Enhancing Distributed Fiber-Optic Sensing (DFOS) data with a Spectral Subtraction-based method

G. Pascucci[1]*, S. Gaviano[1,2], F. Grigoli[1]

[1] Department of Earth Sciences, University of Pisa, Italy
[2] Seismix, Pisa, Italy

*** Contact: giulio.pascucci@phd.unipi.it**

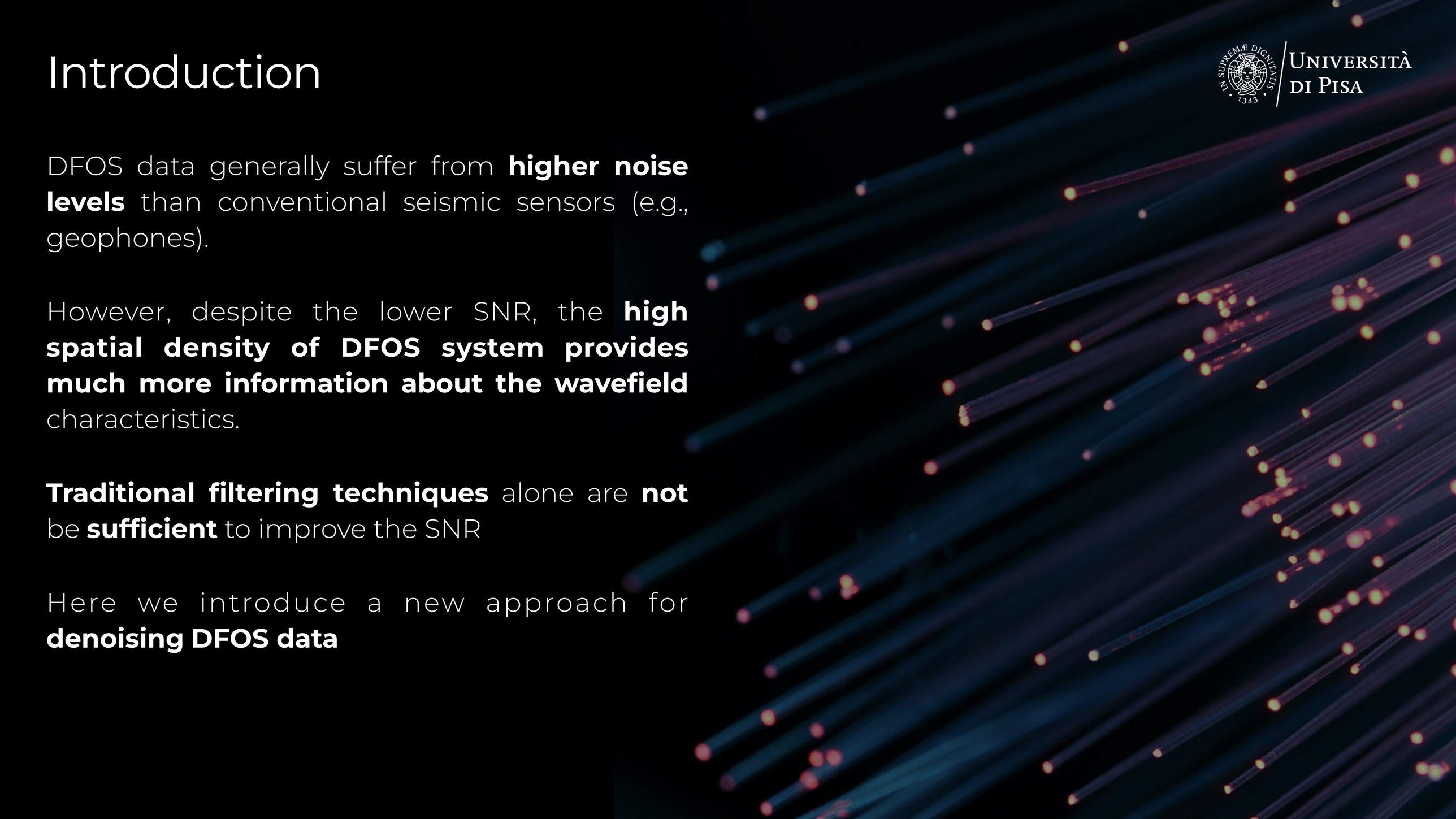
Introduction

DFOS data generally suffer from **higher noise levels** than conventional seismic sensors (e.g., geophones).

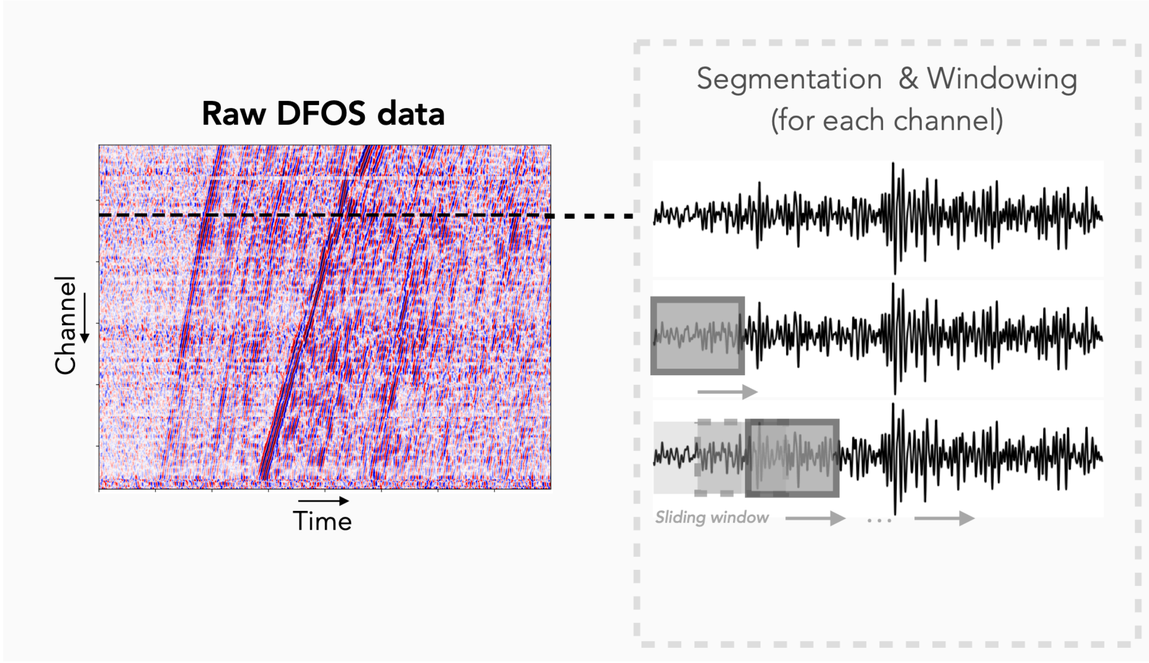
However, despite the lower SNR, the **high spatial density of DFOS system provides much more information about the wavefield** characteristics.

Traditional filtering techniques alone are **not** be **sufficient** to improve the SNR

