STEP'UP PhD Congress 2025:
A Cosmos in motion

CHARACTERIZATION OF THE SOIL PROPERTIES ALONG RAILWAY TRACKS USING DISTRIBUTED ACOUSTIC SENSING

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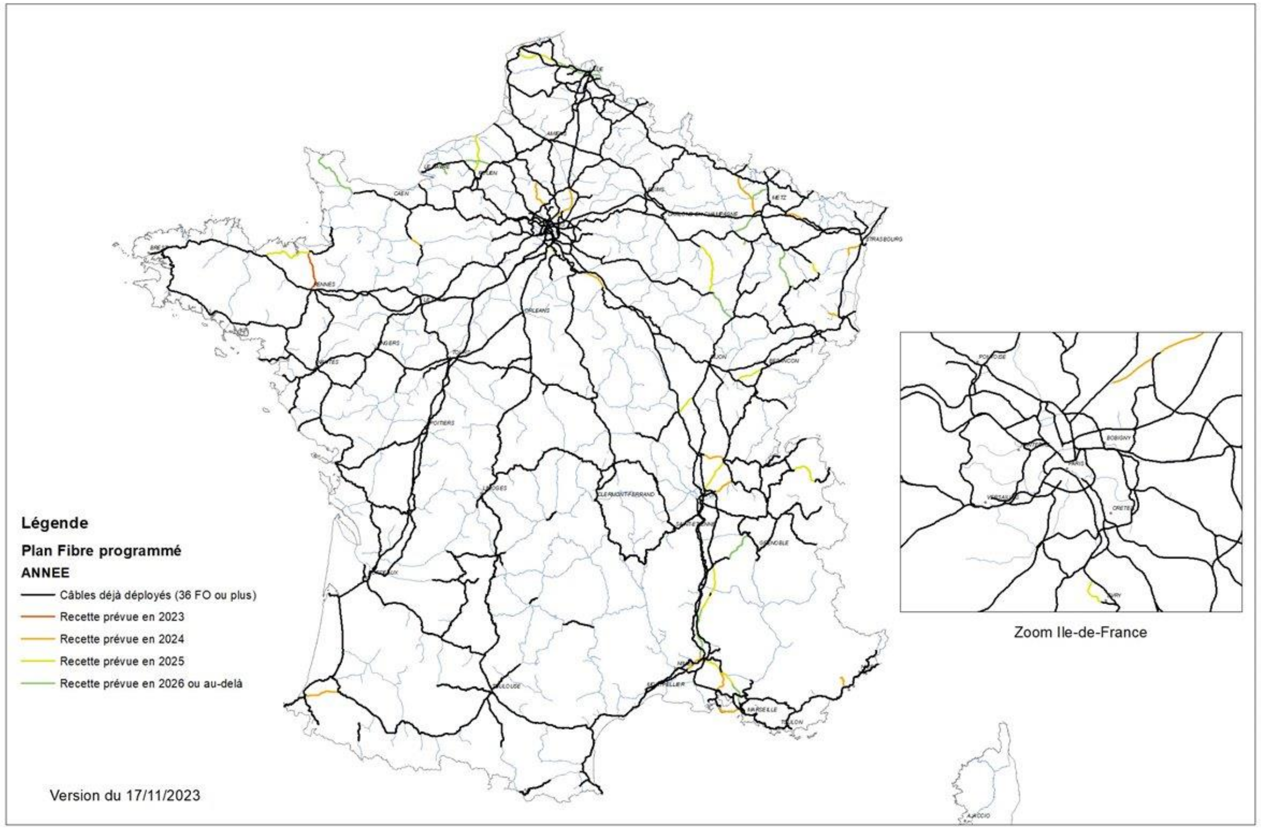
SNCF context

Câbles optiques existants et en projet SNCF Réseau (Plan Fibre et projets régionaux)



- SNCF has optical fiber (OF) cables along its main railway lines, covering more than 28,000 km.

144 = 24 * 6 fibers

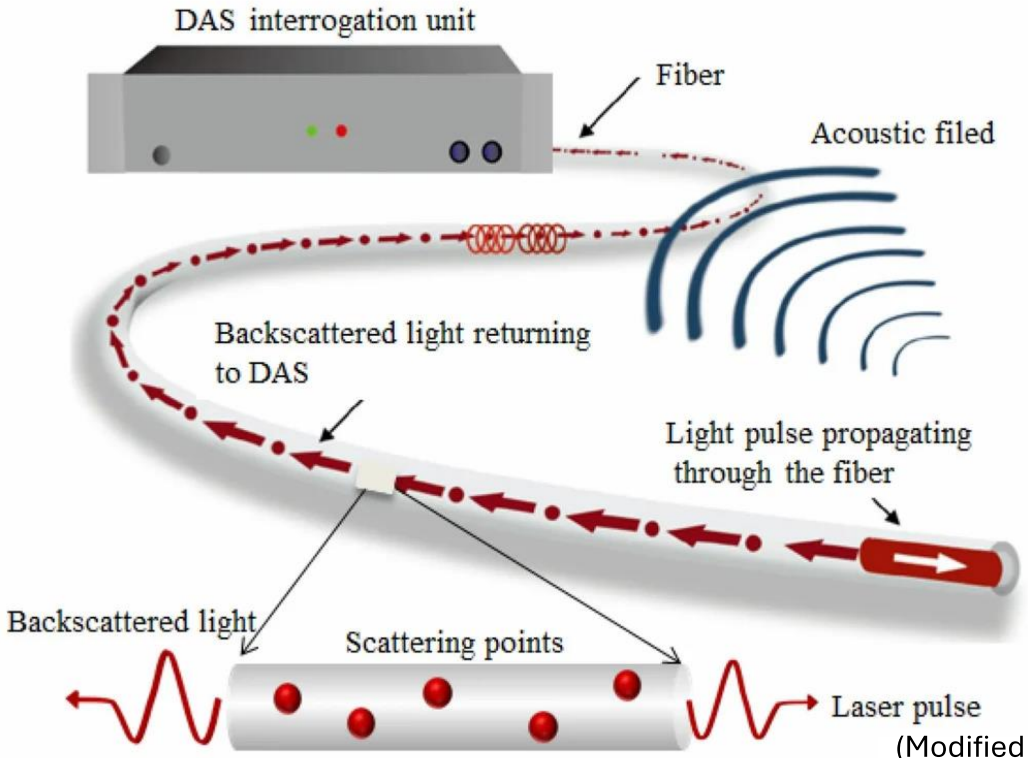
- There is a need to monitor geohazards
- DAS appears a good opportunity

Interne

What is DAS?

DAS: Distributed Acoustic Sensing

- The DAS interrogator unit uses Optical Time Domain Reflectometry (OTDR) to analyze Rayleigh backscattered light (RBL) generated by a probe laser pulse along the fiber.
- This setup provides a geophone-like measurement channel every 40 cm, over distances of up to 50 km



