Tremble sensed as Integrated Noise by frequency Transfer In a Network (TINTIN)

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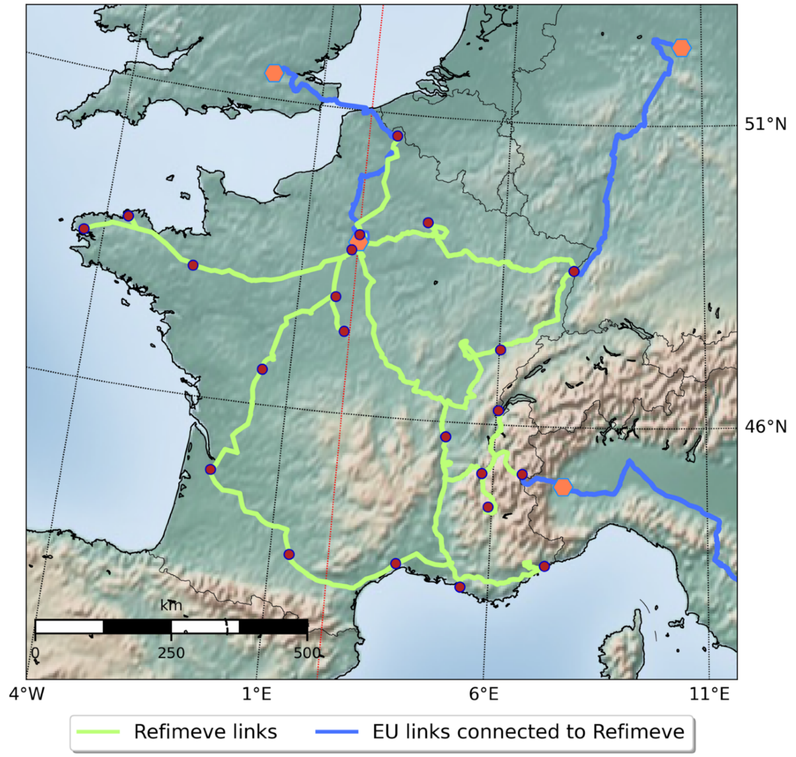
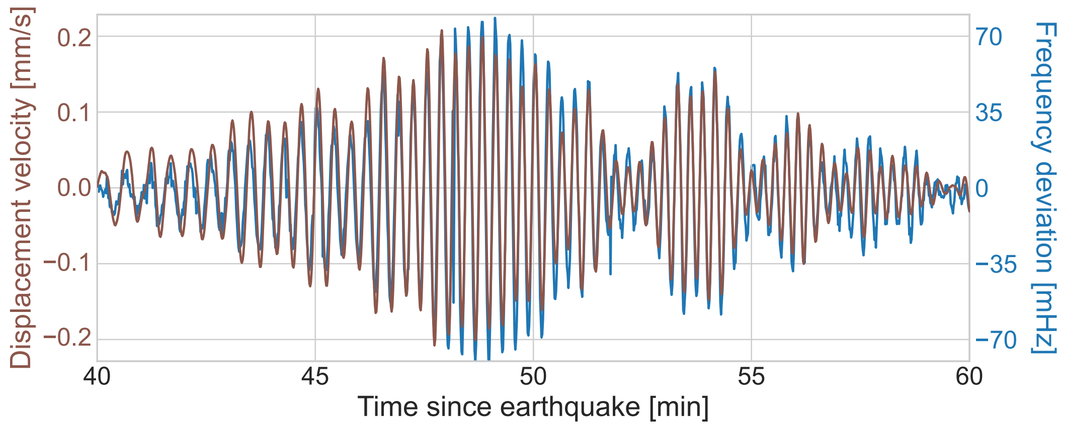
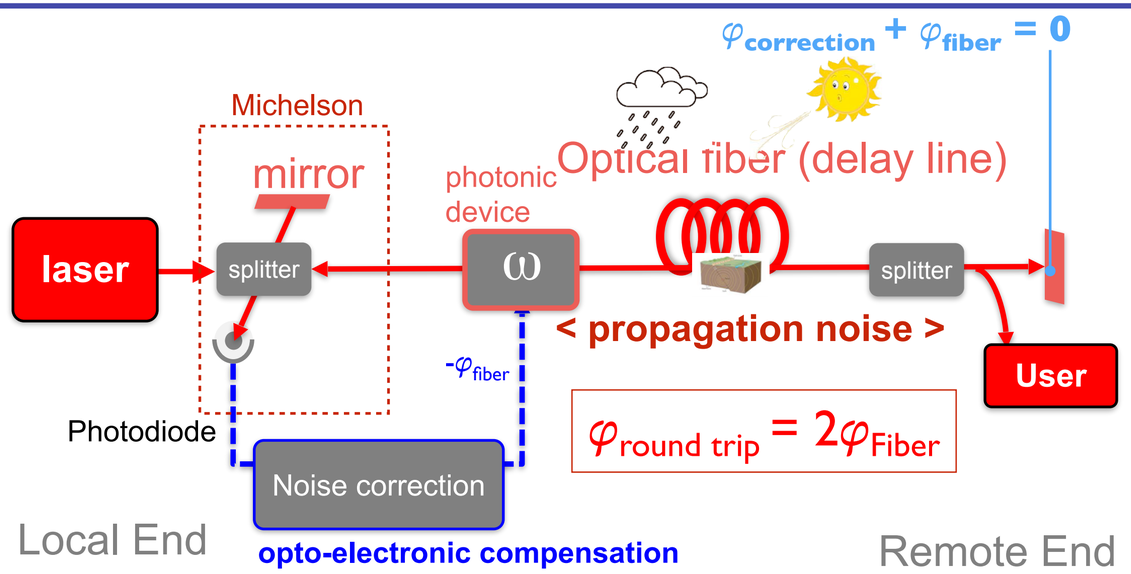
Outline

- REFIMEVE
  - Key elements on fiber links for T/F metrology
  - Laser source
  - Computing center
  - Signal availability
- Seismic detections with REFIMEVE
  - What we see
  - How this can be ? Transfer function ?
- On-going projects, prospects and outlook





Optical frequency transfer : key elements



- Unbalanced Michelson interferometer
- Heterodyne detection: eliminates mutli-path
- Fully bi-directional. A 2nd link transfers back the signal
- Guided propagation: ensure paths reciprocity
- Assumption : Forward noise = ½ Round-trip noise
- → corrects only reciprocal noise
- Coherent regime if coherence length > 2L (need ultra-stable laser !)
- Fundamental limits set at short term by the finite velocity of light in media

A second set-up on a second fiber transfers back the signal: « End-to-end » measurement, out of loop.

Multi-segment approach

- Shorter delay, larger bandwidth
- Signal regeneration with a narrow laser (a few kHz at 1 Hz bandwidth, free running)

Repeater laser station (RLS) functionalities :

- sends back signal to station N-1,
- corrects the noise of next link N,
- provides a user output

Multi-branches Laser Station (Hub station) can correct the noise of several (~5) links

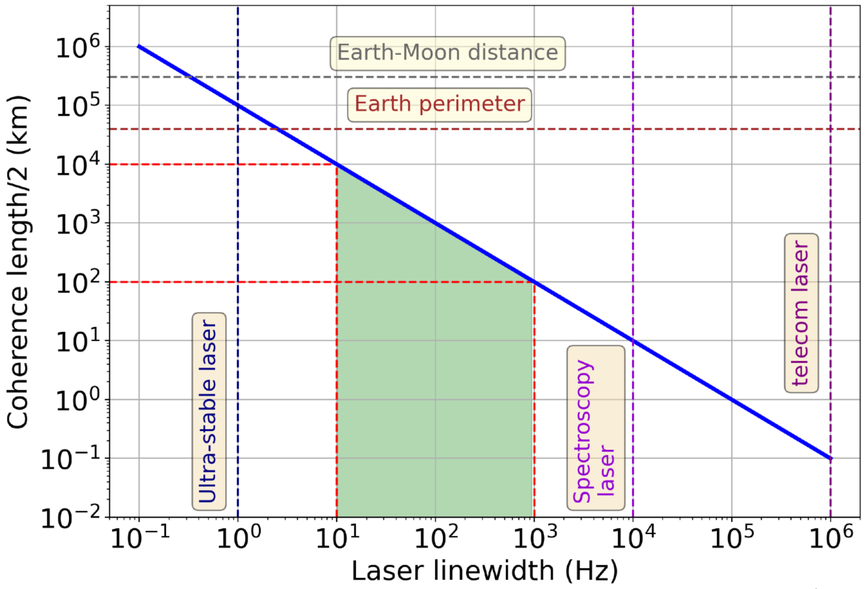
O. Lopez, *et al.*. OE **18**, 16849–16857 (2010).

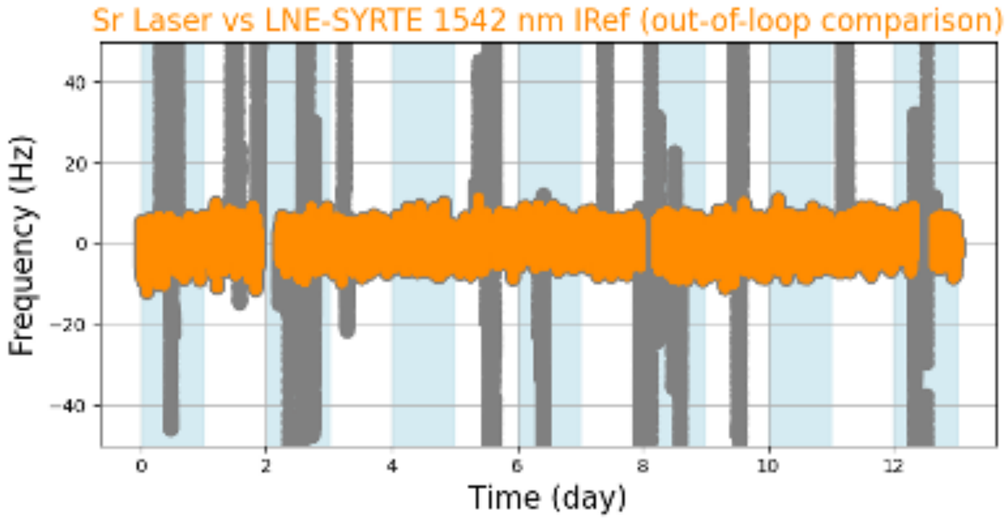
E.Cantin *et al.* New J. Phys. **23**, 053027 (2021).

