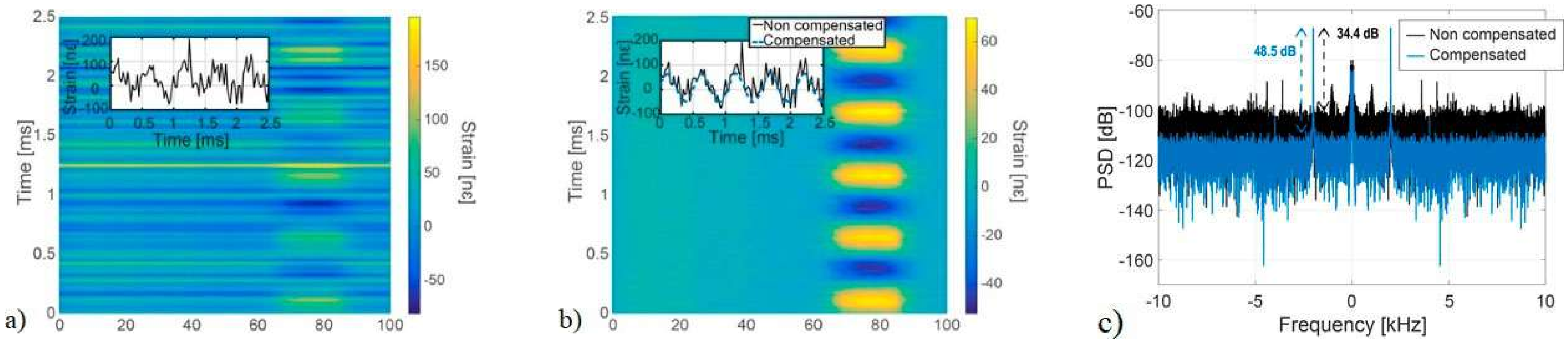
4. DAS in the University of Alcalá

- Chirped pulse DAS:
  - Phase noise compensation methods → Lower requirements in laser source



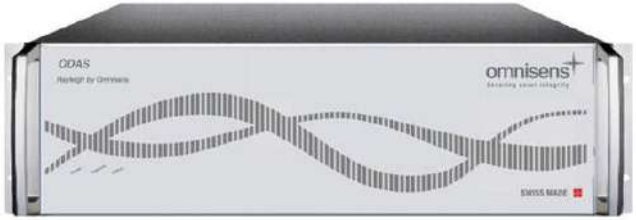


M. R. Fernández-Ruiz et al., J. Lightw. Technol, **36** (4), 2017

4. DAS in the University of Alcalá

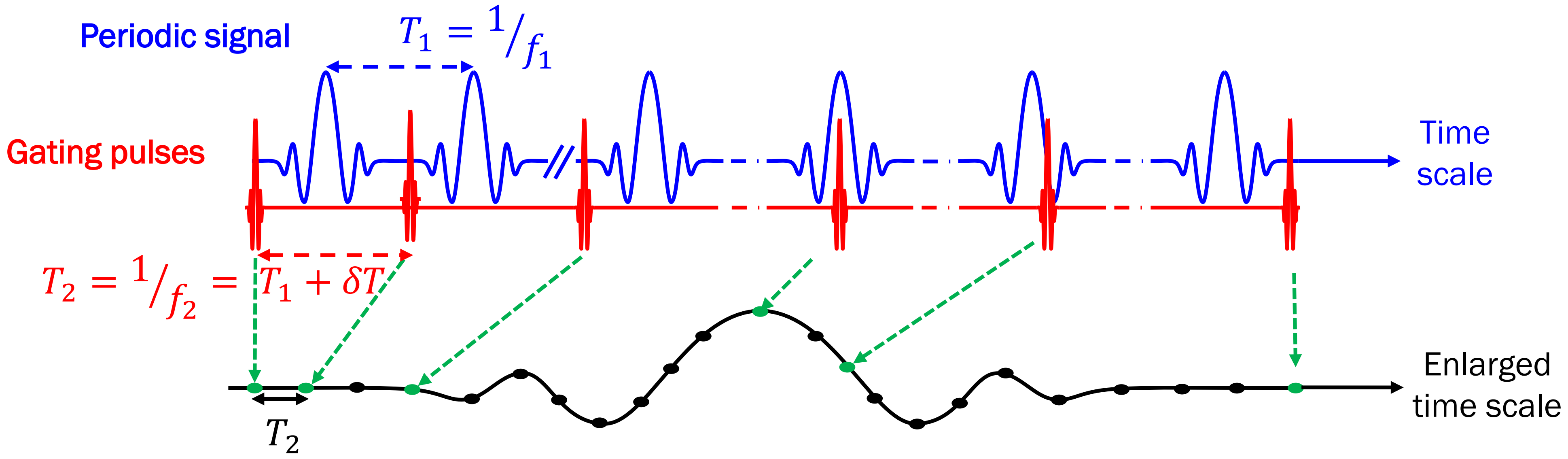
- **Chirped pulse DAS - Summary:**
  - Insensitive to fading noise → Steady sensitivity
  - Phase noise compensation methods → Lower requirements in laser source
  - Use of technique typically employed in time-delay estimation (TDE) techniques → Record sensitivity for a long-range DOFS
  - Broader detection bandwdith → Need for 10x time-bandwidth product pulses

  - These features have made chirped-pulse DAS a highly competitive technology currently commercialized by:
    - ARAGÓN PHOTONICS (Spain)
    - omnisens Securing asset integrity (Switzerland)



4. DAS in the University of Alcalá

- Improvements with respect to typical performance:
  - **High spatial resolution** using ultra-narrow band detection → **Time-expansion DAS**
    - Based on **dual comb spectroscopy** concepts: Optical sampling