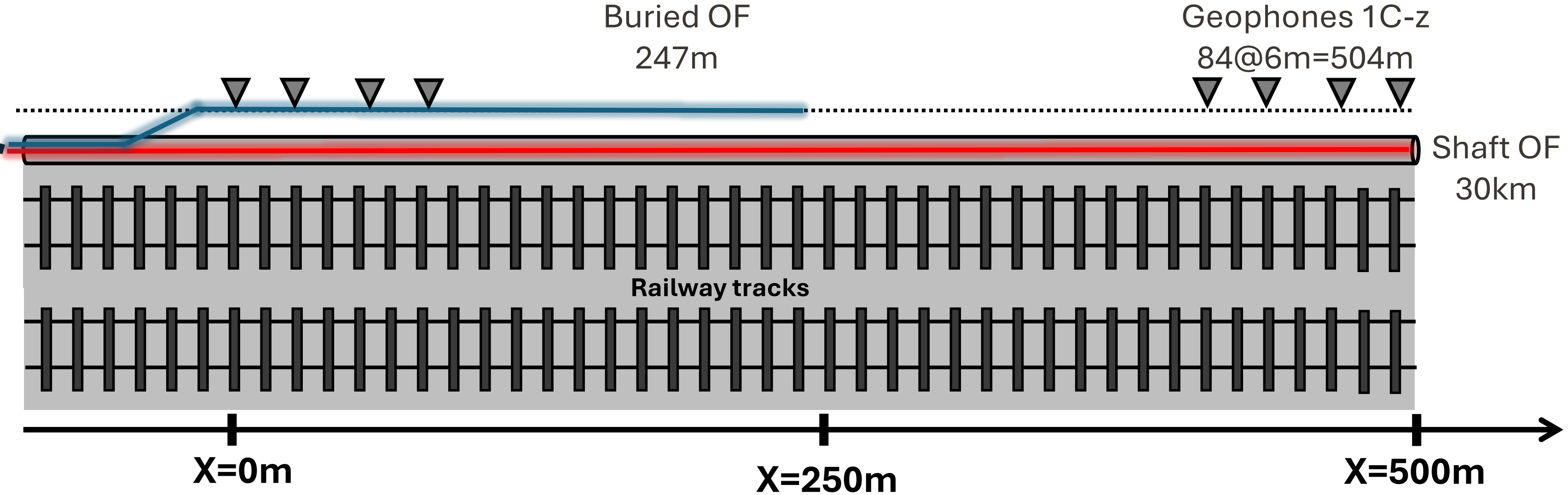
(Modified from www.silixa.com)

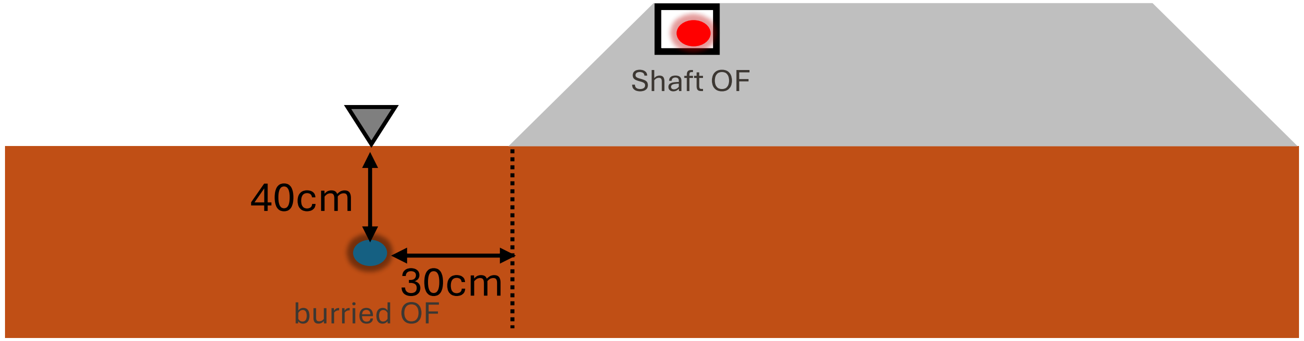
Experimental setup for subsoil monitoring

- 2 days of continuous record
- Active shots

7km from the train station to the test site

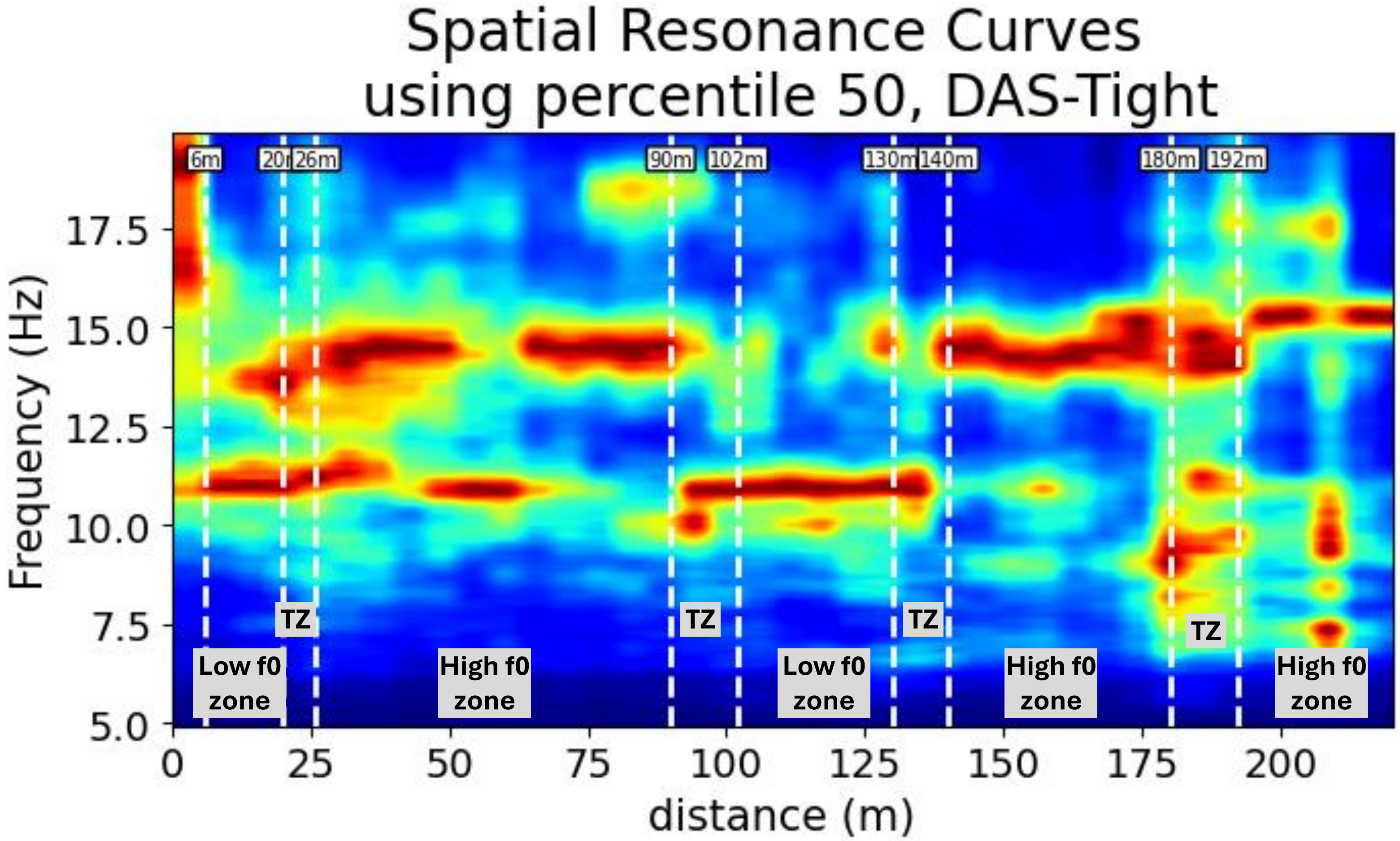
DAS-SNCF Interrogator Unit (in house built)