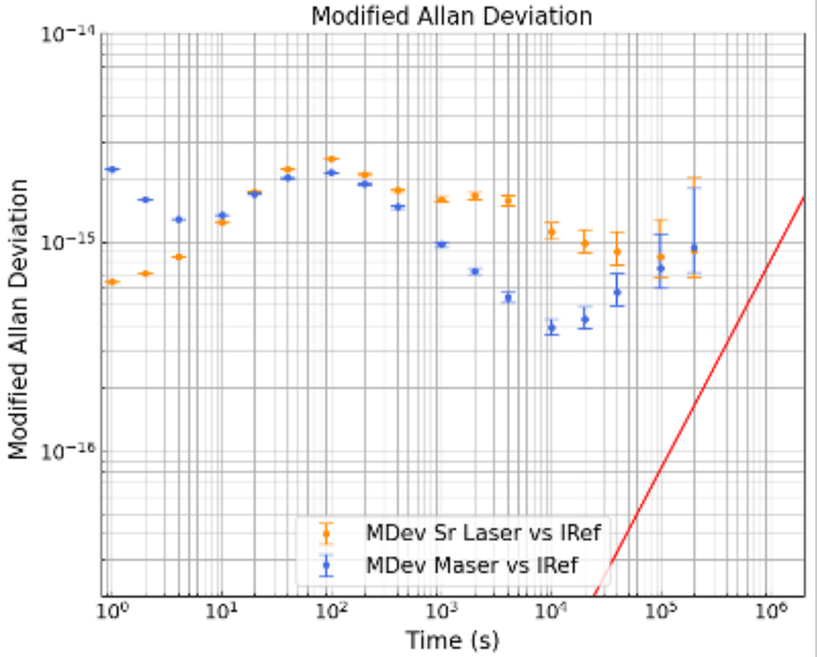
The signal source: principles

Optical oscillator at 194.4 THz (1542 nm)
High finesse Fabry-Pérot cavity > sub-Hz line width laser

- A Fabry-Pérot cavity: stability at time scale < 10 s
- A H-maser : stability at time scale > a few 10 s
- An optical comb (femto-second laser) to compare them and steers the laser on the maser
- The hybrid oscillator source REFIMEVE signal
- REFIMEVE signal frequency at source:
  - 194 400 121 000 000 +/- 25 Hz







Network supervision and REFIMEVE computing center

Pascal Blondé, Maxime Laiguillon, Emmanuel Halbwachs, Ludovic Ishiomin

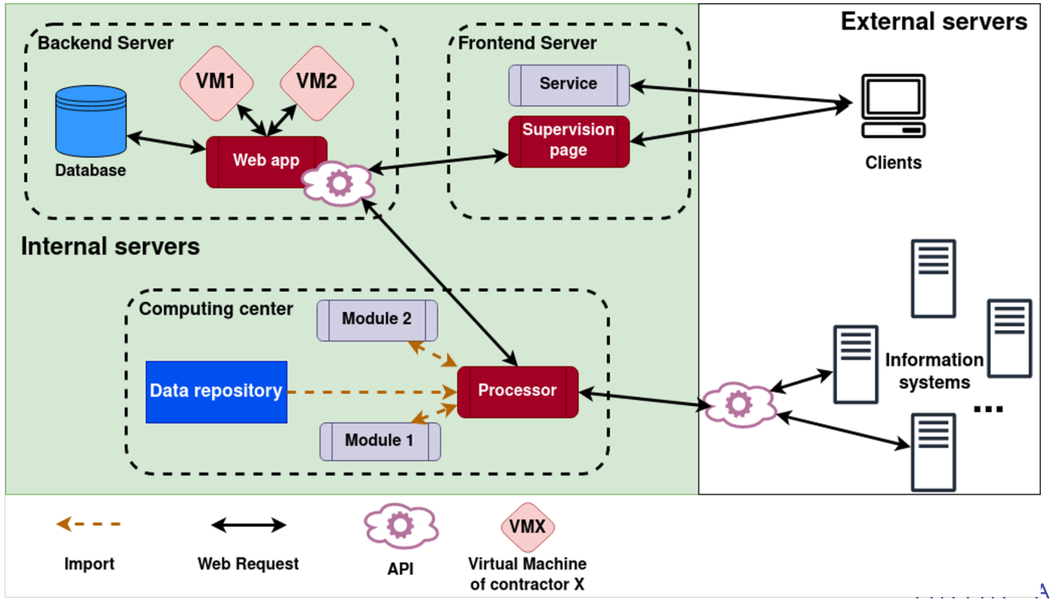
- The issue :
  - access >100 instruments spread all over RENATER network and other third-parties (universities, IN2P3…)
  - While keeping information system security and integrity

Realized with RENATER engineers, DIO, and IT@SYRTE

REFIMEVE computing center

Maxime Mazouth-Laurol

- provide the users with data and metadata
- feed the supervision service
- ensure a cost effective maintenance and management of the network



<u>information system</u>

- A powerful computing server
- a large data server (22 Tb)
- Hosted virtual machine for third-party subcontractors, to host their information systems and running engines.
- A front end server for users
- Application Programming Interface (API

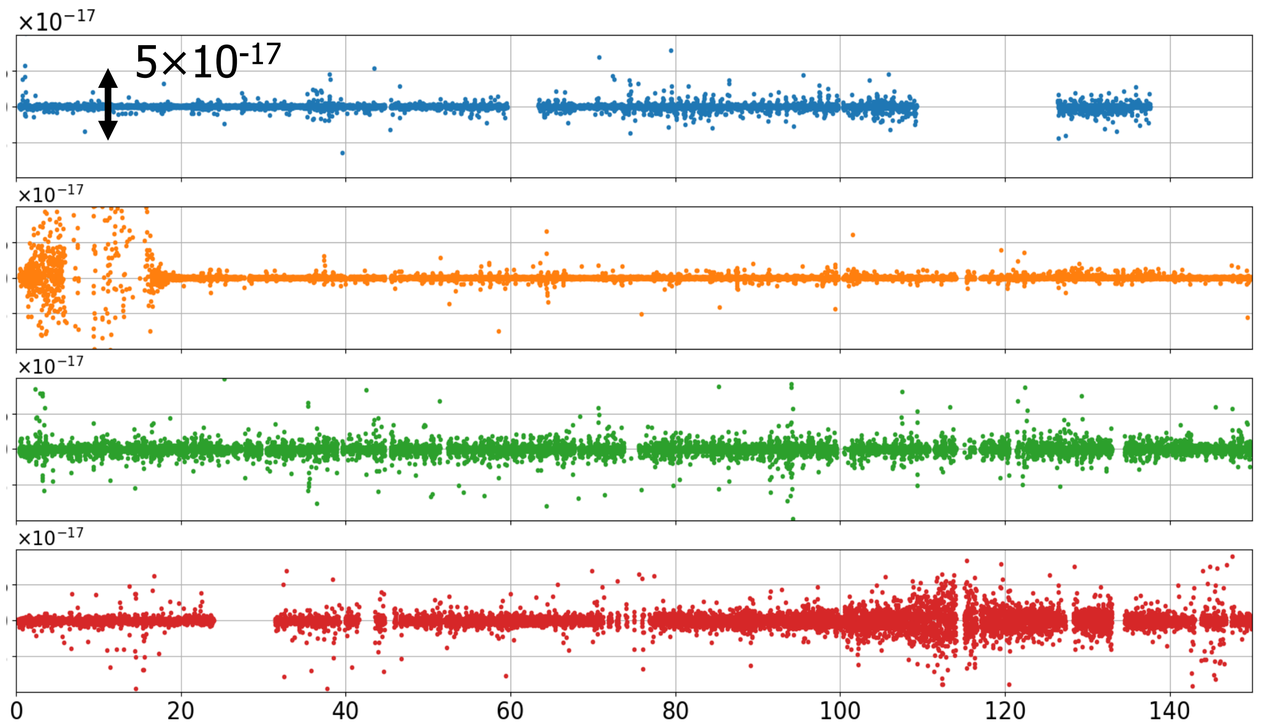
Towards a highly available signal

Paris-Lille-Paris
(2 x 340 km)

Paris-Strasbourg-
Paris (2x650 km)

Paris-Lyon-
Modane-Lyon-Paris
(2x900 km)

Lyon-Marseille-
Lyon (2x440 km)



Uptime 71%

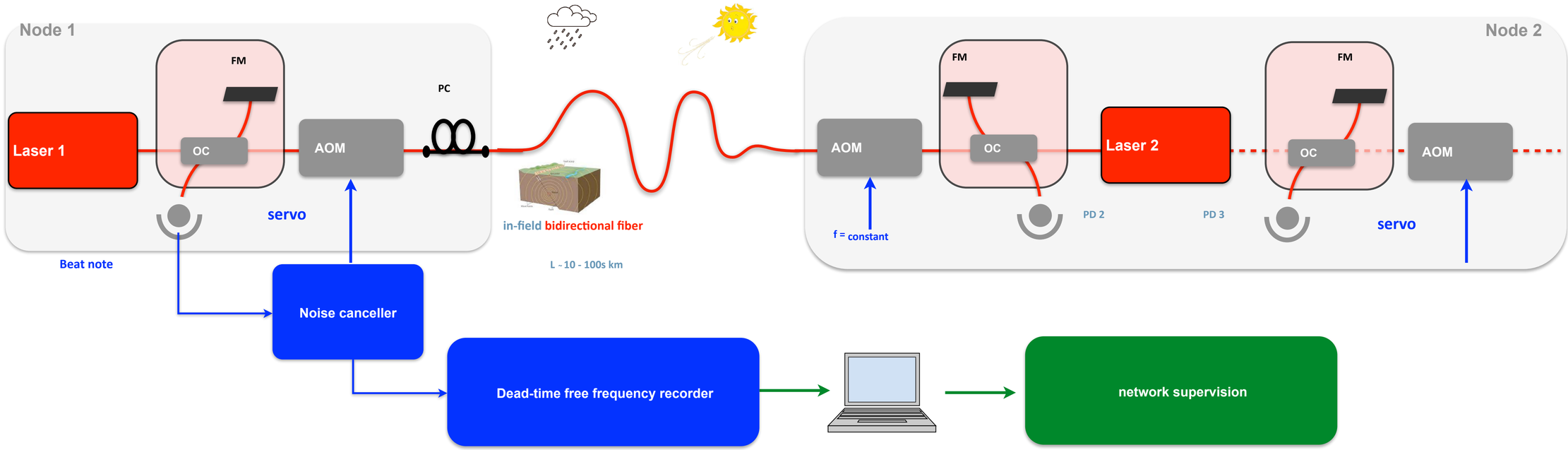
Uptime 85%

Uptime 81%

Uptime 85%

4 links: {340,650,900,440} km x2 = 2x2330 km
>70% / 1/2 year (2022)
>90% uptime for several months
<u>next objective: 90 % / year</u>

REFIMEVE as a wide-scale integrated sensor



FM: Faraday mirror. OC: Optical coupler. PD: Photodiode. AOM: Acousto-optic modulator. PC: Polarisation controller.