The result is a discretized version of the periodic signal, with a period that can become enlarged by orders of magnitude

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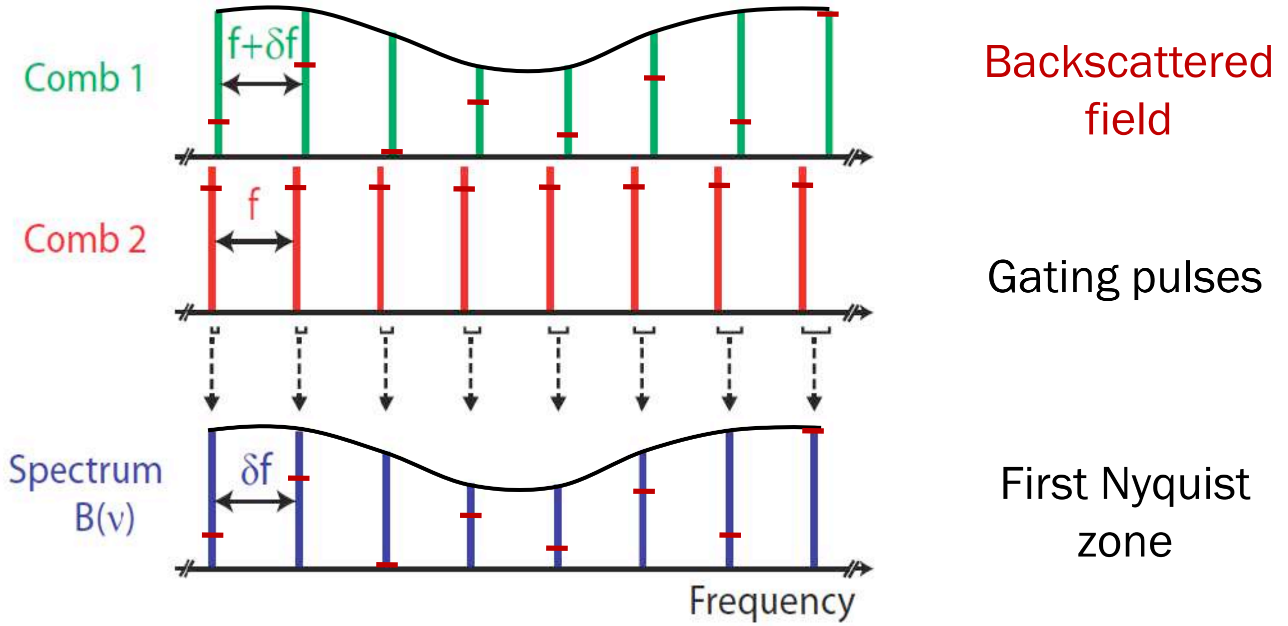
4. DAS in the University of Alcalá

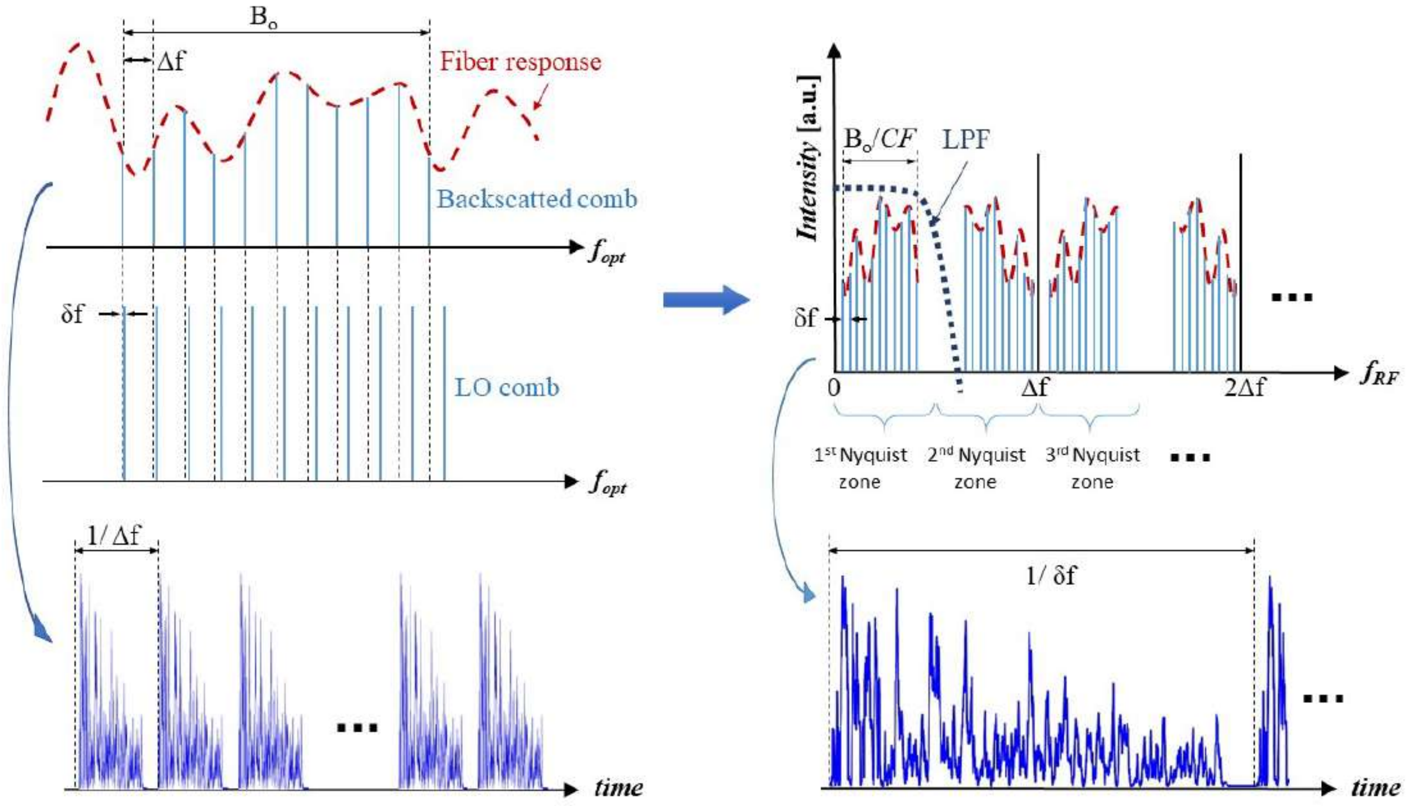
- Improvements with respect to typical performance:
  - **High spatial resolution** using ultra-narrow band detection → **Time-expansion DAS**
    - In spectral domain:



The above down-conversion is governed by the compression factor (CF) given by $CF = f/\delta f$.

4. DAS in the University of Alcalá

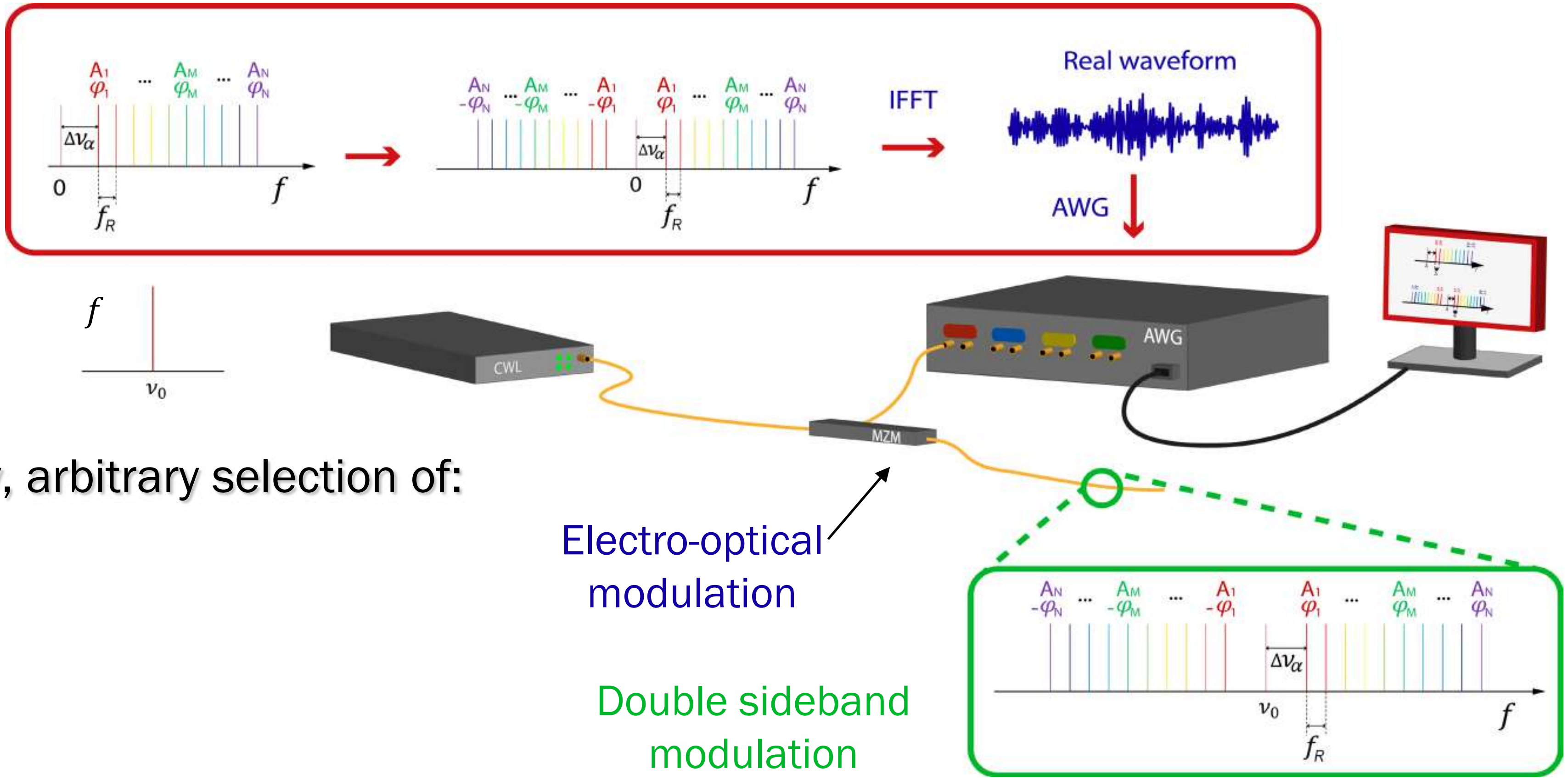
- Improvements with respect to typical performance:
  - **High spatial resolution** using ultra-narrow band detection → **Time-expansion DAS**



M. Soriano-Amat., Ligth: Sci & App. **10** (51), 2021

4. DAS in the University of Alcalá

- Programable optical frequency combs:
  - Arbitrary waveform generator (AWG) → $$$
  - RF-SoC based on field programable gate array (FPGA) → Under study



- Excellent flexibility, arbitrary selection of:
  - Frequency ν_i
  - Amplitude A_i
  - Phase φ_i