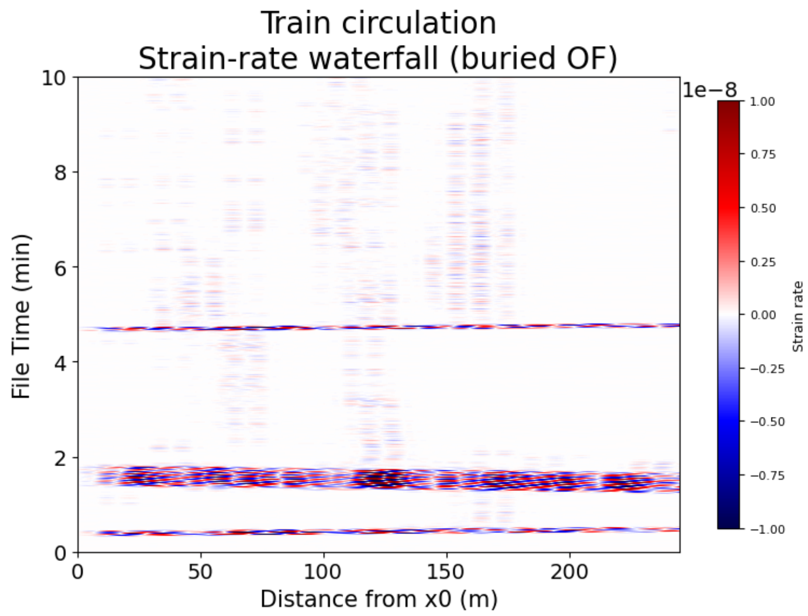
Quick site investigation

- **Resonance curves (like Power Spectrum Density)** allow us to quickly assess the homogeneity of the subsoil following the variation in the predominant frequency
- It can be used as a proxy on where the cross-correlations will be effective

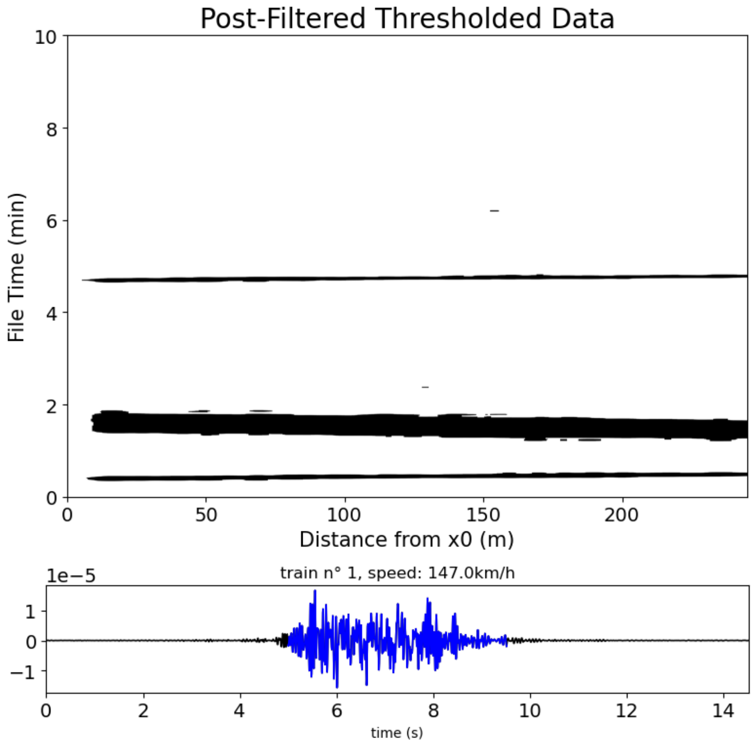


TZ: Transition Zone

DAS data: window selection for cross-correlations

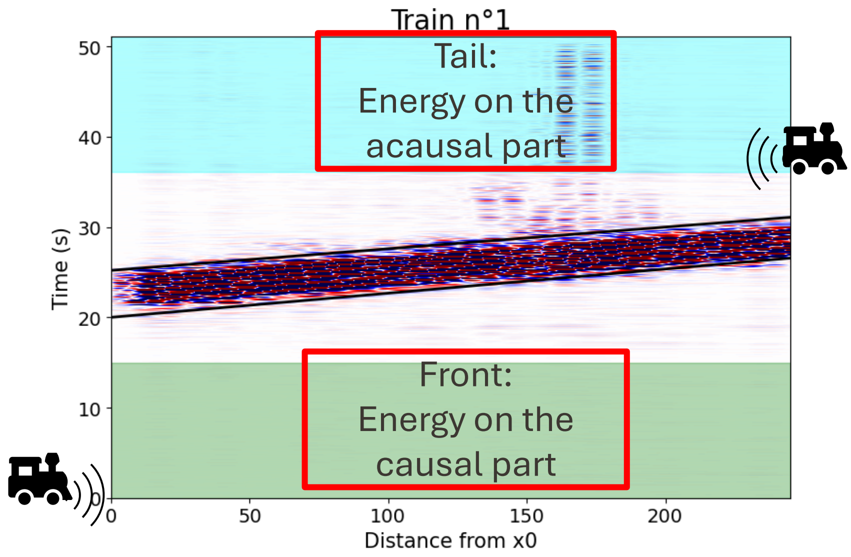


1- Example of a 10 minutes strain-rate record of 3 trains



2- Example of the train identification by thresholding on the absolute median filtered data

- In 2 days of acquisition, we identified 133 trains passages in both directions!

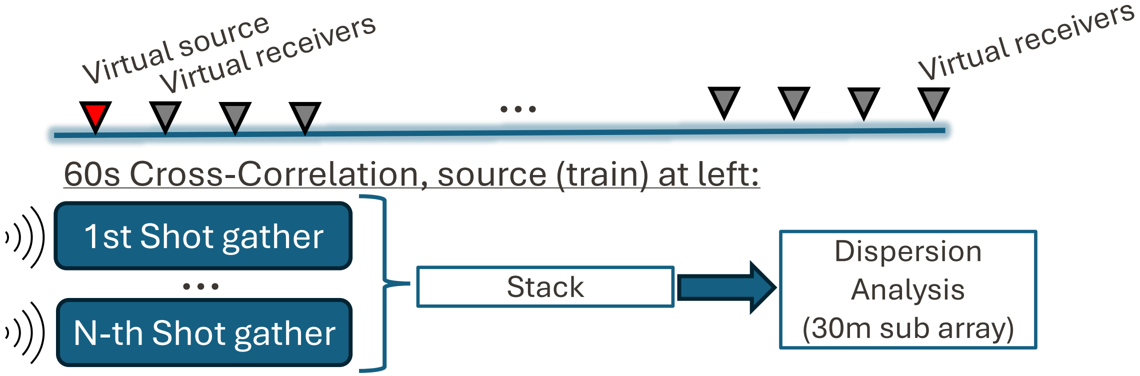


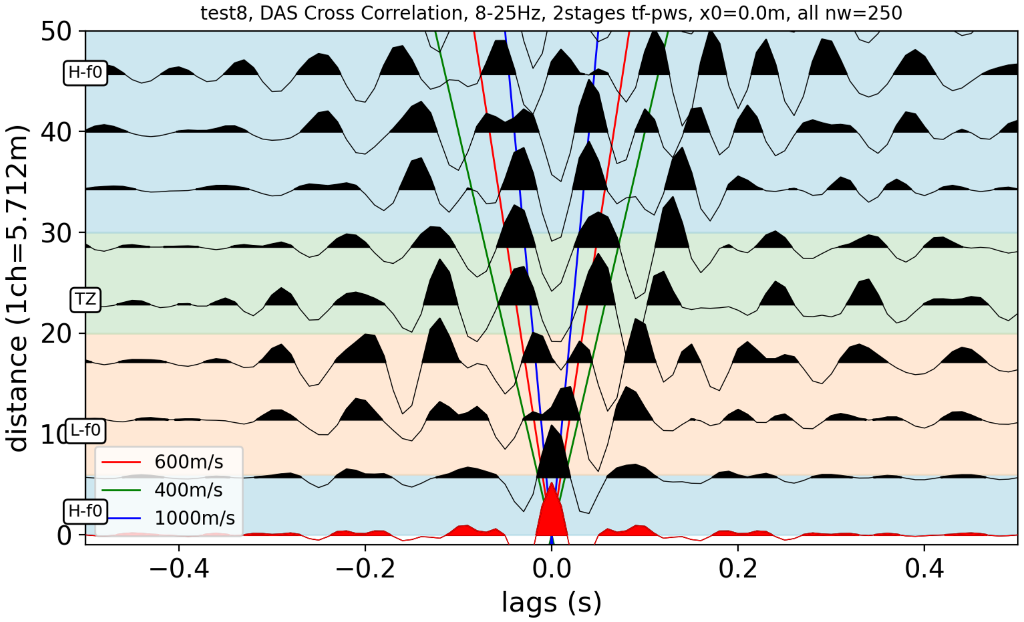
3- Example of window selection

- Spatio-temporal windows are selected 5 seconds before and after the train enters or leaves the test site