Detection:

- Frequency difference in a narrow bandwidth (typ. 50 kHz)
- Altered by propagation time derivative
  - Doppler effect, strain time derivative
  - Stress acts mainly on polarization

Difficulties:

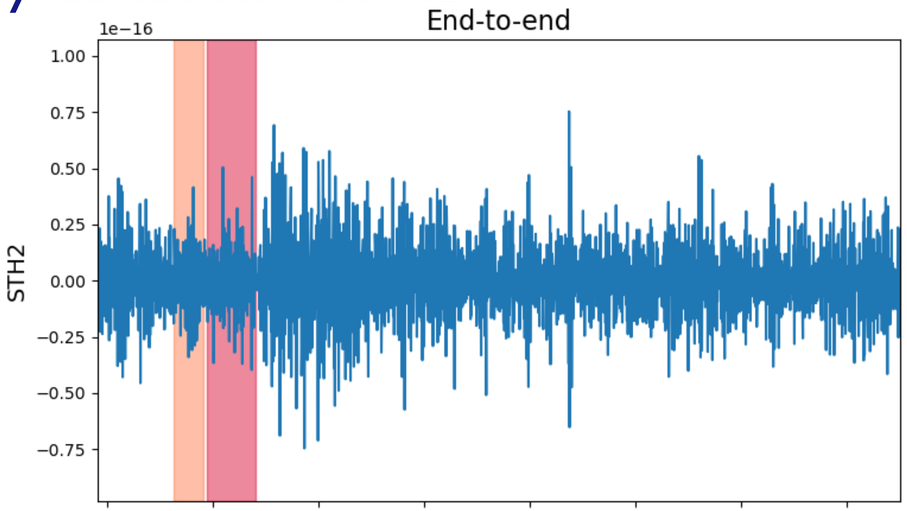
- Stress > strain rate : parameters badly known
- Integration along the fiber path ?
- Dependance with the angle between the seismic source to the leading vector of the fiber ?

Non-stationnary perturbations of REFIMEVE: mid-range case

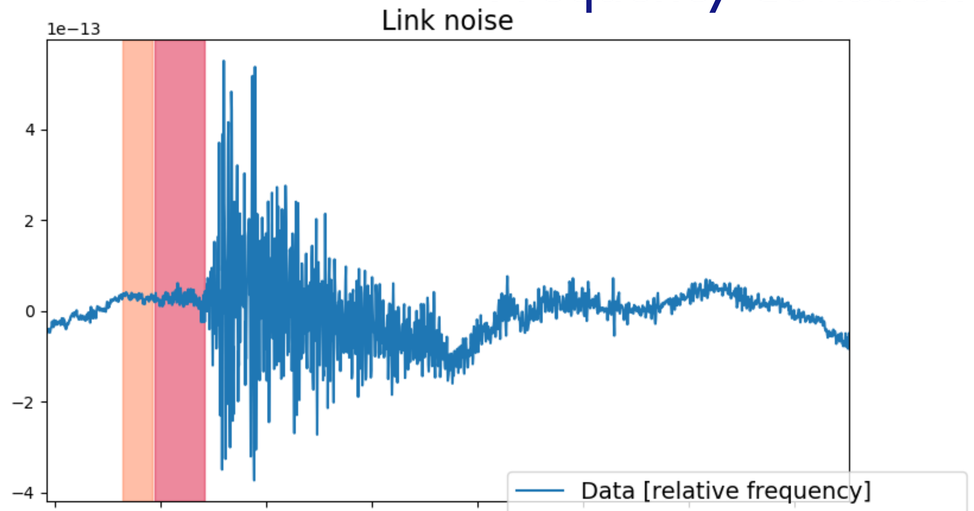
Event at CROATIA, mag. of 6.4
29/12/2020 - 11:19:54

Frequency deviation ~ .1 Hz

Urban link
11 km
SW-NE

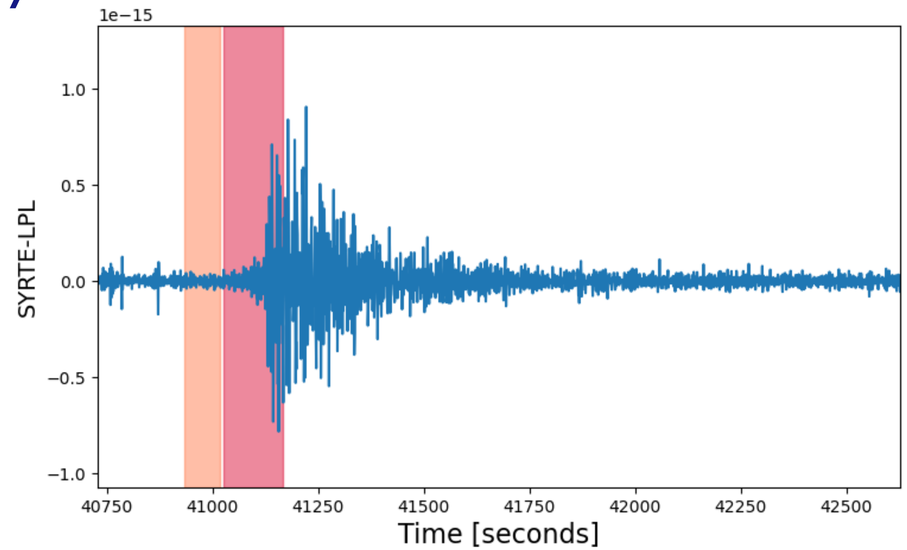


Frequency deviation ~ 100 Hz

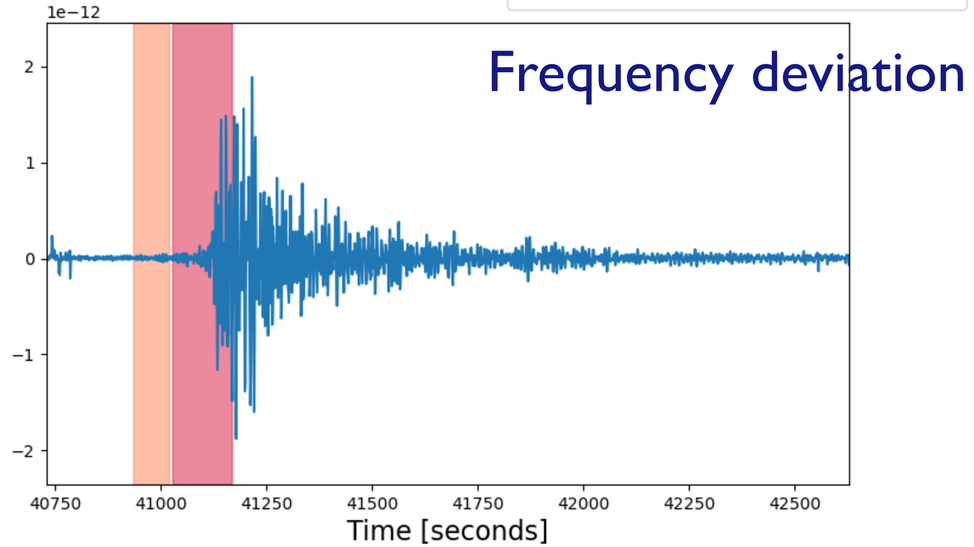


Frequency deviation ~ 1 Hz

Urban link
43 km
South-North



Frequency deviation ~ 1000 Hz



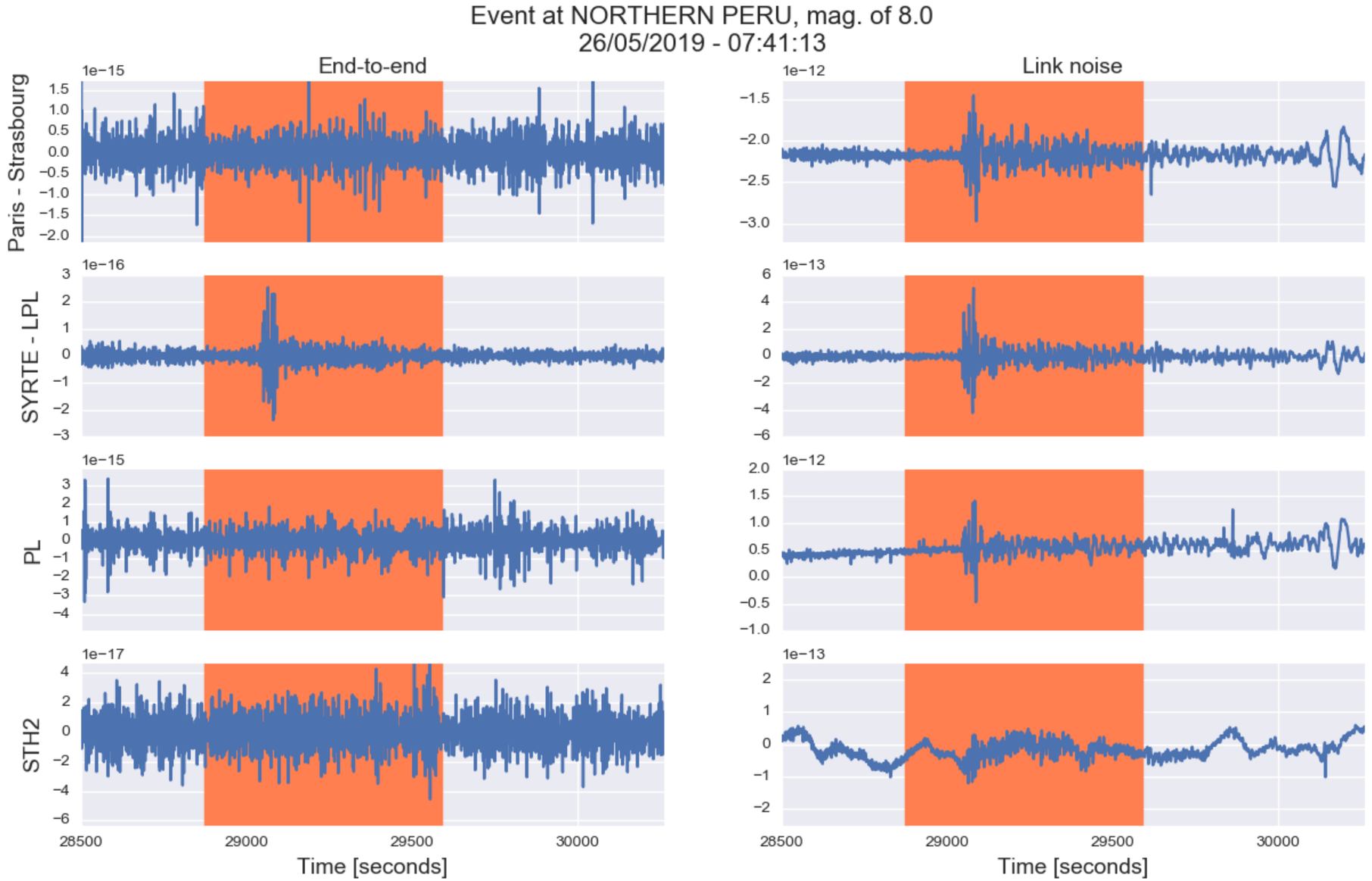
Non-stationnary perturbations of REFIMEVE: long-range case