Here we introduce a new approach for **denoising DFOS data**

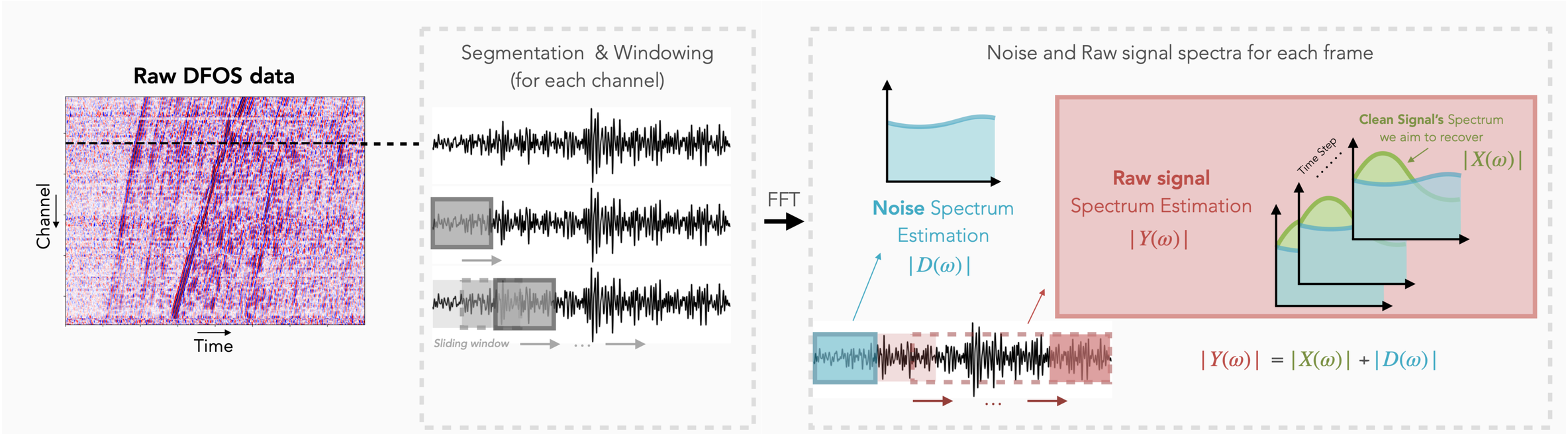


Spectral Subtraction Denoising Method



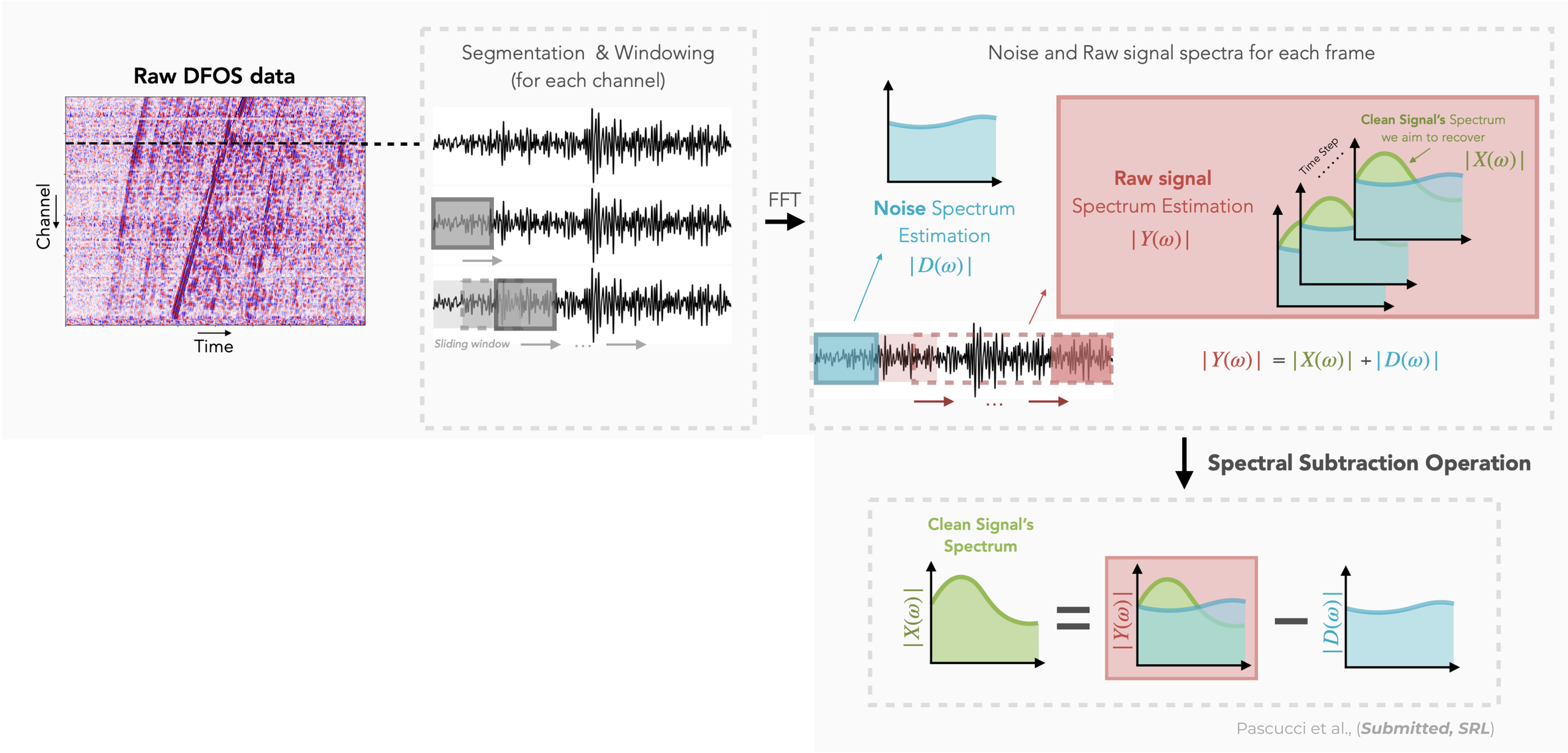
Pascucci et al., (***Submitted, SRL***)

Spectral Subtraction Denoising Method



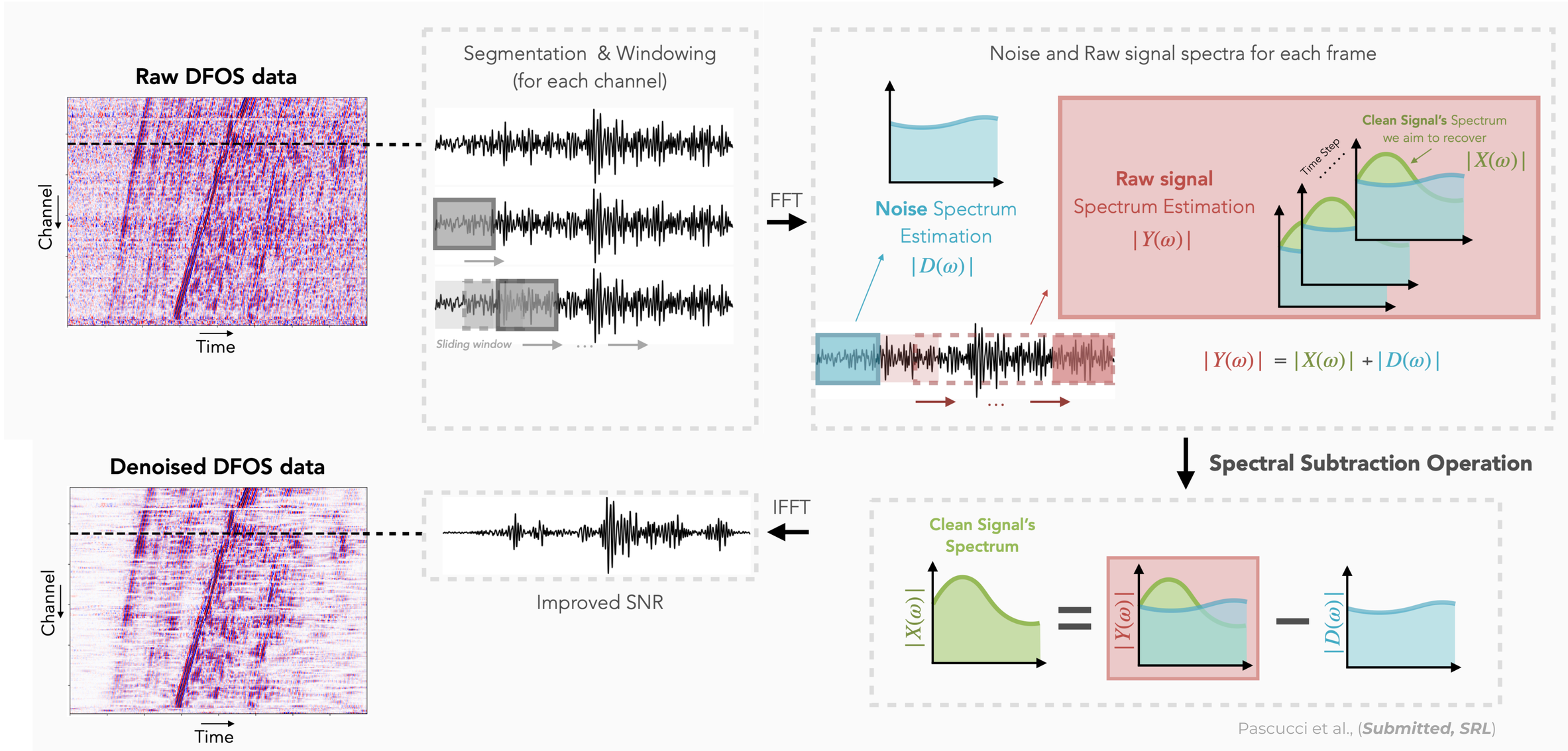
Pascucci et al., (***Submitted, SRL***)

Spectral Subtraction Denoising Method



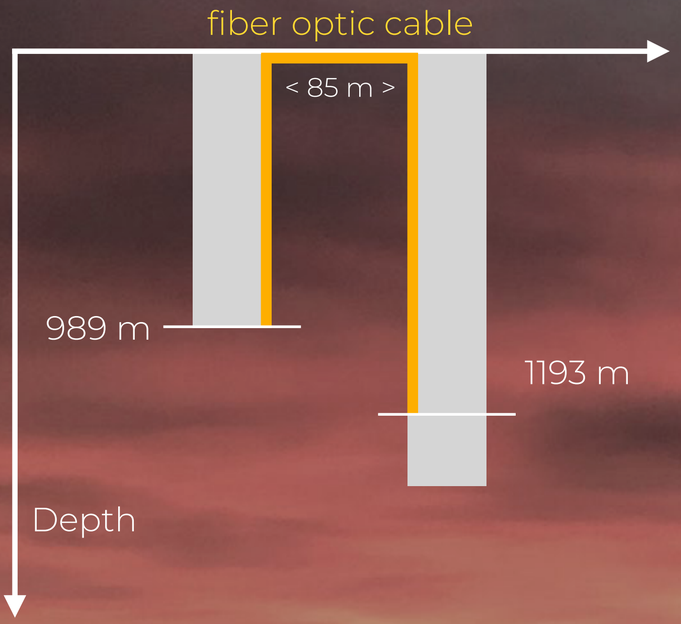
Pascucci et al., (***Submitted, SRL***)

