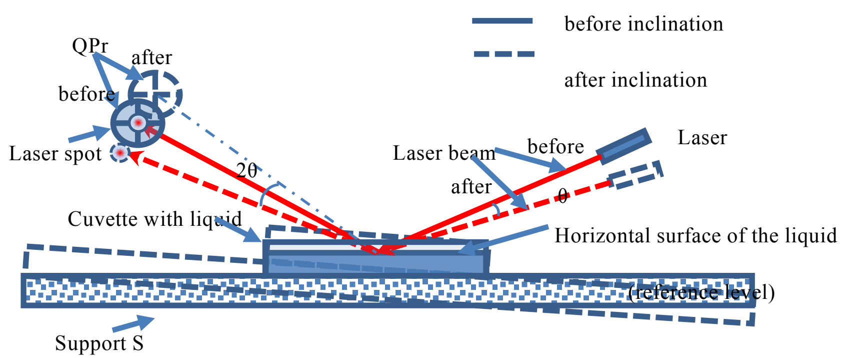


The Precision Laser Inclinometer: a novel instrument for seismic events

Beniamino Di Girolamo (CERN ATS/DO)

N. Azaryan, I. Bednyakov, J. Budagov, B. Di Girolamo, V. Glagolev, M. Lyablin, A. Pluzhnikov, G. Trubnikov (CERN & JINR)

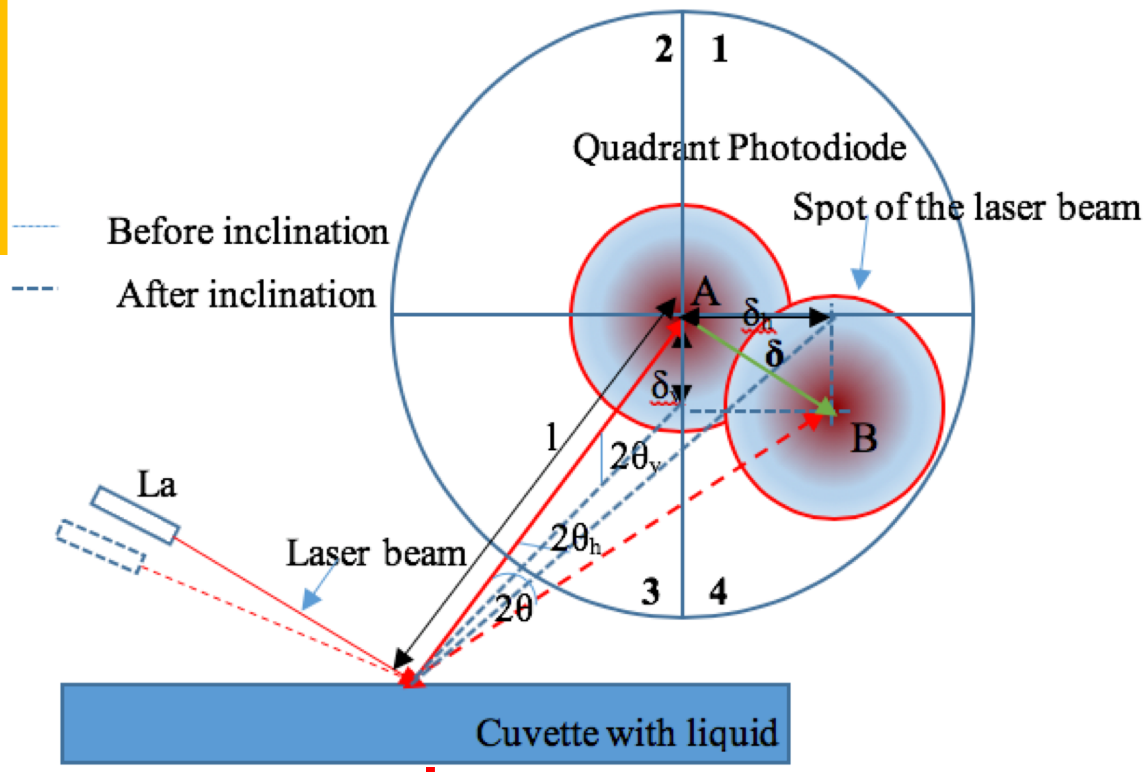
INFN Pisa – Seminar – 21 October 2019

Outline

- Working principle of the instrument
- Installed units
- Instruments results and figures of merit measured at CERN
- The PLI-Virgo
- First results from Virgo experience
- Early Earthquake Warning (EEW) systems
- Future
- Conclusions

PLI working principle

Actual implementation of course more complicated and equipped with reference and calibration features



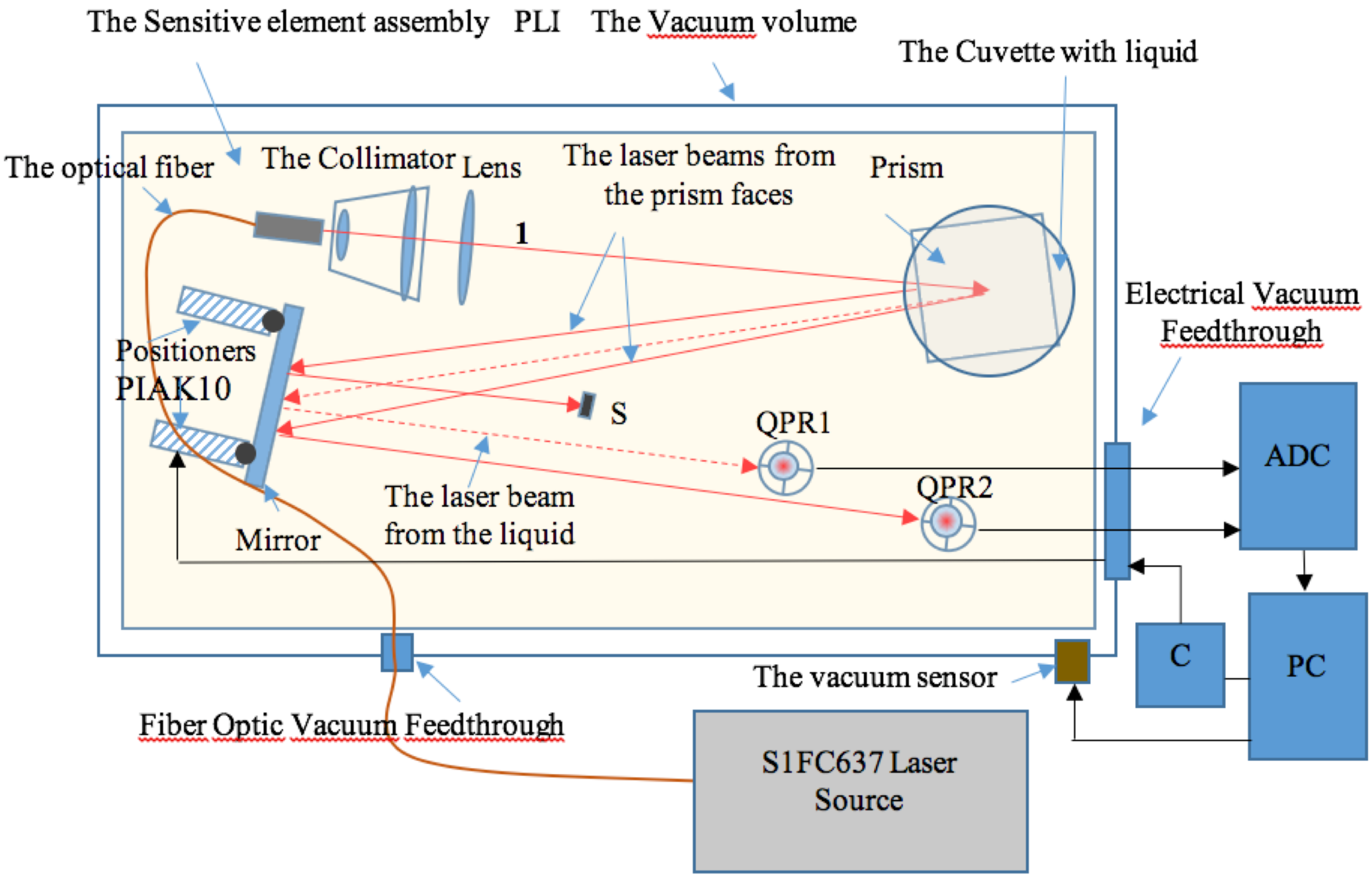
g is known with high precision

- The PLI uses the displacement of the laser ray reflected from a liquid surface when the base support is tilted by ground oscillations
- The angle of the reflected light is twice larger than the support tilt angle θ.
- The detection is in both planes, therefore the combined slope and azimuth can be easily calculated

Main characteristics

- The size of the liquid container and the liquid quantity make the instrument free from resonances
- The beam spot on the liquid mirror is dimensioned to average fast transient effects
- The choice of the liquid is a compromise between achievable frequency range, readout speed, compatibility with vacuum conditions
- The very moderate vacuum allows to avoid the effects of the air temperature gradient and reduces the laser light scattering with air
- It measures two coordinates at the same time

PLI schematics



PLI schematics

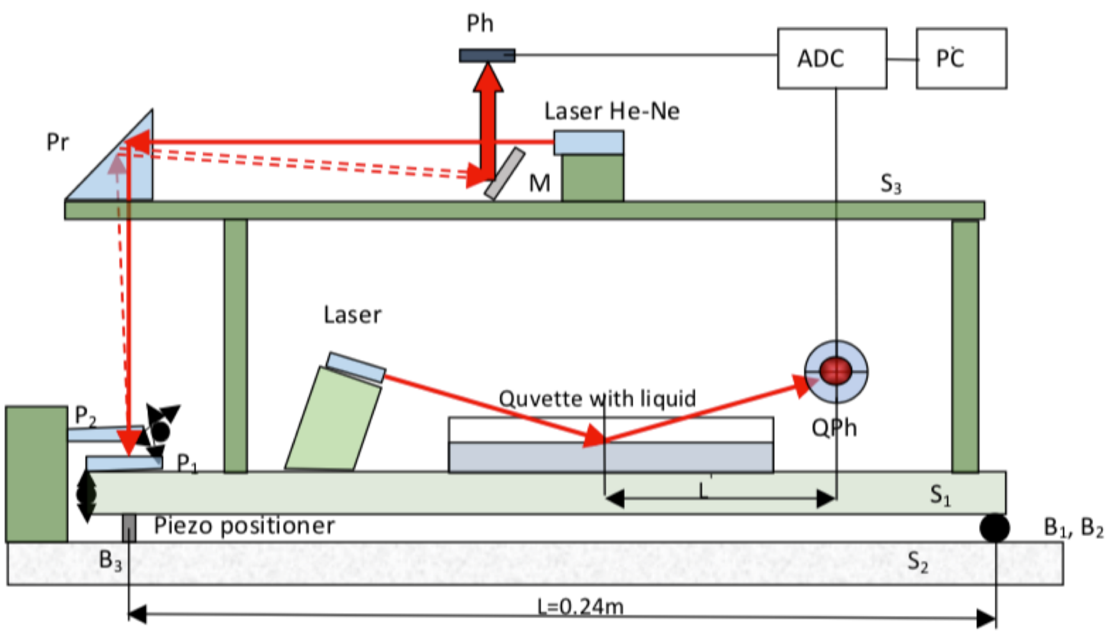
- A single mode laser fibre provides the light source
- The beam splits between a path going to be reflected by the liquid mirror and a path of reference
- The reference beam allows to subtract noise from laser output variations with time and it is not subject to Sun-Moon cycle effects as instead the main beam

PLI output and readout

- Typical signal level spanning from ±0.05 mV to ±50 mV (near earthquakes)
- Use of a 24-bit ADC with low input noise (-140 dB) even at low frequencies (10^{-5} Hz, the day)
- Need of ADC with 6 10^{-8} resolution in the frequency range 10^{-6} Hz – 100 Hz
- We use a 4.8 kS/s/ch, 4-synchronized channels ADC https://www.mccdaq.com/Products/24-Bit-DAQ-Modules/DT9824