270 km SW-NE

43 km S-N

340 km S-N

11 km SW-NE



Frequency deviation ~ .01 Hz - 1 Hz

Frequency deviation ~ 100 Hz - 1 kHz

More motivations

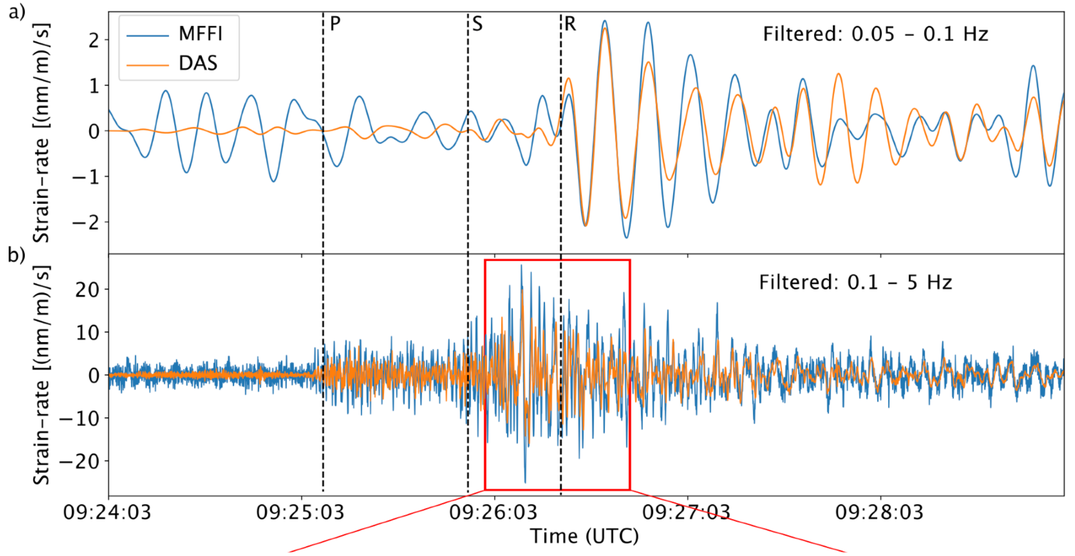
Fiber sensing

- Distributed acoustic sensing
  - 1-m localization, range < 100 km
- Integrated sensor
  - longer distance, submarine / seafloor
  - Access telecom fibers

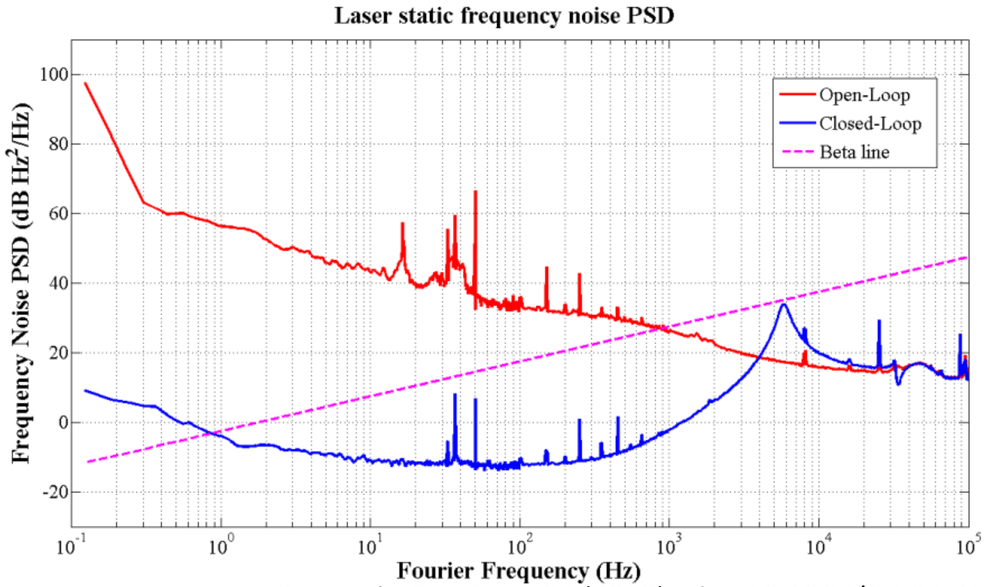
For longer range:

- line-width → 0
- repetition rate → 0

see also experiments on transatlantic cable:
G. Marra et al., Science (2022) doi: 10.1126/science.abo1939.



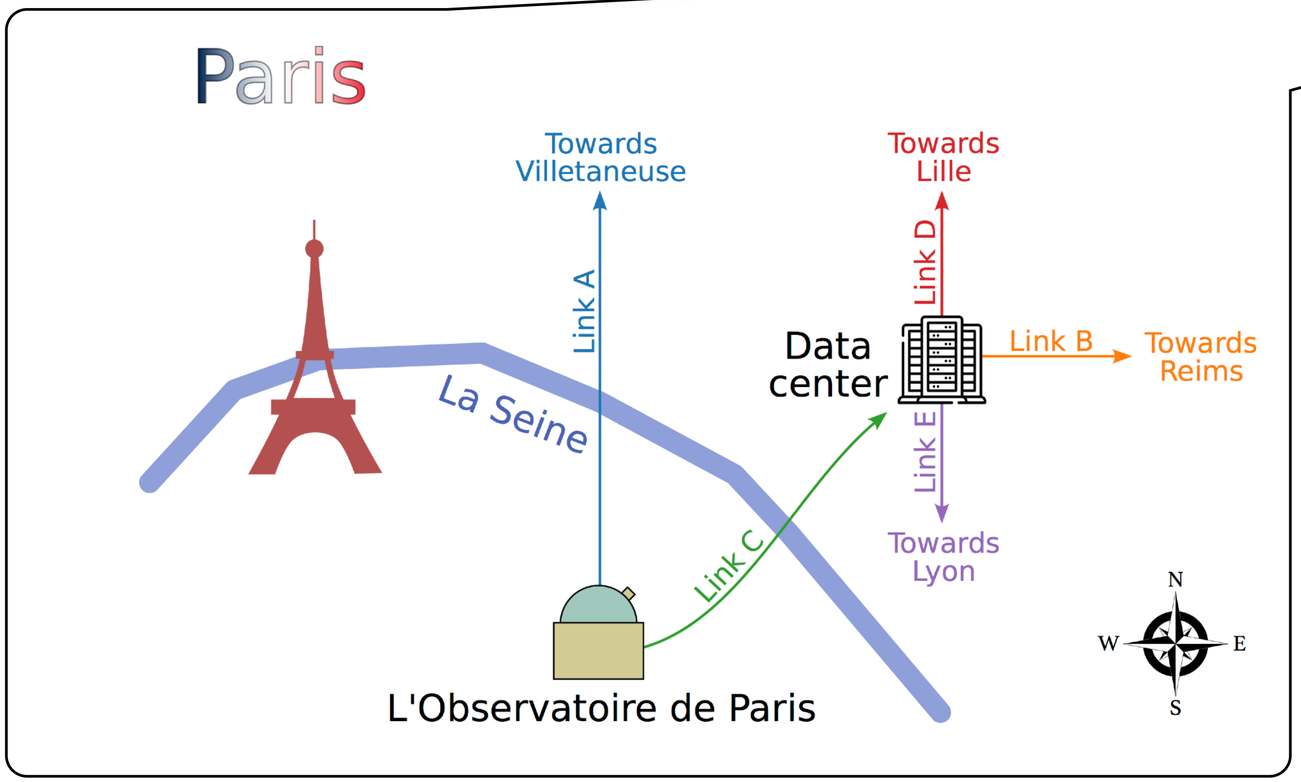
D. C. Bowden et al., Geo. Res. Lett. (2022) doi: 10.1029/2022GL098727.