Spectral Subtraction Denoising Method



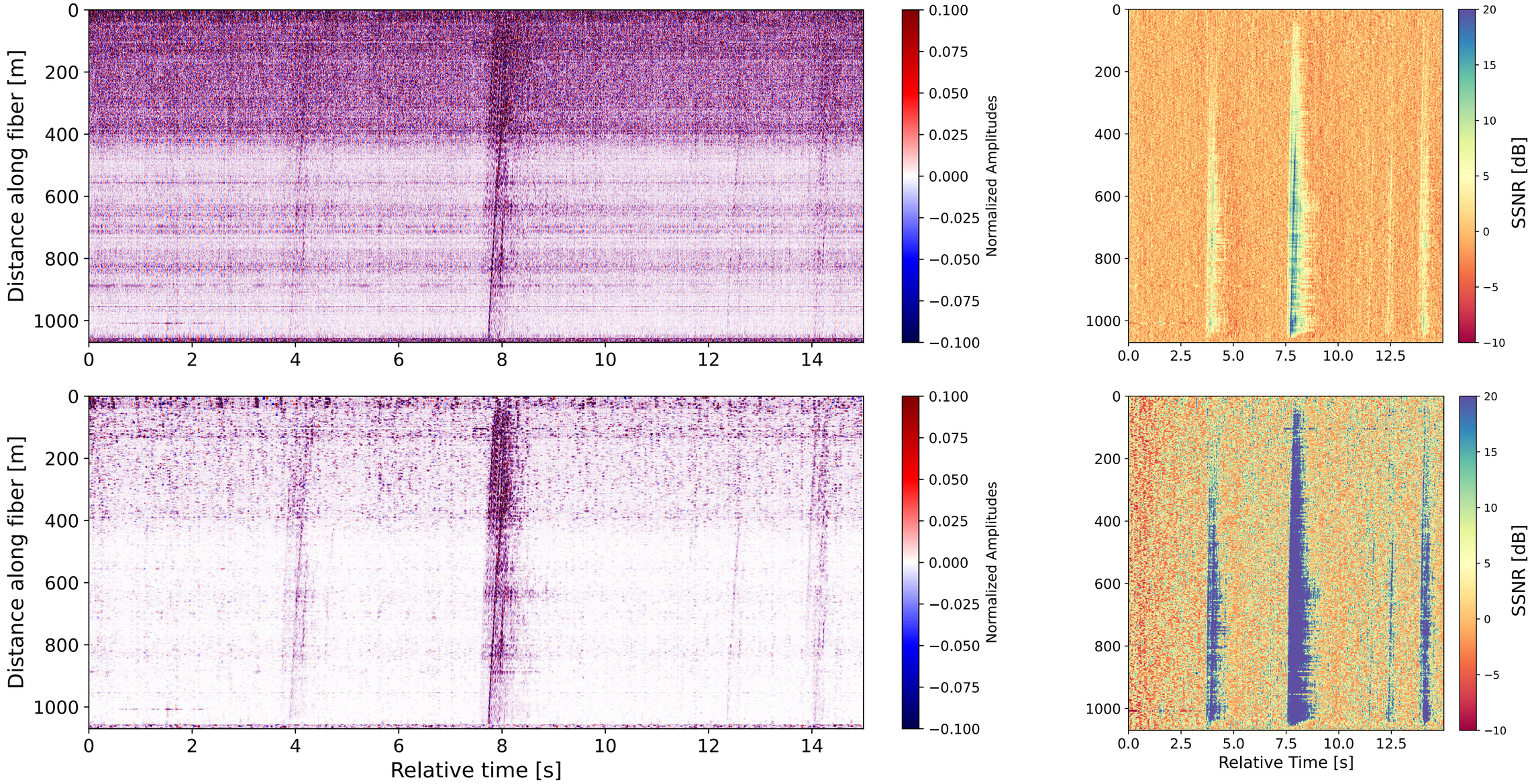
Pascucci et al., (***Submitted, SRL***)

Utah FORGE EGS Site

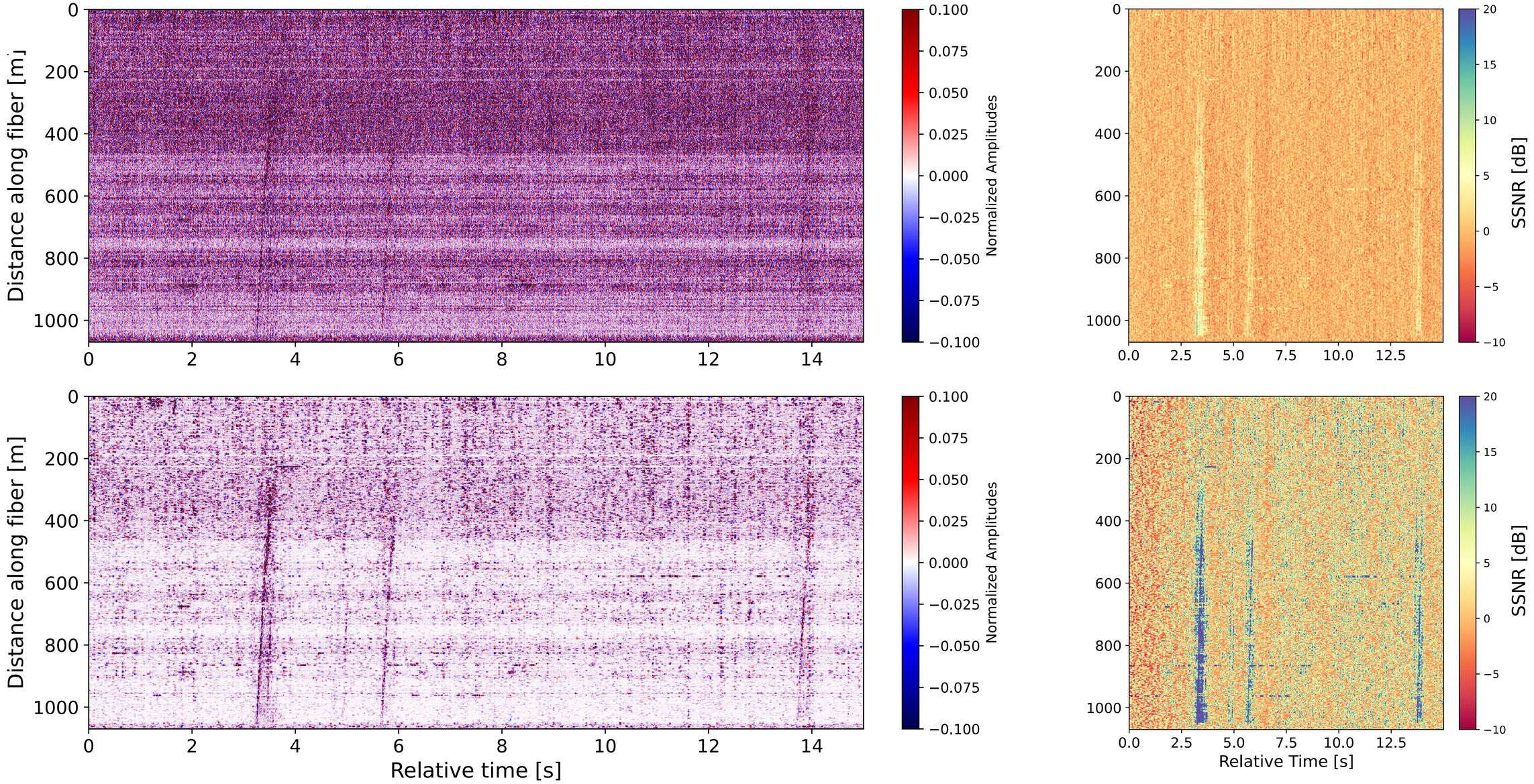


Induced seismicity data collected during the **April 2022** stimulation;
Fiber optic cable in 2 monitoring wells;
1050 **channels**; 1m **channel spacing**; 10m **gauge length**; data 4 kHz **sampling frequency**.