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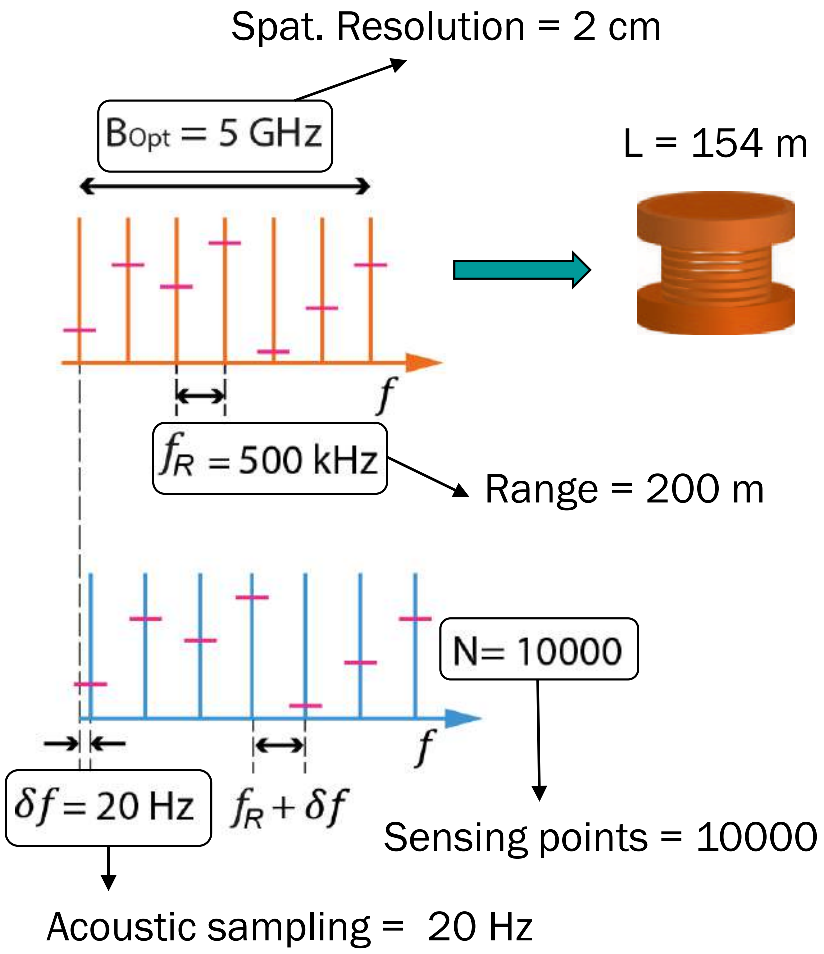
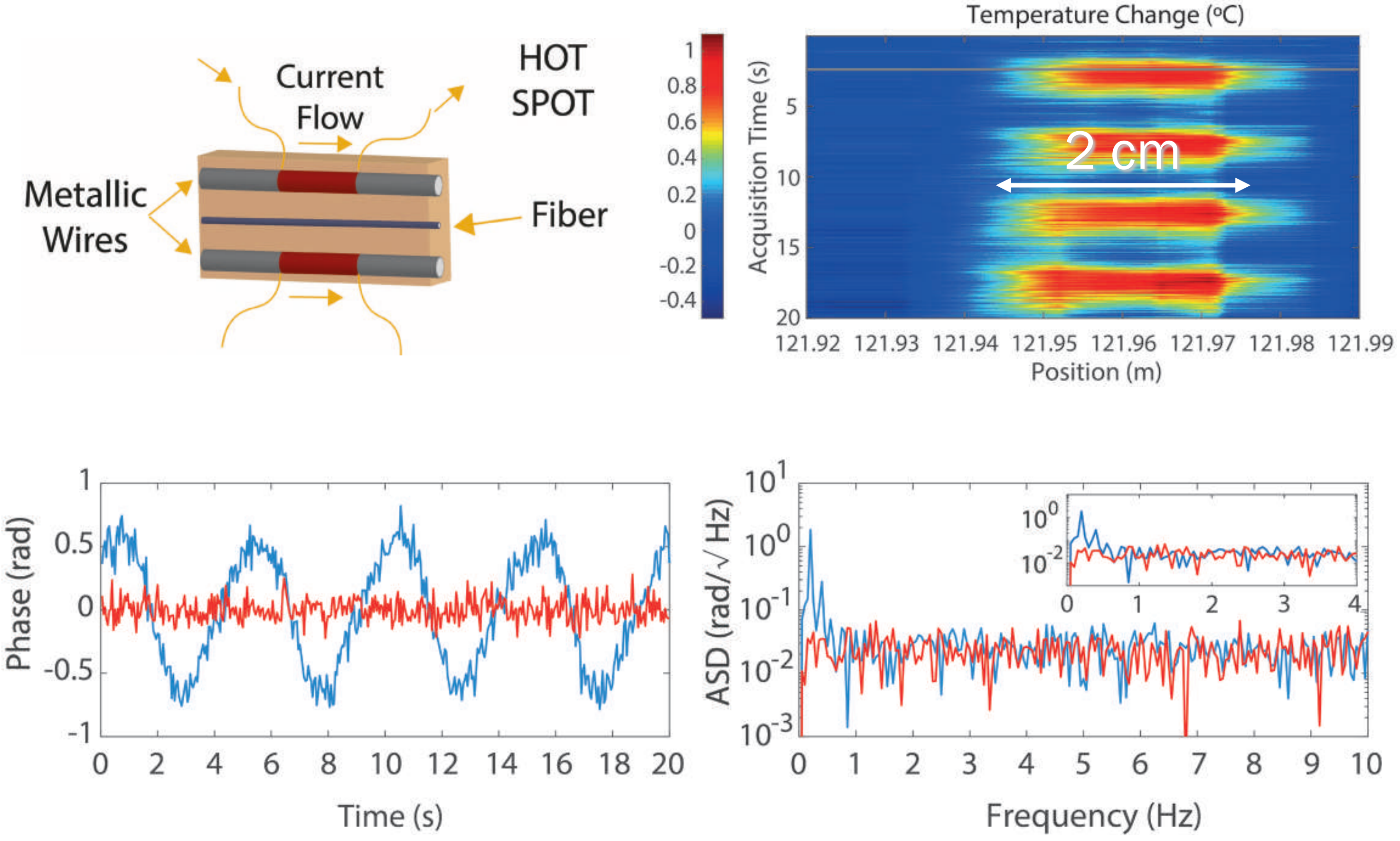
4. DAS in the University of Alcalá