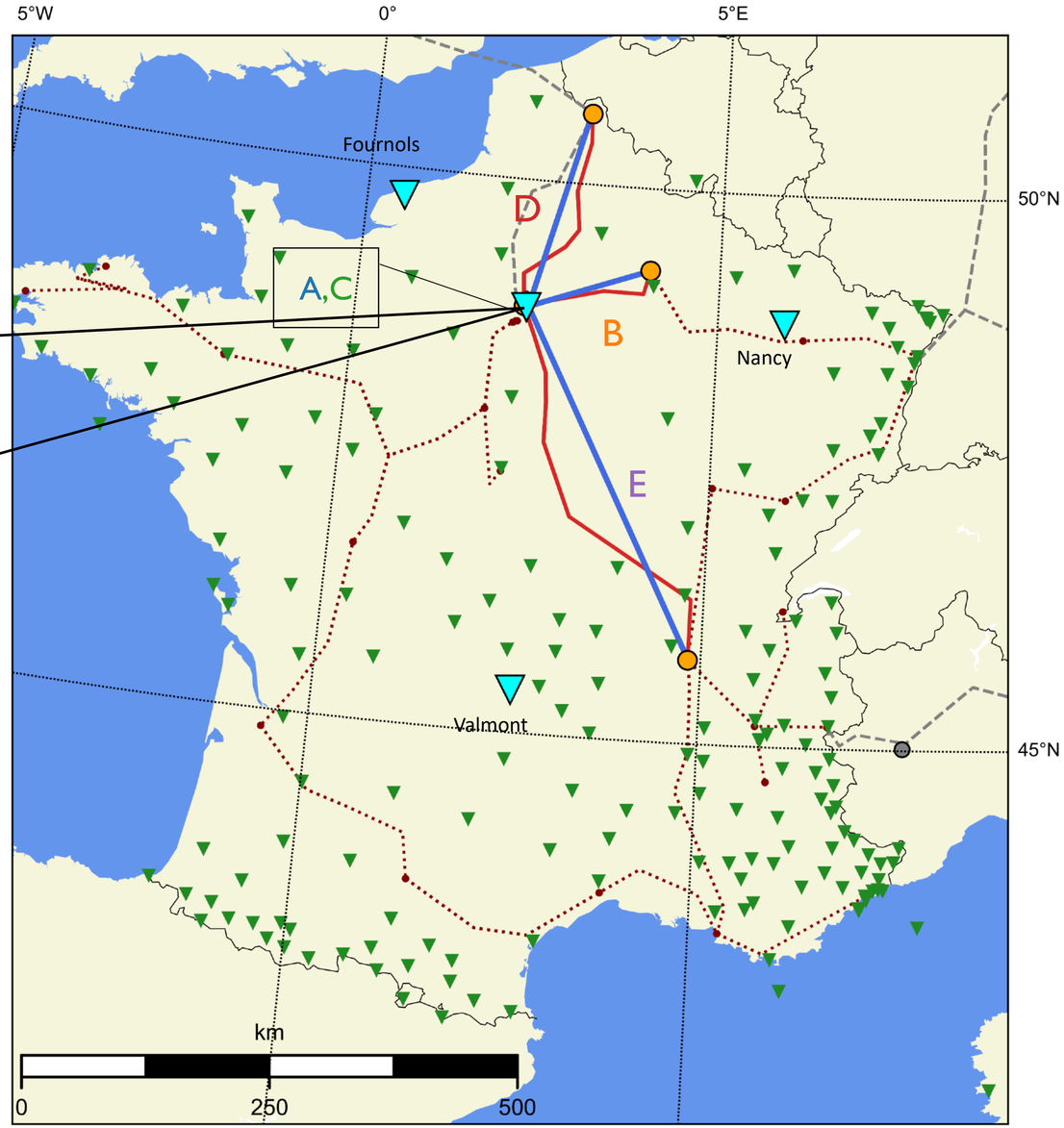


J. Qin et al., Opt. Expr. 27 (2019), doi: 10.1364/OE.27.019359.

Study of seismic detection by REFIMEVE

- In this study: use 4 spans departing from Paris.
- Spans where « free-link » is recorded
- Use sismo. data collected in RESIF (EPOS-FRANCE).
- Thank you, Open Access !

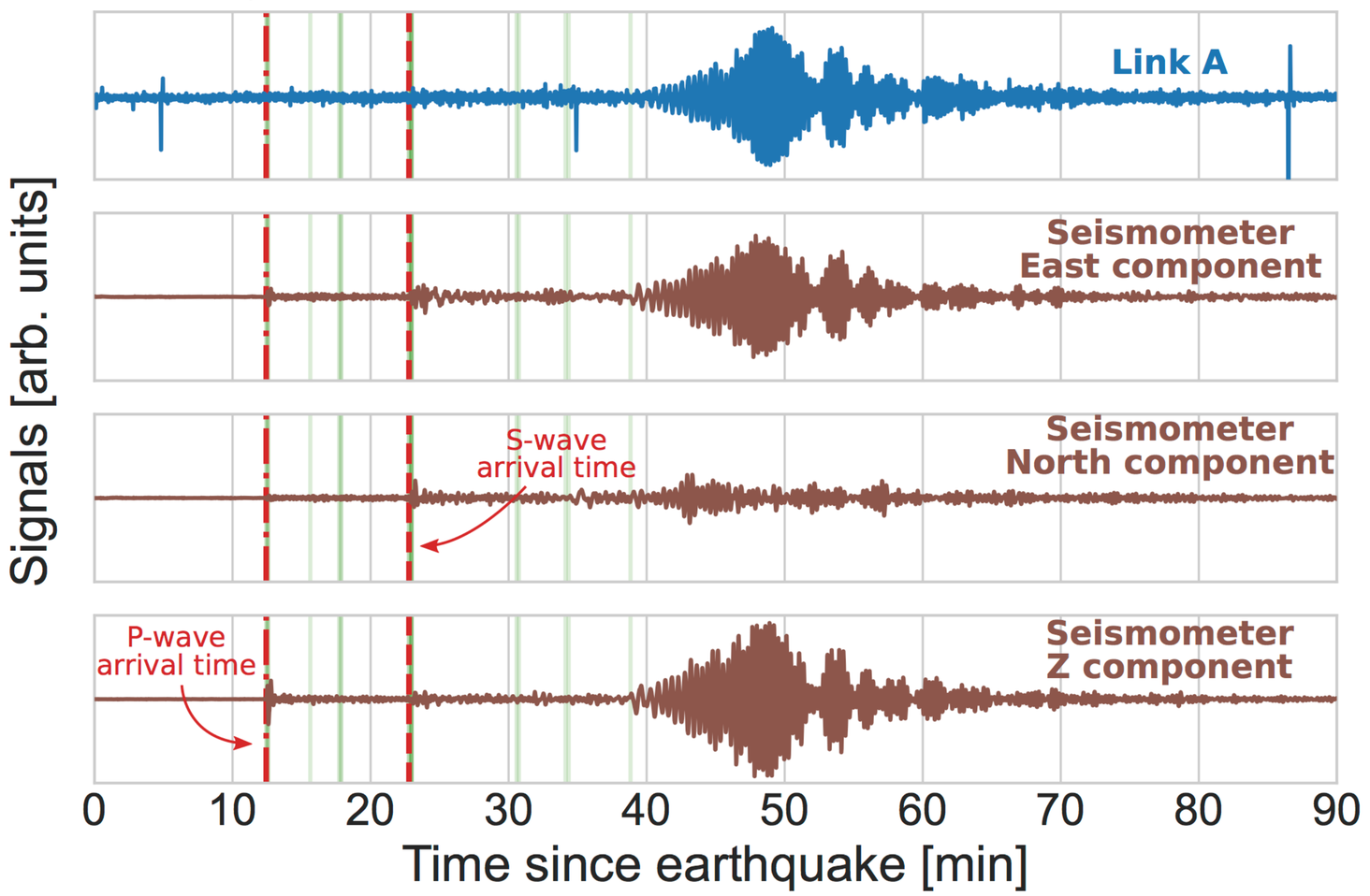




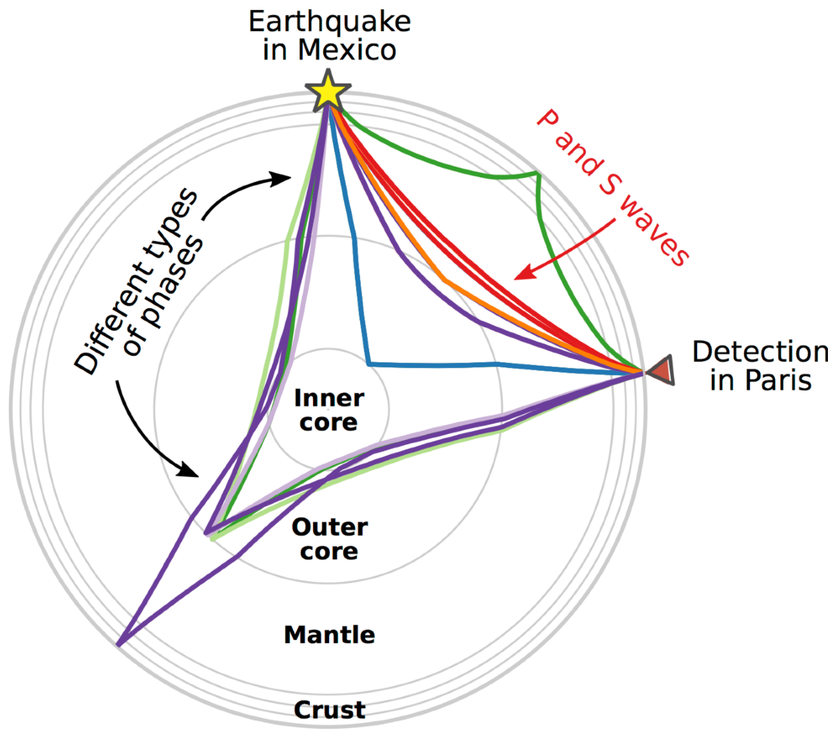
PhD thesis M. B. K. Tønnes, https://hal.science/tel-03984045

The seismic signals (before compensation)

This example: 43-km link, oriented S-N



Mw 7.4 earthquake

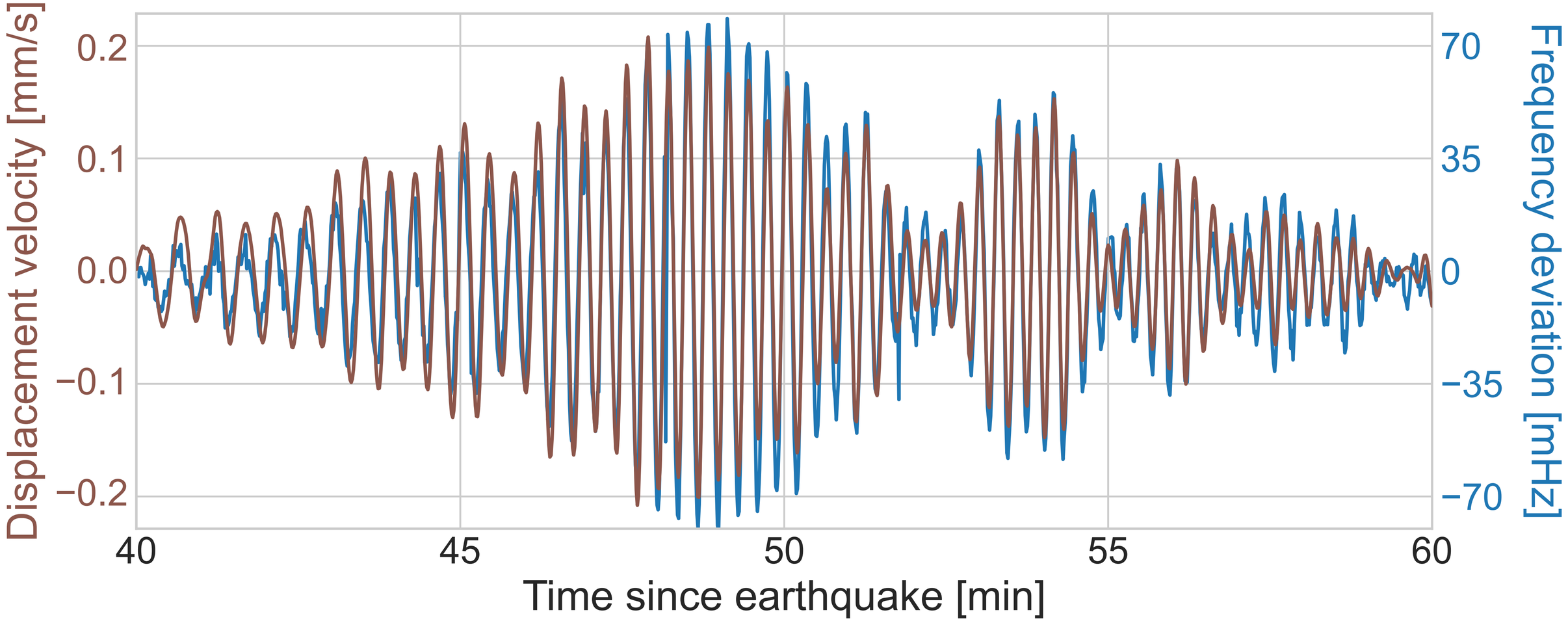


- Signals from integrated sensing and from seismometers are highly correlated.
- Arrival of S- and P-waves in very good agreement with existing model and data (ObsPy).