PLI calibration system

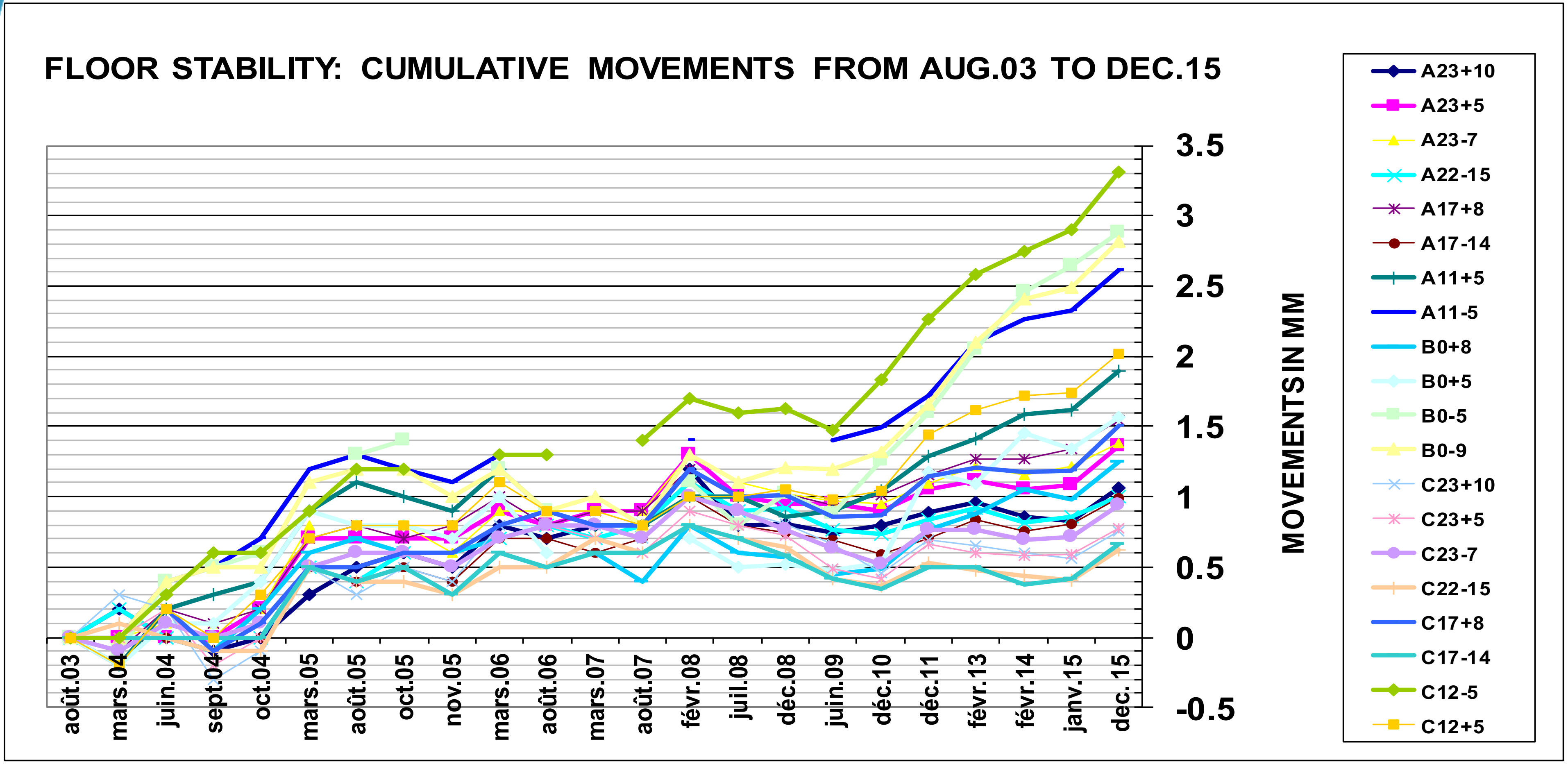
- A calibration system allows to determine the conversion between ADC value and angle by using an interferometer and varying the angle with a piezo actuator with an iterative procedure



What was it invented for and what has it been also used for:

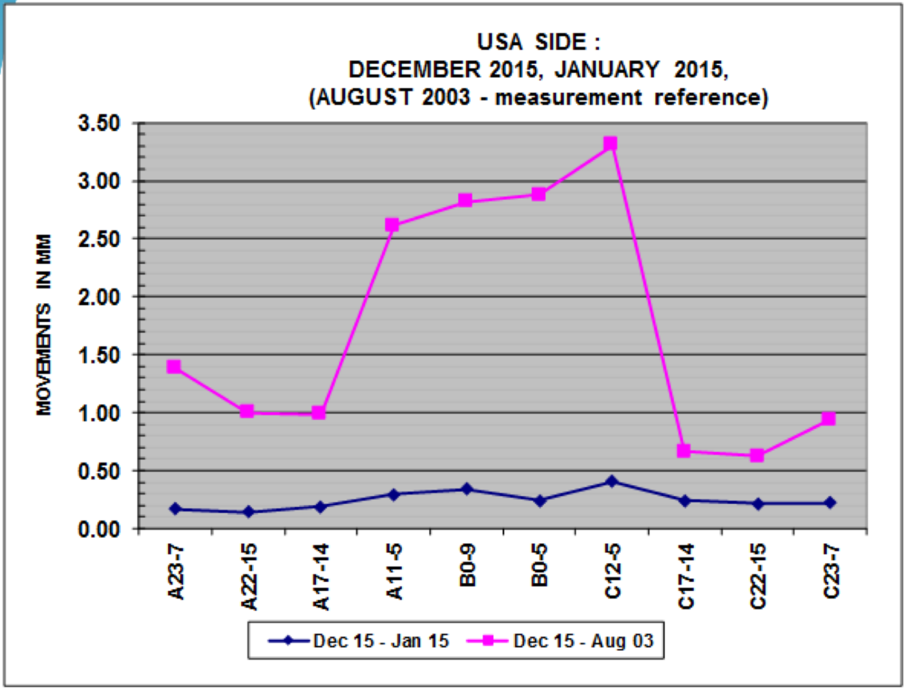
Monitoring of inclination of underground caverns at CERN and as part of a complex metrology system at JINR

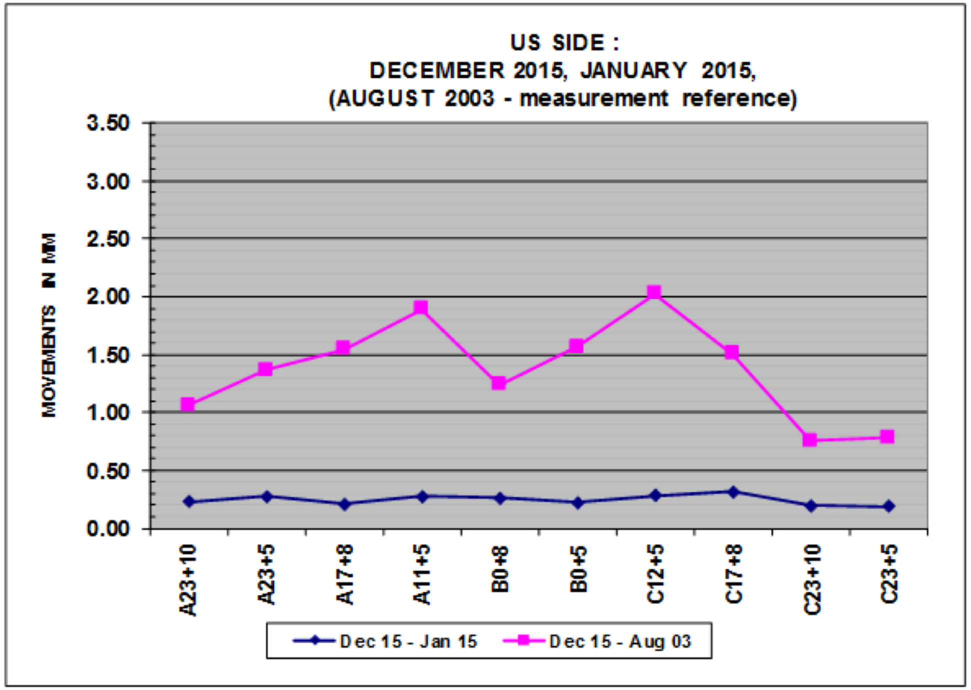
ATLAS Floor Stability Aug 03 – Dec 15



- Reference are deep references in LHC tunnel close to IP1
- Time between measurements varies from 3 to 18 month
- Precision for single epoch 0.2 mm/1 sigma; 0.3 mm between 2 epochs

ATLAS Floor Stability Aug 03 – Dec 15





- Movement close to detector is asymmetric and larger on USA side
  - ATLAS detector asymmetric to cavern axis
- Measurements done in different detector configurations (open/close)
- Distance between lateral walls -20 mm/12 years

Published articles

<u>**List of publications**</u>

Batusov, V., Budagov and Lyablin M., “A laser sensor of a seismic slope of the earth surface”, Phys. Part. Nucl. Lett. 10 (2012), Issue 1, 75-83

N. Azaryan et al., “The precision laser inclinometer long-term measurement in thermo-stabilized conditions (First Experimental Data)”, Phys. Part. Nucl. Lett 12 (2015), Issue 4, 532-535

Batusov V. et al., “The Sensitivity Limitation by the Recording ADC to Laser Fiducial Line and Precision Laser Inclinometer”, Phys. Part. Nucl. Lett 12 (2015), Issue 7, 1264-1271

Batusov V. et al., “The calibration of the Precision Laser Inclinometer”, Phys. Part. Nucl. Lett 12 (2015), Issue 7, 1272-1278

Di Girolamo B. et al., “The Monitoring of the Effects of Earth Surface Inclination With the Precision Laser Inclinometer for High Luminosity Colliders”, Proceedings of the 25th Russian Particle Accelerator Conference, Saint Petersburg, Russia, 21 - 25 Nov 2016, 210-212

Azaryan N. et al., “The innovative method of high-accuracy interferometric calibration of the Precision Laser Inclinometer”, Phys. Part. Nucl. Lett 14 (2017), Issue 1, 62

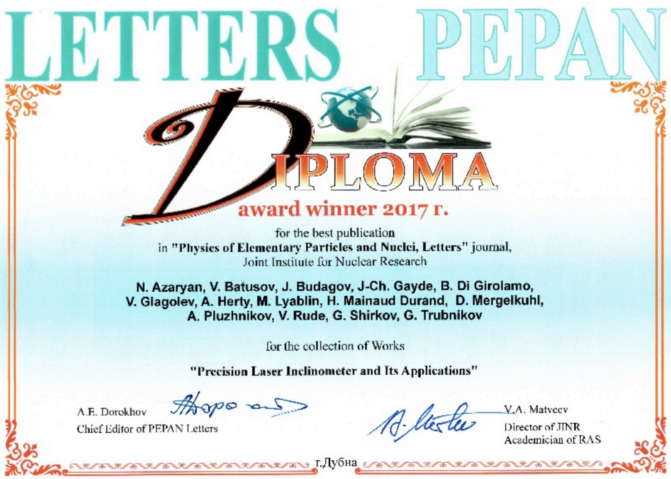
Azaryan N. et al., “Comparative analysis of earthquakes data recorded by the innovative Precision Laser Inclinometer instruments and the classic Hydrostatic Level System”, Phys. Part. Nucl. Lett 14 (2017), Issue 3, 285

Azaryan N. et al., “The temperature stability of 0.005°C for the concrete floor in the CERN Transfer Tunnel #1 hosting the Precision Laser Inclinometer”, Phys. Part. Nucl. Lett 14 (2017), Issue 6, 639-648

Azaryan N. et al., “Determination of the maximum recording frequency by the Precision Laser Inclinometer of an Earth surface angular oscillation”, Phys. Part. Nucl. Lett 14 (2017), Issue 6, 649-660

Azaryan N. et al., “The compensation of the noise due to angular oscillations of the laser beam in the Precision Laser Inclinometer”, Phys. Part. Nucl. Lett 14 (2017), Issue 6, 661-672