Cross-Correlation function (CCF)

Cross-correlation scheme

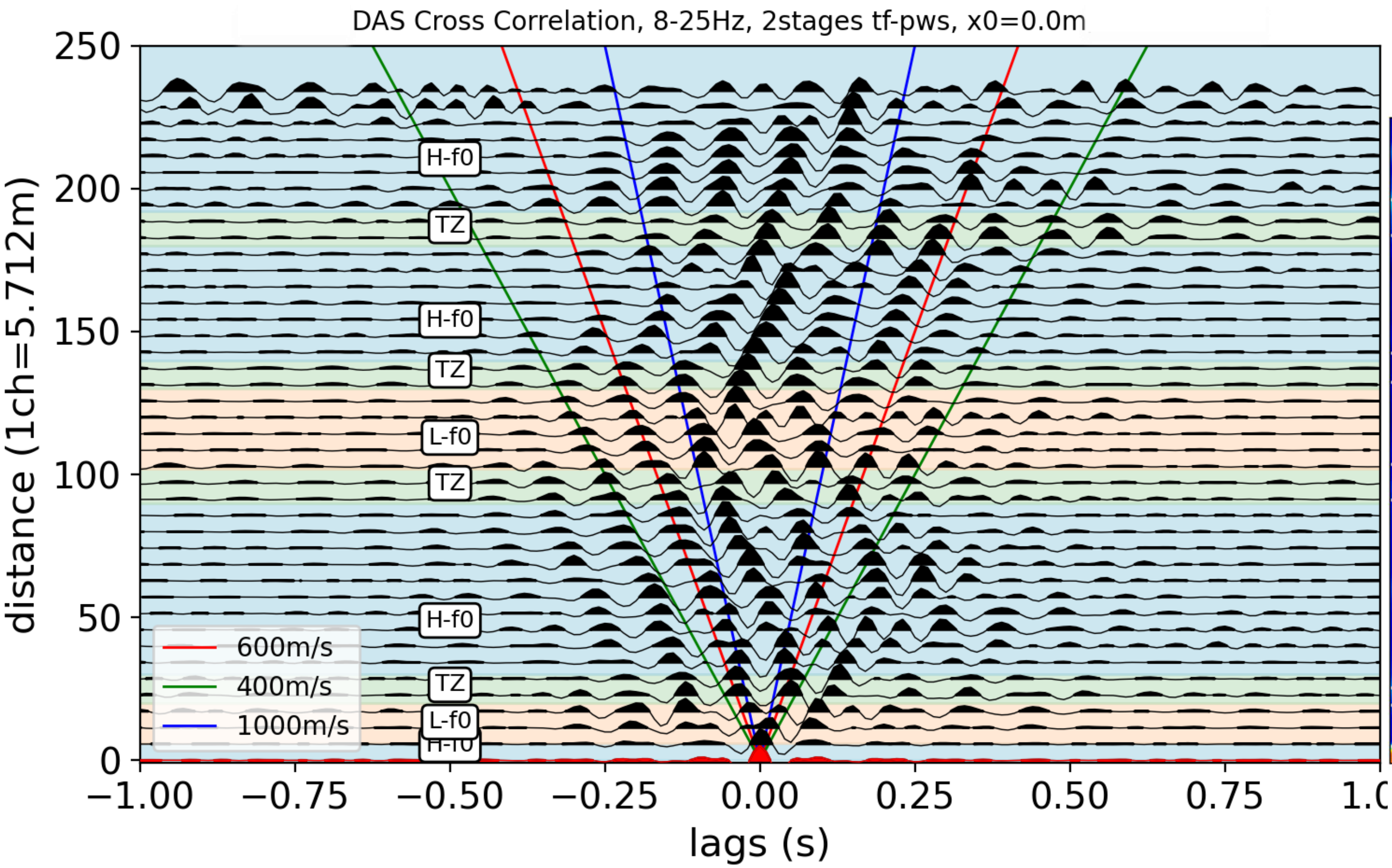


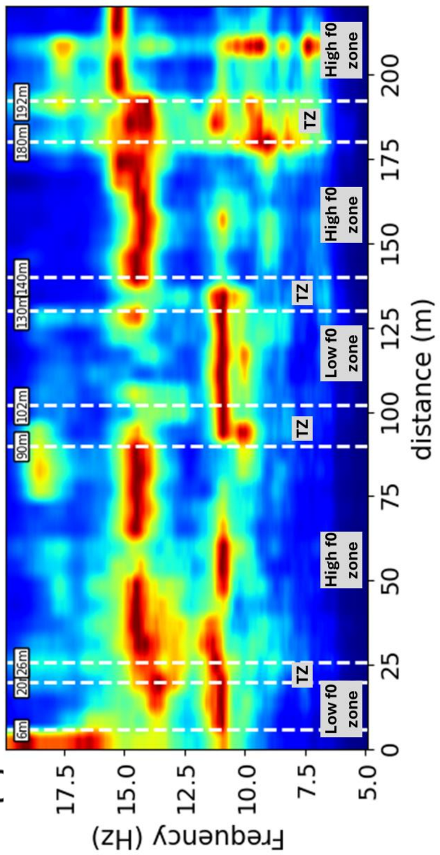


Stacked cross-correlation function of the first 50m

- Approximates the Green's function
  - Represents the "impulse response of a media between two points"
    - Used as a virtual shot gather for the **dispersion analysis of surface waves (MASW)**