https://docs.obspy.org/

PhD thesis M. B. K. Tønnes, https://hal.science/tel-03984045

Signals correlations with Curie / z component



- Correlation factor for this event ~. 94
- sub-Hz frequency deviations are observed.
- Need resolution better than 10^{-15} at 1 second integration time

Doppler model

- Assumption: frequency variations arise from Doppler effect.
- From radar theory the frequency shift:

$$\Delta\omega = \omega_{RX} - \omega_{TX} = -2\vec{k} \cdot \vec{v}$$

v: speed vector of the source
k : wave vector of light

We use afterwards a simplified expression neglecting the angle.

Kinetic energy ratio :

$$\frac{v^2}{v_x^2 + v_y^2 + v_z^2}$$

Fiber

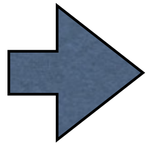
Seismometer

Order of magnitude :

Absoprtion of near IR light in a gas cell, ambiant temperature:

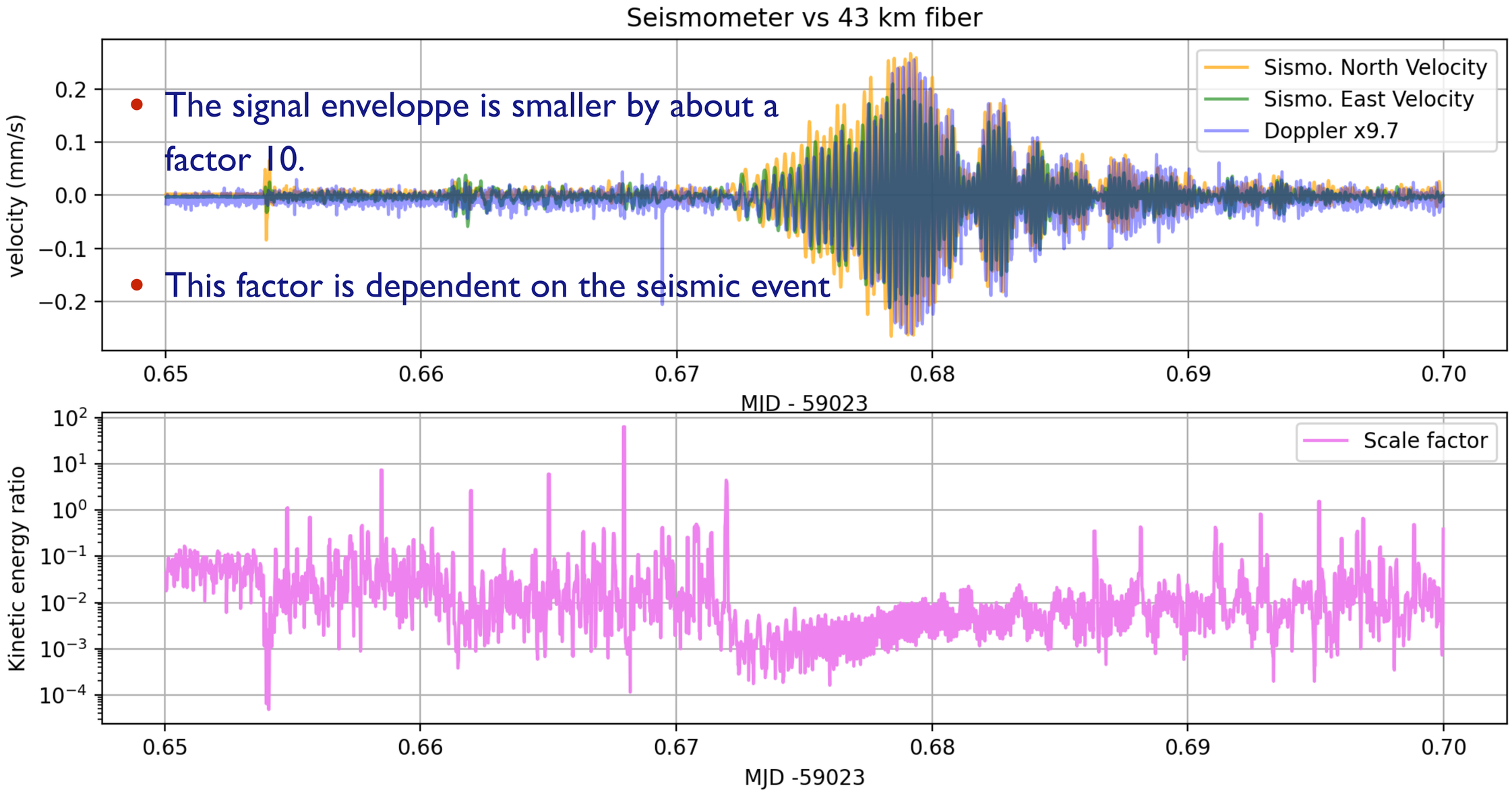
Doppler broadening ~ 500 MHz;

Velocities ~330 m/s



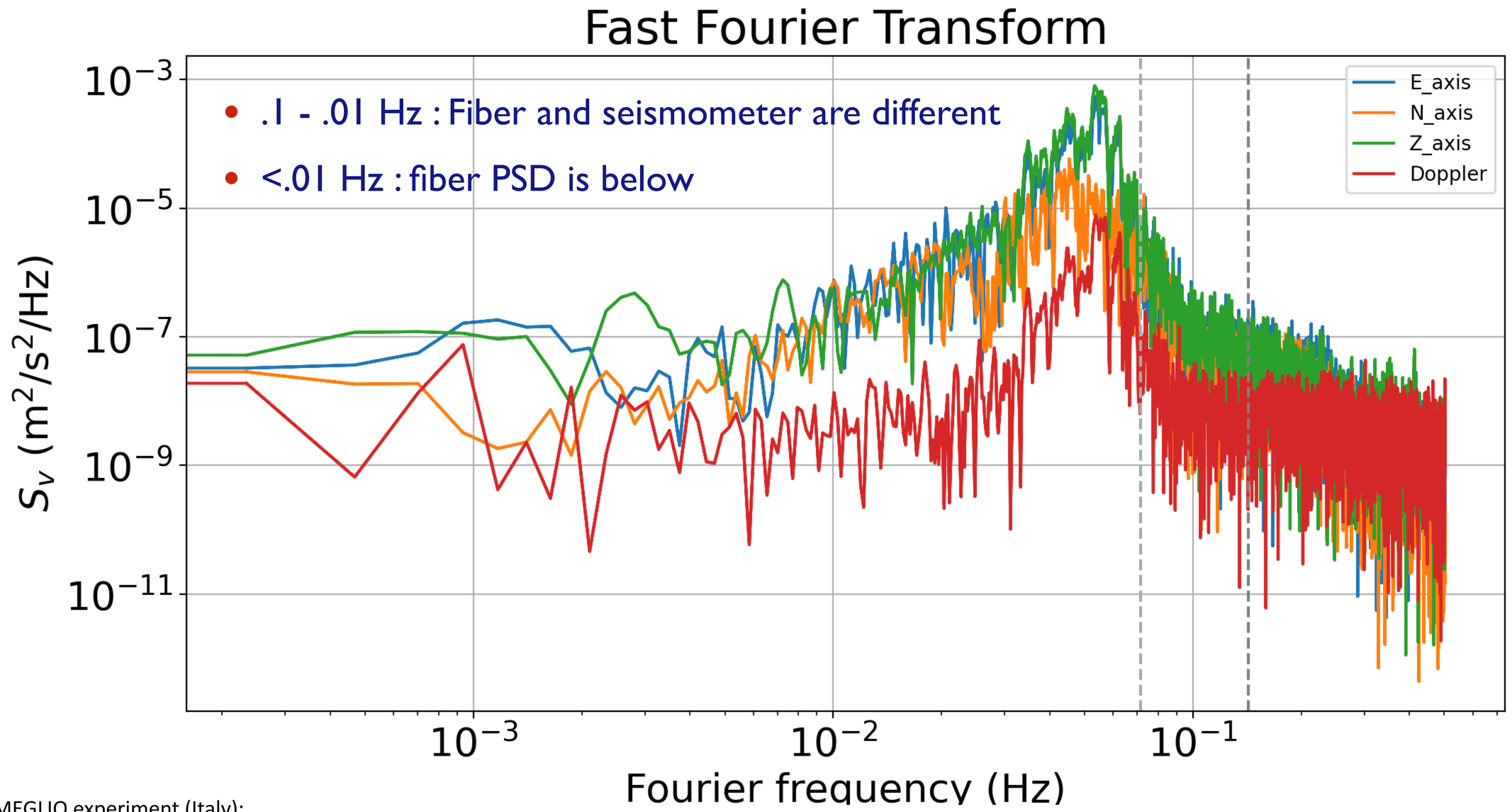
About 1.5 MHz / (m/s)

Signals correlations with Curie / z component



- The signal enveloppe is smaller by about a factor 10.
- This factor is dependent on the seismic event
- Events with similar emission mechanism might exhibits varying scale factor (??).