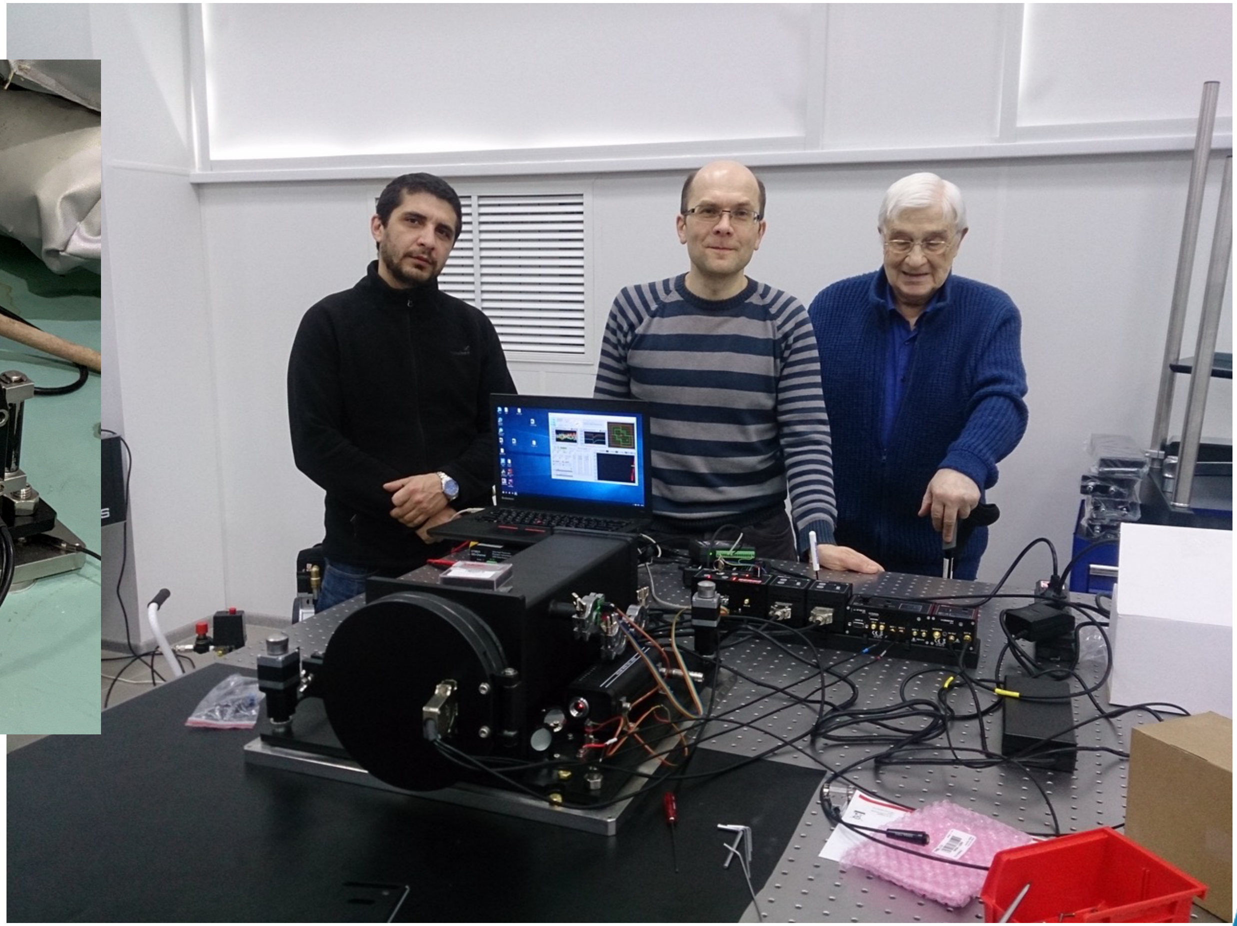
Azaryan N. et al., “Colliding beams focus displacement caused by seismic events”, Submitted to Phys. Part. Nucl. Lett (2018)



5 more articles being published in Phys. Part. Nucl. Lett. and one in preparation for Rev. Sci. Instr.

PLI pictures and form factor

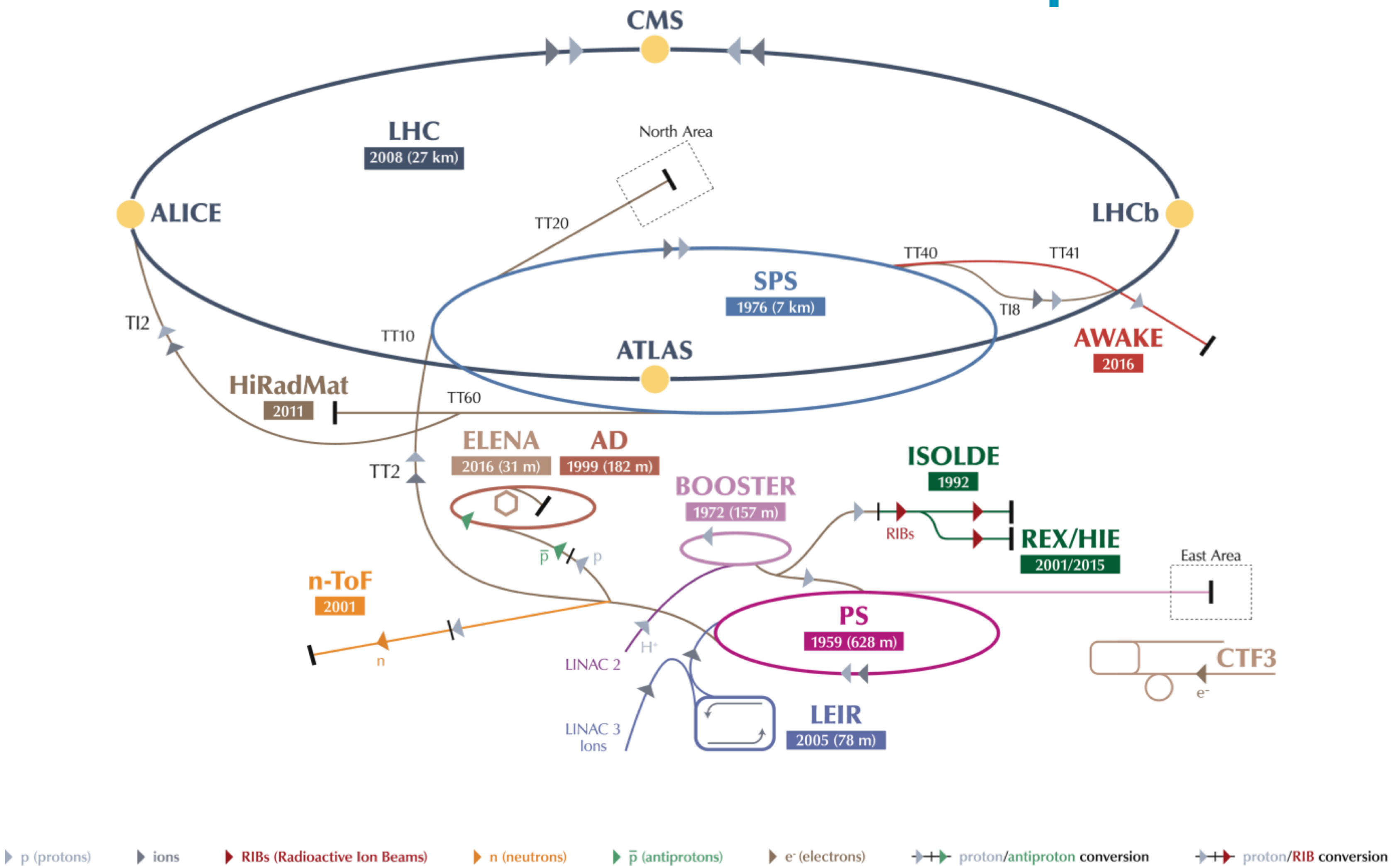
- The PLI is quite compact: 40x40x20 cm^3



PLI installed units

- PLI units installed at JINR and CERN and in continuous data taking since March 2015
- A production unit installed at CERN since end 2017
  - Latest version installed in March 2019
  - 6 more units produced, three already instrumented, the others being instrumented
- 1 unit installed in Armenia in 2018
- 6 August 2019: 1st unit installed at VIRGO
- 22 October 2019: 2nd unit being installed at VIRGO

CERN accelerators complex

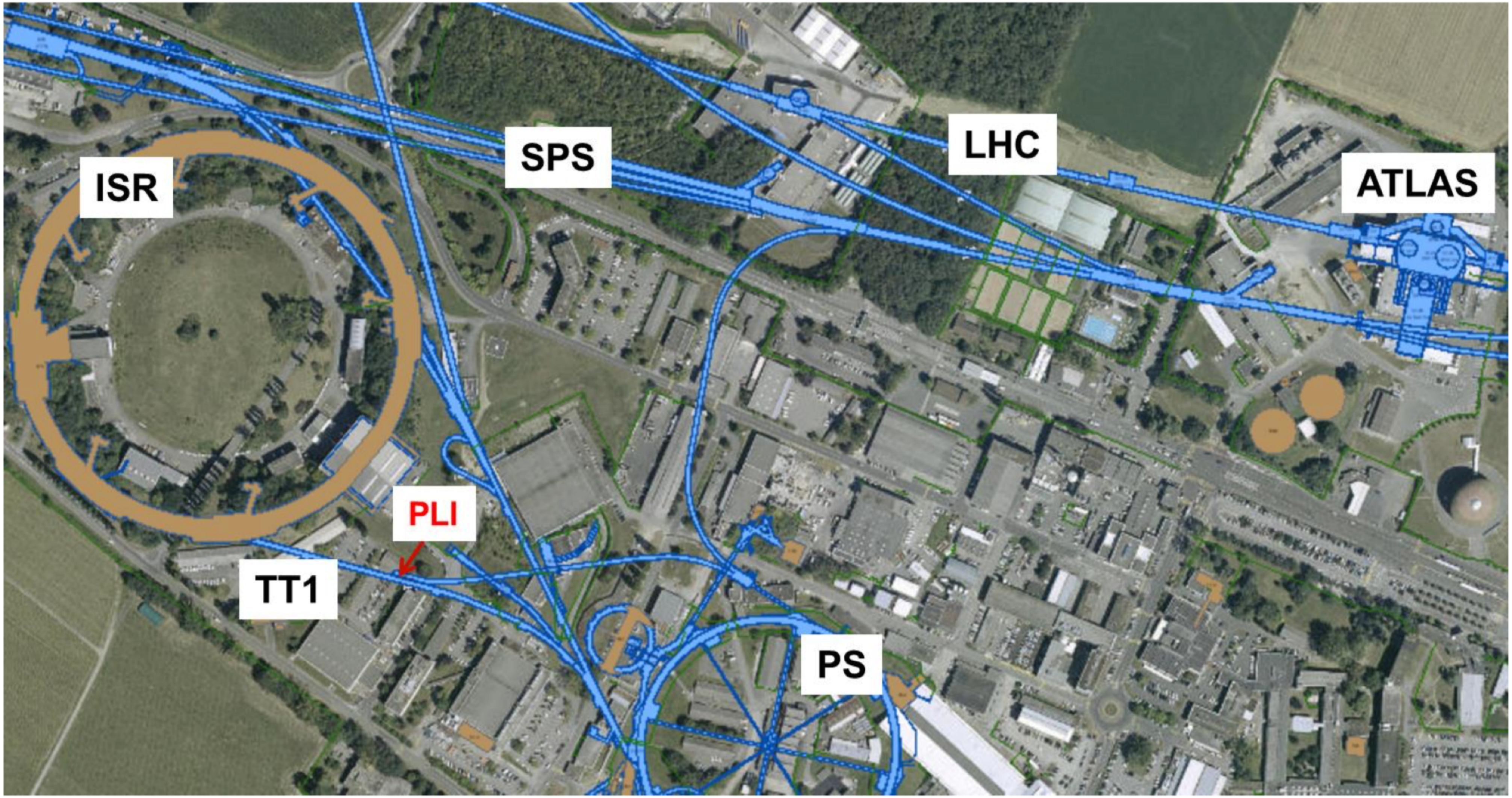


LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

AWAKE Advanced WAKefield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

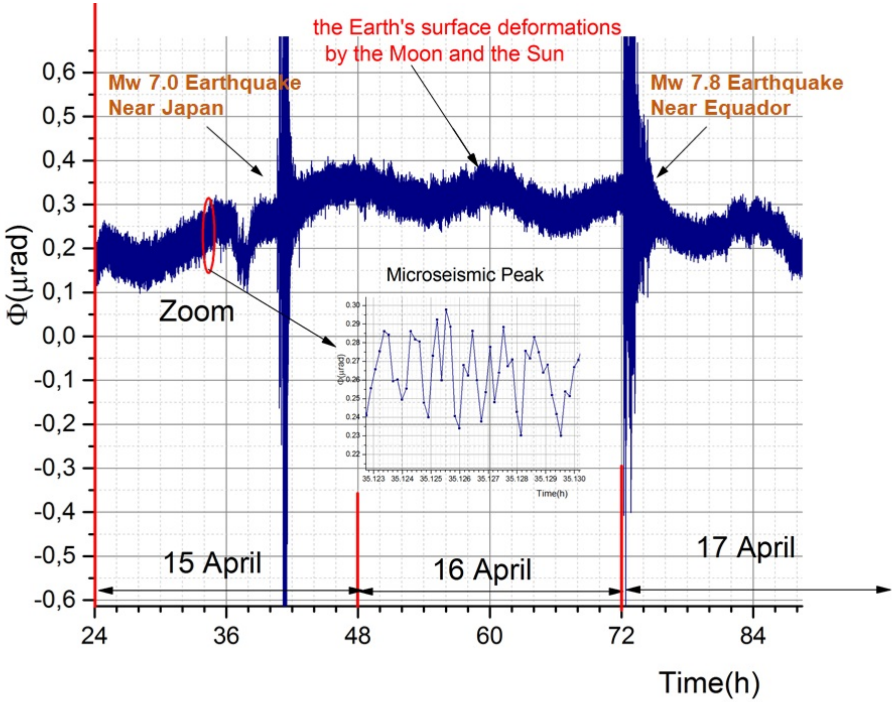
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

