Signal Fading in Distributed Acoustic Sensors: Analysis and Mitigation Strategies

Ali Masoudi

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In this presentation

1. Introduction to distributed optical fibre sensing technology
    - Single-point and multiplexed sensing systems VS. Distributed sensing systems
    - Operating principle of distributed optical fibre sensing systems
2. Distributed optical fibre acoustic sensors (DAS)
    - Operating principle of DAS systems
    - Basic DAS sensing setup
3. Signal fading in DAS systems and mitigation strategies
    - Signal fading and its effect of DAS systems
    - Signal fading mitigation techniques & their implementations
4. Applications of DAS systems
    - Subsea high-voltage cable condition monitoring
    - Railway condition analysis
    - Seismology

1 Classification of Sensing Systems

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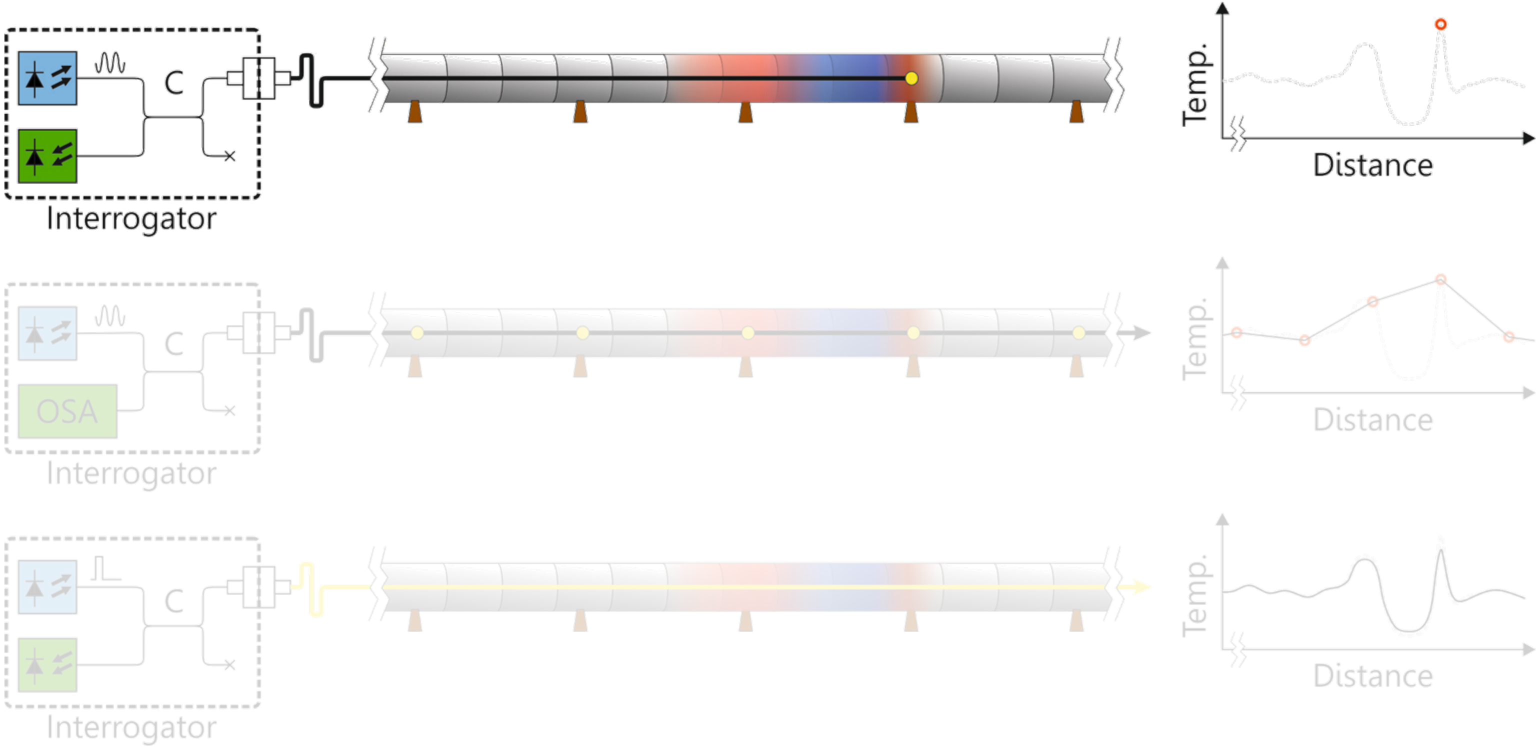
Optical Fibre Sensing Systems fall into 3 categories:

a Point Sensor

b Quasi-Distributed Sensor

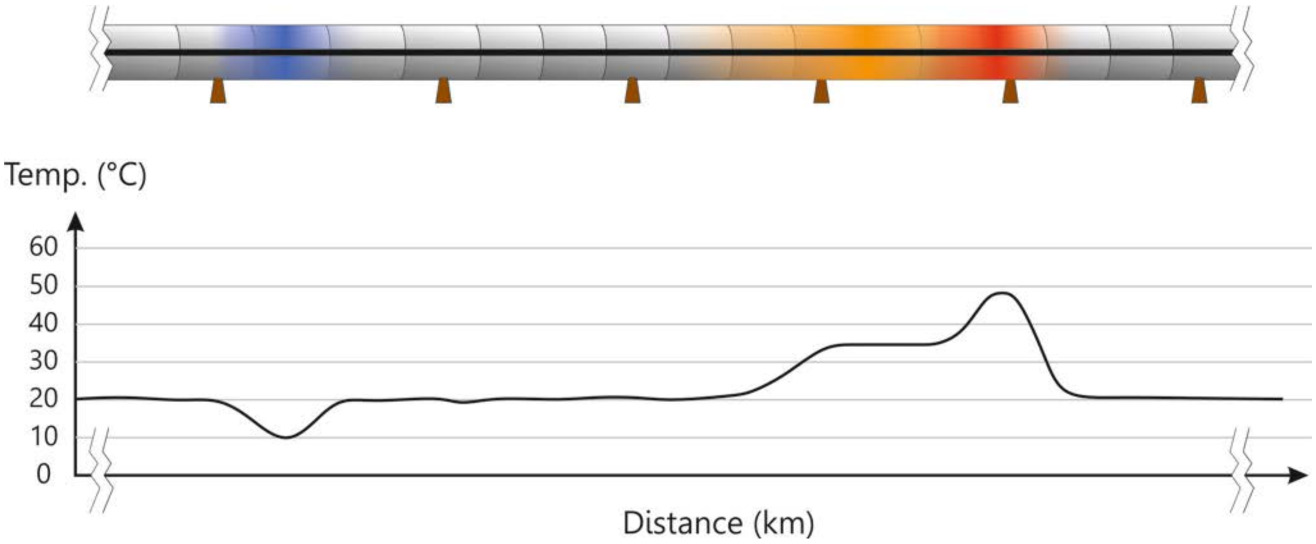
c Distributed Sensor



1 Distributed Optical Fibre Sensing (DOFS)

A distributed optical fibre sensing (DOFS) system is defined as an intrinsic sensor that is able to determine the spatial distribution of one or more physical parameters such as temperature and vibrations at each and every point along an optical fibre.

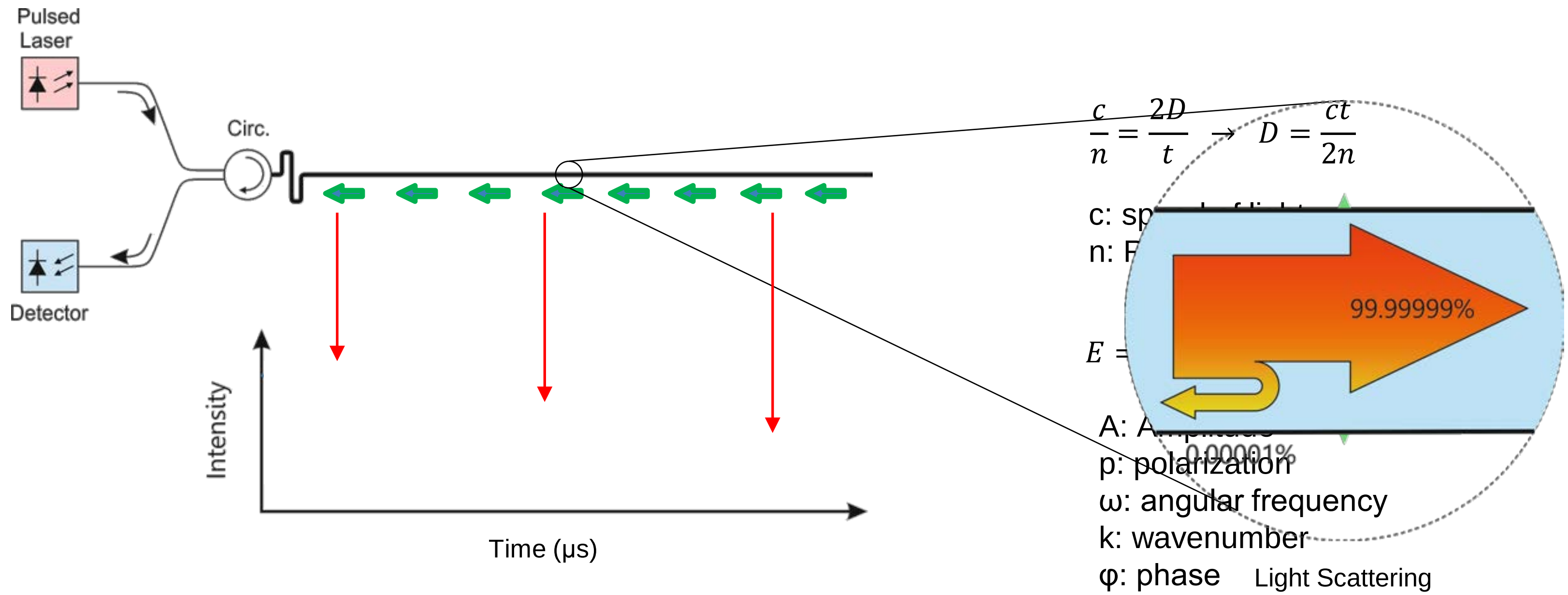
The following figure shows what is expected from a DOFS:



Distributed Optical Fibre Sensing (DOFS)

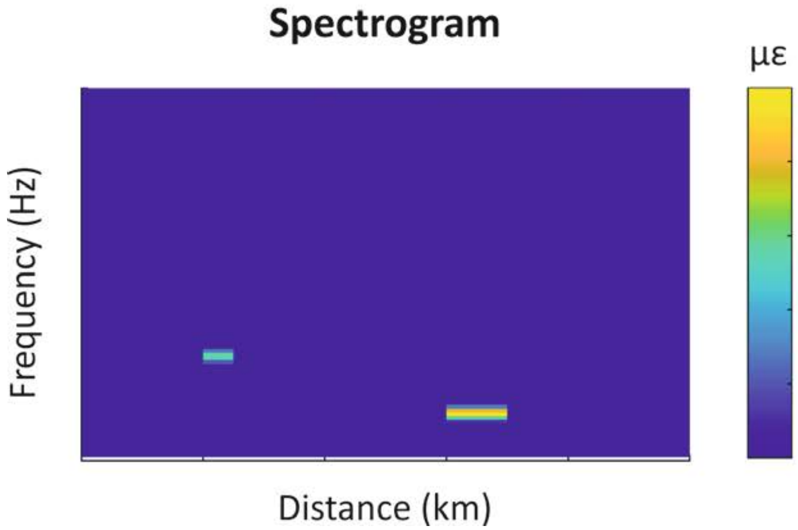
A distributed optical fibre sensing (DOFS) system is defined as an intrinsic sensor that is able to determine the spatial distribution of one or more physical parameters such as temperature and vibrations at each and every point along an optical fibre.

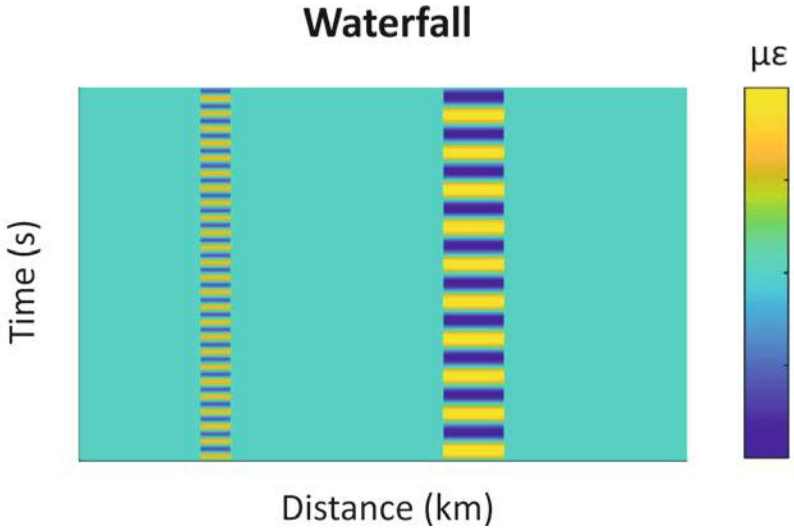
Here is how it works:



Distributed Acoustic Sensor Output

A Distributed Acoustic Sensor measures vibration at each point on the sensing fibre. The output of DAS is visualised in a waterfall plot or a spectrogram. Waterfall plot shows strain variation as a function of time while spectrogram shows frequency content of the vibrations.





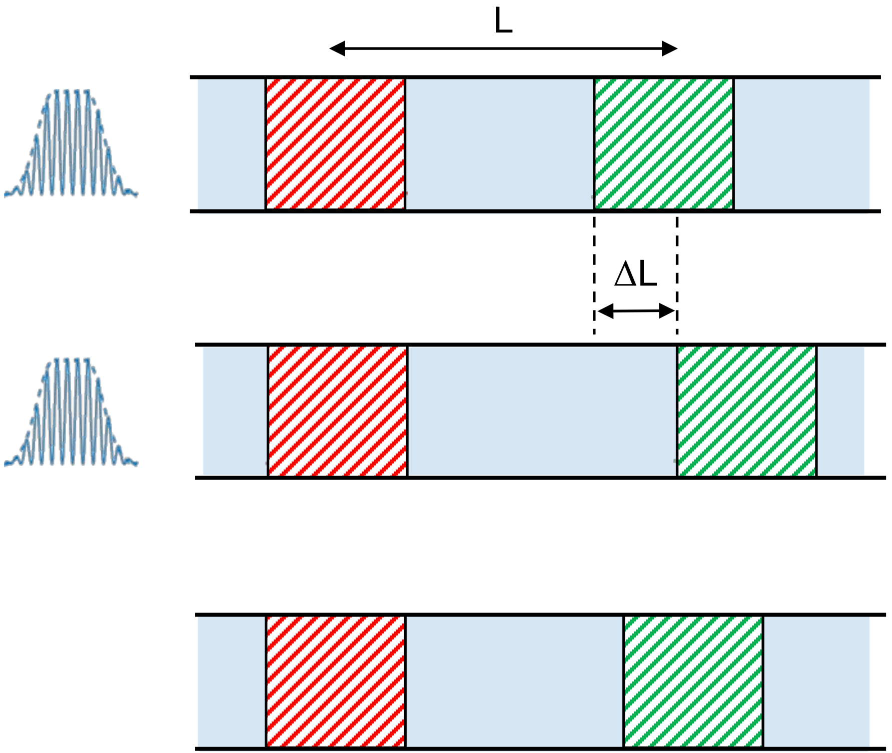
2 Sensing Procedure

By comparing the changes in the phase-difference of the Rayleigh backscattered light from two regions of sensing fibre, L meters apart, the changes in the length of that section of the fibre can be very accurately measured.

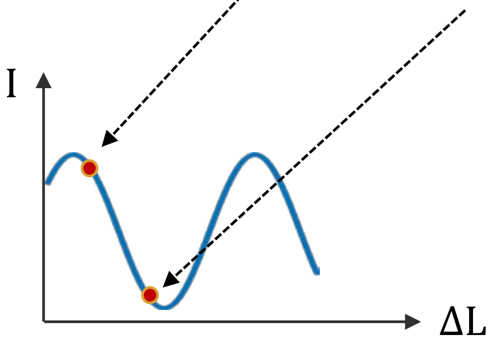
$$\Delta\varphi = \varphi_1 - \varphi_2 = \xi \frac{2\pi n}{\lambda} 2L$$

$$\overline{\Delta\varphi} = \overline{\varphi_1} - \overline{\varphi_2} = \xi \frac{2\pi n}{\lambda} 2(L + \Delta \mathrm{L})$$

$$\overline{\Delta\varphi} - \Delta\varphi = \xi \frac{4\pi n}{\lambda} \Delta \mathrm{L}$$



$$I = I_0\,[1 + \cos(\Delta\varphi)]$$



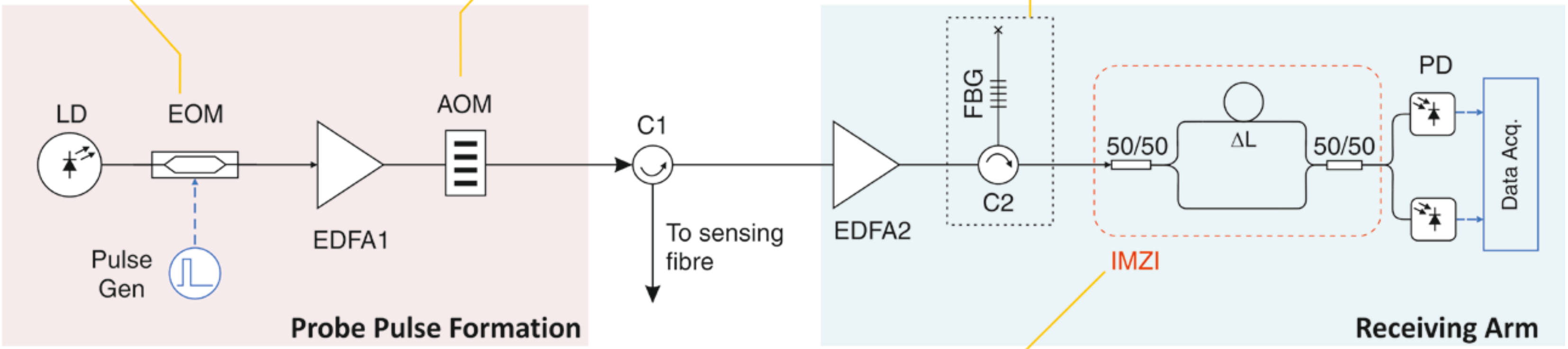
2 DAS Sensing Setup

The following diagram shows the basic building blocks of a DAS system. Due to dynamic nature of DAS measurement, very high-speed acquisition system is need for DAS interrogator.

Instead of direct modulation, laser is externally modulated to maintain the frequency stability of the seed.

AOM is used as a pulse picker.

An optical filter is used to reduce ASE noise from EDFA.



An imbalanced Mach-Zehnder interferometer is used to mix the light from adjacent points on the sensing fibre.