Denoising Results on a **Medium SNR** seismic event



Denoising Results on a **Low SNR** seismic event

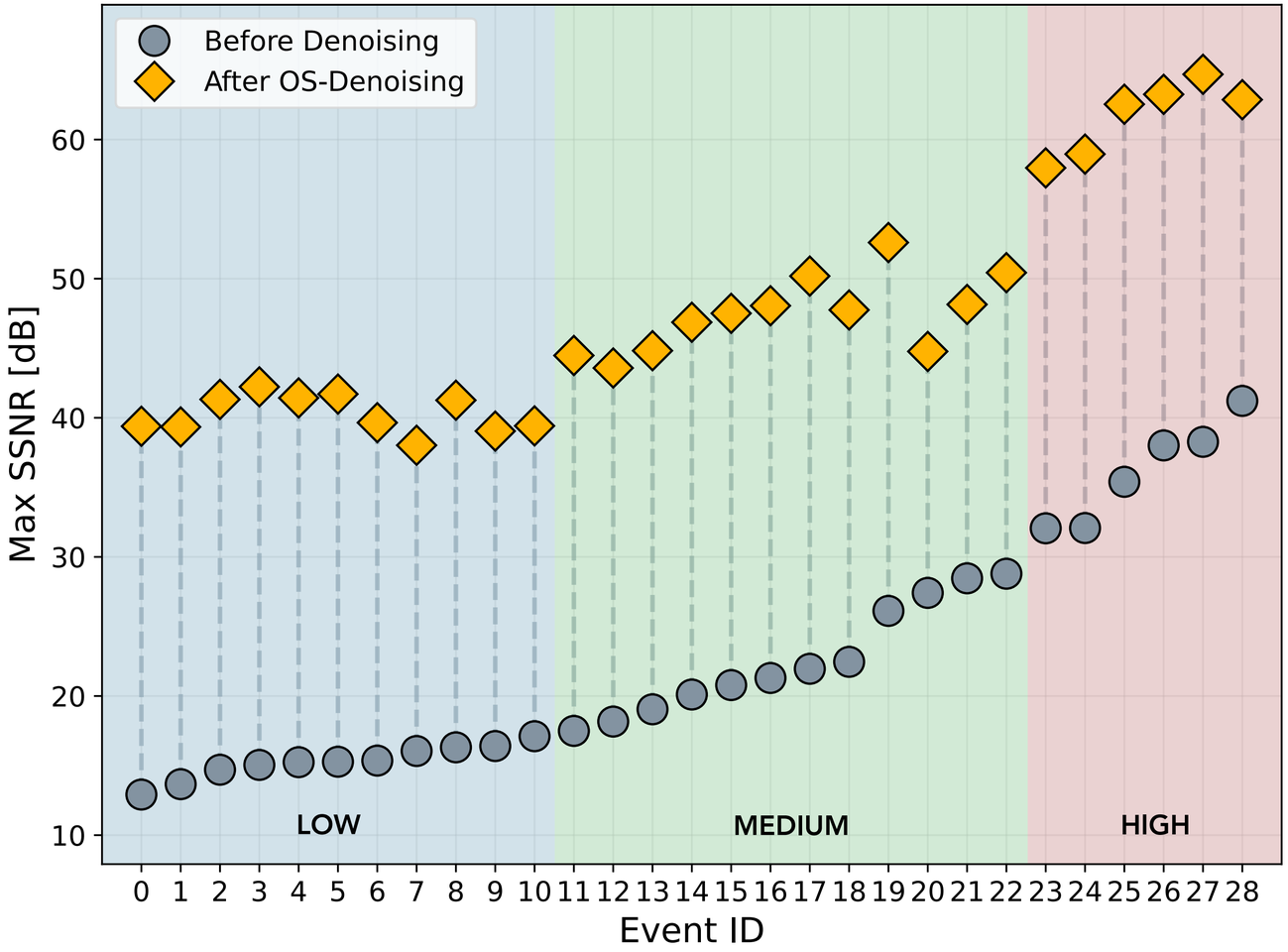


Overall FORGE results

Improved the SSNR for 29 real DFOS microseismic events.

Better performances with LOW SNR

Traditional filtering techniques alone **not sufficient** to enhance the LOW SNR data



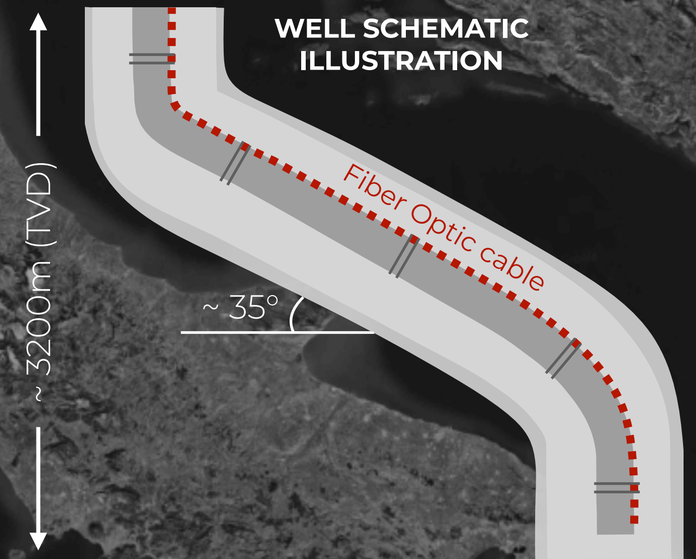
FORGE denoising performance (Pascucci et al., *Submitted, SRL*)

CCS site Offshore Italy

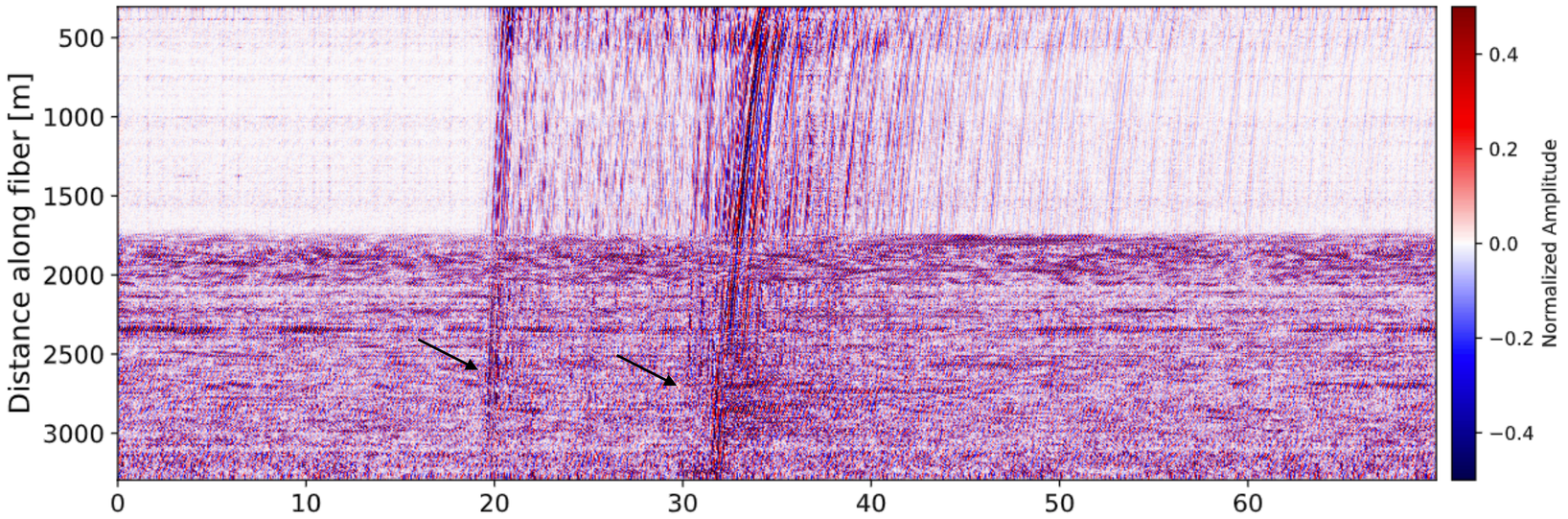
First CO_2 storage project in Italy, started early 2024, and is currently one of the few in operation across Europe.

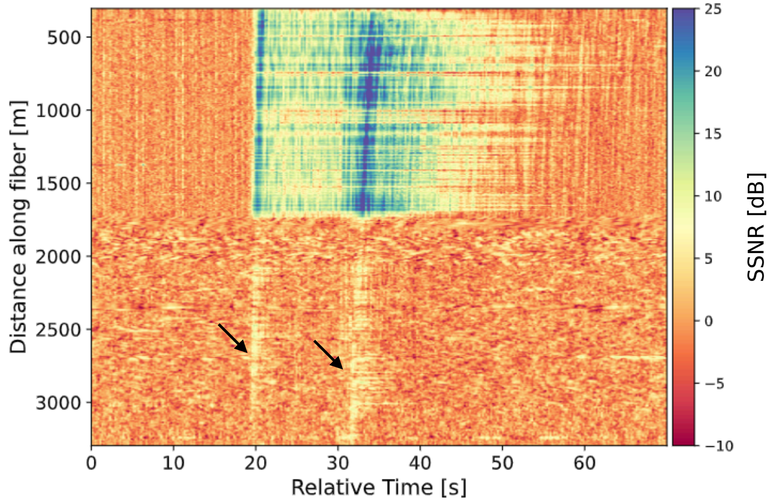
DFOS system deployed **in the CO_2 injection well** (~35° max. inclination) and it's clamped outside the well's production's tubing.

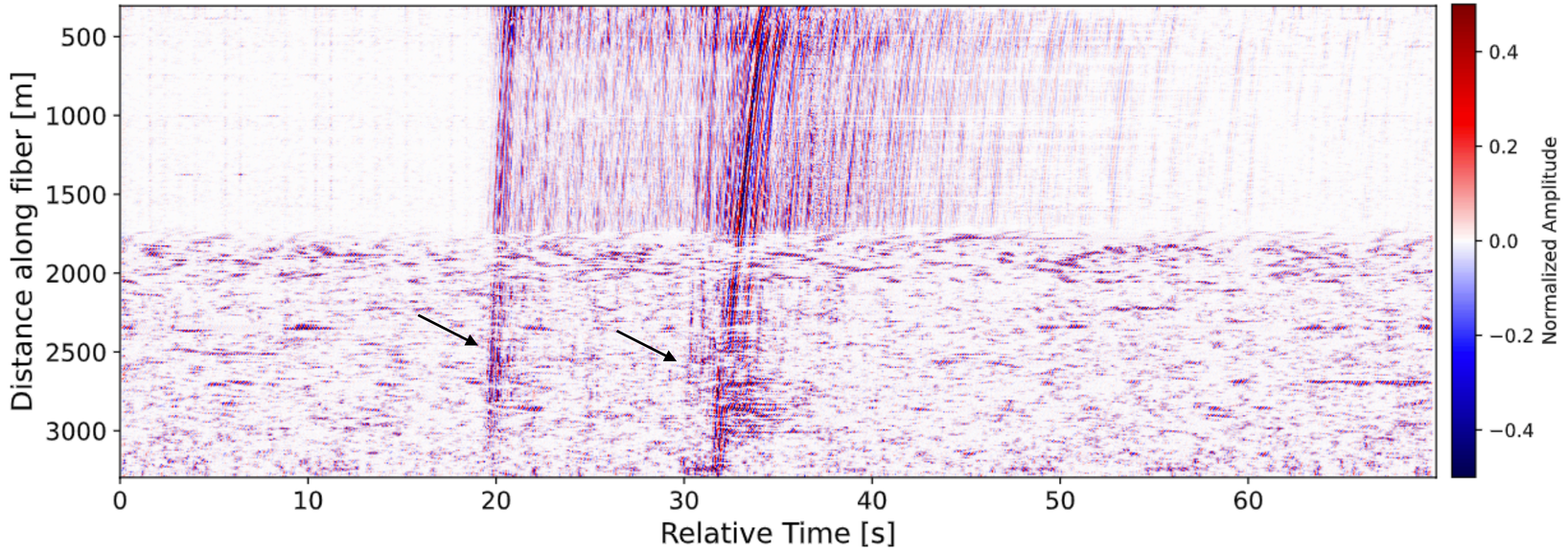
The dataset: only **regional events** detected.
1627 channels; **2 m** channel spacing (dx); **15m** spatial resolution; sampling frequency of **500 Hz**.