Installation at CERN: TT1 Tunnel

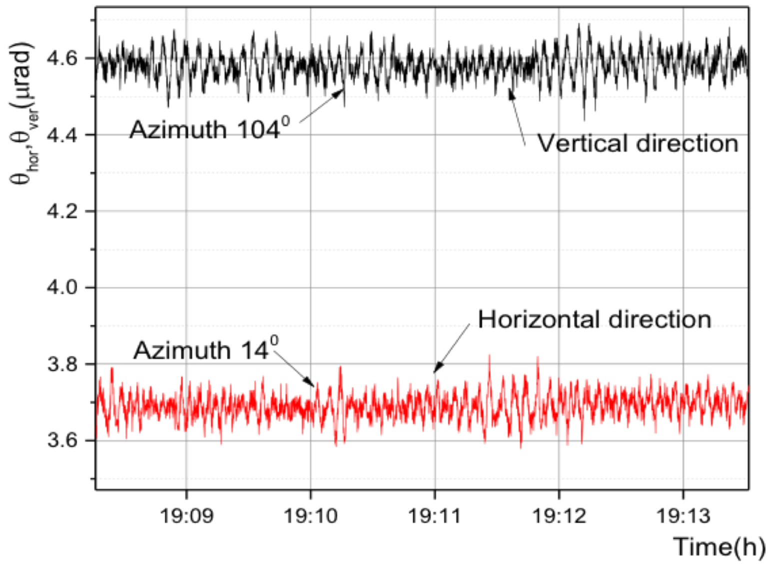


Very stable ground and temperature conditions

PLI: just some initial results



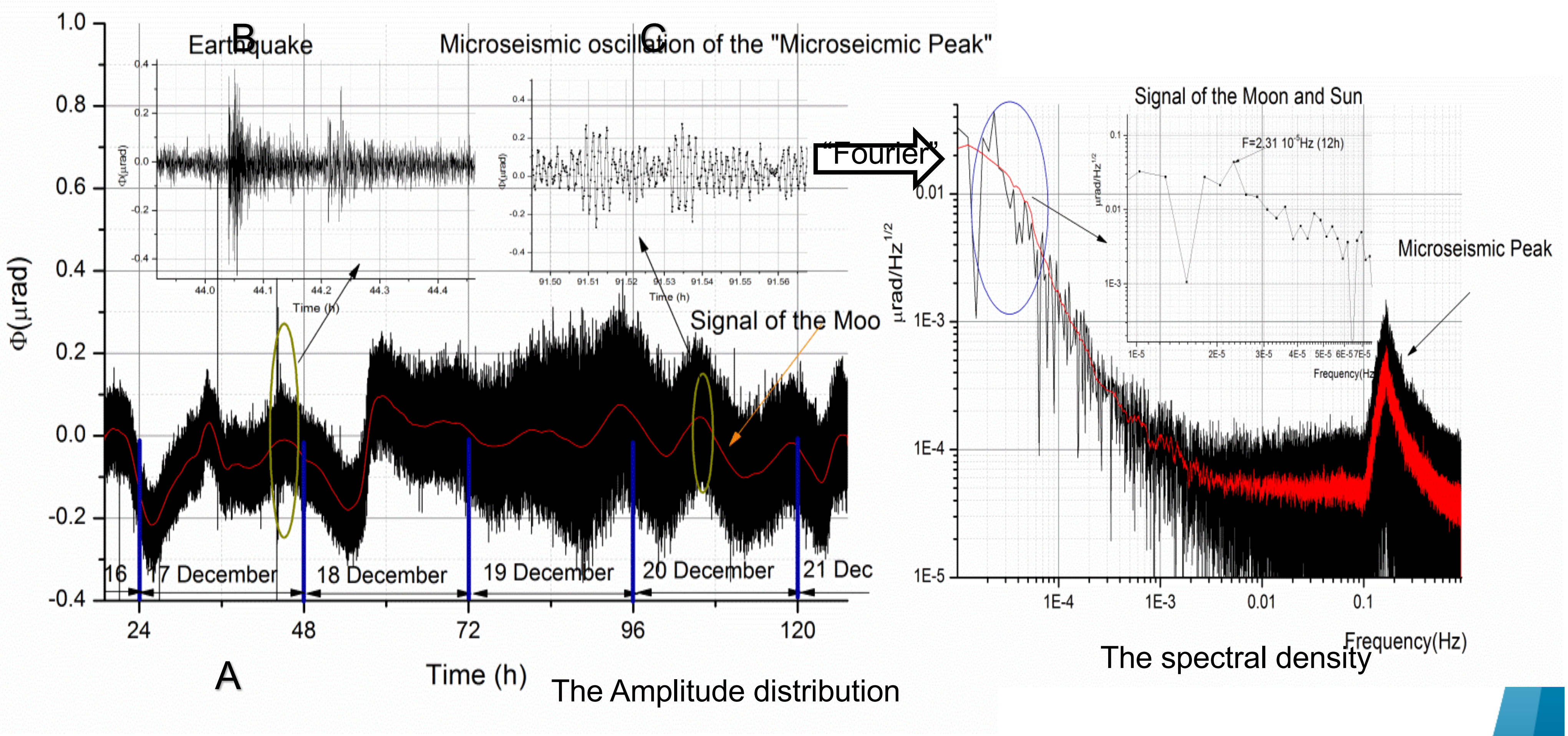
2016
Simultaneous recording of earthquakes, micro-seismic peak and Sun-Moon cycle



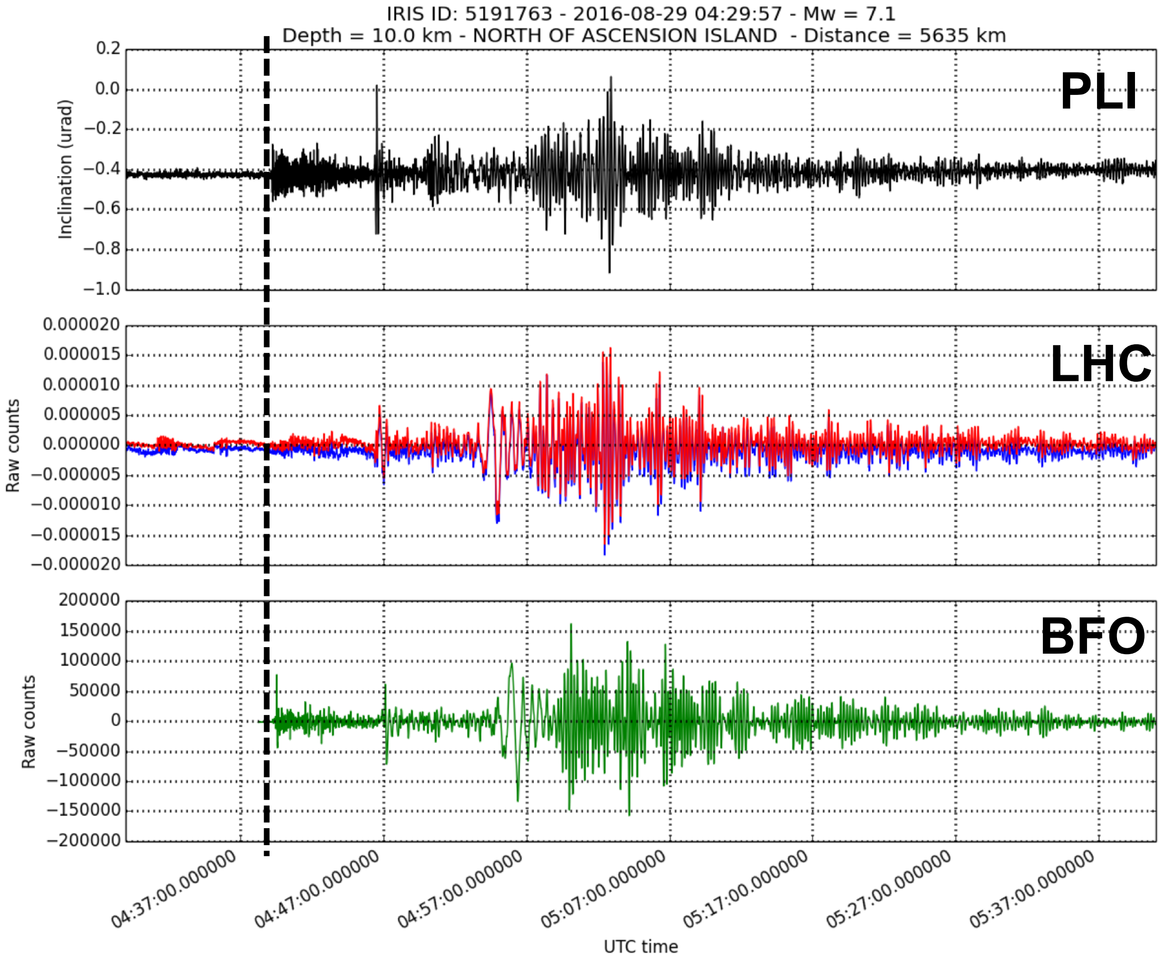
Micro-seismic in the Geneva area

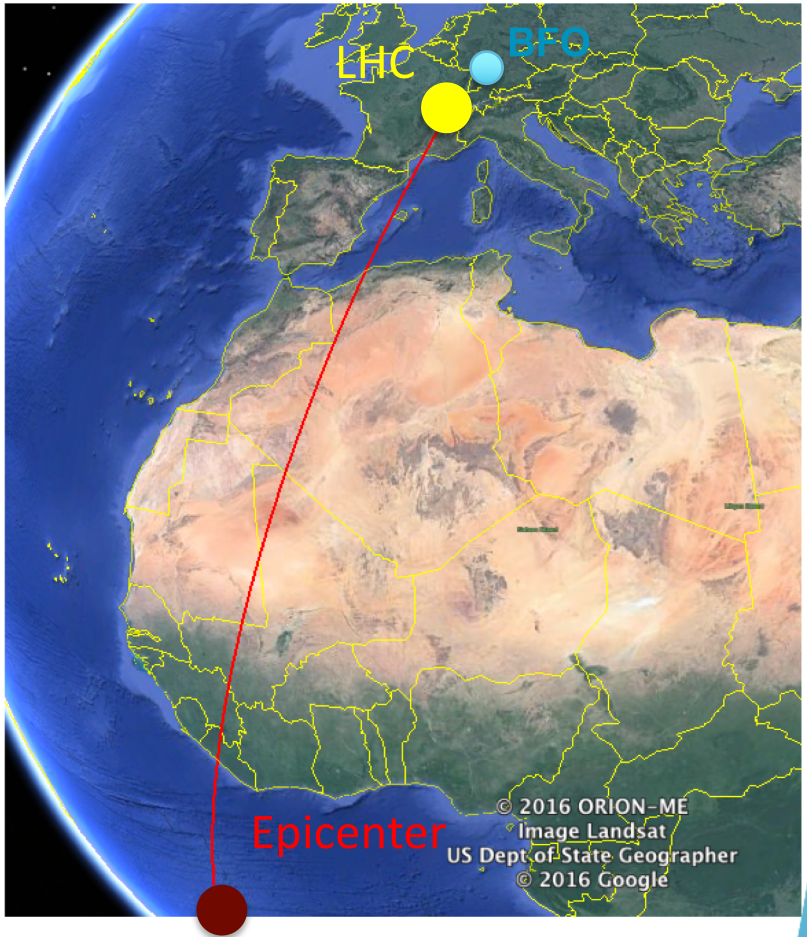
First basic results

These PLI-detected ground motions are caused by the Moon and Sun (**A**); by an Earthquake in Mexico (**B**); by the “microseismic” kicks (**C**).