Effects of the site variability on the CCF





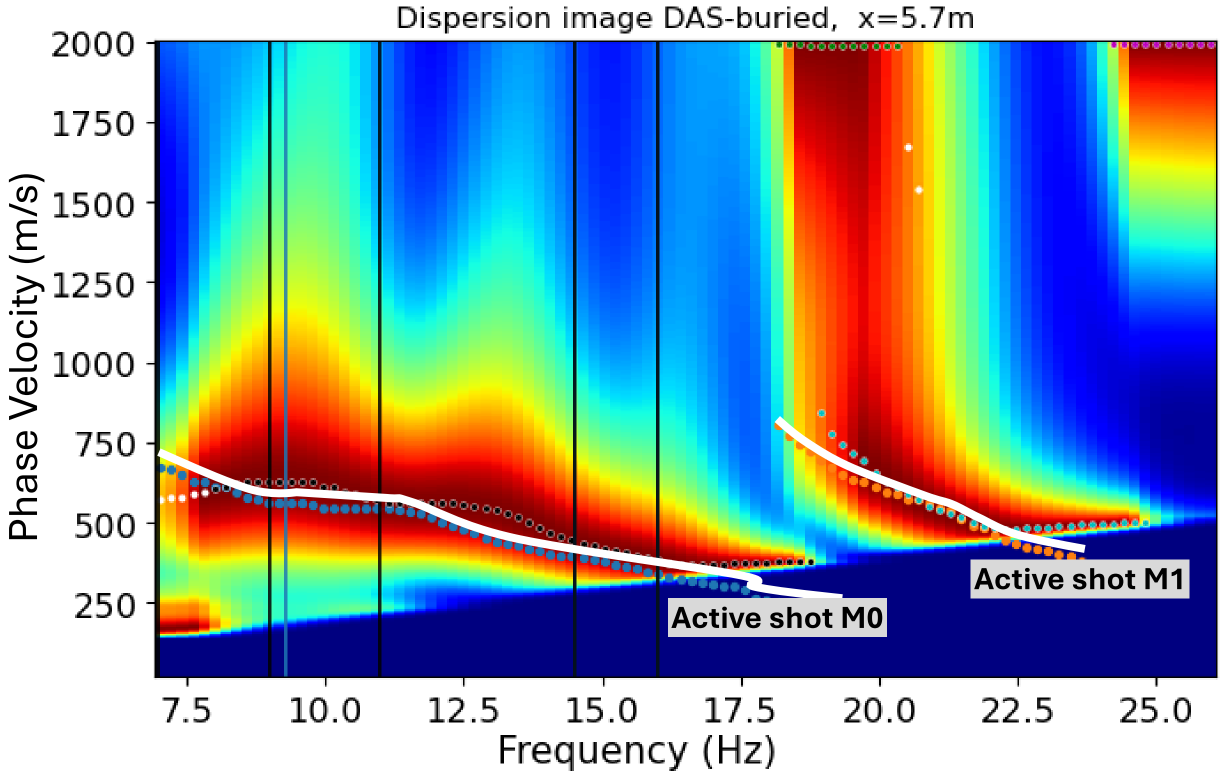
H-f0: high predominant frequency

L-f0: Low predominant frequency

TZ: Transition Zone

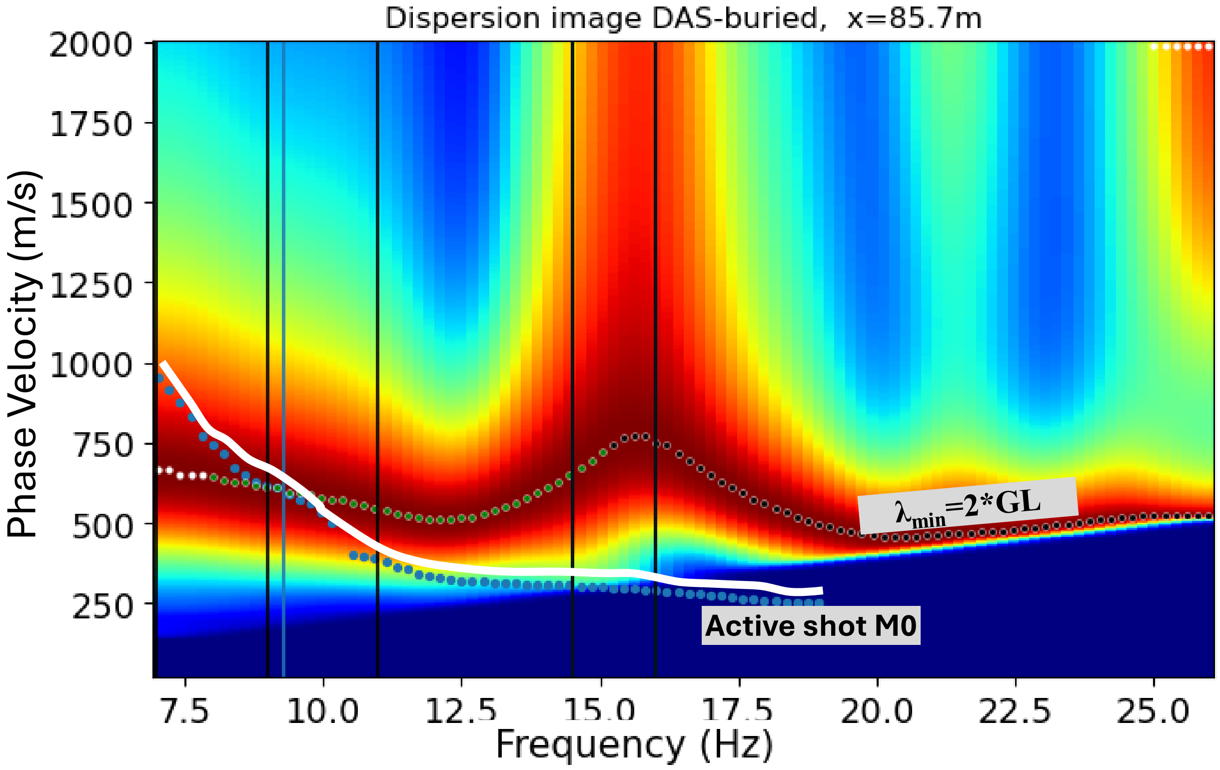
Dispersion images

- **Slant Stack** on the causal part of cross-correlation using sub arrays of 30m
- **Dispersion curves**: reflects how different frequencies travel at different speeds, depending on the subsurface structure.



Dispersion on a homogenous site:

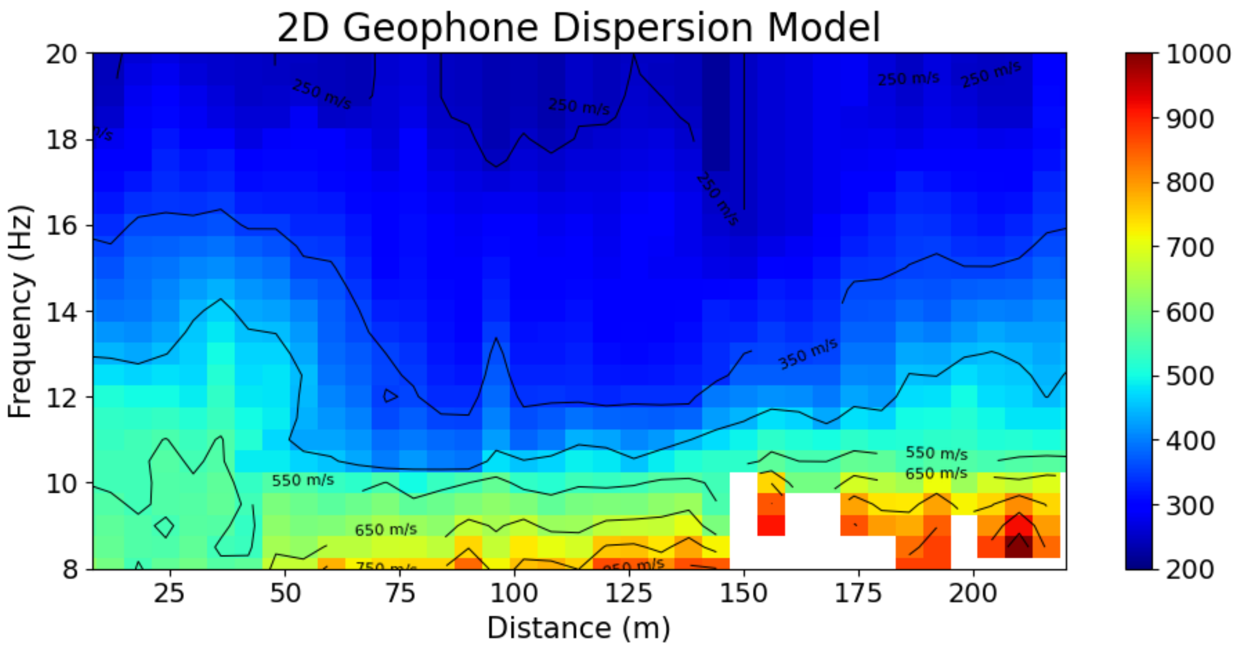
- Good match between active geophones and passive DAS