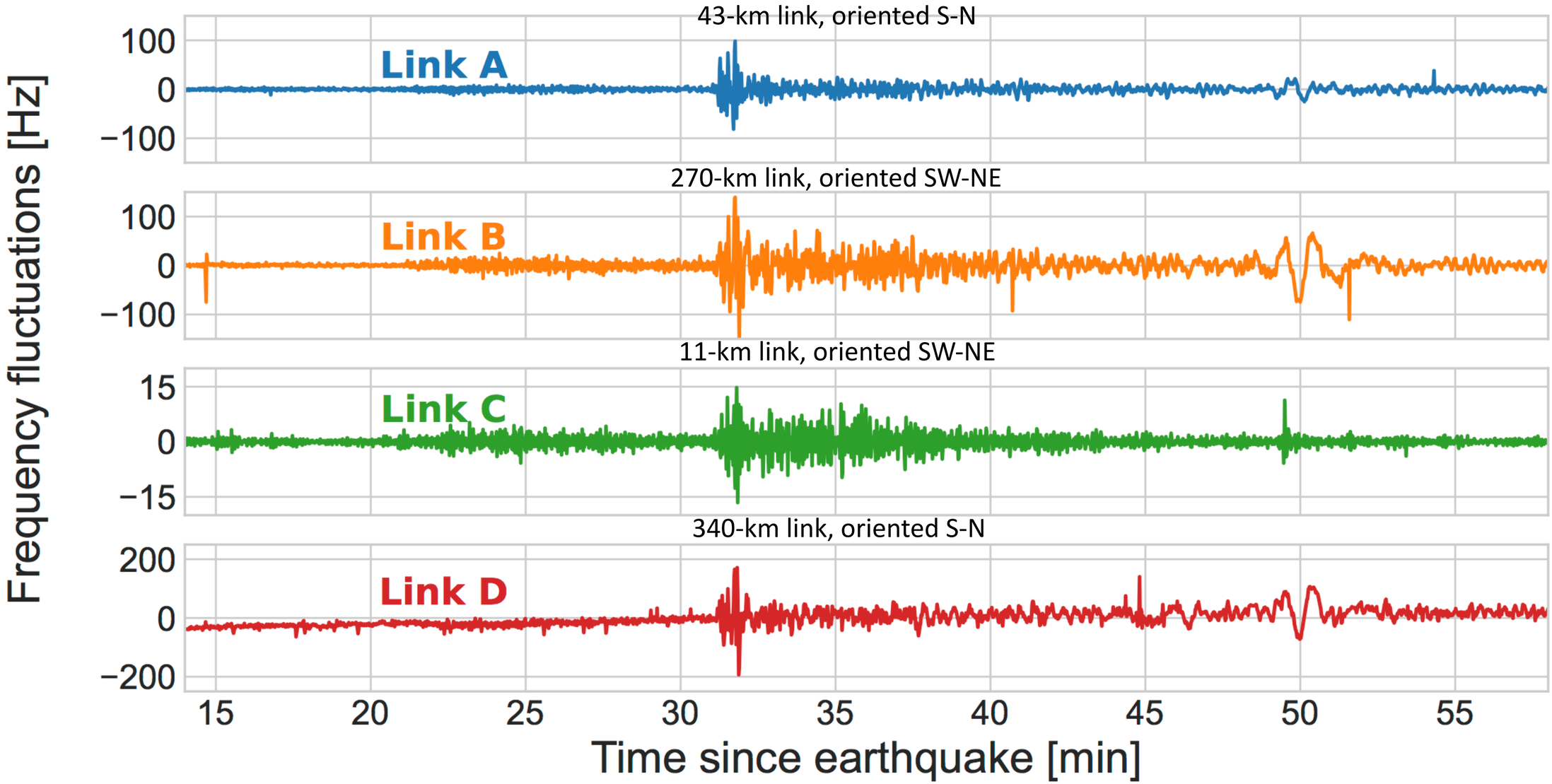
PSD comparison with Curie / (x,y,z) components



see also MEGLIO experiment (Italy):

S. Donadello et al., « Seismic monitoring using the telecom fiber network », Commun Earth Environ, vol. 5, no 1, p. 1-9, avr. 2024, doi: 10.1038/s43247-024-01338-2.

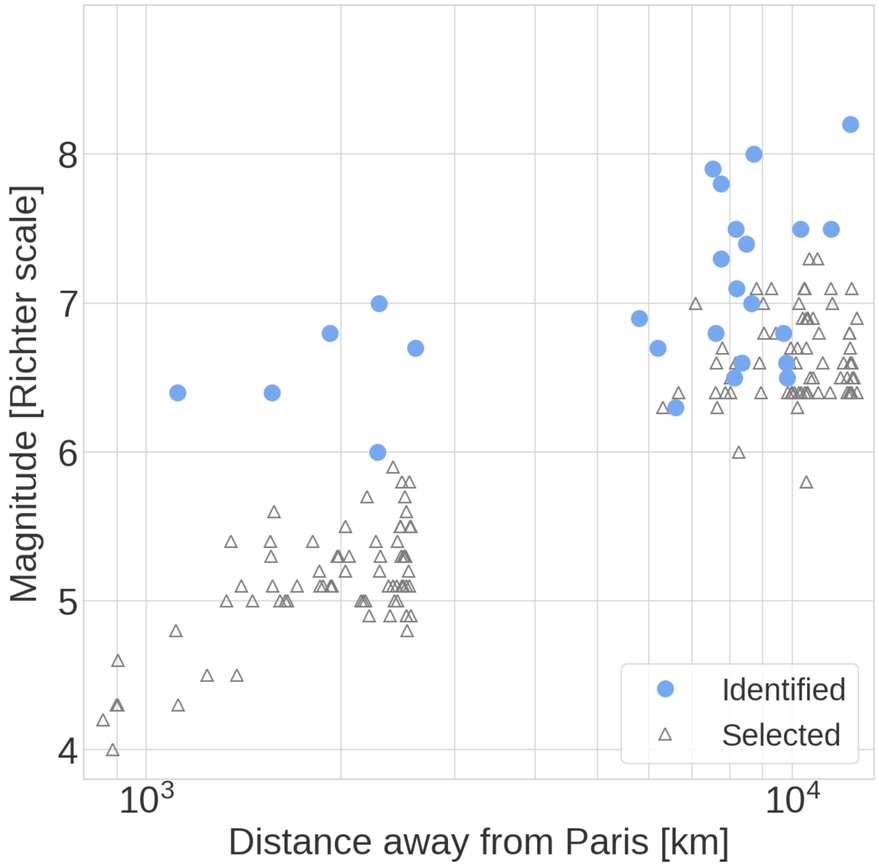
Detection with a fiber network

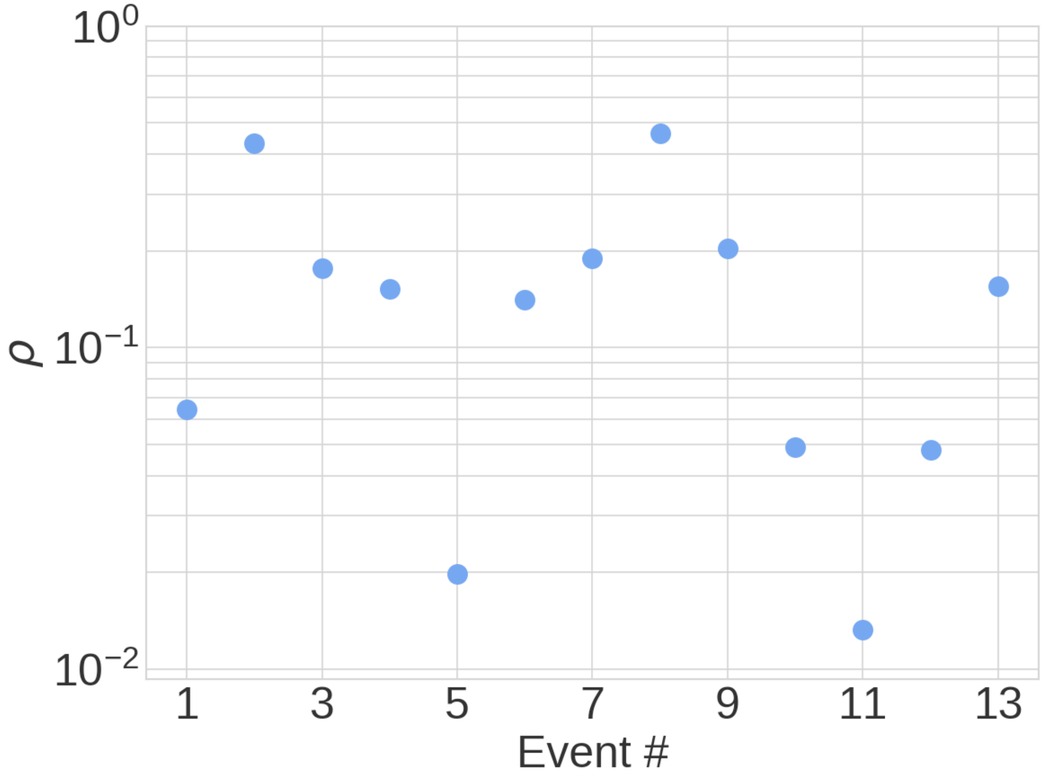


- Simultaneous operation of REFIMEVE allows for the observation of waves over several links, with different locations and lengths, over the REFIMEVE fiber network.