Far earthquakes: Ascension Island



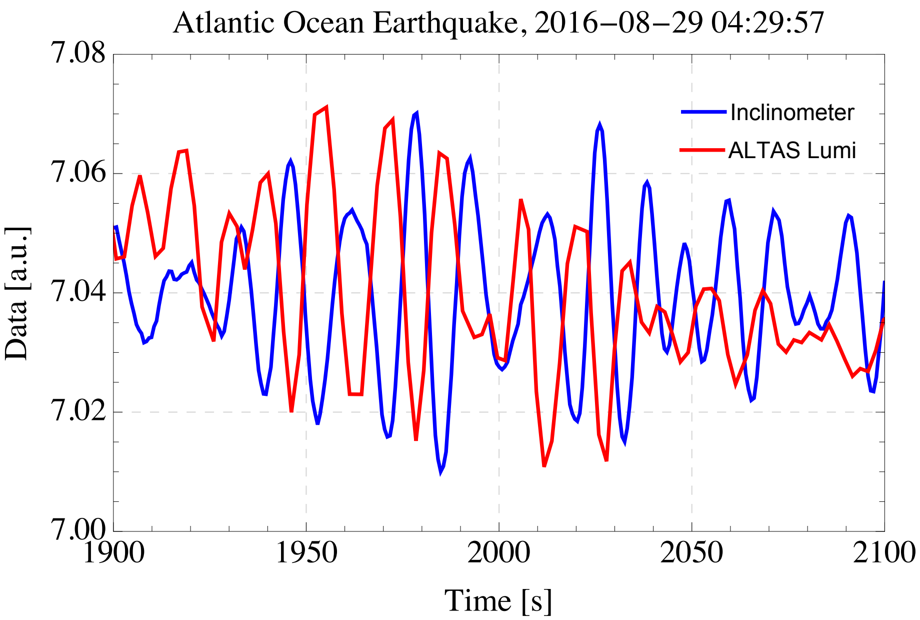


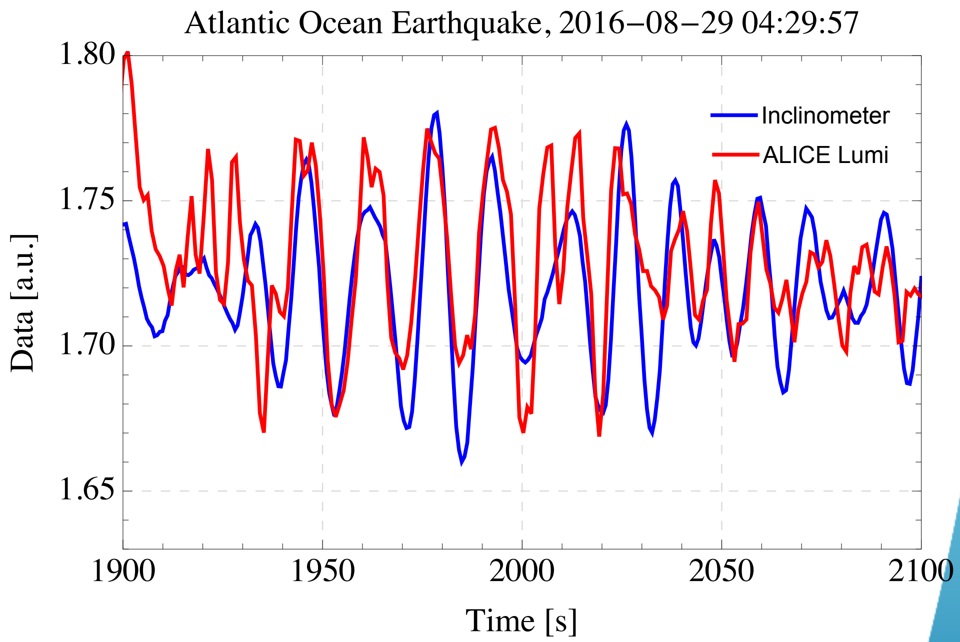
The PLI detection compared to the horizontal orbit oscillations of LHC. As confirmation also the seismogram from the Black Forrest Observatory (which receives it later as expected).

Correlations of Ground Motion with Luminosity

Luminosity shows good correlation with ground motion in TT1.

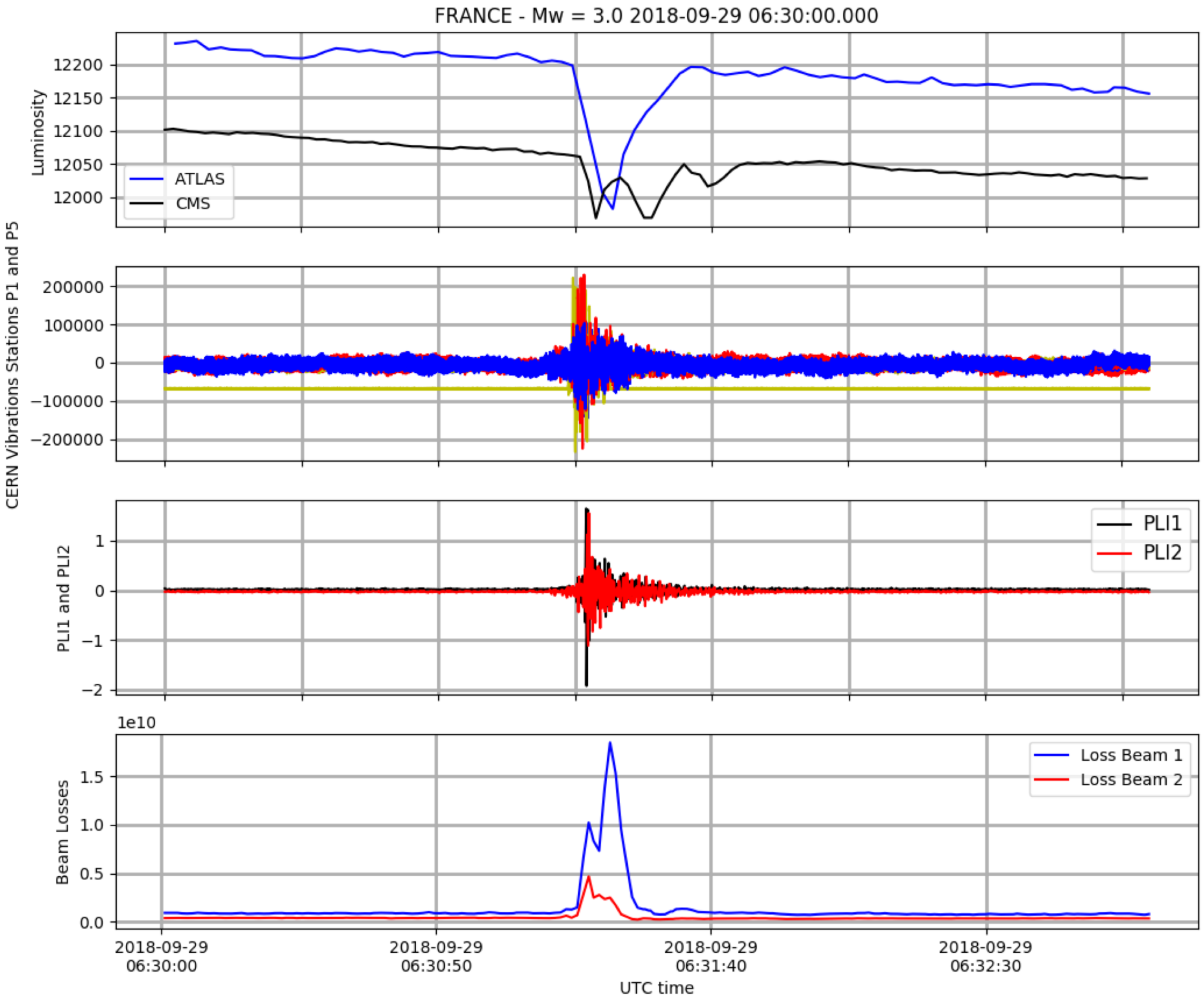
- ALICE/LHCb oscillate in phase with the ground motion.
- ATLAS/CMS oscillate with π/2 phase difference.





Near earthquakes

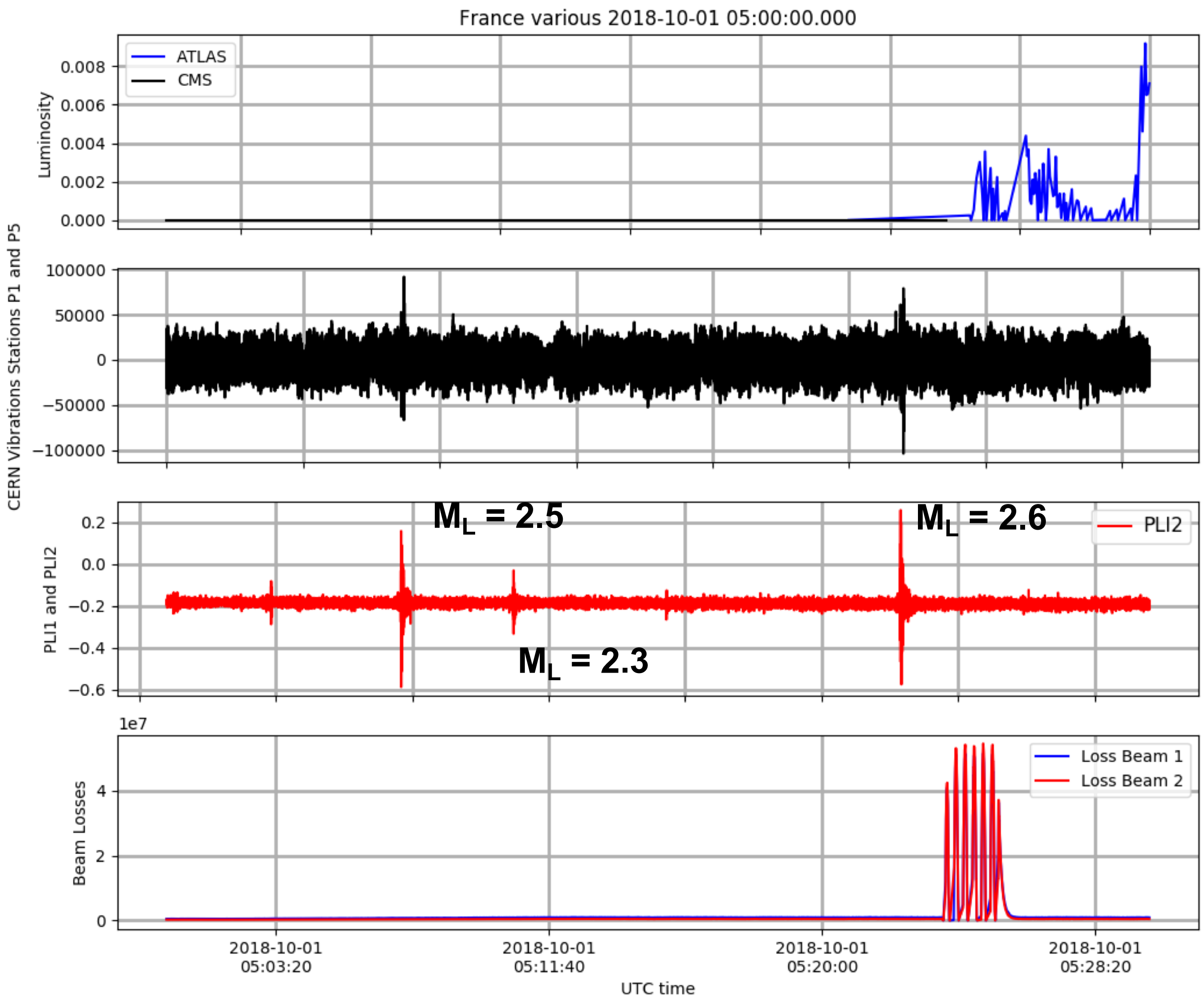
France 29 September 2018



Effect on beam losses and luminosity

Tiny near earthquakes and comparison with seismometers

France 1 October 2018



No effects on LHC

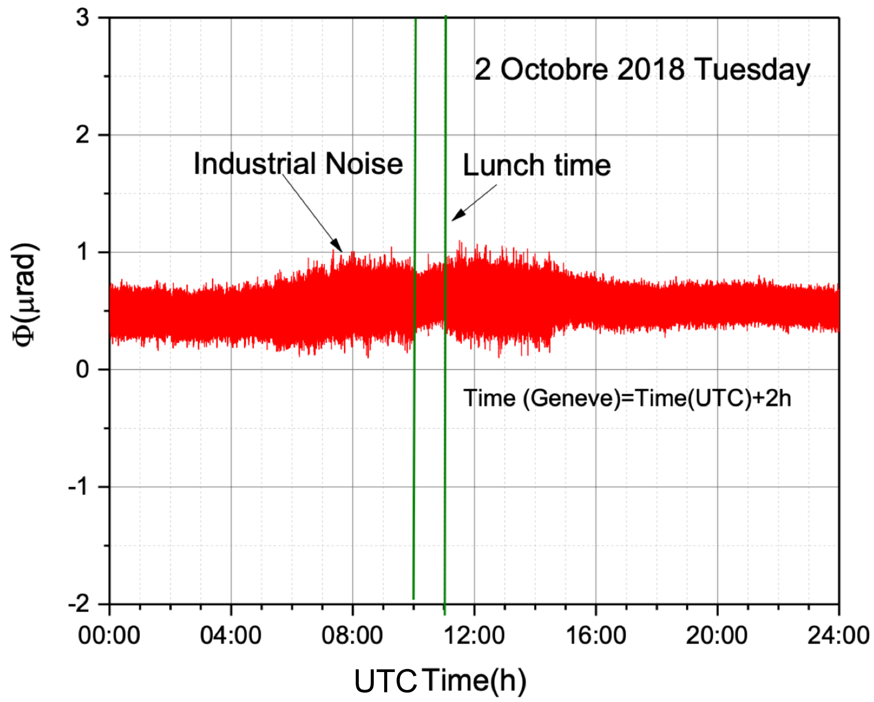
Comparison with seismometers in P1 and P5

Small magnitude earthquakes

Precision of detection

- The precision is dependent on the observation period and the frequency of calibration
- Comparative measurements with well-established HLS system at CERN has shown for monitoring ground earth oscillation
  - A precision of $2.4 \cdot 10^{-11}$ rad/Hz$^{1/2}$ in the frequency range $[10^{-3}, 12.4]$ Hz
  - A precision better than 10^{-9} rad/Hz$^{1/2}$ in the frequency range $[10^{-6}, 10^{-3}]$ Hz