The interferometer should be thermally and acoustically insulated to eliminate the effect of environmental noises on the measurement.

3 Signal fading in DAS systems

- The most basic DAS systems cannot guarantee a uniform signal-to-noise ration (SNR) for the strain measurements along the sensing fibre.

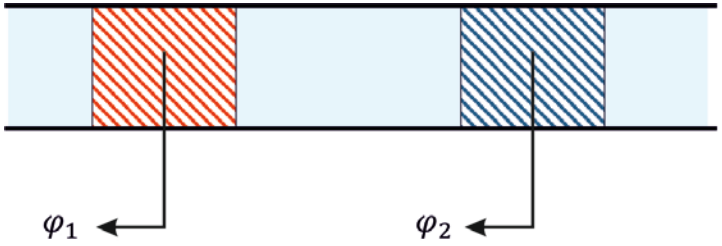
- The uneven SNR is mainly due to the spatial fluctuations in the signal levels reaching the optical interrogator from each point on the sensing fibre. A low signal level results in a poor SNR while a strong signal level results in a high SNR.

- The variation in the signal level at the receiver can be linked to the sensing principle of the DAS systems which rely on interference between the Rayleigh backscattered signal from adjacent points on the sensing fibre. Signal fading occurs when the interference between the backscattered Rayleigh light generates a signal which is zero or close to zero.

- DASs suffer from three types of signal fading: phase fading, polarization fading, and intensity fading. The origin of each fading and the techniques used to mitigate each one will be discussed next.

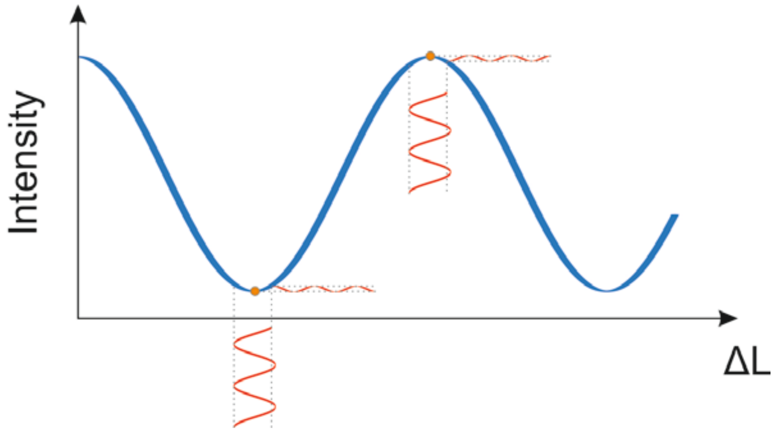
3 Phase Fading: Root cause

Phase fading occurs when the phase-difference between the backscattered light from adjacent points on the fibre is a multiple of π which translates to intensity peak or intensity null on the interference pattern. In such scenario, a small variation in the length of the fibre translates to a minute intensity variation at the detector which, consequently, results in 'signal fading' at the detector.



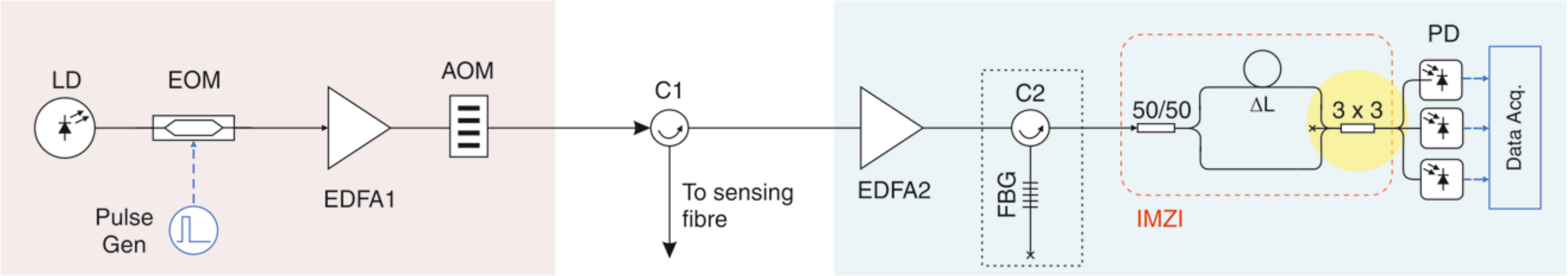
$$\Delta\varphi = \varphi_2 - \varphi_1 = \xi \frac{2\pi n}{\lambda} 2L$$

$$I = I_0\,[1 + \cos(\Delta\varphi)]$$



3 Phase Fading: Solution

Phase fading can be eliminated by replacing a 50/50 coupler at the output of the interferometer with a symmetric 3 x 3 coupler. The 3 × 3 fiber coupler has a symmetrical structure with a 2π/3 phase difference between the output ports.



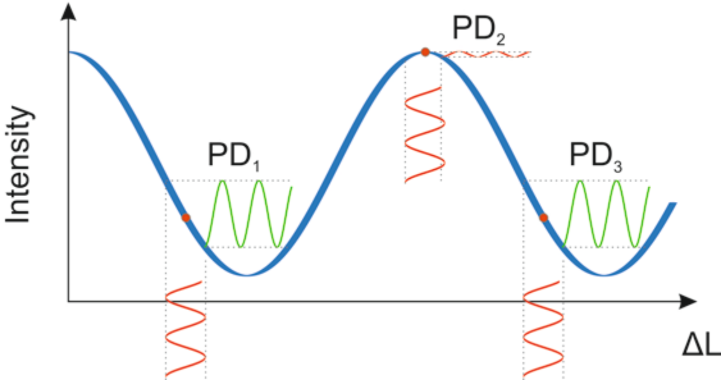
The outputs at the three arms of the interferometer is given by:

$$\Delta\varphi = \varphi_1 - \varphi_2 = \xi \frac{2\pi n}{\lambda} 2\Delta L$$

$$I_1 = I_0 \left[1 + \cos\left(\Delta\varphi + \frac{2\pi}{3}\right)\right]$$

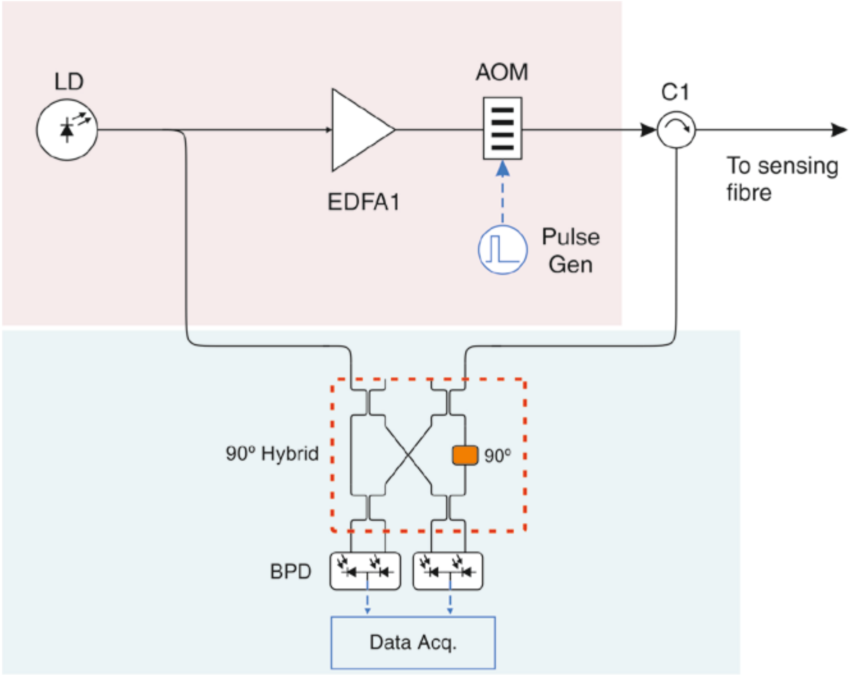
$$I_2 = I_0 \left[1 + \cos\left(\Delta\varphi\right)\right]$$

$$I_3 = I_0 \left[1 + \cos\left(\Delta\varphi - \frac{2\pi}{3}\right)\right]$$



3 Phase Fading: Alternative Solution

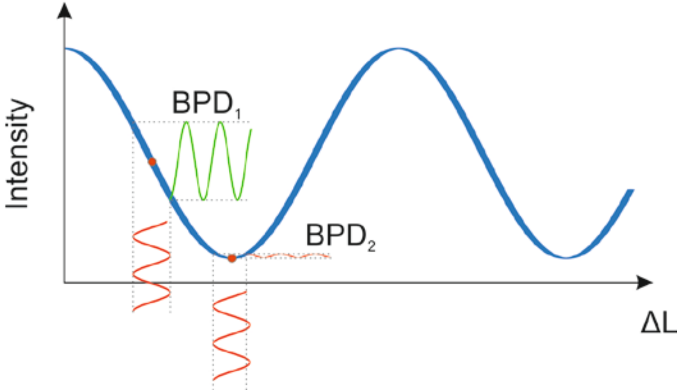
An alternative solution, offered by coherent-based DAS system, is based on the use of a 90° optical hybrid at the receiver to generate two beat signal with $\pi/2$ phase difference, hence, eliminating phase fading.