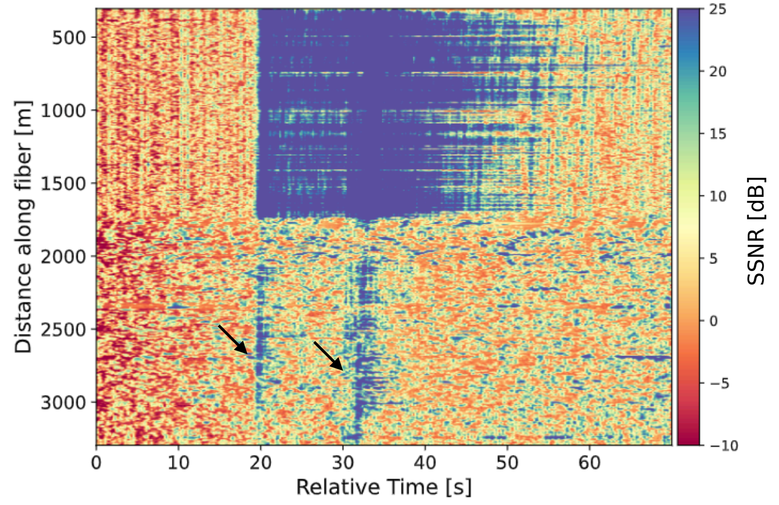


Denoising Results on a M_L 2.6 seismic event

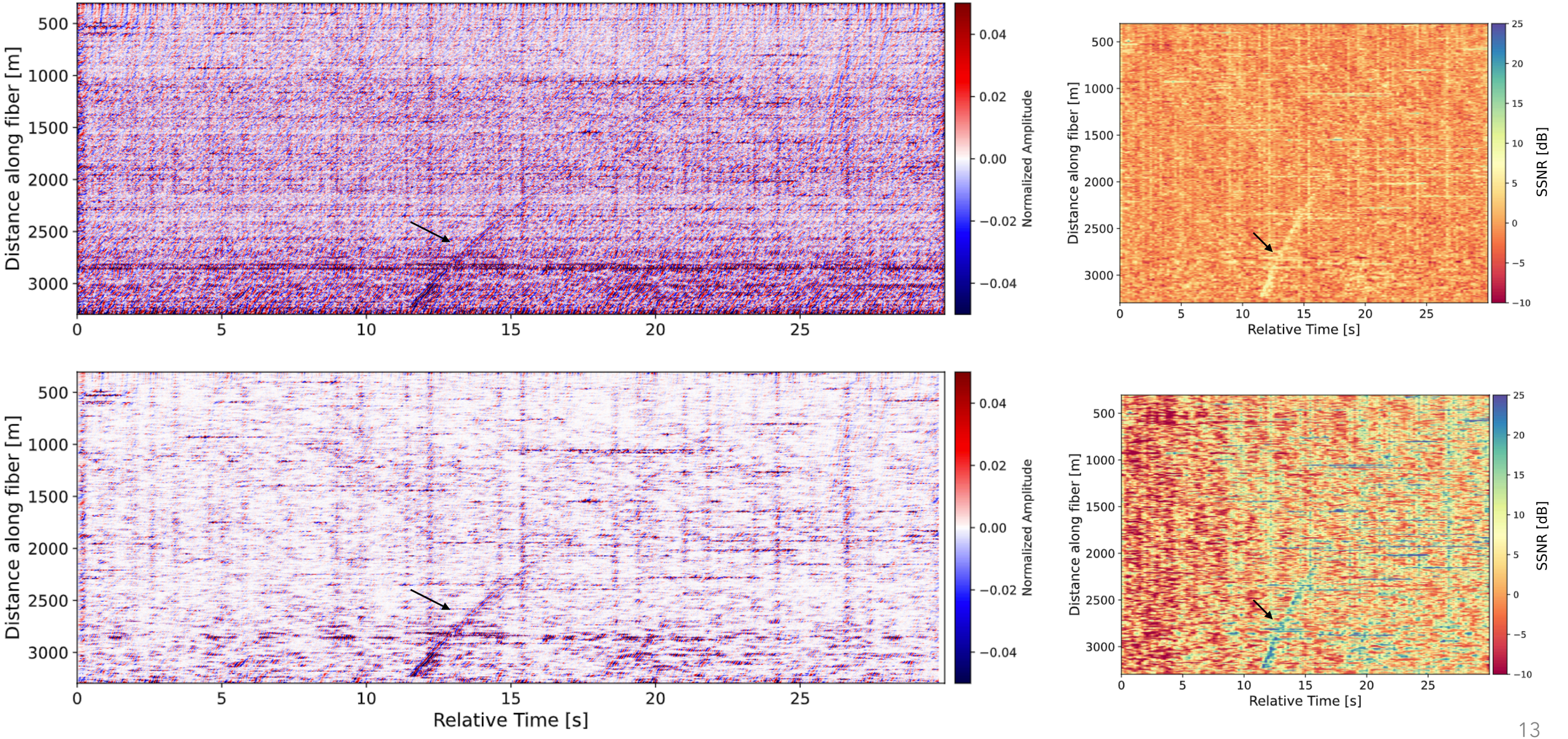








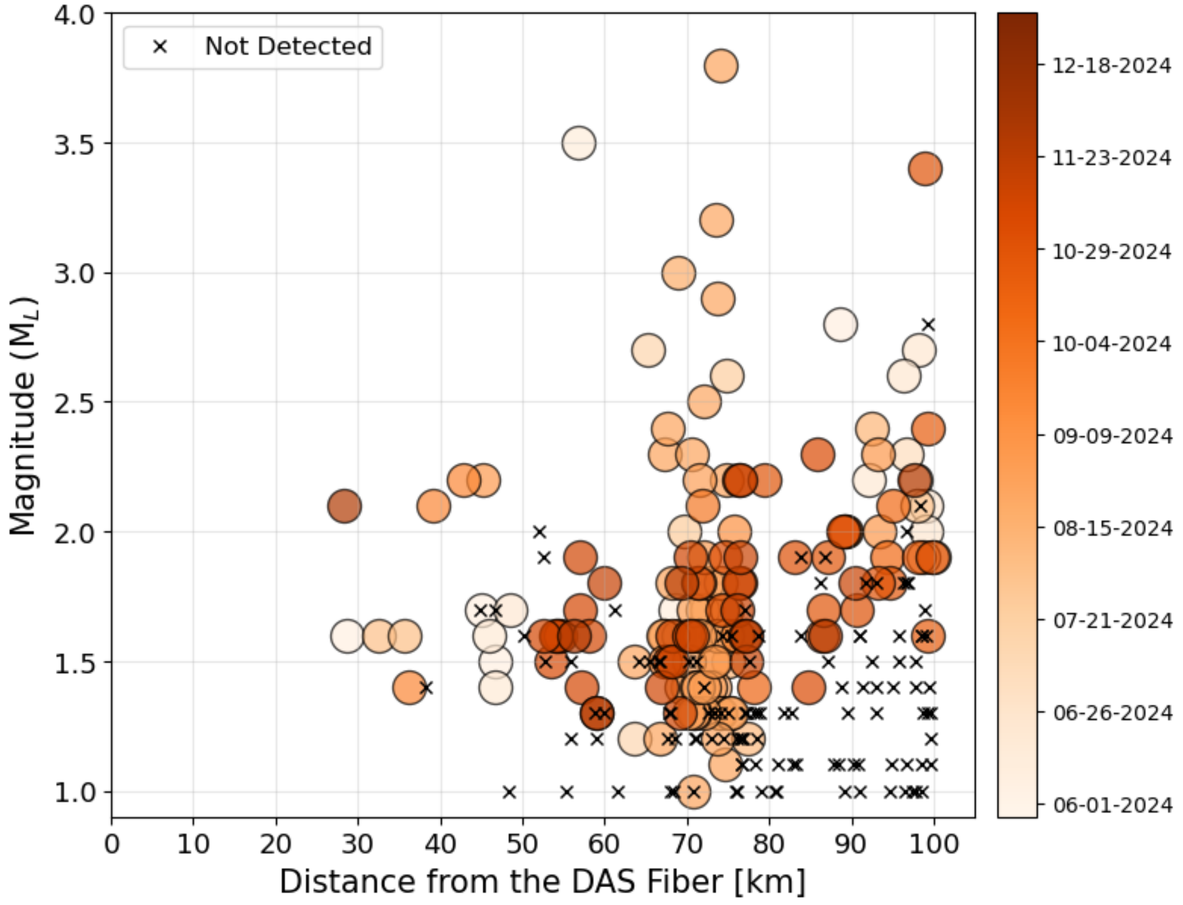
Denoising Results on a M_L ?? event

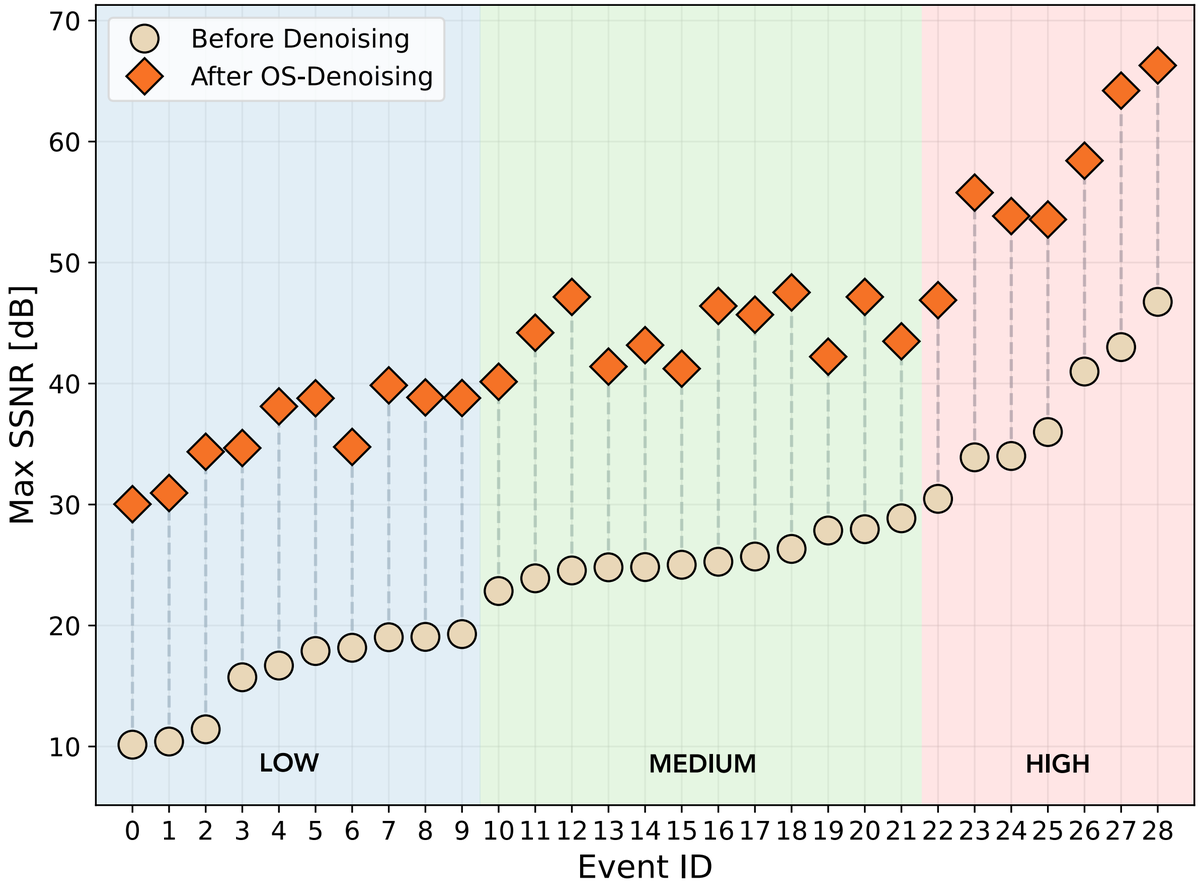


Overall Italy CCS results

DFOS shows great monitoring performances event with fiber-optics cable installed in the injection well.

Improved the SSNR of real DFOS regional earthquakes data.





Conclusions

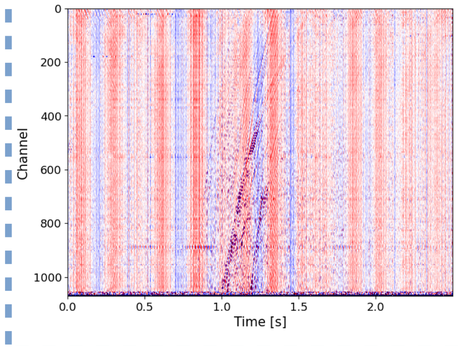
- Proposed an **effective** solution to **DFOS data denoising** based on **spectral-subtraction** algorithms.