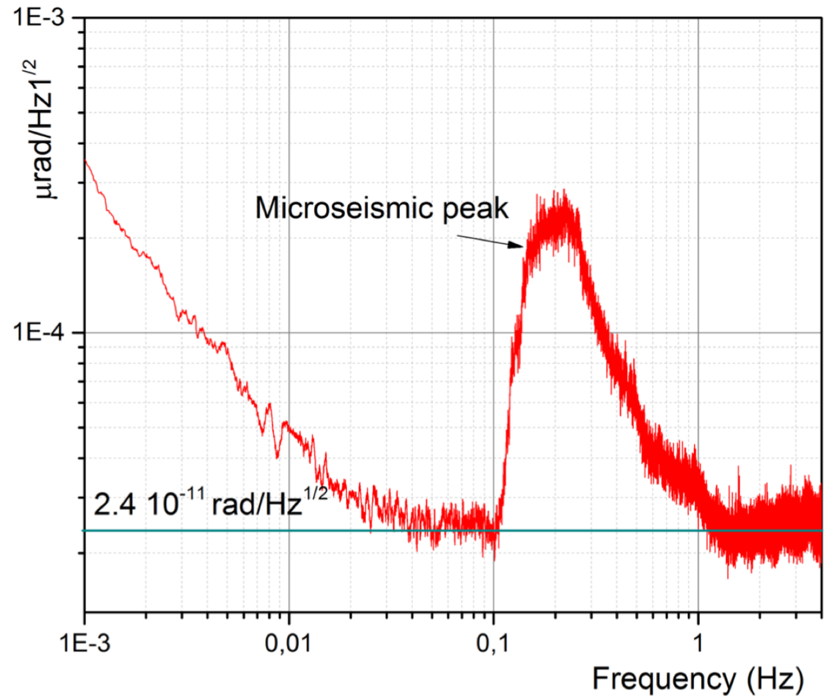
The seismic effects of CERN and surrounding



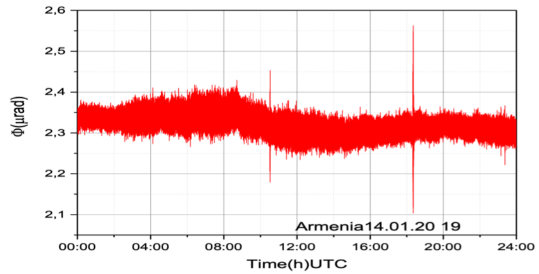
Local time = UTC + 2

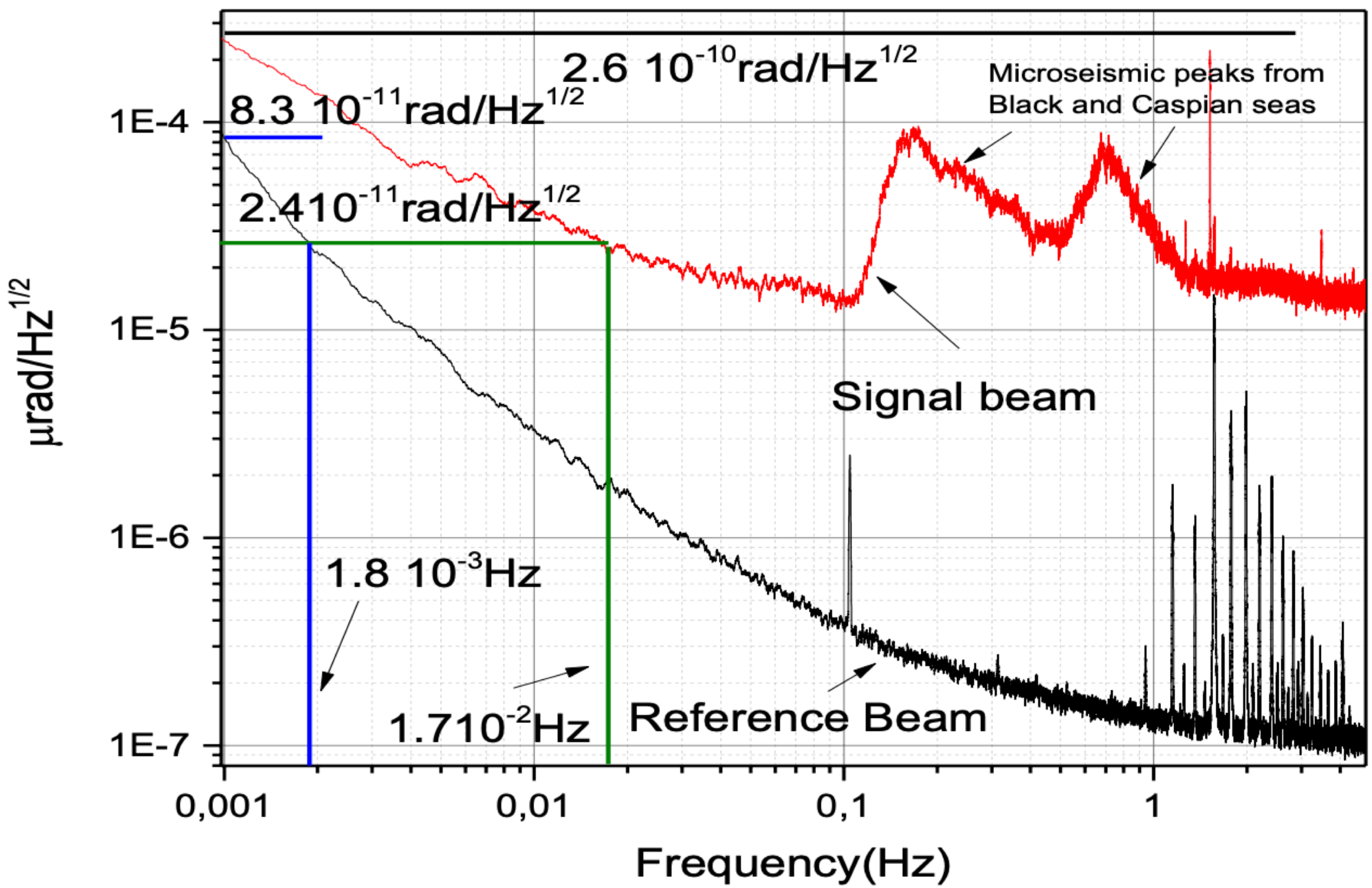
Working day: 0.5-1 μrad during the day
~ 0.3 μrad during lunch
CERN daily "noise"

This plot is obtained everyday, here a specific day with no Earthquakes, no significant CERN "noise" and minimal micro-seismic peak amplitude (~ 50 nrad)



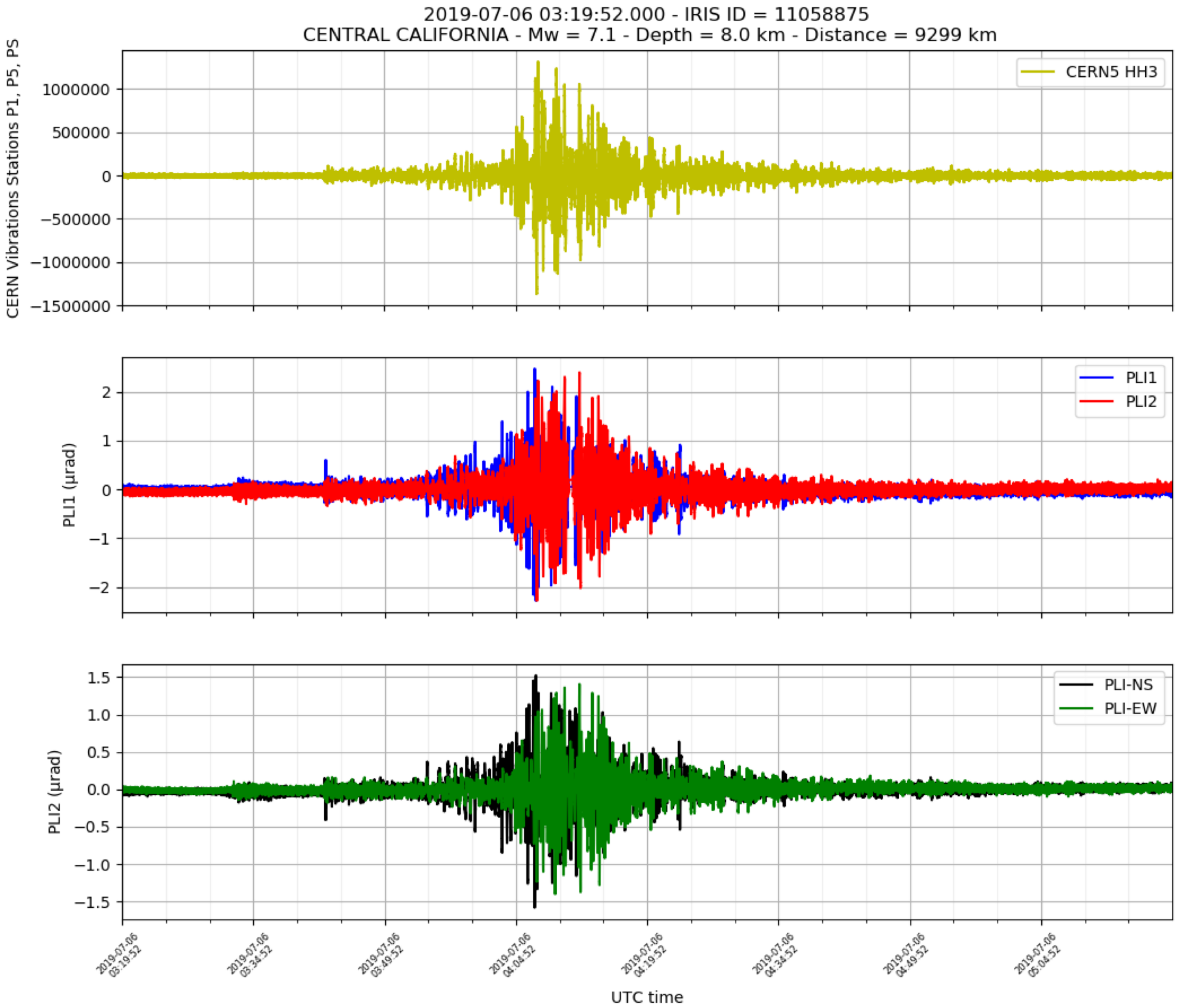
Detection in Armenia: ground oscillations and reference signal