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

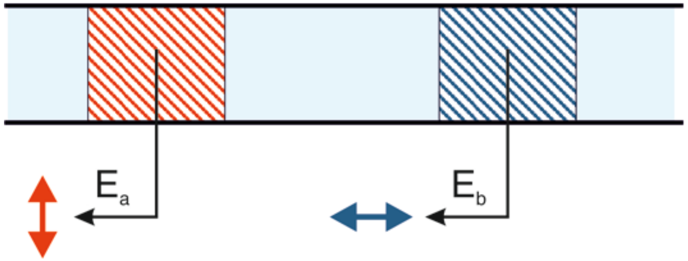
$$I_{BPD1} = I_0 \left[1 + \cos\left(\Delta\varphi + \frac{\pi}{2}\right)\right]$$

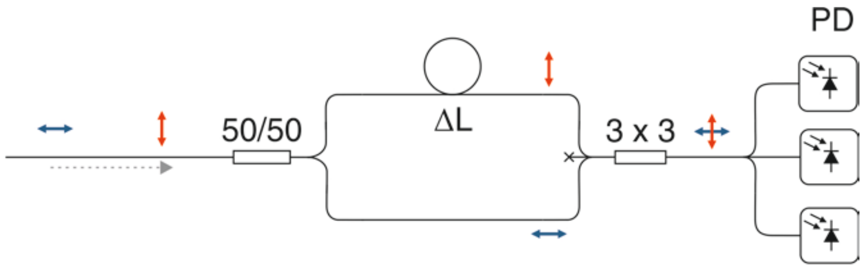
$$I_{BPD2} = I_0 \left[1 + \cos\left(\Delta\varphi\right)\right]$$



3 Polarization Fading: Root cause

Polarization fading occurs when the polarization states of the backscattered signals from adjacent points on the fibre are nearly or completely orthogonal. In such scenario, the backscattered signals will not mix to create interference pattern. Consequently, no signal variation at the receiver will be detected (irrespective of the intensity and phase of the backscattered light) resulting in ‘signal fading’.





$$\overrightarrow{\boldsymbol{E_{bs1}}} = E_a \hat{x} e^{j(\omega t - \varphi_a)}$$

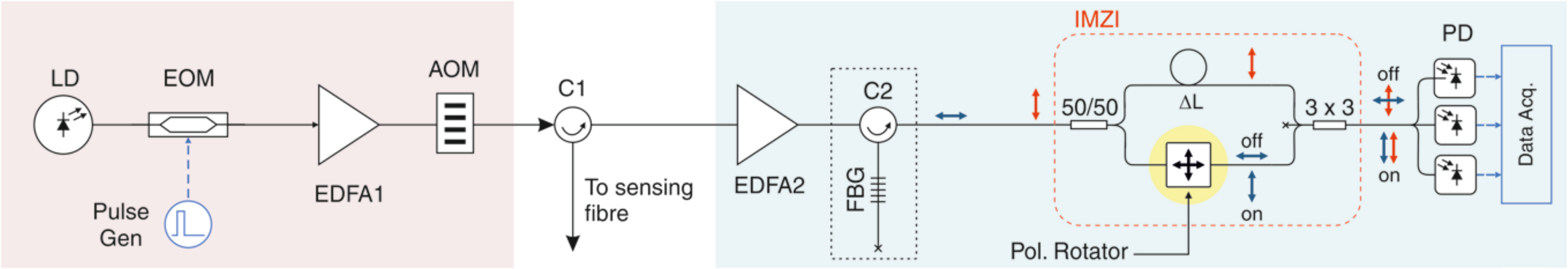
$$\overrightarrow{\boldsymbol{E_{bs2}}} = E_b \hat{y} e^{j(\omega t - \varphi_b)}$$

The two electric fields are orthogonal

$$I = \left|\overrightarrow{\boldsymbol{E_{bs1}}}\right|^2 + \left|\overrightarrow{\boldsymbol{E_{bs2}}}\right|^2 = E_a{}^2 + E_b{}^2$$

3 Polarization Fading: Solution

To eliminate polarization fading, a polarization rotator can be introduced in one arm of the interferometer to sequentially switch the state of polarization between two orthogonal states. Using this approach, the results obtained from mixing the backscattered signals from the orthogonal polarization state can be combined to eliminate the effect of mismatch polarization on the measurement.



$$\overrightarrow{\boldsymbol{E_{bs1}}} = E_a \hat{x} e^{j(\omega t - \varphi_a)}$$

$$\overrightarrow{\boldsymbol{E_{bs2}}} = E_b \hat{y} e^{j(\omega t - \varphi_b)}$$

off: $$I = \left|\overrightarrow{\boldsymbol{E_{bs1}}}\right|^2 + \left|\overrightarrow{\boldsymbol{E_{bs2}}}\right|^2 = {E_a}^2 + {E_b}^2$$

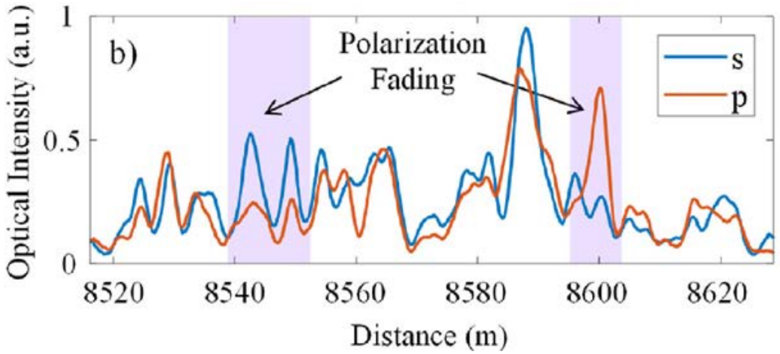
on: $$I = \left|\overrightarrow{\boldsymbol{E_{bs1}}} + \overrightarrow{\boldsymbol{E_{bs2}}}\right|^2 = {E_a}^2 + {E_b}^2 + 2E_a\, E_b \cos(\varphi_a \text{-}\ \varphi_b)$$

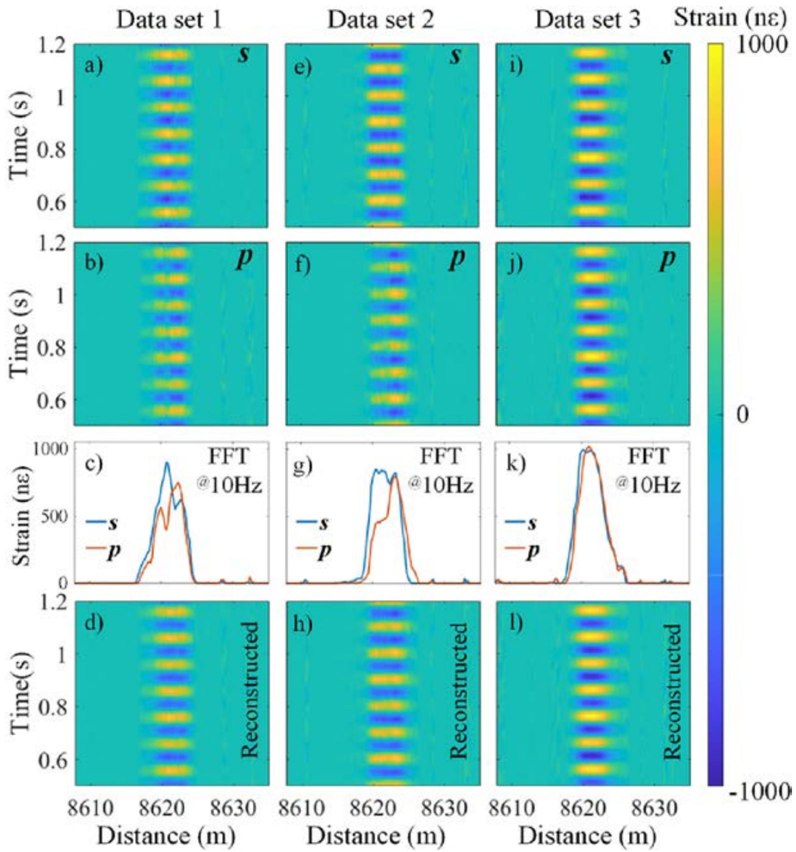
Polarization Fading: Results

The following plots show the effect of polarization rotator on the output of the DAS system.

The diagram at the bottom shows the OTDR traces at the end of the test fiber corresponding to the two SoPs of s and p showing that the polarization fading effect can occur at certain positions along the fiber.

The diagram on the right shows how s and p SoPs can be combined to diminish the impact of polarization fading on the output of the DAS system.





Polarization Fading: Alternative Solution

An alternative solution, offered by coherent-based DAS system, is based on the use of dual-polarization 90° optical hybrid at the receiver.

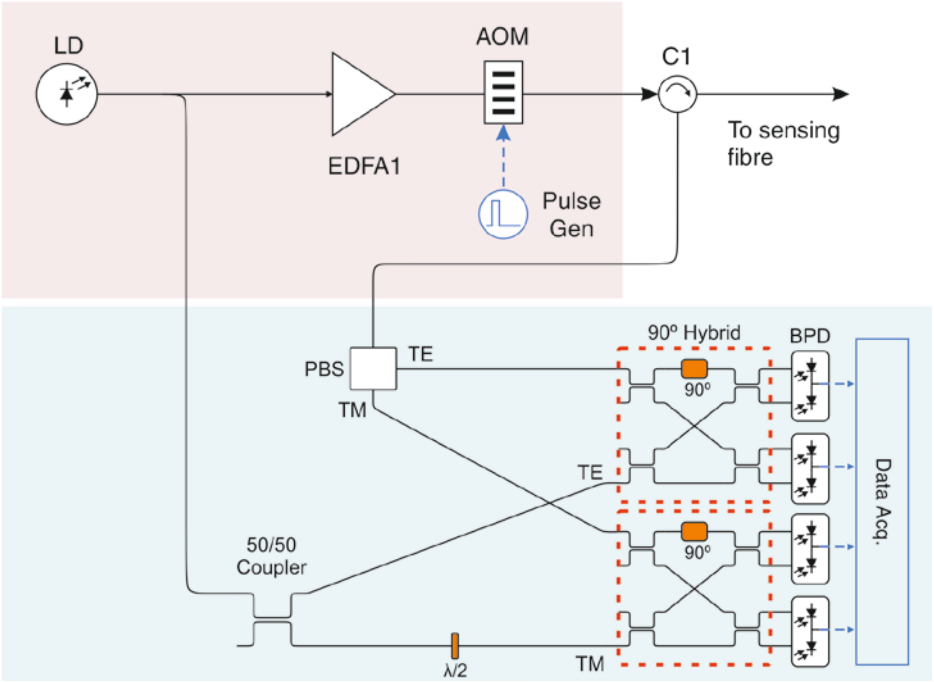
In this arrangement, a polarization beam splitter (PBS) is used to split the polarization of the backscattered light into to orthogonal polarization, each of which is then mixed with optical local oscillator (OLO) to generate beat signal.