- **Improved the SNR** of real DFOS data acquired during both **CCS** and **EGS** operations.
- **Effective in different** fiber-optic **deployments**, **low computational cost** and **few parameters** to set.

Grazie!
Thank You!

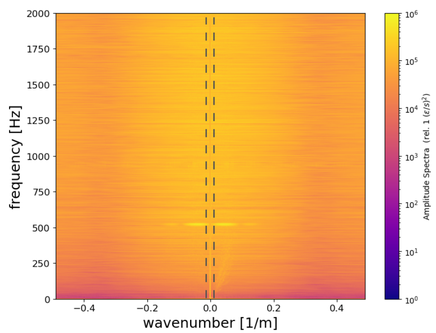
Contact: **giulio.pascucci@phd.unipi.it**

Full Denoising Workflow | General Flowchart

Raw DFOS data



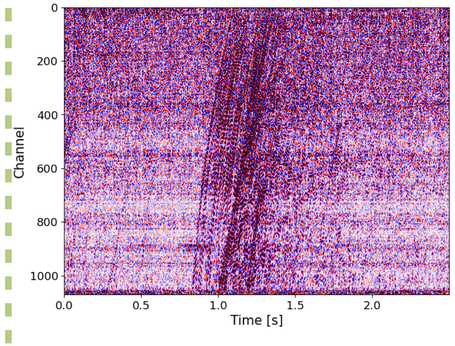
F-k raw

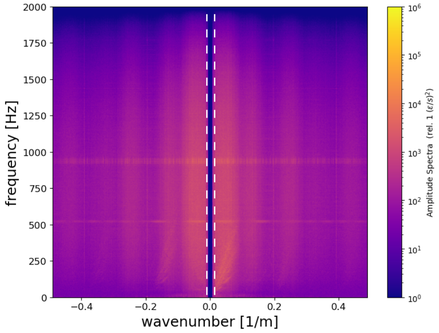


Pre-Processing

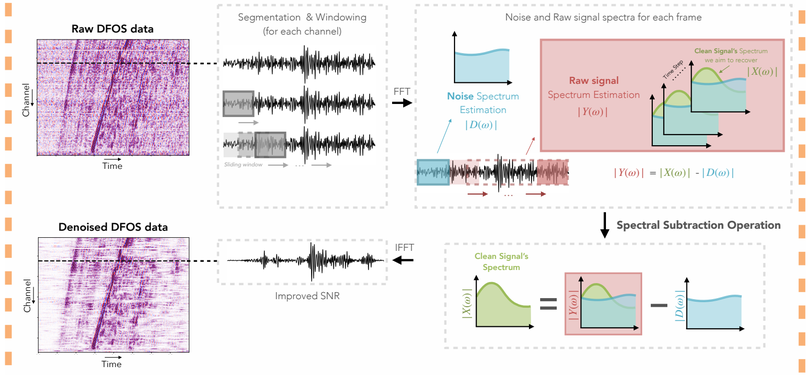
1. De-mean, De-trend
2. f-k filter (around k=0)
3. Trace Normalization