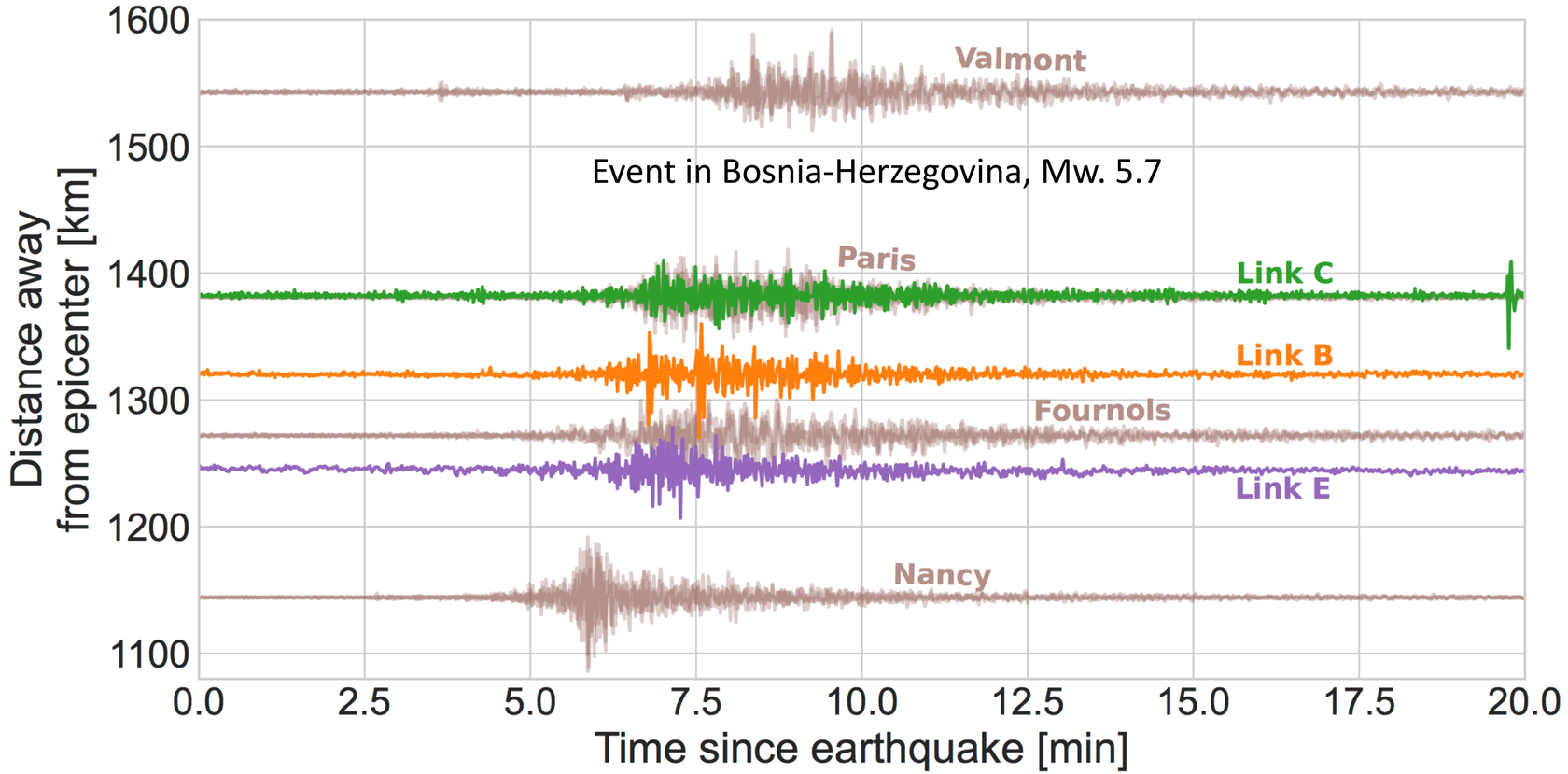
Sensitivity

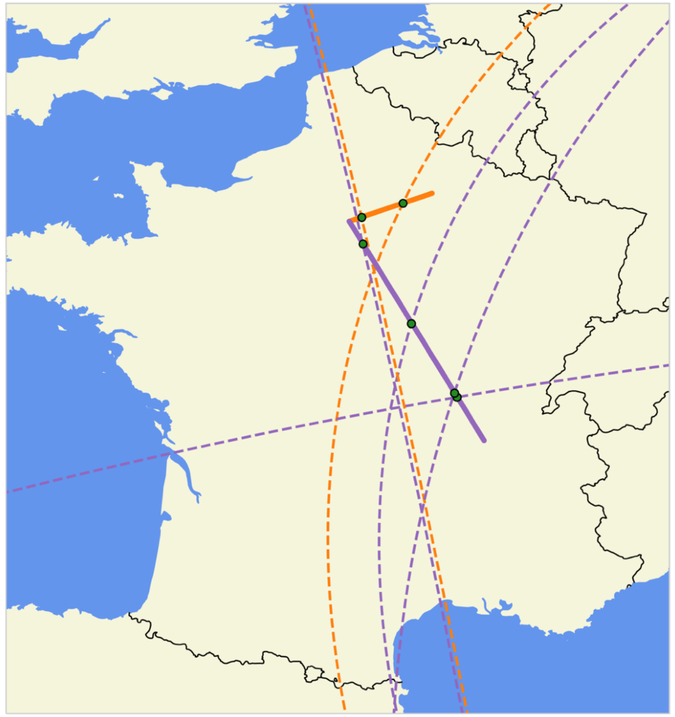
- Mag. 5 and above (preliminary)
- Detection of event from all over the Earth
- SNR is usually less than with a broadband high gain seismometers (Trillium 120-QA)





Localisation

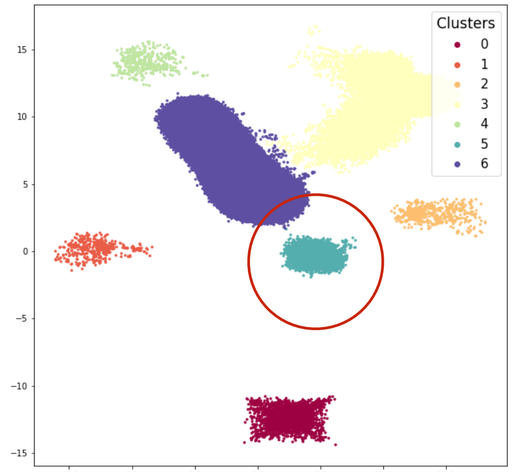


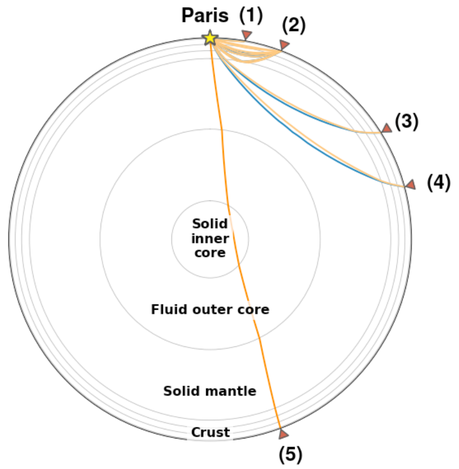


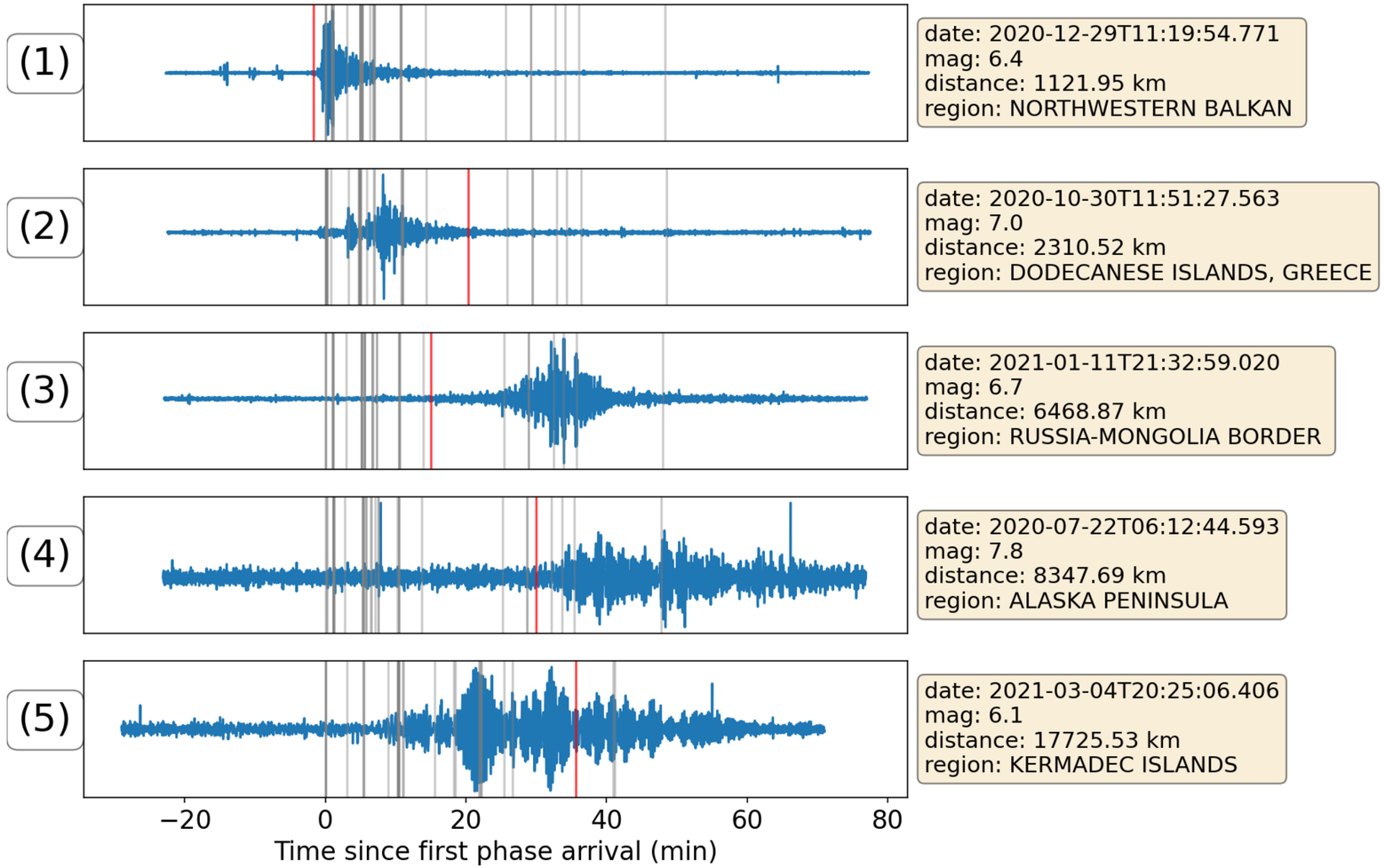
- Observation of time of arrival differences
- A first study with a fiber network:
  - Determine the nearest seismometer position.
  - From a simultaneity hypothesis, we deduce the barycentric position.
  - The barycenter depends on the event we are looking at.

see also recent report in Switzerland:
N. Müller, S. Noe, D. Husmann, J. Morel, et A. Fichtner, « Earthquake source inversion by integrated fiber-optic sensing », Seismica, vol. 3, no 2, juill. 2024, doi: 10.26443/seismica.v3i2.1405.

Machine learning







- Unsupervised machine learning algorithm applied successfully on a 1-year unlabelled data set for one of the link of REFIMEVE (link A).
- Catalog of about 30 events were confirmed.

Outlook

Summary - take away message

- Seisms are detected by fiber network for Time-frequency metrology (integrated noise).
- SNR is below the one of modern seismometer.
- Localisation of an event is difficult as the barycenter depends on the angles.
- Machine learning approach seemingly successful.
- Hundred of events unambiguously identified with REFIMEVE, and we observe curiously undetected events that should be.

Outlook

- Build catalog and open data to scientific community.
- Analyse integrated signals and compare with array of seismometer : signals and noises
- Develop a transfer function model of the fiber, try to obtain new informations on the soil or on the epicenter.
- SNR improvement with specific modulation format should be doable.

Thank you for your attention !