Phase is calculated by combining the signals from both polarization with inverse-variance weighting:

$$\Delta\varphi = A_x \Delta\varphi_x + A_y \Delta\varphi_y$$

where

$$A_{x,y} = \frac{\sigma_{y,x}^2}{\sigma_x^2 + \sigma_y^2}$$



3 Intensity Fading: Root cause

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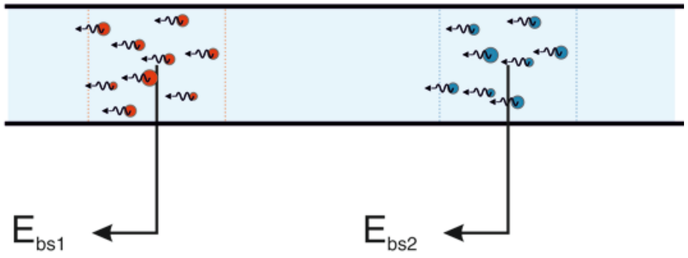
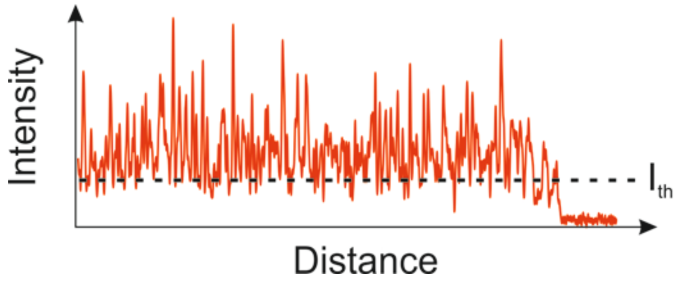
Intensity fading occurs when the backscattered Rayleigh radiations from the inhomogeneities within a certain section of the sensing fibre are added destructively to form dips in the intensity of the backscattered coherent Rayleigh trace. At the regions with intensity fading, the amplitude of the backscattered light is too low to allow for the phase of the Rayleigh signal to be accurately extracted, creating blind spot in strain measurement.



$$E_{bs} = \sum_{i=1}^{m} E_{bs}(i)\, e^{j(\omega t - \varphi_i)} \longrightarrow I_{bs} = |E_{bs}|^2 e^{j(\omega t - \phi)}$$

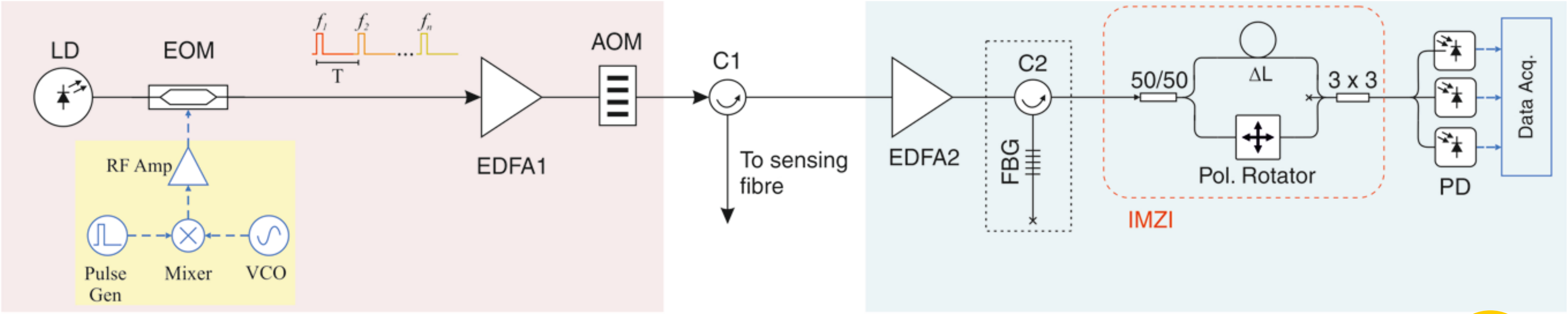
$$|E_{bs}|^2 = \sum_{k=1}^{m}\sum_{l=1}^{m} E_{bs}(k) E_{bs}(l) \cos(\varphi_k - \varphi_l)$$

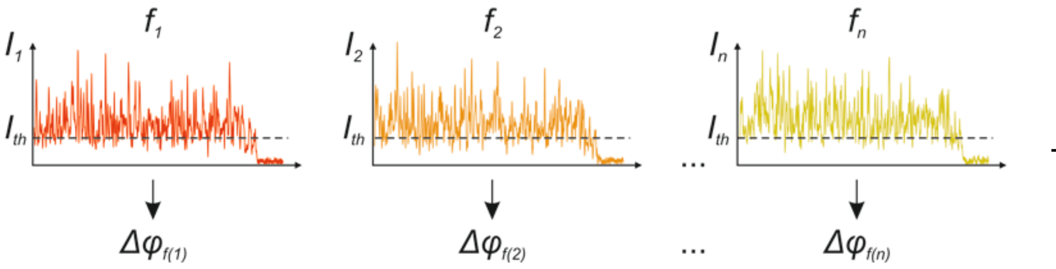


Signal fading occurs at any point on the fibre where $I_{bs} < I_{th}$

3 Intensity Fading: Solution

To eliminate intensity fading, frequency diverse interrogation approach can be used in which a train of optical pulses, each with slightly different optical frequency, are launched into the sensing fibre to generate several statistically independent Rayleigh backscattered traces with different coherent Rayleigh noise (CRN) patterns. The results can be combined to eliminate signal fading.





$$I_{f(i)} = I_0\,[1 + \cos(\Delta\varphi_{f(i)})]$$

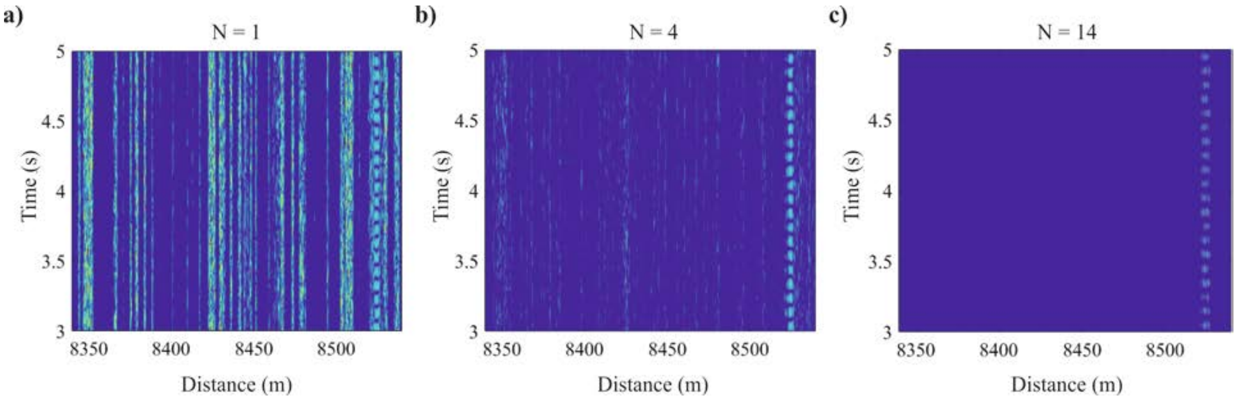
$$\Delta\varphi = \sum_{i=1}^{n} \Delta\varphi_{f(i)}$$

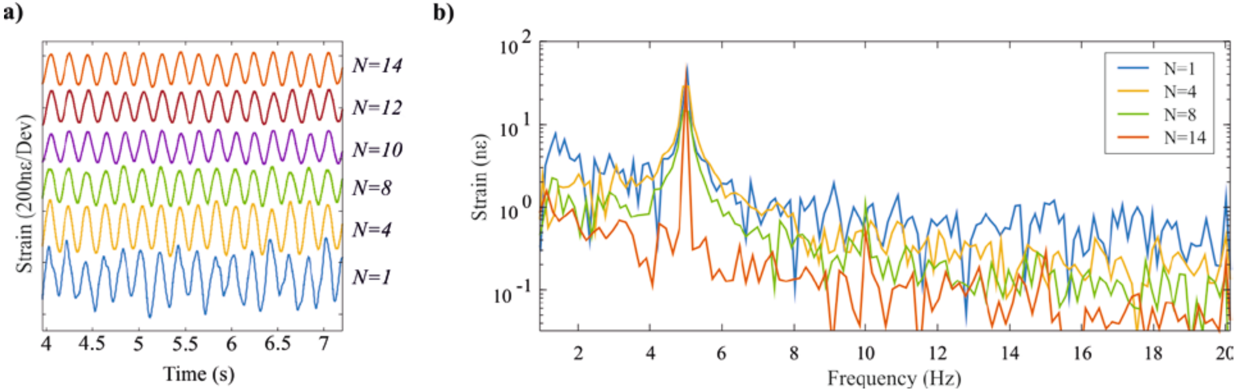
3 Intensity Fading: Results

The plots on the right show the how frequency diverse data acquisition can be employed to eliminate intensity fading.