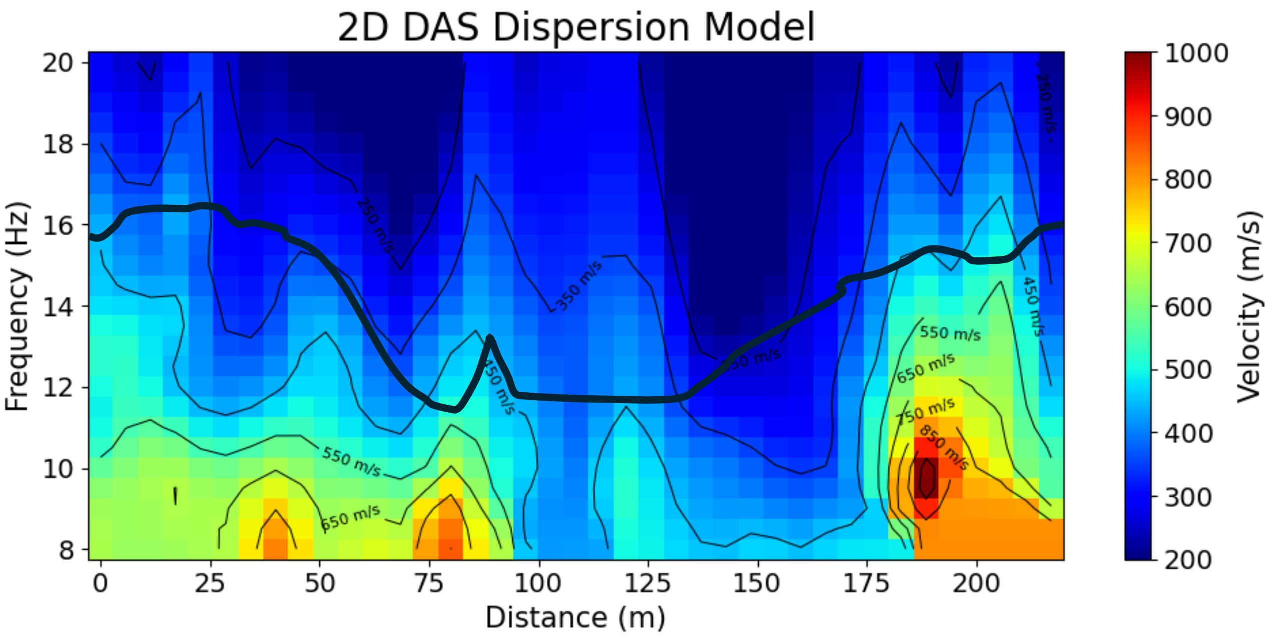


Dispersion on a transition zone site:

- Mode superposition
- Mismatch between active geophone and passive DAS

IV. Results: pseudo 2D phase velocity models





- ➢ The model obtained with the buried OF is consistent with the one obtained using the geophones
- ➢ We also see a good match between depth changes and f0 changes

Conclusions:

- DAS is a promising technology for railway monitoring

- Resonances curves emerge as :
  - A good option for subsoil monitoring, as a variation in the site's f0 could indicate changes in mechanical properties
  - A great tool to optimize the analysis of the CCF

- Passive methods for subsoil characterization have shown good reliability

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Thank you for your attention!

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Contents

III. A – Experimental setup

Shaft OF

buried OF

Geophones

Train passage

I. Context: Hazards related to the soil in the railway context

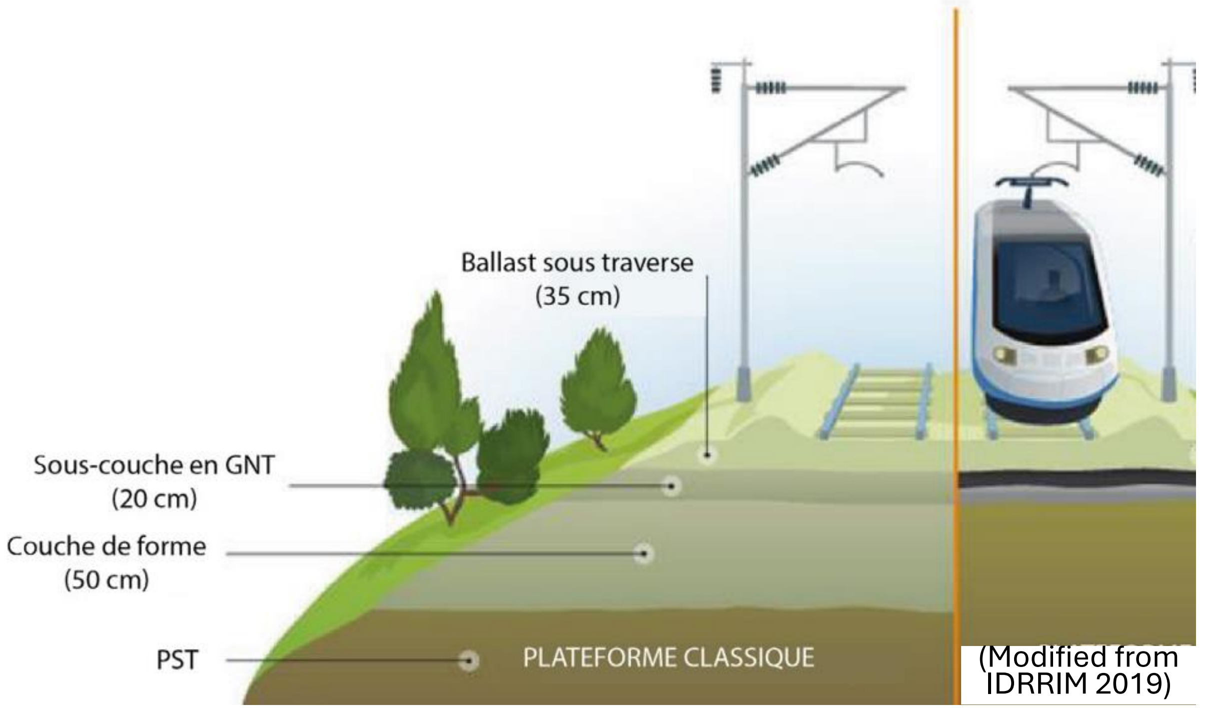
Landslide
Derailment of RER B, June 12, 2018. —
GEOFFROY VAN DER HASSELT / AFP

Landslide
Derailment of the TGV Strasbourg-Paris March 5th, 2020 – https://www.ville-rail-transports.com/
« According to SNCF, initial indications suggest that the land subsidence was very sudden. Five trains had previously passed on this line, the last one at 6:55 a.m., and no driver reported any anomalies.»

Rockfall
Derailment of an RER, January 19th, 2024
https://c.vosgesmatin.fr/faits-divers-justice/2024/01/19/deraillement-de-train-a-jarmenil-la-ligne-sncf-epinal-saint-die-bloquee

I. Context: Objective of the Study

- Develop a DAS-based methodology to monitoring the railway platform:
  - Characterize the geophysical properties of the subsoil
  - Monitor these properties over time
  - Identify any potential changes



(Modified from IDRRIM 2019)

III. B - Data Acquisition and Preprocessing

Strain-rate estimation

Continuous recording
- 10 minutes long raw data file (electric field of the RBL)

Channel selection

Strain Rate Extraction:
- Phase demodulation
- Phase difference (Δθ = ε(x, t), GL=10m)
  - Phase unwrapping : θ(x, t)
    - Phase differentiation ($\frac{d\epsilon}{dt} = \dot{\epsilon}$(x, t))(strain rate)
    - Down sampling (1600Hz to 200Hz)

Signal shaping

Preprocessing:
- Bandpass filtering (1-40Hz)
- Low pass k-filter (k<1/GL)
- Channel down sampling (dx=0,4m to dx=6m)

Window selection:
- Train identification using an absolute median filter
- Keep 60s before and after the train
- Separate windows based on the train direction