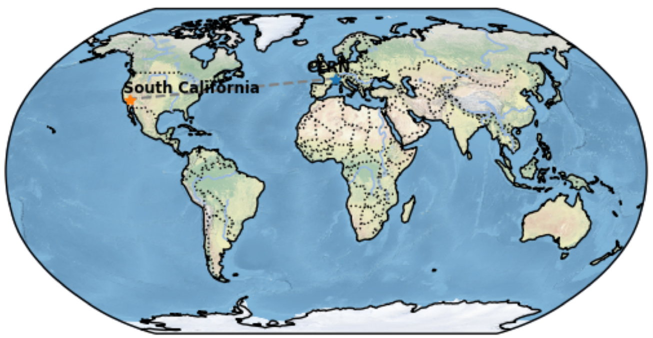




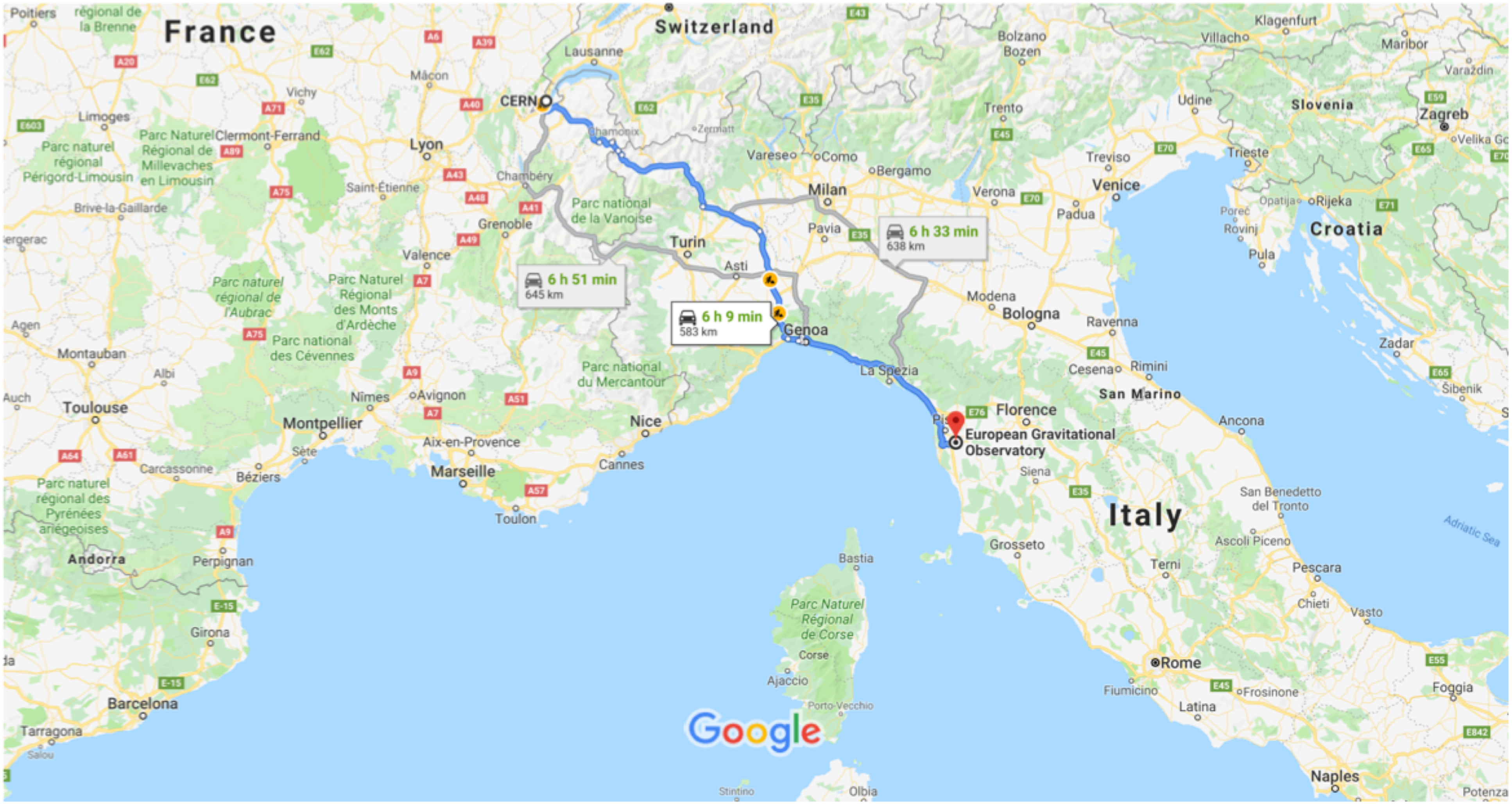
The PLI for Virgo

PLI-Virgo at CERN
M 7.1 California Earthquake





Comparison with the other PLI installed at CERN and Seismometer from CERN Seismic Network



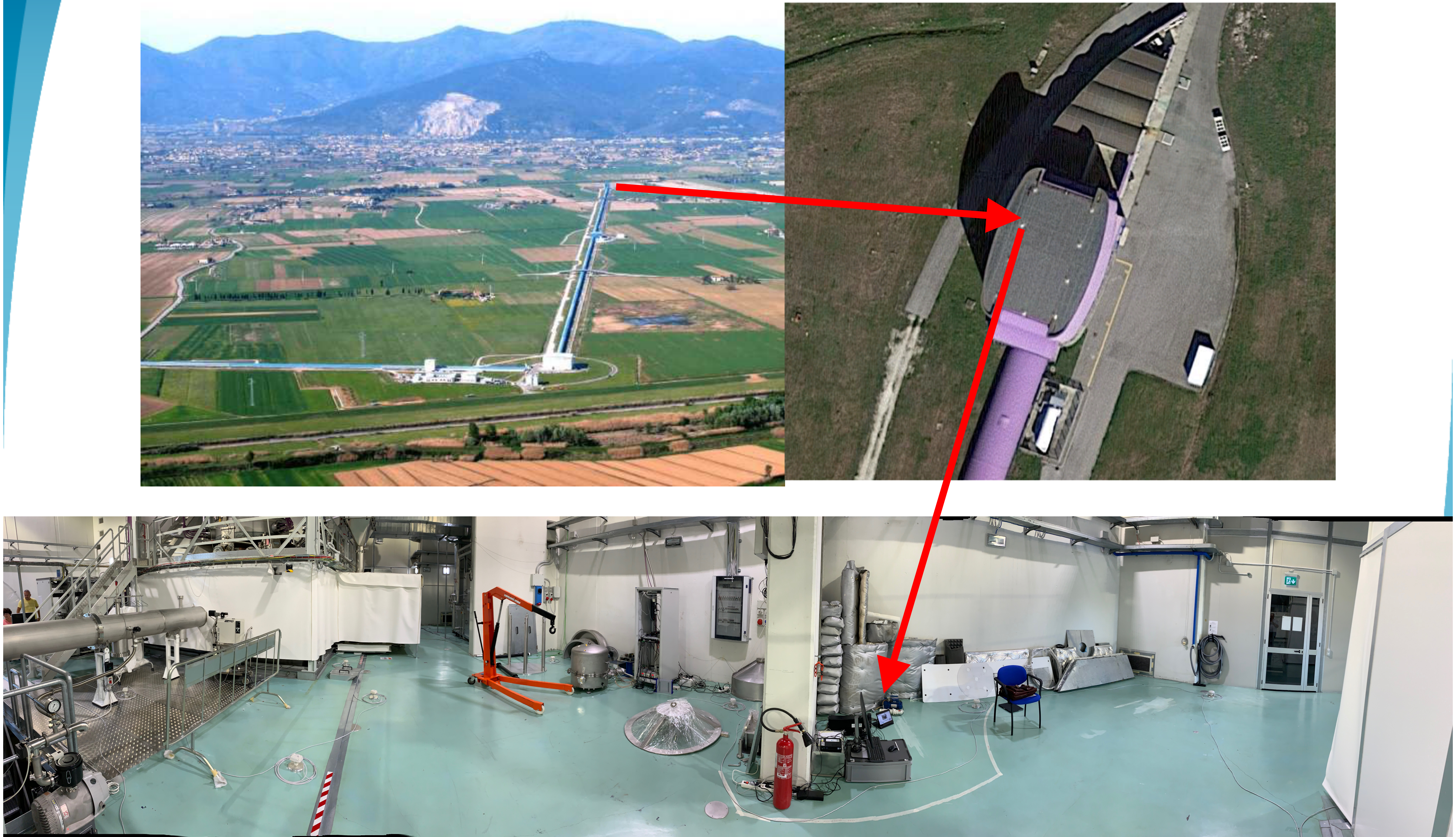
Map data ©2019 Google, Inst. Geogr. Nacional, GeoBasis-DE/BKG (©2009) 100 km

600 km later…

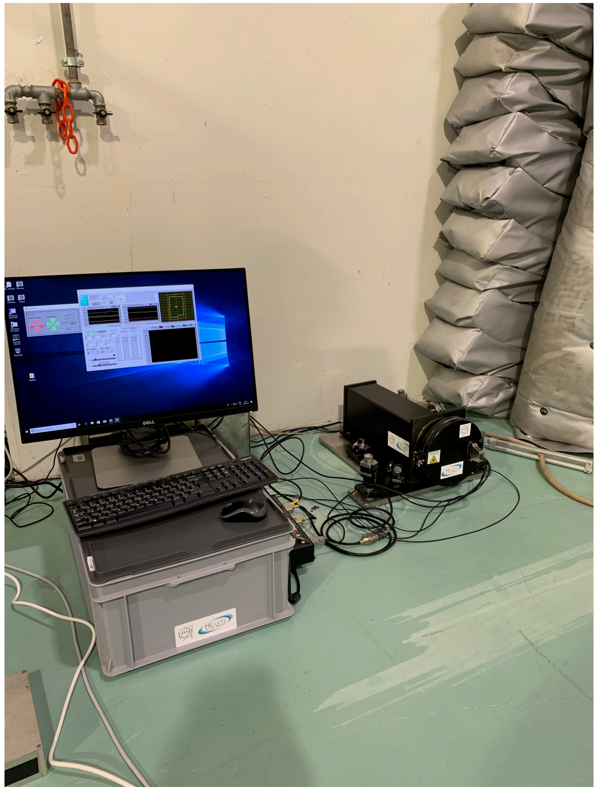
Installation at Advanced Virgo

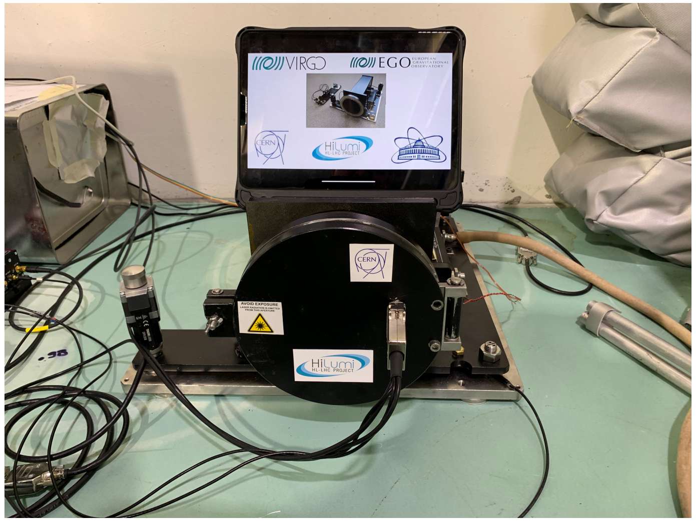
- A collaboration was established between CERN-JINR-INFN to install one PLI device at Advanced Virgo
- Tested at CERN until end of July, installed in North End Building of Adv Virgo on August 6th
  - It started data taking immediately
  - New intervention on August 13th for final tuning
  - In continuous data taking
  - Working with F. Carbognani for integration in Virgo data frame