The waterfall plots on the top right show the dynamic strains for a system interrogated with a single (a), four (b) and fourteen (c) frequencies.

The plots at the bottom right shows a) response of the DAS to dynamic strain at a single sensing channel as a function of time for single frequency (N=1) and multi-frequency (N=4 ~ 14) and b) frequency spectrum of the time-domain data at the same sensing channel.





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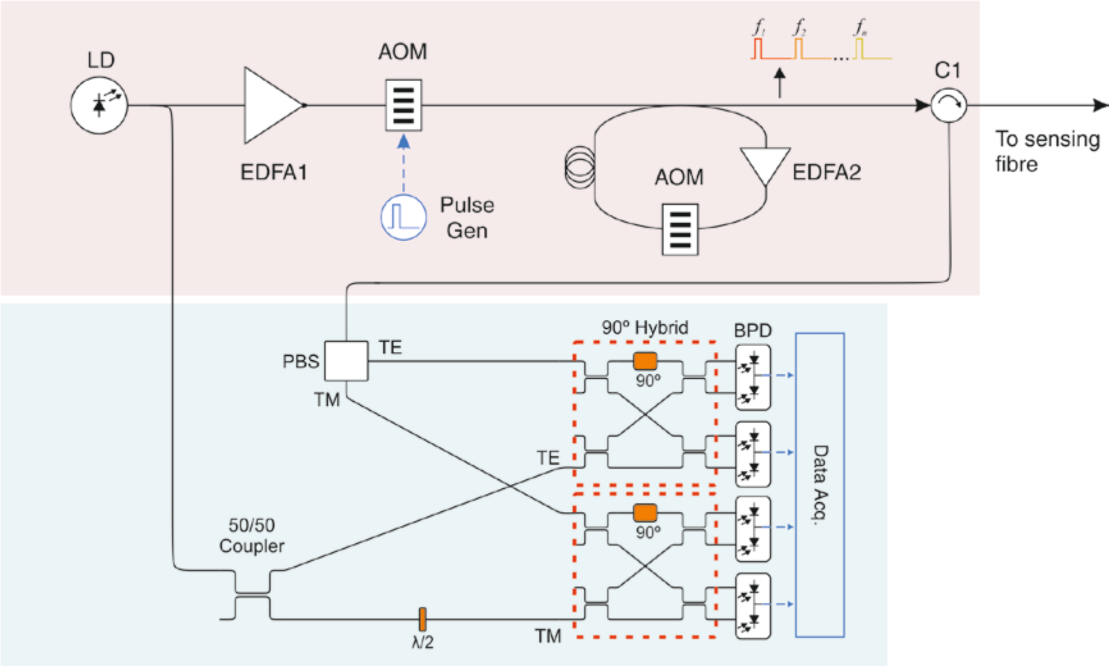
Intensity Fading: Solution

A similar solution based on frequency diverse interrogation is adopted in coherent-based DAS system to eliminate intensity fading.

The arrangement used to realise a frequency diverse interrogation is based on a frequency-shifting optical ring where an AOM is used in an optical ring along with an optical amplifier and a delay fibre to generate a train of pulses where each pulse is frequency shifted by the frequency of the AOM.

Data from different frequencies can then be combined to eliminate intensity fading.



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Applications: Subsea Cable Monitoring

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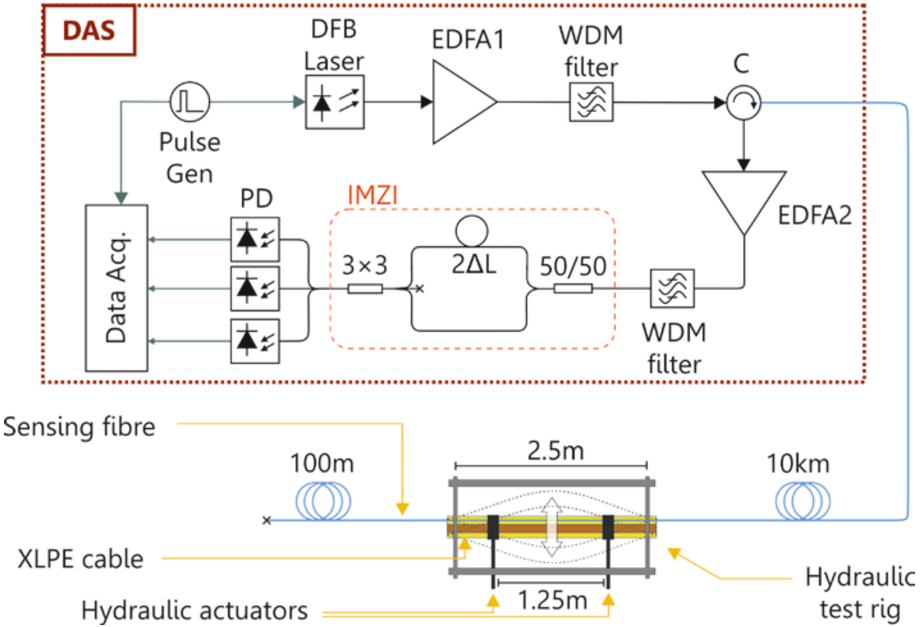
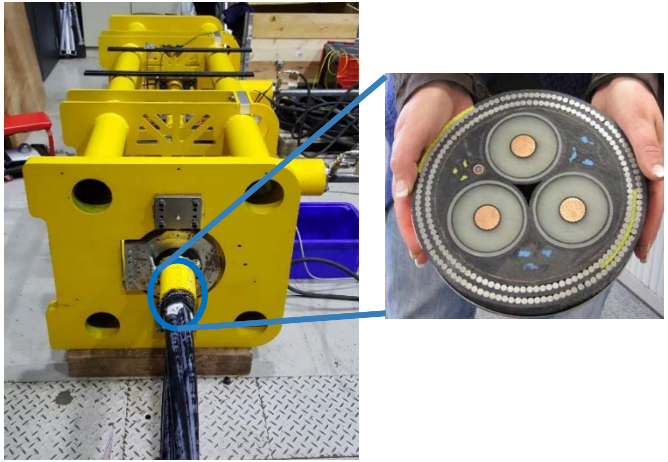
- Submarine cable failure is extremely costly due to Loss of wind farm production and Repair costs
- These failures are predominately mechanical and occur during the unloading and installation phase





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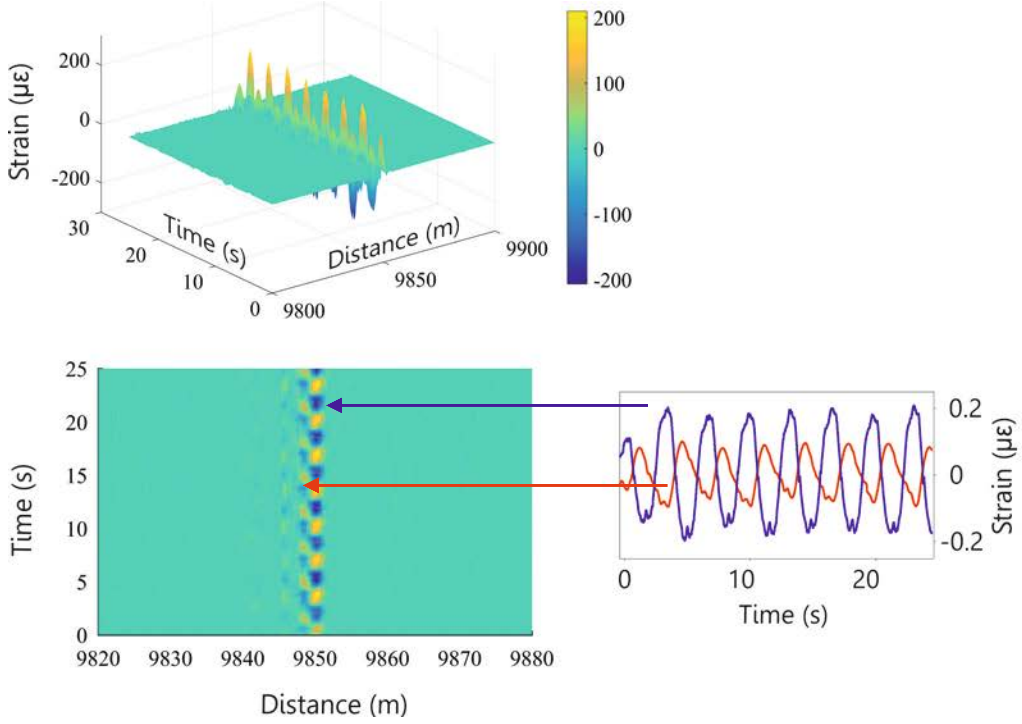
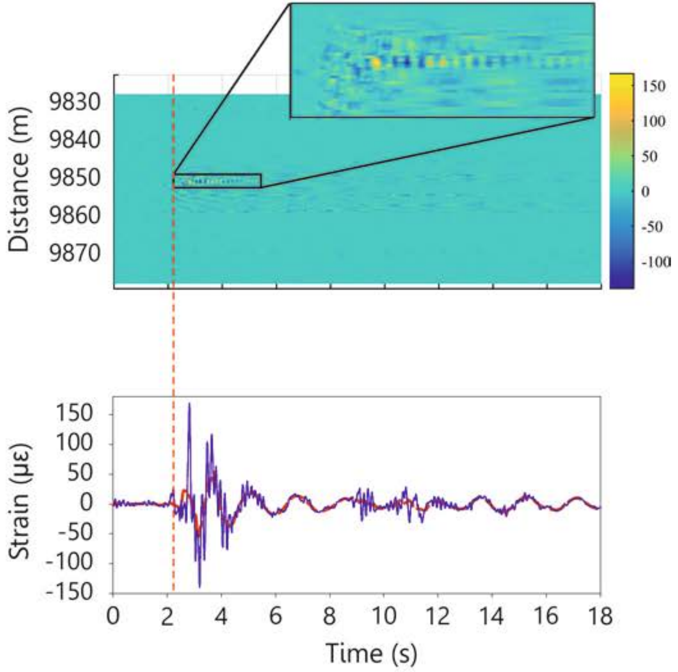
Applications: Subsea Cable Monitoring