III. B -Data Preprocessing: Cross-Correlation

Phase CWT Cross-Correlation

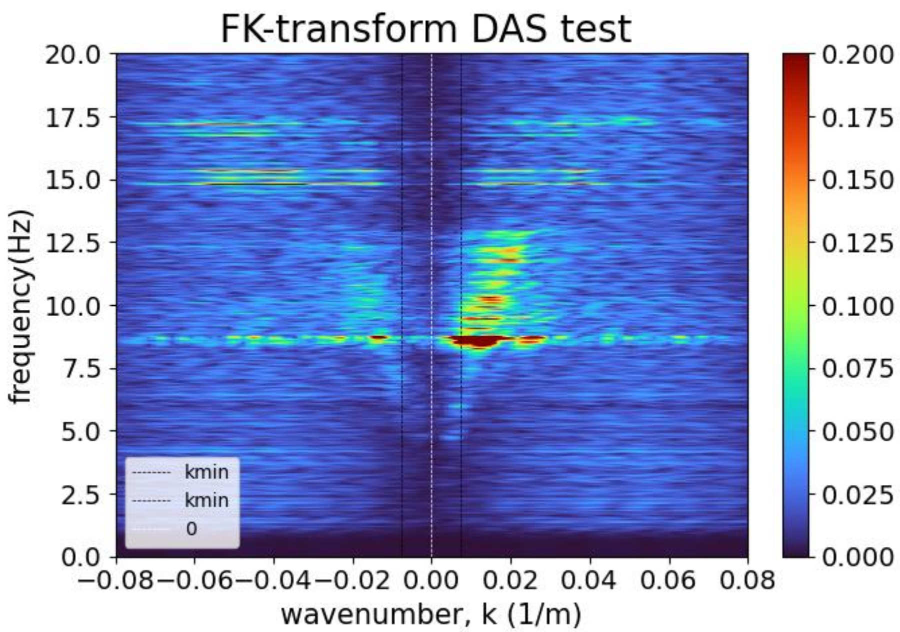
- We cross correlate each channel against all other channels
- We work with only one kind of window at the time (causal or acausal)

2 stages tf-pws:

- Correlations of the same channel pair are stacked
- First, we separate them in n-bins and apply a linear stack to enhance the cross-correlation curve quality
- Then we stack the results using the time-frequency phase-weighted stack

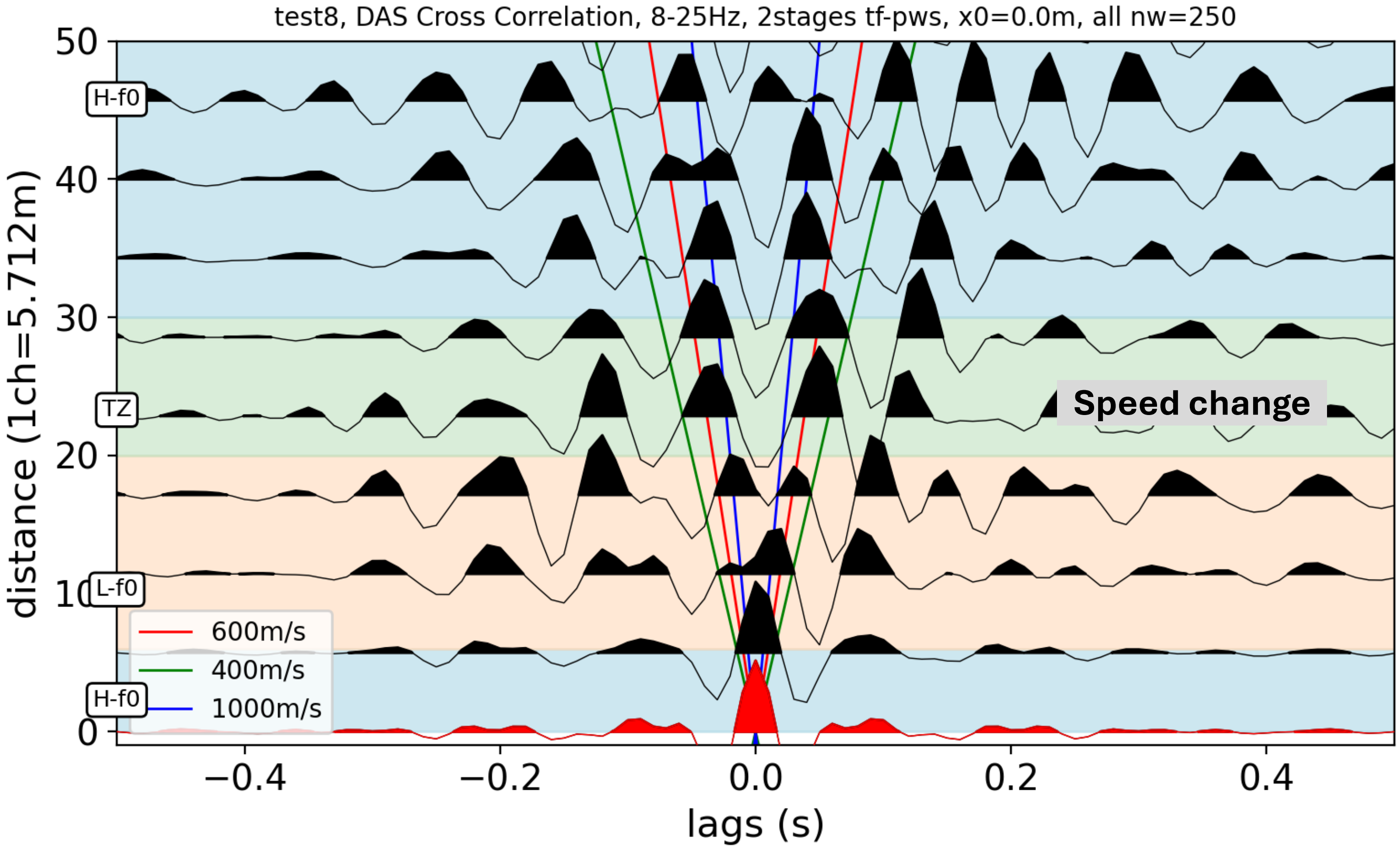
Dispersion curves:

- Slant-stack transform on the stacked Cross-Correlation Function
- Dispersion curve extraction



Example of the Frequency-wavenumber transform of a window with most of the energy on the causal (right) part (buried OF)

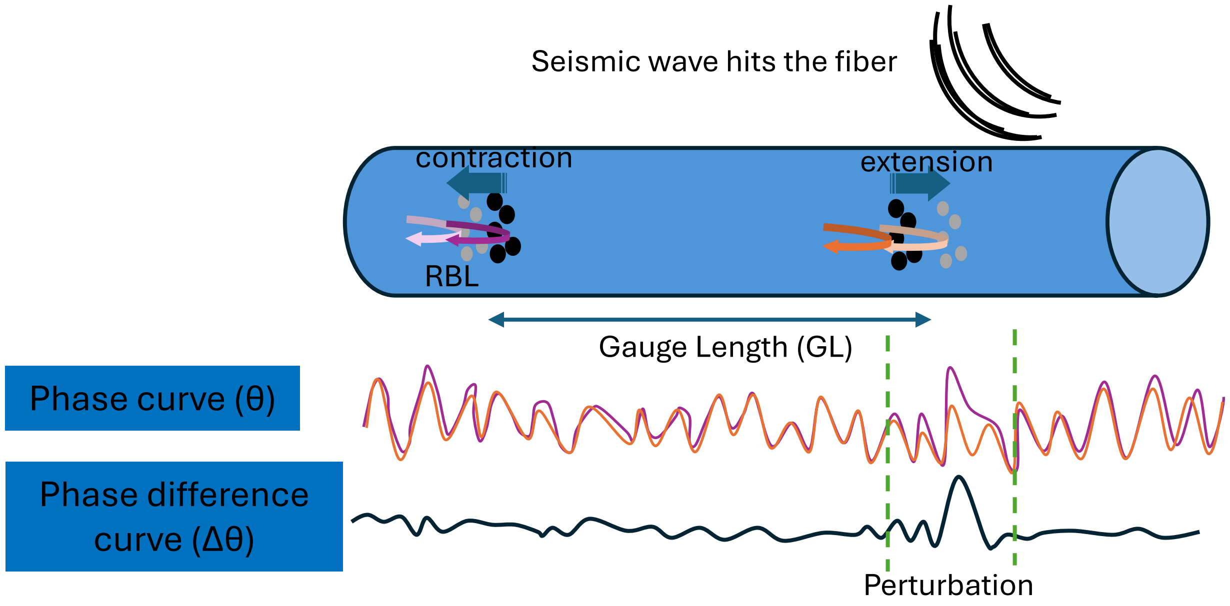
IV. Results: Cross Correlation Function



Interne

II. What is DAS?

- The DAS measures the phase of the backscattered light
- The phase difference between two points on the fiber is linearly proportional to the cable's deformation
- DAS cable can only sense the axial component