F-k after PP

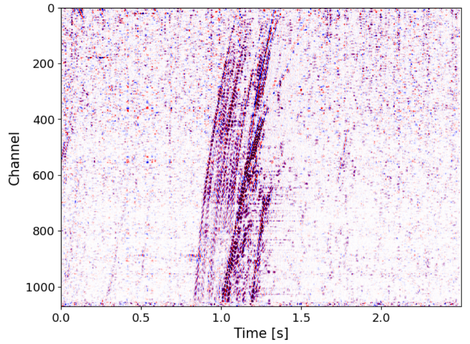




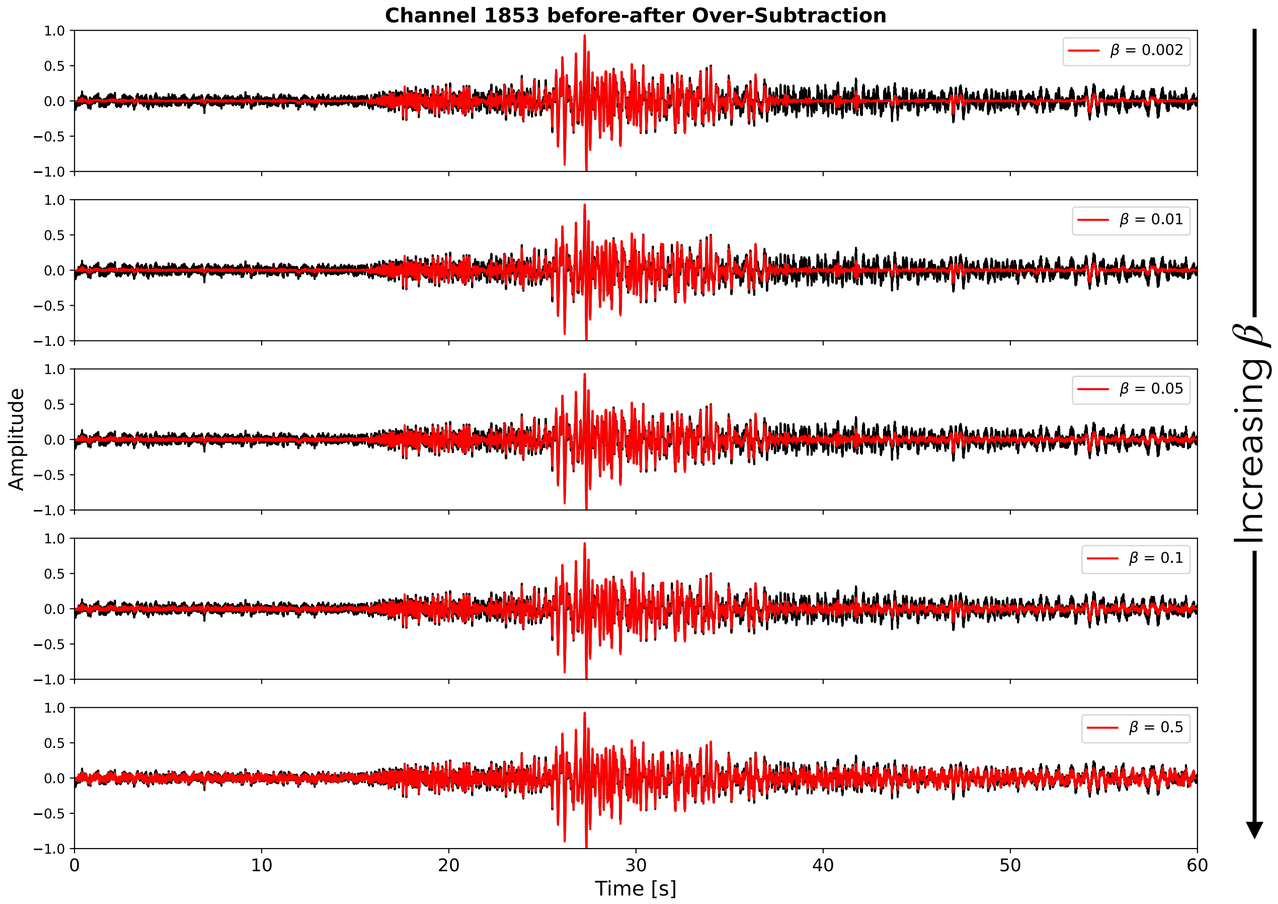
Spectral Subtraction Denoising Workflow



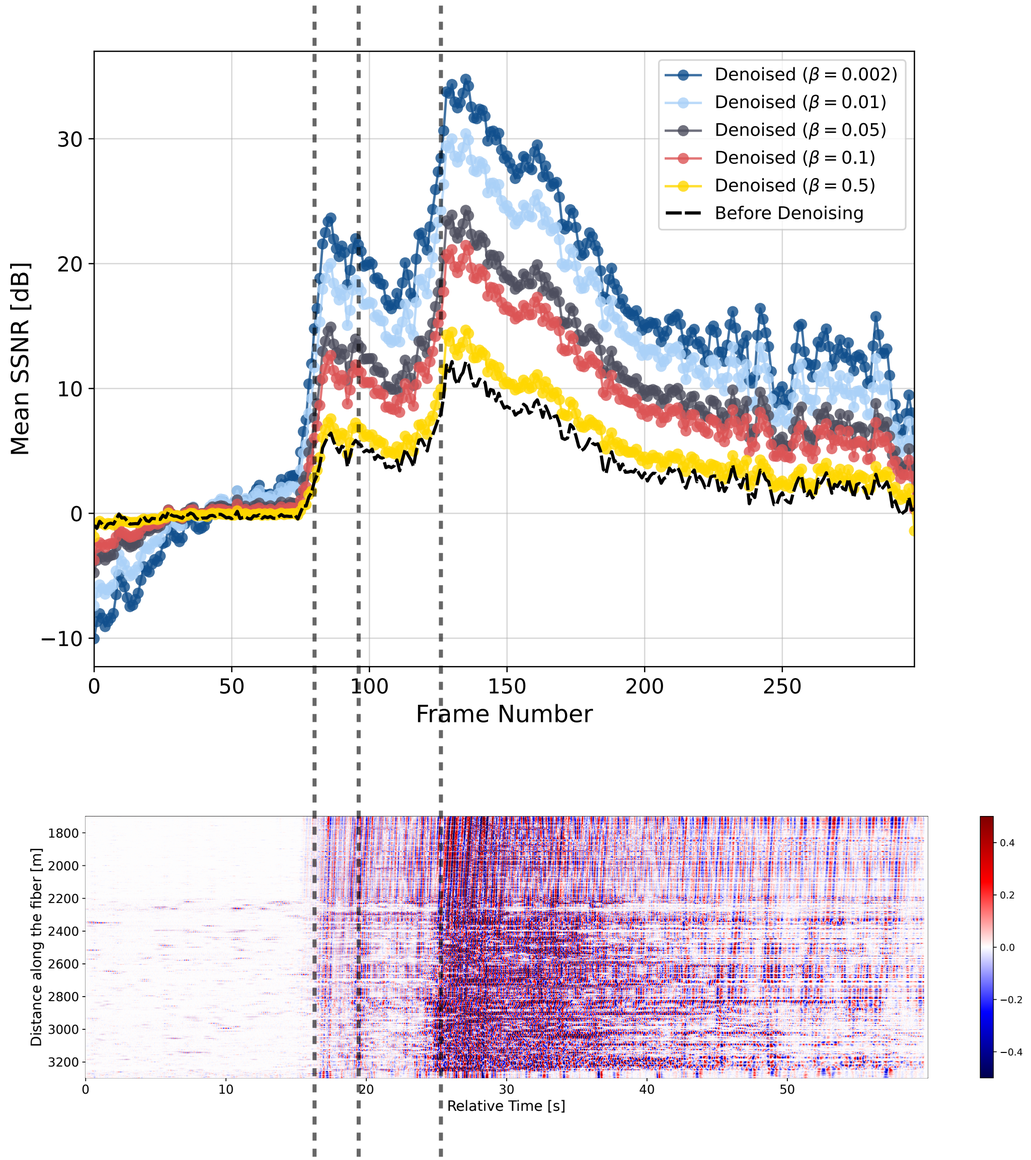
Enhanced DFOS data



Over-Subtraction: **Parameters (β)**

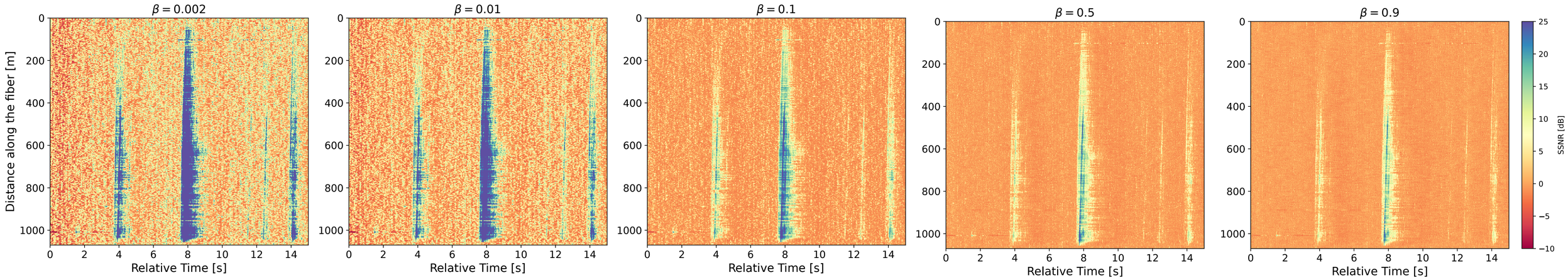


Increasing β



$$|\tilde{X}(\omega)|^2 = \begin{cases} |Y(\omega)|^2 - \alpha|\tilde{D}(\omega)|^2 & \text{if } |Y(\omega)|^2 > (\alpha+\beta)|\tilde{D}(\omega)|^2 \\ \boxed{\beta|\tilde{D}(\omega)|^2} & \text{otherwise} \end{cases}$$

Over-Subtraction: **Parameters (β)**



$$|\tilde{X}(\omega)|^2 = \begin{cases} |Y(\omega)|^2 - \alpha|\tilde{D}(\omega)|^2 & \text{if } |Y(\omega)|^2 > (\alpha+\beta)|\tilde{D}(\omega)|^2 \\ \beta|\tilde{D}(\omega)|^2 & \text{otherwise} \end{cases}$$

Over-Subtraction: **Parameters (α)**

A general, but effective **rule of thumb** to set α :

- Smaller values for high-SNR frames (i.e., when signal is present)
- Larger values for low-SNR frames (i.e., when noise is present)

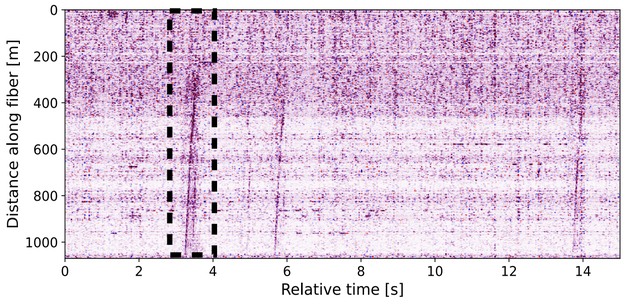
$$\alpha = \begin{cases} 5 & \text{SNR} < 0 \text{ dB} \\ 3 - (3/20)\,\text{SNR} & \text{if } 0 \text{ dB} \leq \text{SNR} \leq 20 \text{ dB} \\ 1 & \text{SNR} > 20 \text{ dB} \end{cases}$$