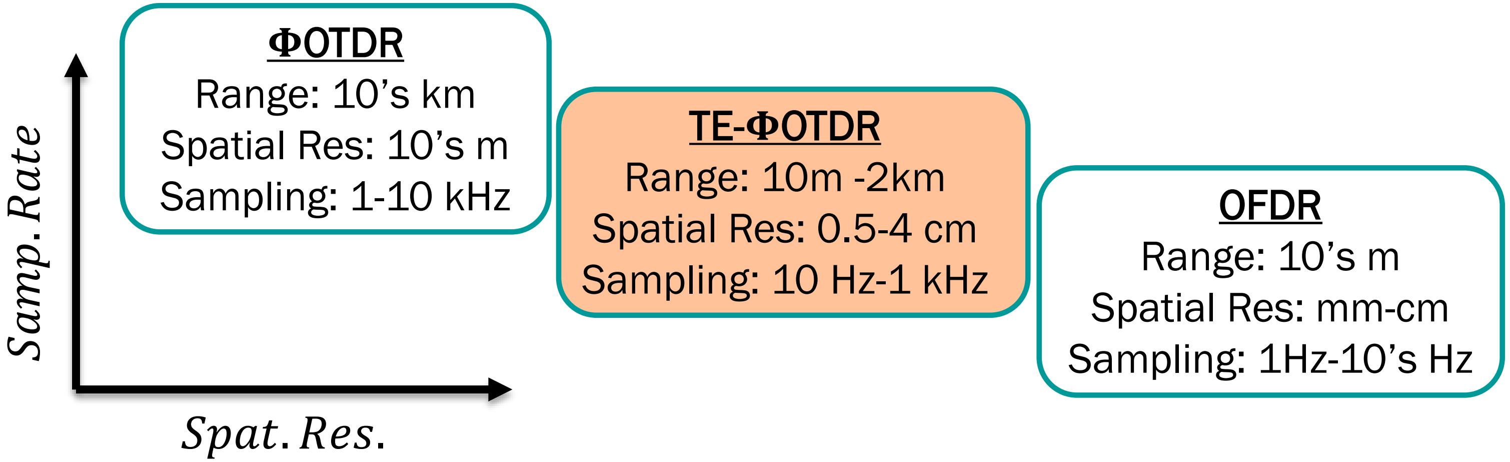


- **Detection bandwidth is 200 kHz !!!**

Accuracy = 0.09 rad (55 mK, 490 $n\epsilon$)

4. DAS in the University of Alcalá

- **Time-expansion DAS - Summary:**
  - TE-ϕOTDR technology arises as a novel optical fiber interrogation method that covers a performance gap between OFDR and ϕOTDR technologies.

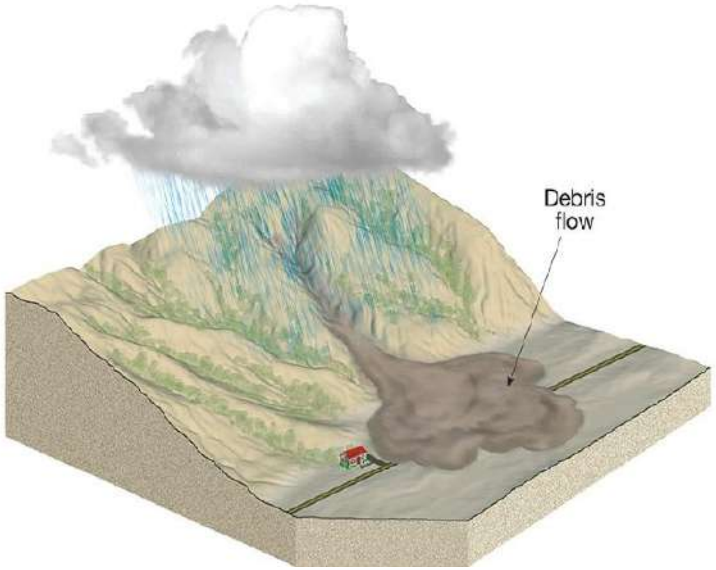


  - Fibers of hundreds of meters (500 m) could be monitored dynamically (1 kHz sampling rate) with centimeter spatial resolution (2 cm) with low-detection bandwidth (sub-MHz).
  - Such performance may open the door for the use of DAS to entirely new areas of application, e.g., aeronautics, medicine, transportation, manufacturing, etc.
  - Technology patented by ARAGÓN PHOTONICS