Phase difference:

$$\Delta\Theta(x,t) = \Theta(x - GL/2, t) - \Theta(x + GL/2, t)$$

Phase difference and strain relationship:

$$\epsilon(x,t) = \Delta\Theta(x,t)\frac{\lambda}{4\pi n\gamma GL}$$

III. B – DAS Data: Problems and solution

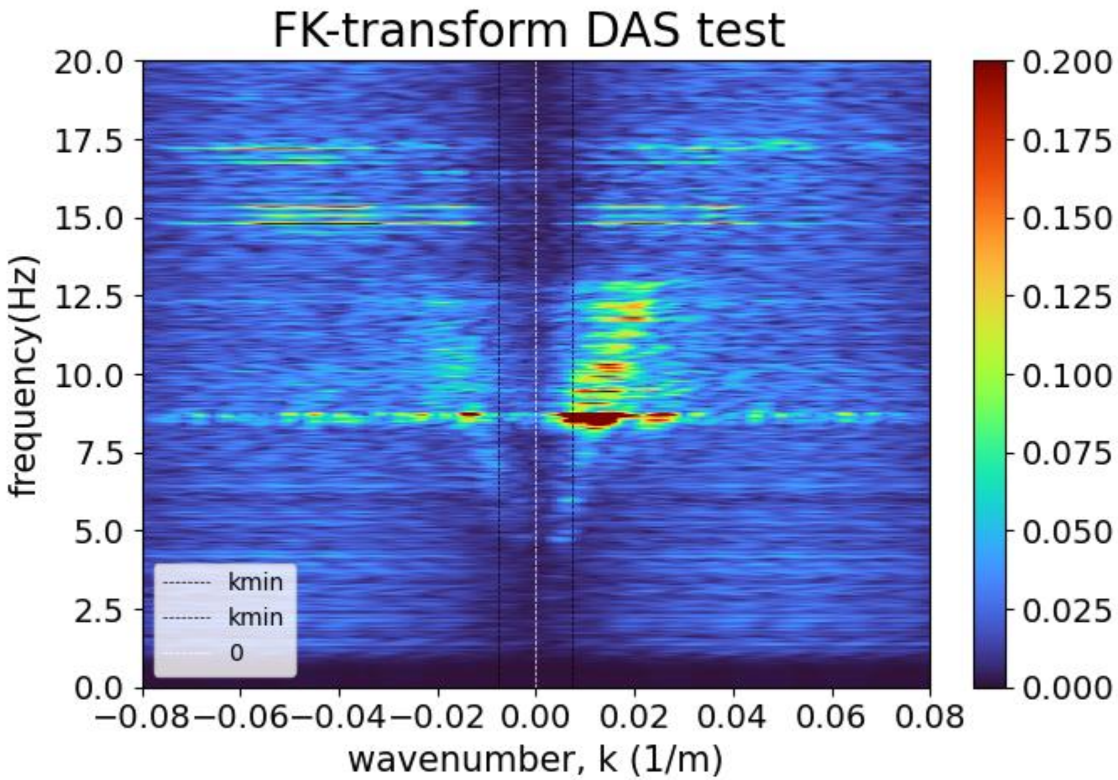
Working with DAS has a few inherent problems:

- Large data sets:
  - For 42 km and a 10-minute recording at 2000 Hz → approximately 30 TB
  - For reference: ~70 GB per minute per kilometer
- Noisy data:
  - Self-noise
  - Poor coupling
  - Signal fading

→ A robust signal processing workflow is required to:

- Successfully image the subsoil
- Determine the homogeneity of the medium

→ We use running trains as seismic source



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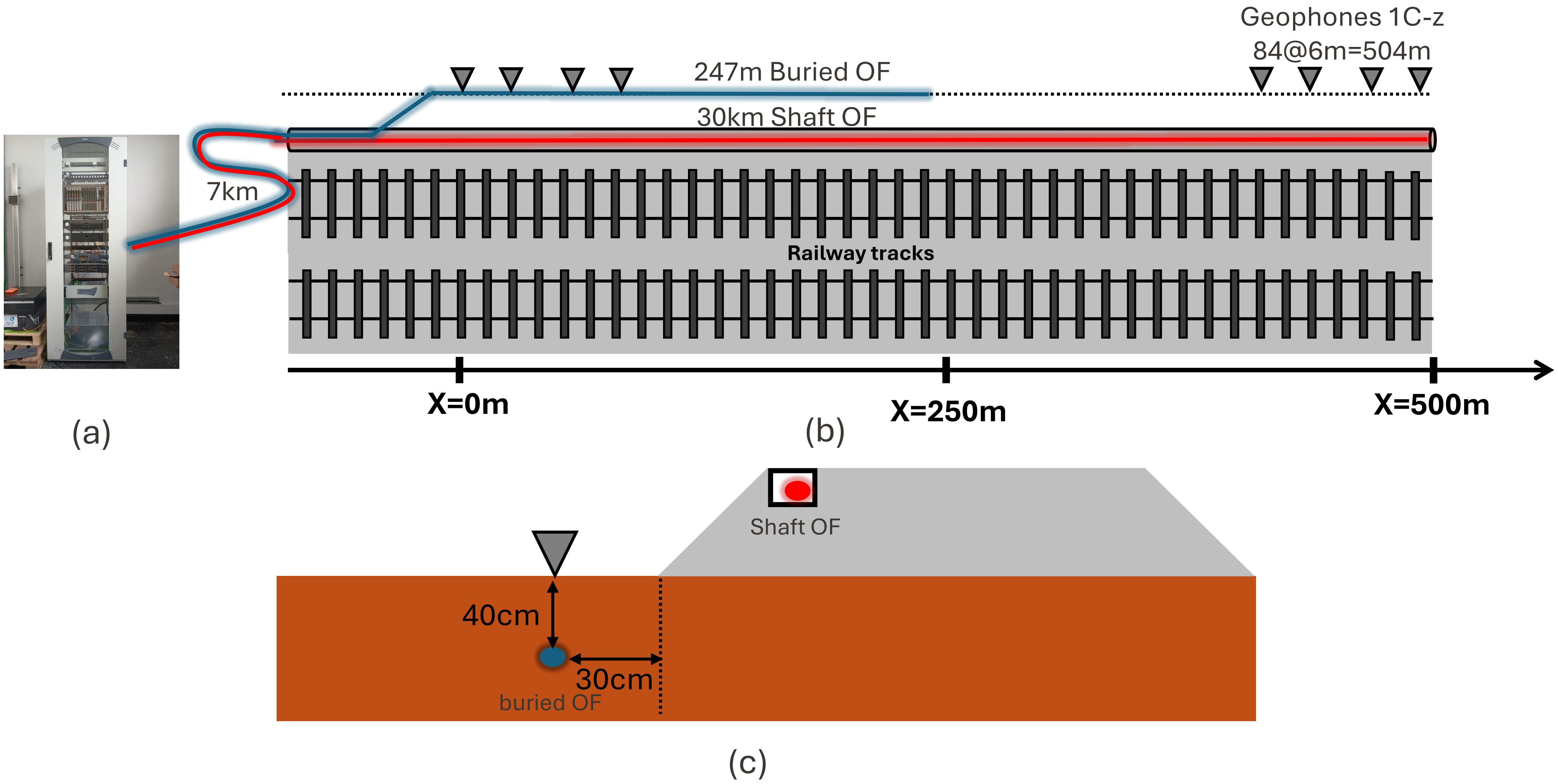
Geophones 1C-z
84@6m=504m
247m Buried OF
30km Shaft OF
7km
Railway tracks
X=0m
X=250m
X=500m
(a)
(b)
Shaft OF
40cm
30cm
buried OF
(c)