Cyclic Loading Test

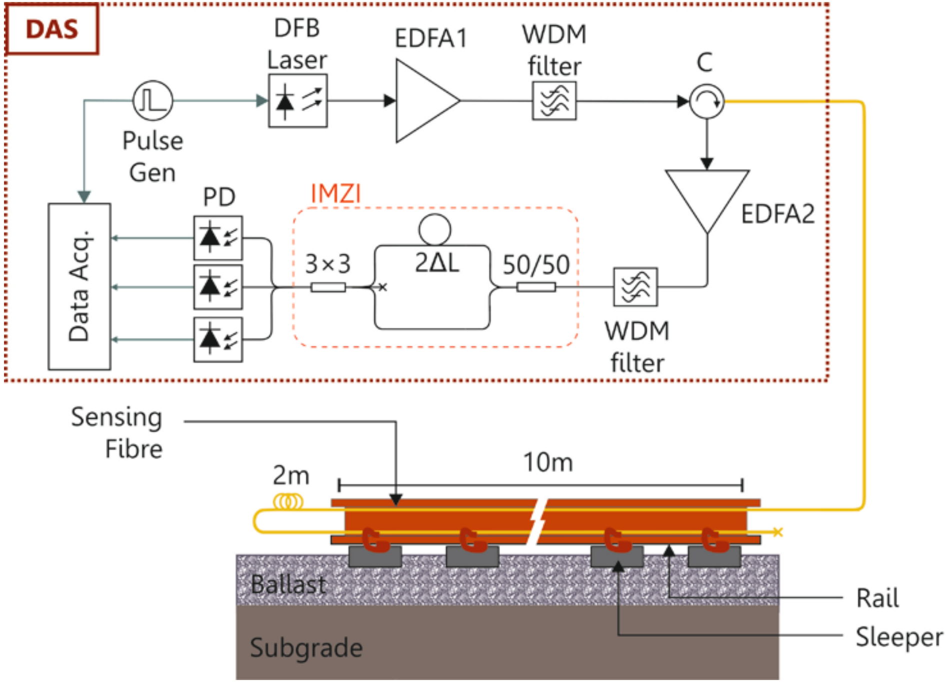


Impact Test



Applications: Beam Deflection Analysis

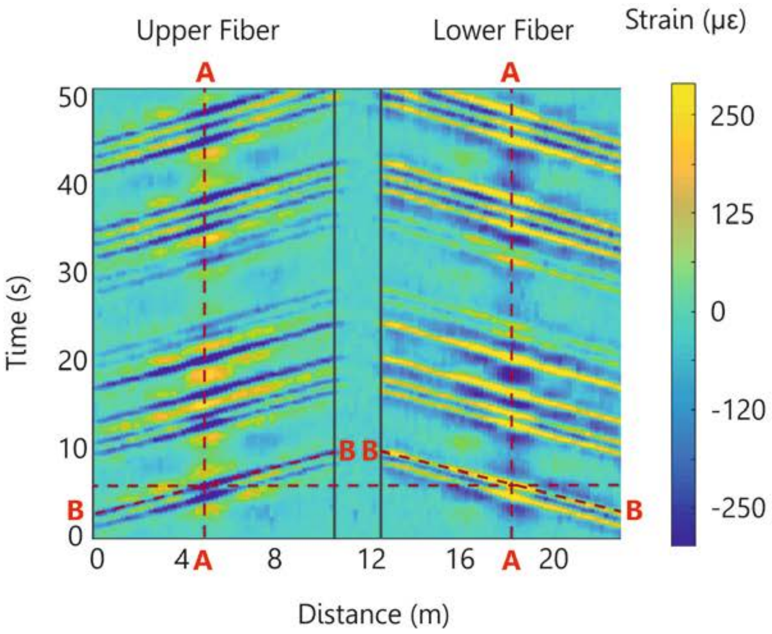
Condition monitoring is essential to ensuring safe and cost-effective train operation in the railroad transportation industry. Do carry out such test in distributed format offers a significant advantages over conventional measurement techniques such as using point strain gauges and load cells.

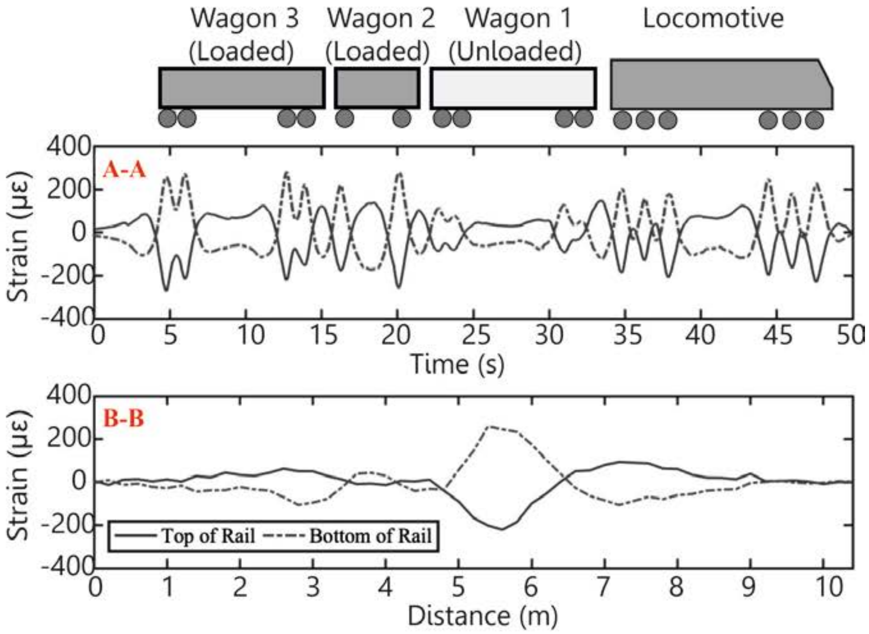


Rail Optical fibre

Applications: Beam Deflection Analysis

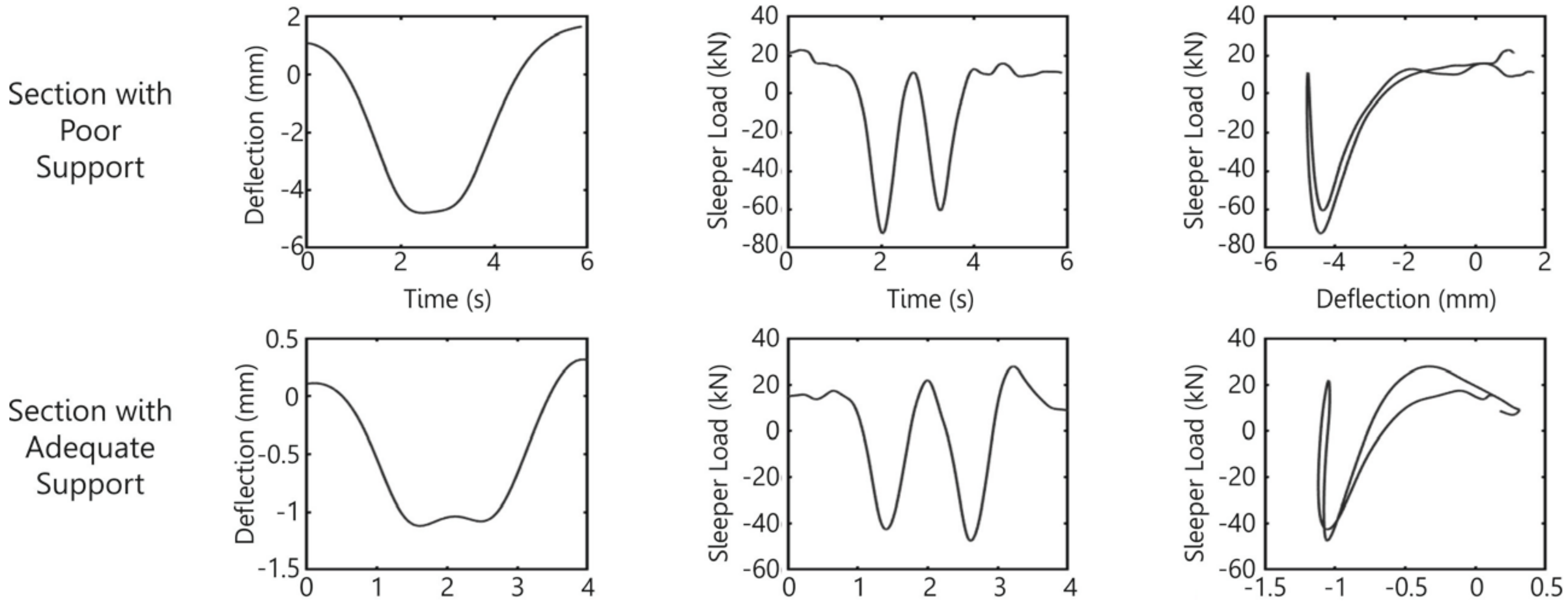
The waterfall plot analysis of the waterfall plot not only shows the location, and speed of each wheel on the train, but it can be further analysed to extracted additional information such as the sleeper loading and rail deflection.