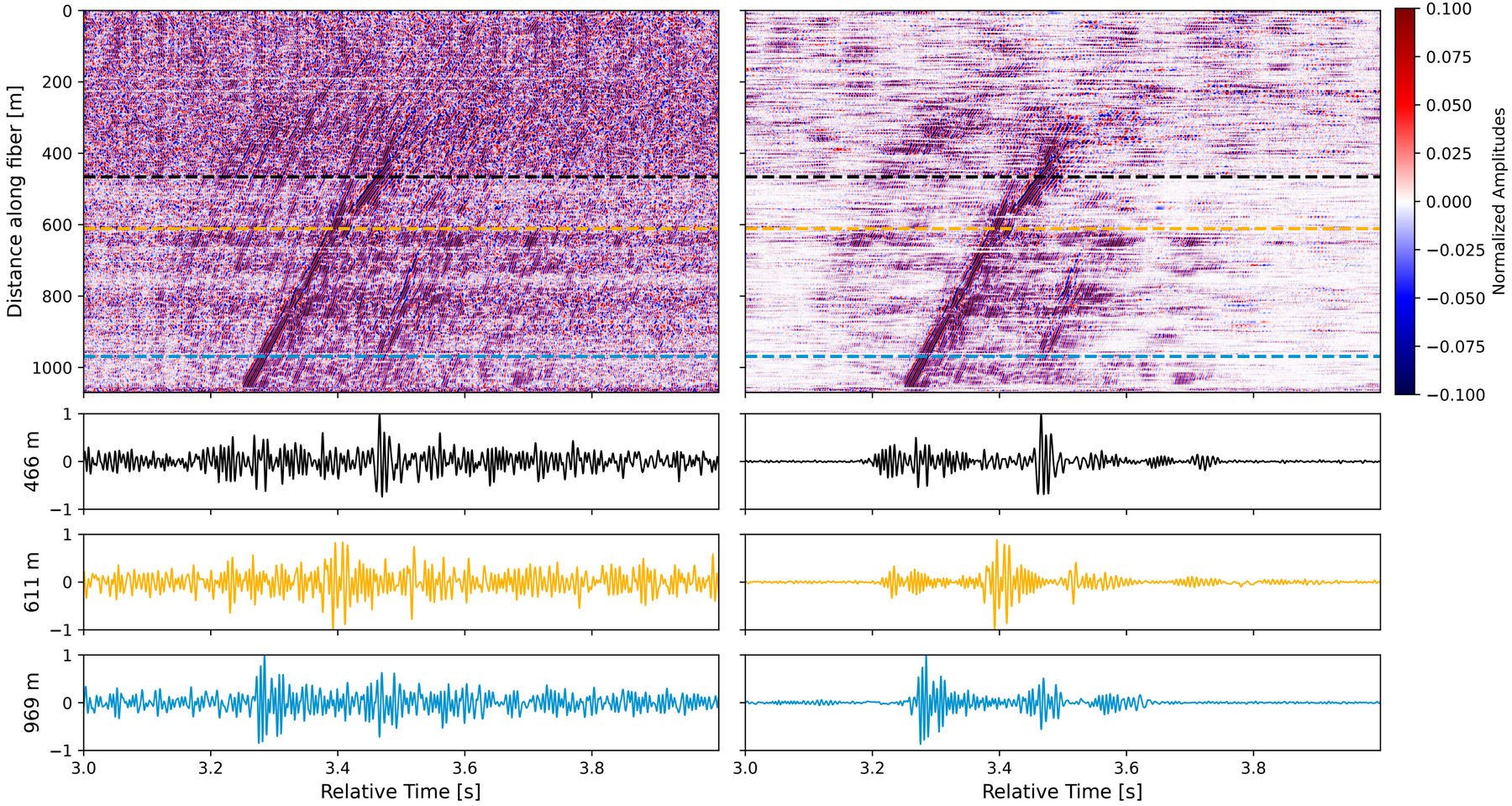
The SNR in the previous equation is estimated frame-by-frame for each channel of the DFOS data and is calculated using the **Segmental Signal-to-Noise Ratio (SSNR) :**

$$SSNR_i = 10 \log \left(\frac{\sum_{k=1}^{N} |Y_k(\omega)|^2}{\sum_{k=1}^{N} |\tilde{D}_k(\omega)|^2} \right)$$

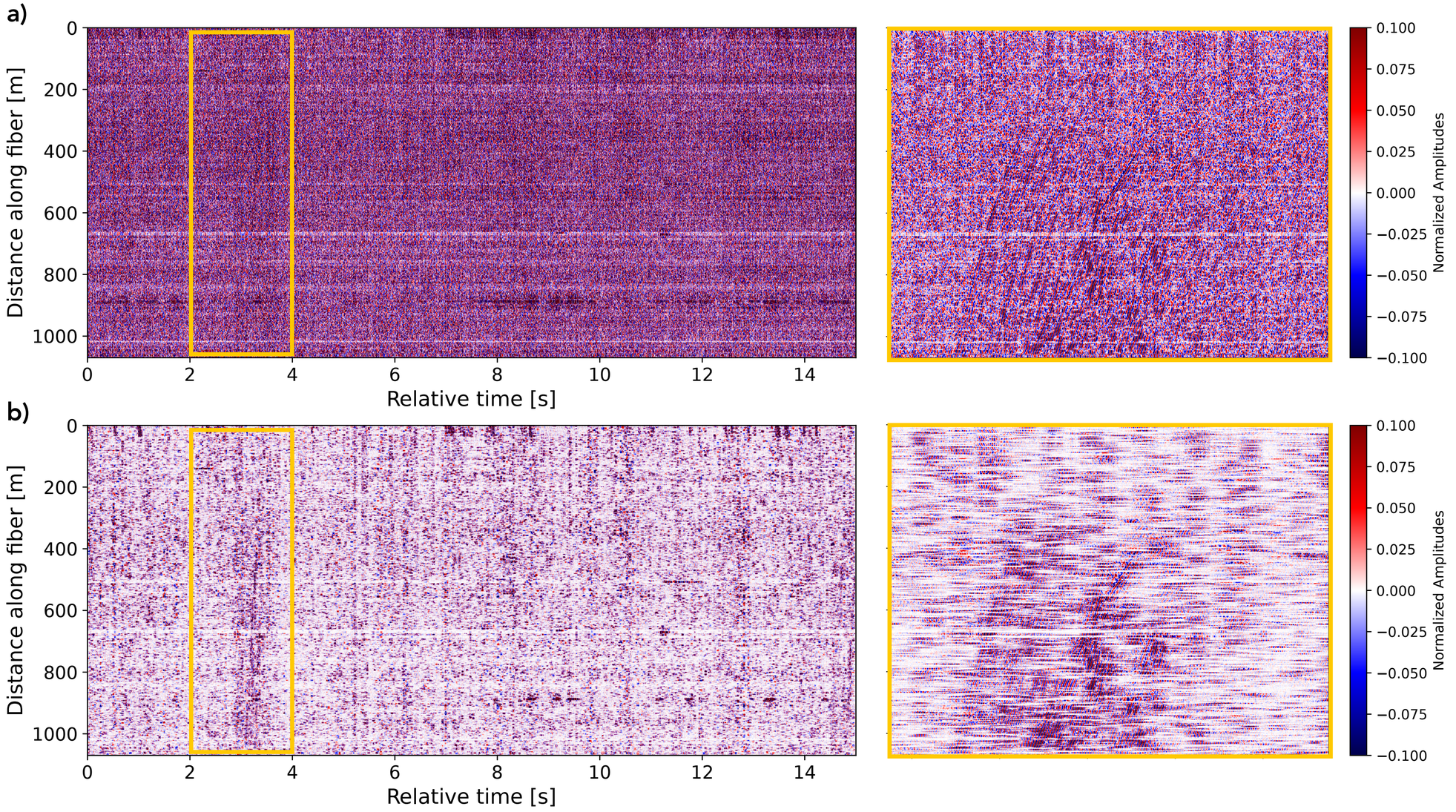
FORGE | Example on a Low SNR seismic event

- **Zoomed-in section** around the seismic event observed at 3.2 s.

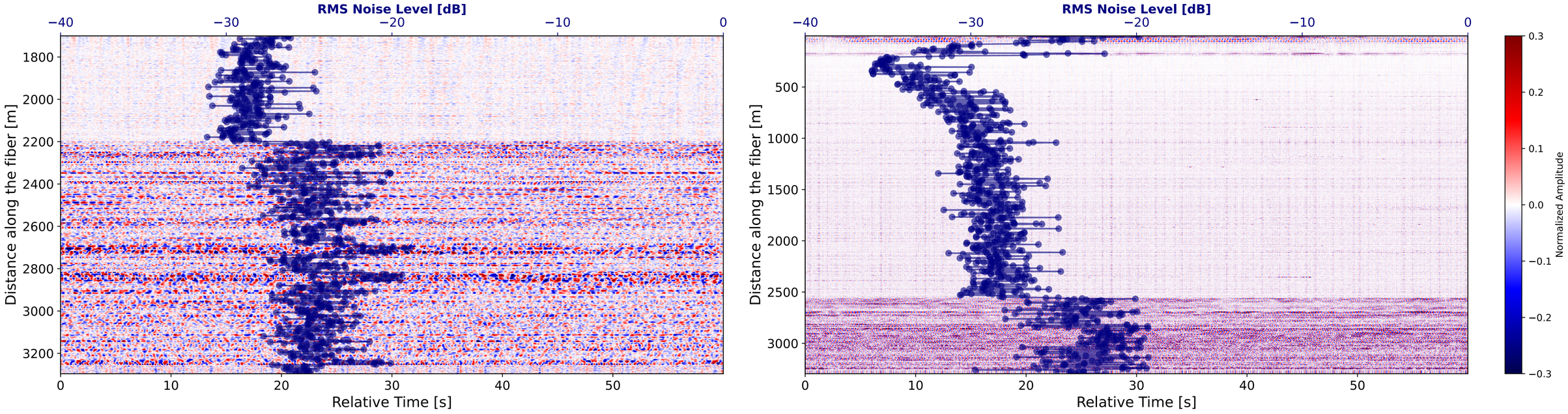




FORGE | Example on a Very-Low SNR seismic event



DAS Noise Levels in CCS data



During the **pre-CO_2 injection** stage of the CCS project, higher noise level were observed starting from different channels over time.