Table of contents

5. Applications of DAS

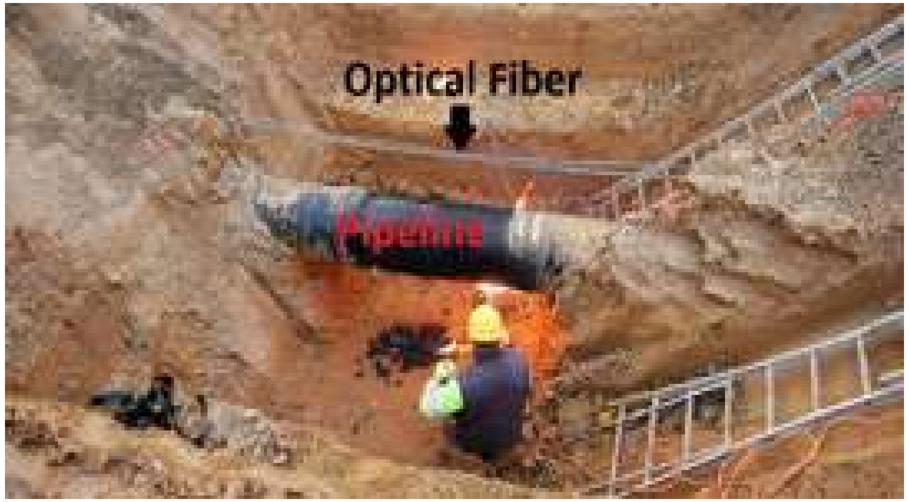
- UAH projects:
  - DOMINO: Dikes and debris flows monitoring by novel optical fiber sensors
    - European research project that aims at developing novel optical fiber sensors for the monitoring of dikes and debris flows.

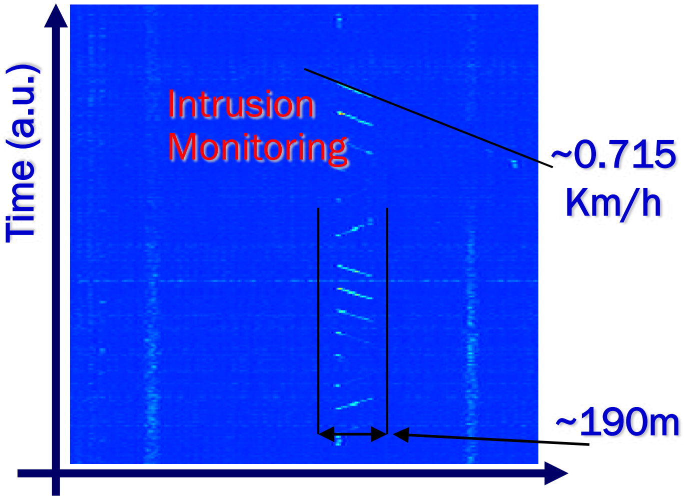


https://domino.dei.unipd.it/

5. Applications of DAS

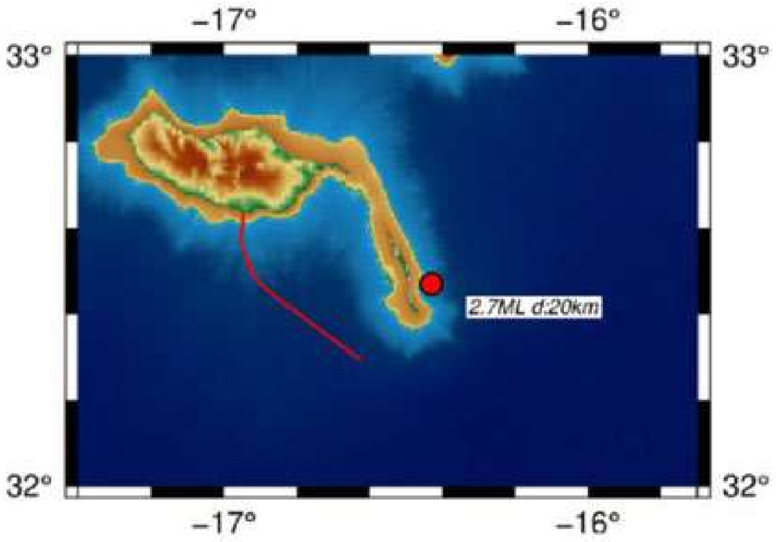
- UAH projects:
  - PIT-STOP: Detección Temprana de Amenazas a la Integridad de Gasoductos usando Tecnología de Fibra Óptica
    - Use of a non-linear DAS to monitor potential threats (e.g., movements of heavy machinery) nearby a gas pipeline

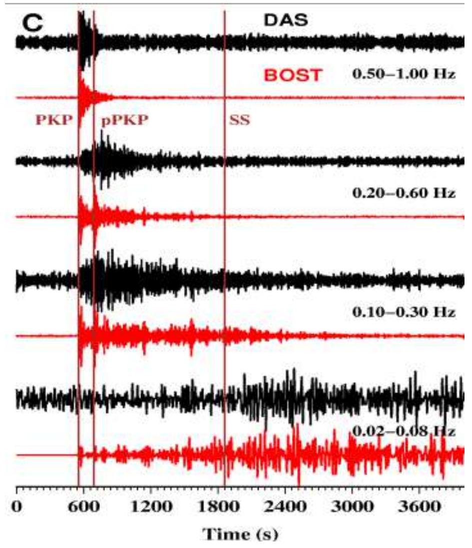




5. Applications of DAS

- UAH projects:
  - SUBMERSE: Submarine cables for research and exploration
    - EU-funded project which aims to utilise existing submarine cables, already used by the research and education networking community, to monitor the Earth and its systems: seismology, continental plate movement, etc.