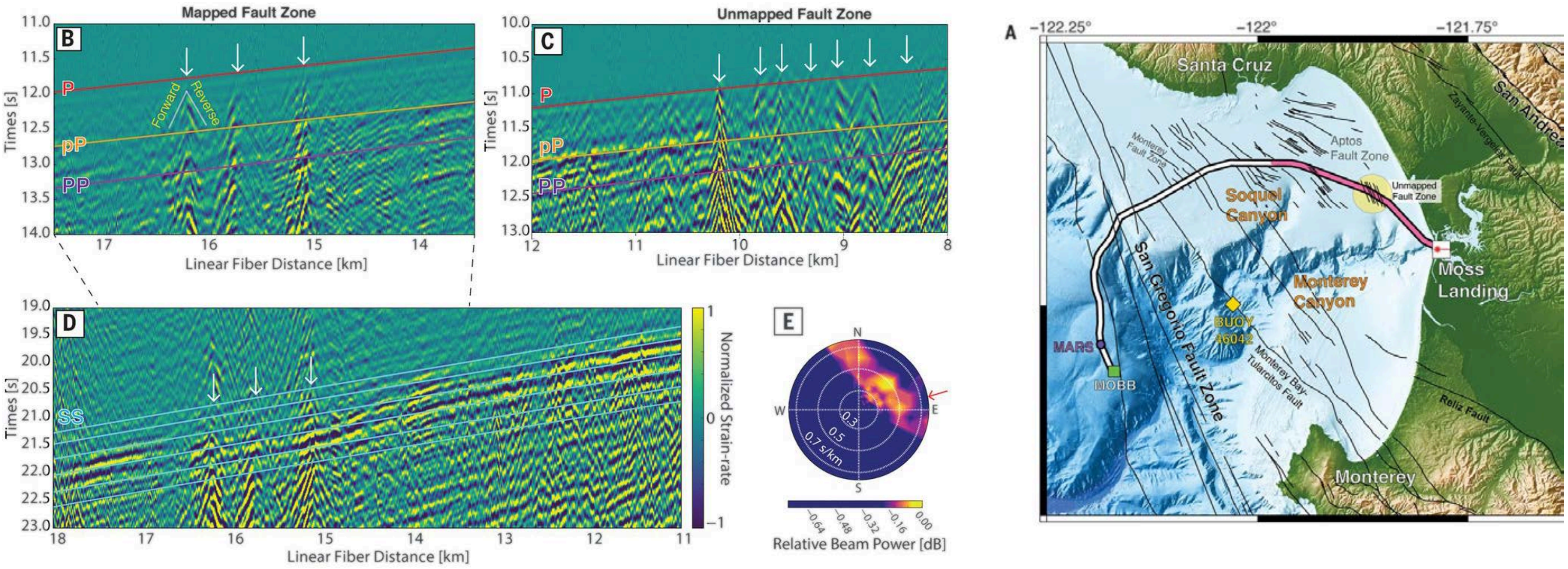
4 Applications: Beam Deflection Analysis

The sleeper loading vs deflection diagram is of outmost importance for in track behaviour analysis.



Applications: Seismology

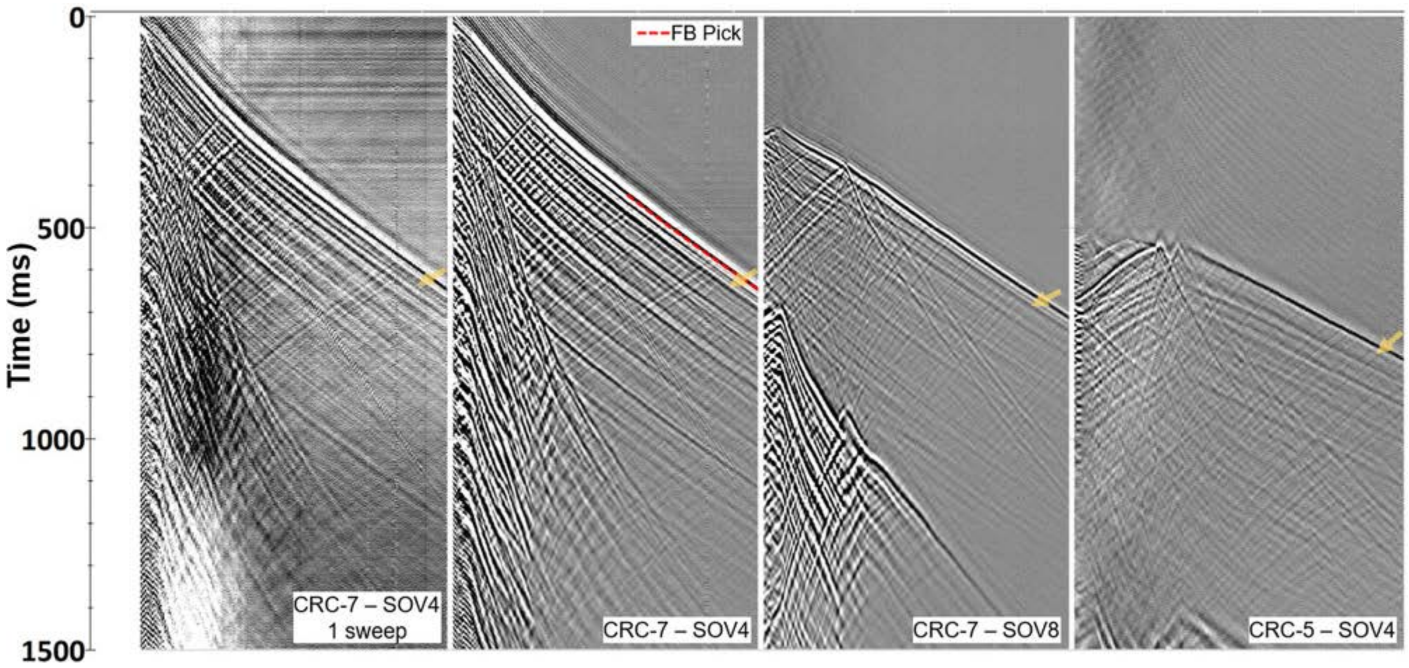
DAS systems have been used extensively to map geophysical phenomena such as: Mapping fault zones



Lindsey et al. "Illuminating seafloor faults and ocean dynamics with dark fiber distributed acoustic sensing." Science 366.6469 (2019): 1103-1107.

Applications: Seismology

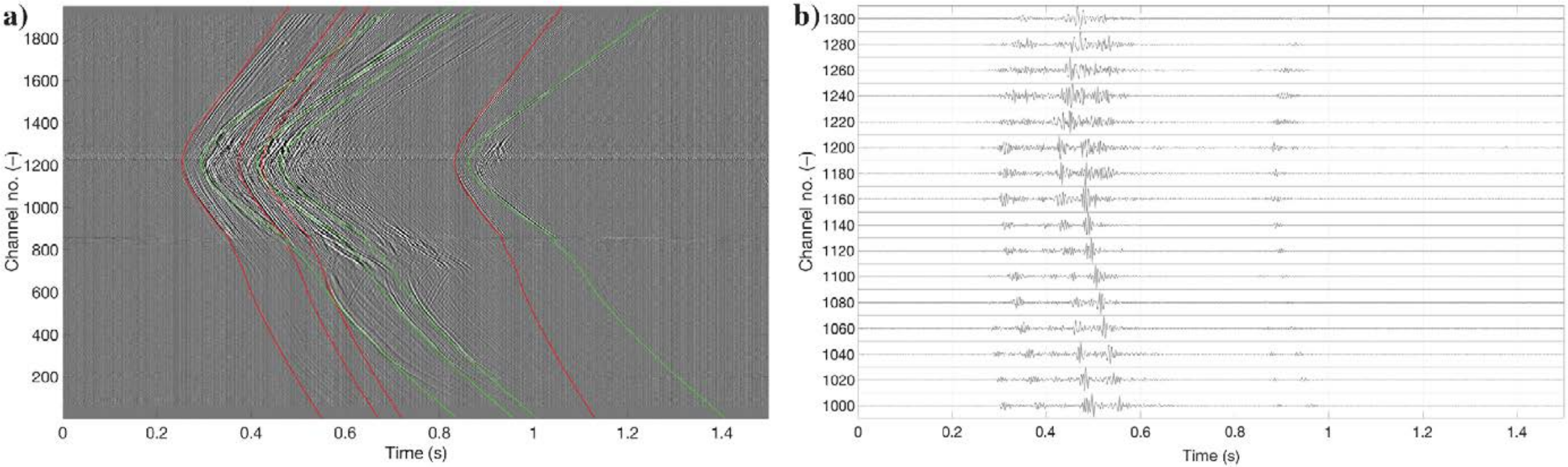
DAS systems have been used extensively to map geophysical phenomena such as: Vertical Seismic Profiling



Yavuz et al. "Processing of multi-well offset vertical seismic profile data acquired with distributed acoustic sensors and surface orbital vibrators" Geophysical Prospecting 69.8-9 (2021): 1664-1677.

Applications: Seismology

DAS systems have been used extensively to map geophysical phenomena such as: Detection of microseismic activities



Verdon et al. "Microseismic monitoring using a fiber-optic distributed acoustic sensor array Microseismic monitoring using a DAS array." Geophysics 85.3 (2020): KS89-KS99.

Questions

Email: a.masoudi@soton.ac.uk