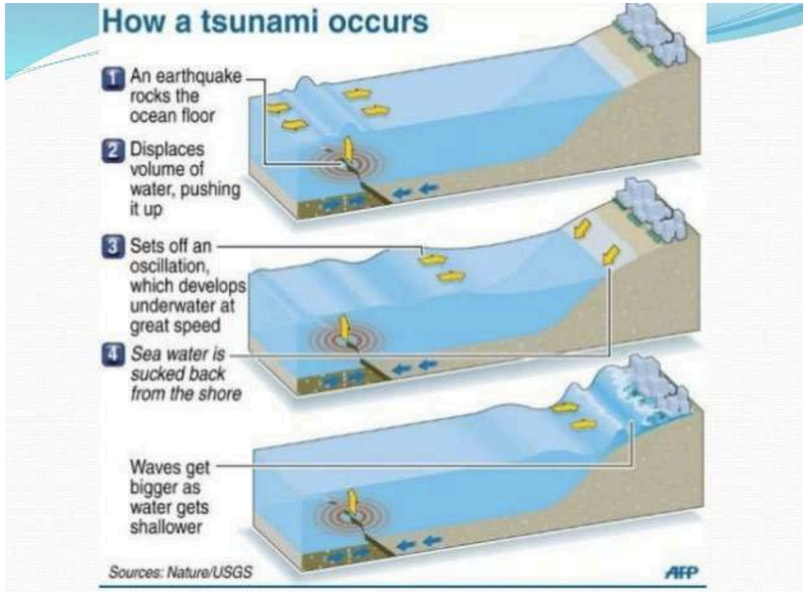




https://submerse.eu/

5. Applications of DAS

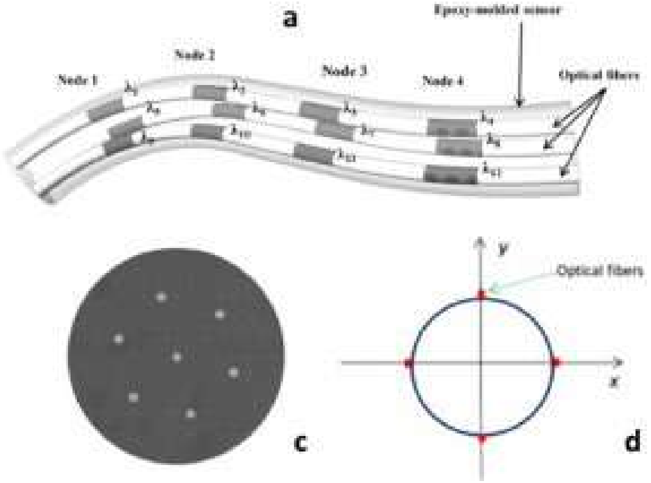
- UAH projects:
  - SAFE: Tsunami early warning system using available seafloor fiber cables
    - EU-funded project that targets the repurpose of already-available fiber-optic cables installed for communication purposes as key sensor for tsunami early warning at a marginal extra cost.



https://cordis.europa.eu/project/id/101098992

5. Applications of DAS

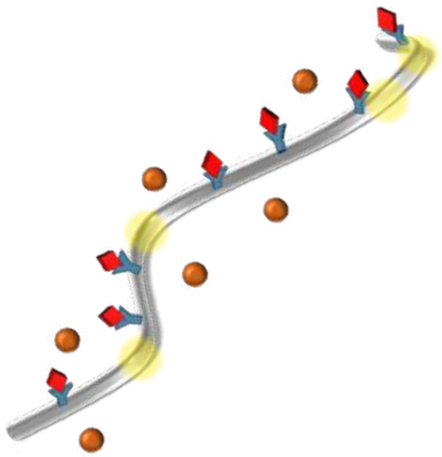
- UAH projects:
  - SEASNAKE+: Industrial upscale of surface protection system & fibre optic-based condition monitoring for the SEASNAKE MVC (Medium Voltage Cables)
    - EU-funded project that uses of TE-DAS for implementation of **distributed, dynamic shape sensing**

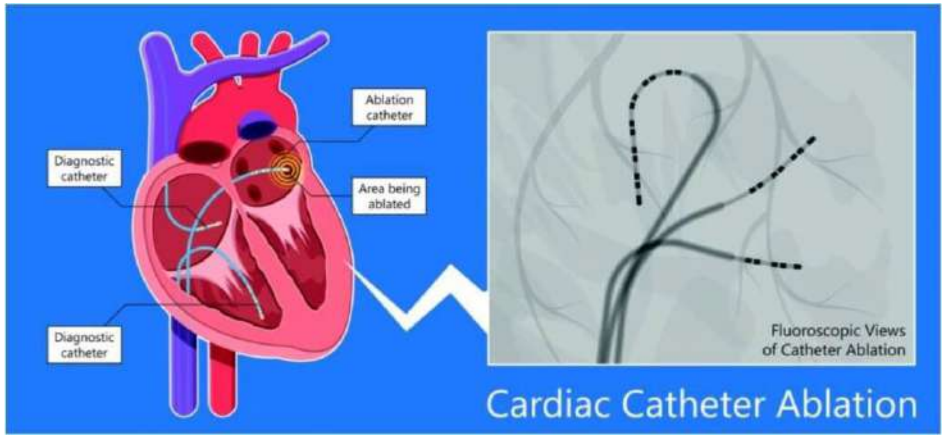


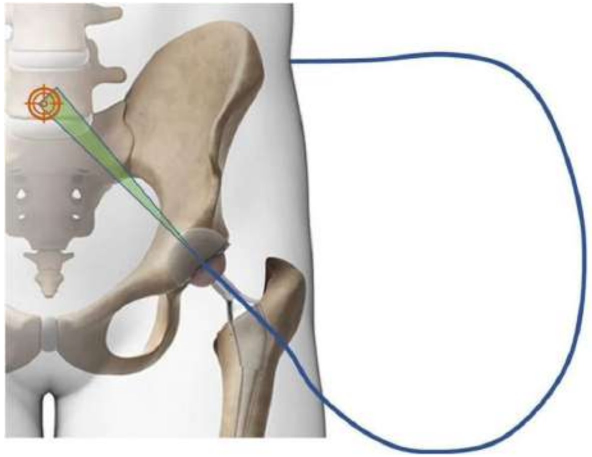
https://cetpartnership.eu/index.php/calls/funded-project/seasnake

5. Applications of DAS

- UAH projects:
  - MOTION: Sondas para instrumentación inteligente basadas en sensado acústico distribuido de tiempo expandido
    - National-funded project that uses of TE-DAS for implementation of **distributed, dynamic shape sensing** on specialty fibers engineered to also perform **chemical sensing**.



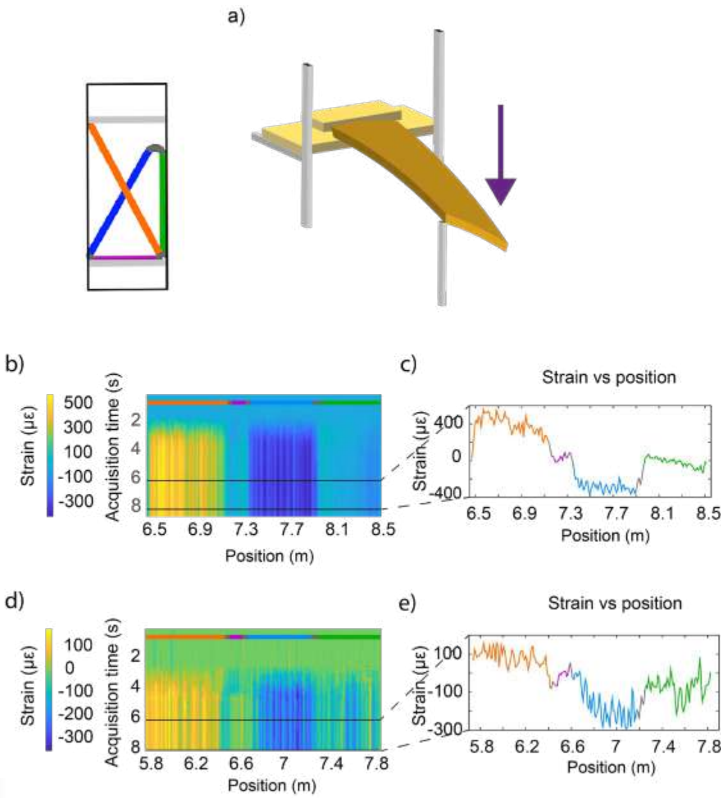


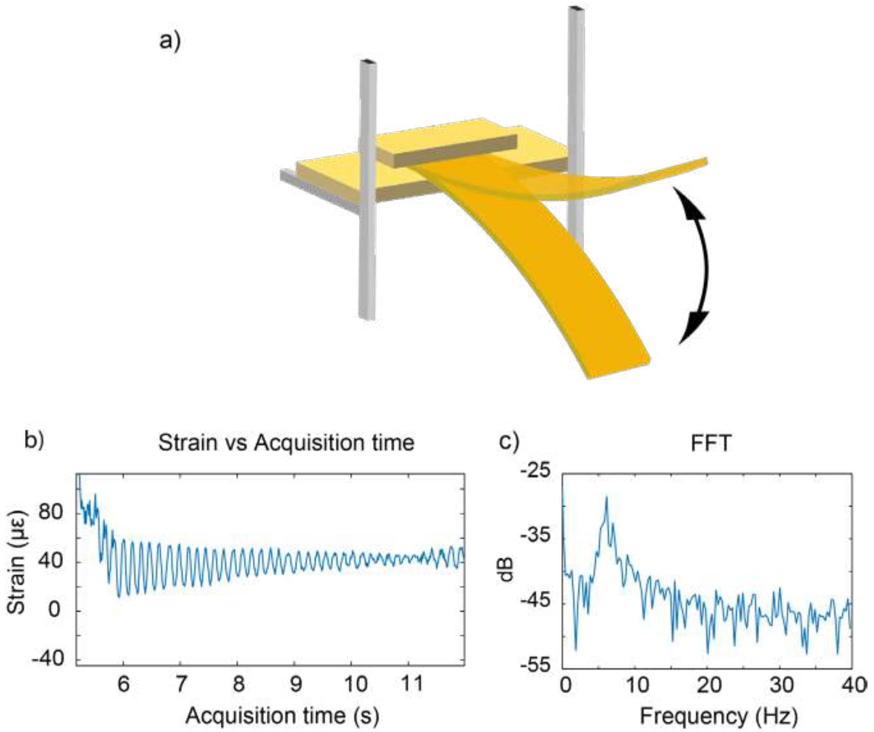


Reference: https://shapesensing.com/fiber-optic-medical-applications/

5. Applications of DAS

- Lab tests:
  - Monitoring of the flexible wing of an unmanned aerial vehicle (UAV), in colaboration with Capgemini S.L.





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6. Conclusions

- A distributed optical fiber sensor (DOFS) is capable of measuring the spatial distribution of one or more physical parameters (or measurands) at each and every point along a sensing fiber.
- Today, DOFS systems have gained widespread usage, primarily for real-time monitoring of the structural integrity of expansive civil infrastructures and the changes in environmental conditions.
- A distributed acoustic sensor (DAS) is a DOFS with a sampling rate in the acoustic regime.
- Recent developments in UAH target:
  - **Linear DAS** with steady (robust against fading noise) and ultra-high sensitivity along tens of kilometers of fibers
  - **Ultra-high spatial resolution DAS** with low-cost and low-power consumption scheme, covering a gap between state-of-the art DAS in the market.
  - Analysis and adaptation of DAS for its use in **novel areas of application**

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Acknowledgements

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Thank you for your attention!