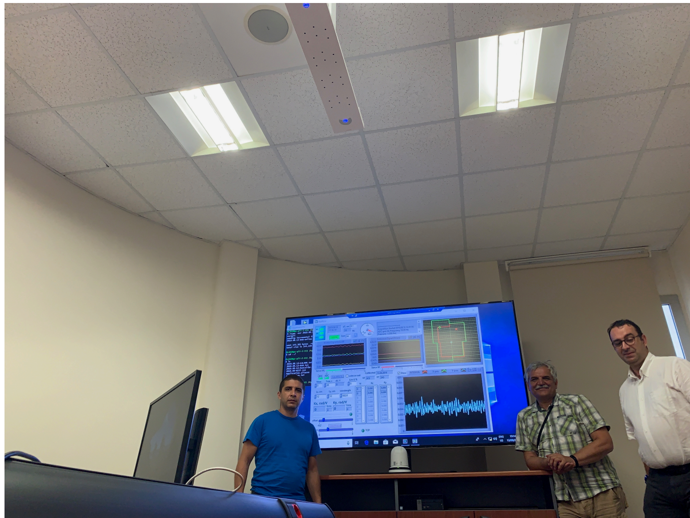
PLI-Virgo in its position at NEB



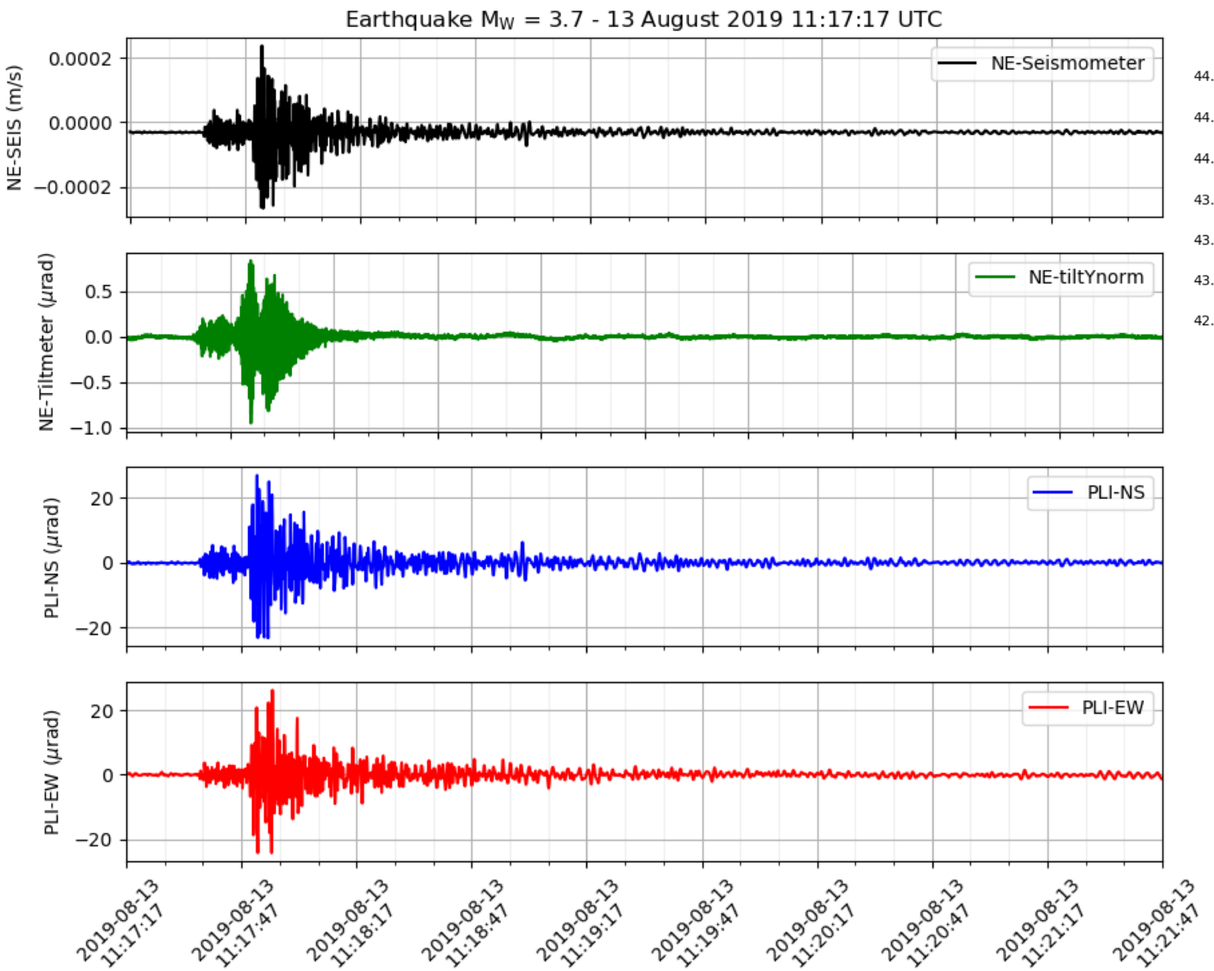
PLI-Virgo in its position at NEB

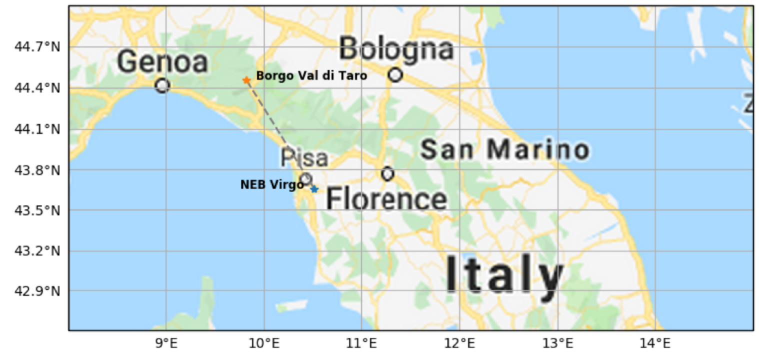






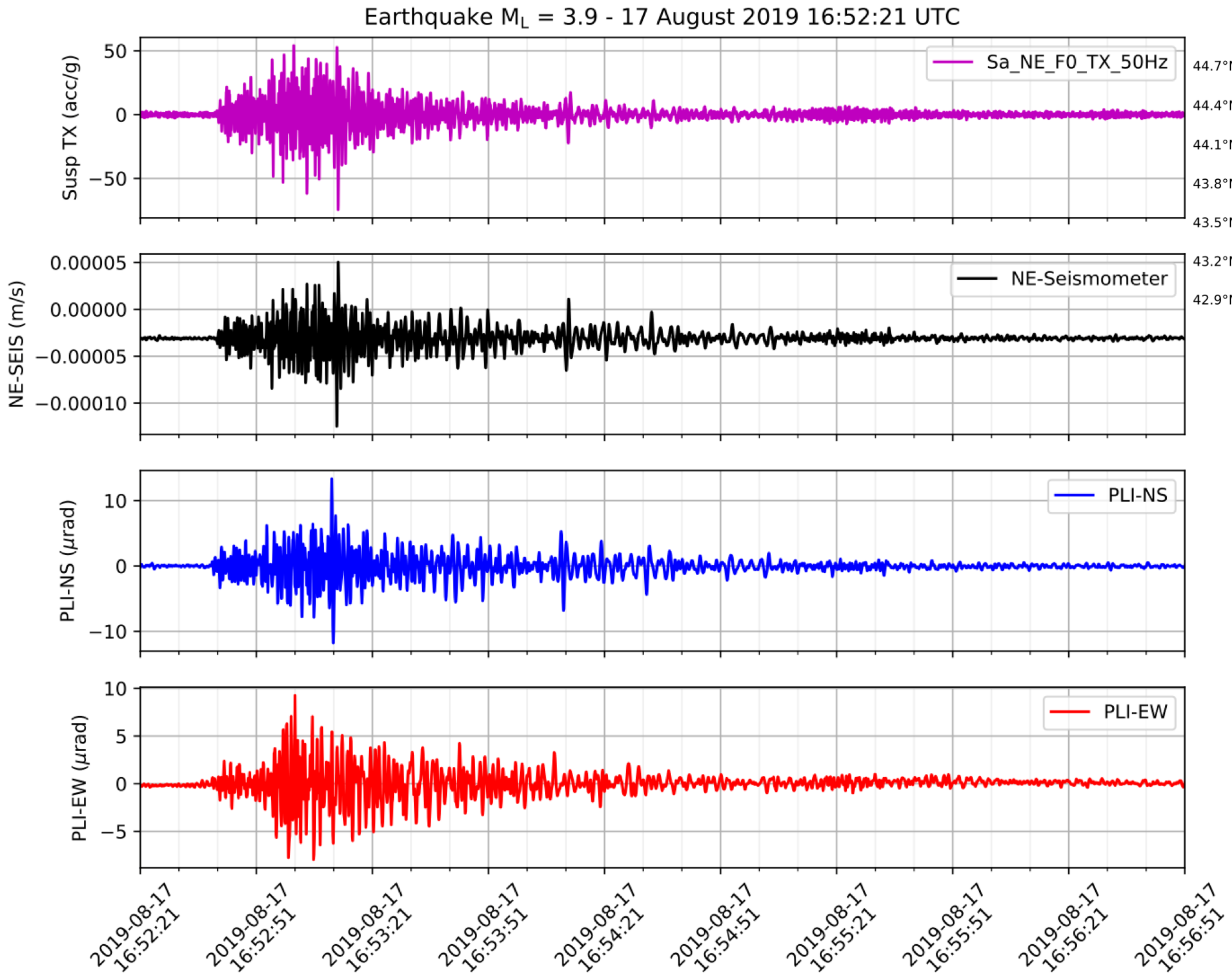
Several tiny earthquakes recorded: examples





105 km from Virgo
M_W = 3.7
Clear arrival of P waves after ~ 20 s
Comparison with Napoli's tiltmeter and seismometer in NEB

Several tiny earthquakes: examples



113 km from Virgo

M_L = 3.9

Clear arrival of P waves after ~ 20 s

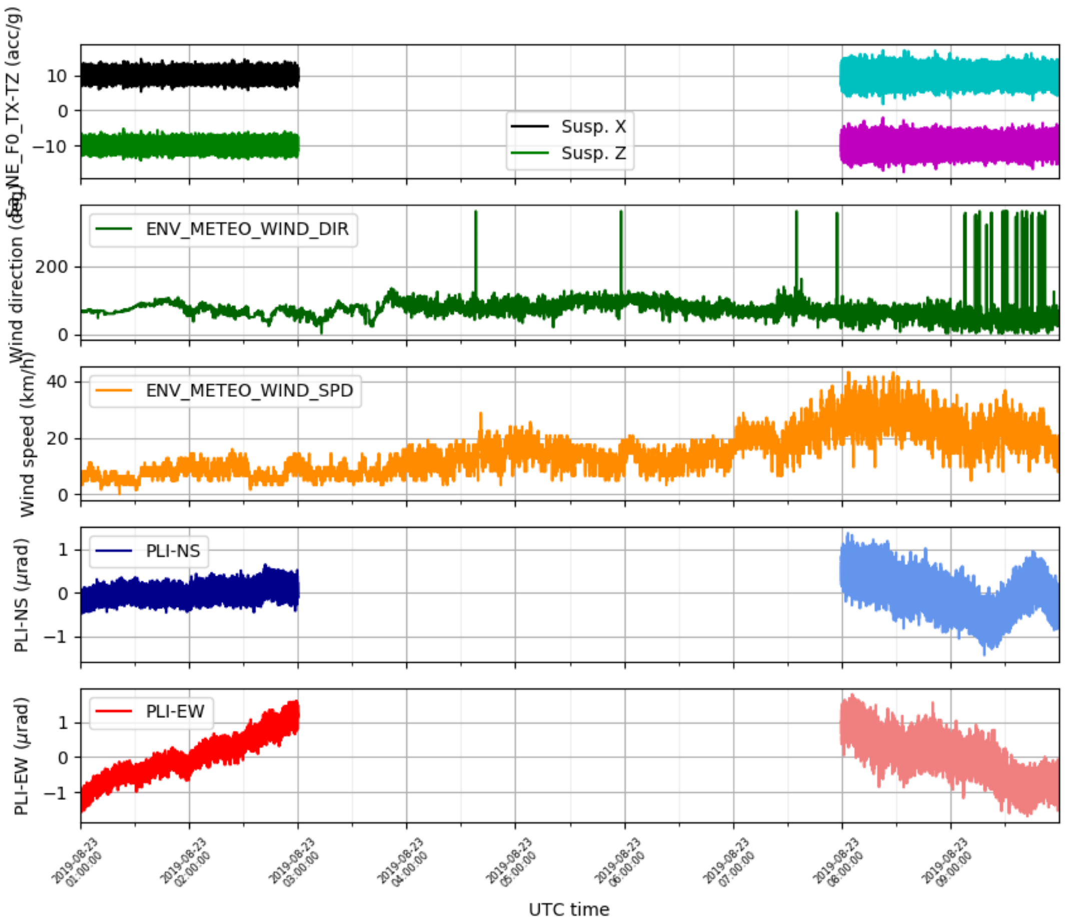
Comparison with signals from suspensions and from seismometer in NEB

Analysis of wind effects on NEB

- Wind effects are a powerful tool to check coherence with other sensors
- Wind effects under 150 mHz are mostly due to rotation
- The wind effects however also manifest on the micro-seismic peak
- Results are nice, although deeper studies are needed
  - The non uniformity in wind speed is not corrected and certainly source of oscillations in coherence

Effect of the wind: comparison low-high wind

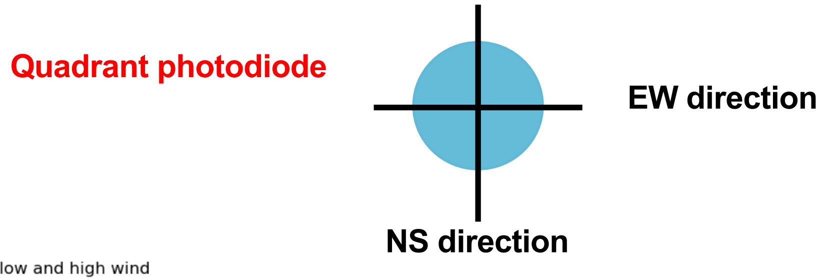
- Low wind ~ 0 to 5 km/h
- High wind ~ 20 to 30 km/h with constant direction
- Looking at effects on PLI, seismometers and suspensions

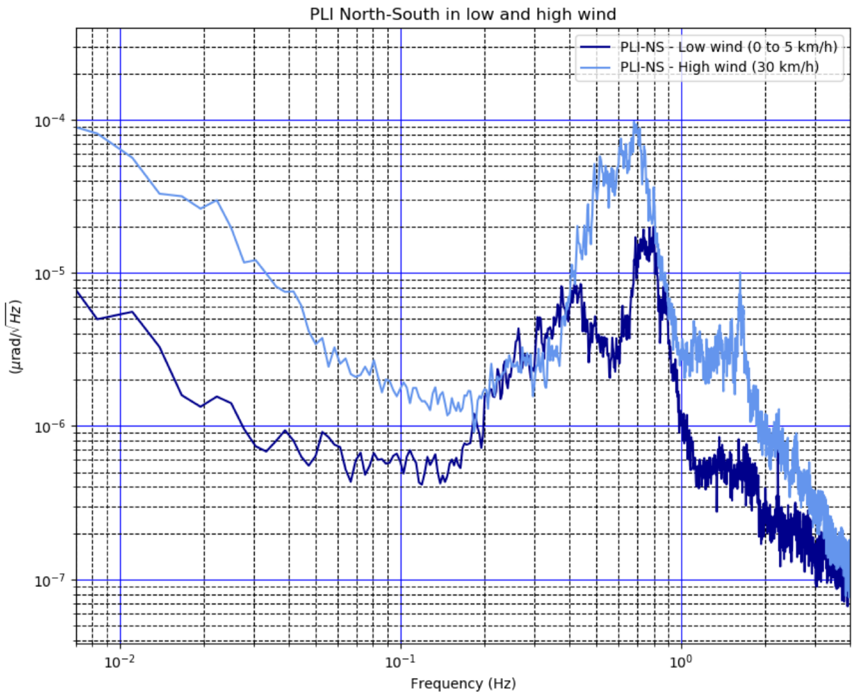


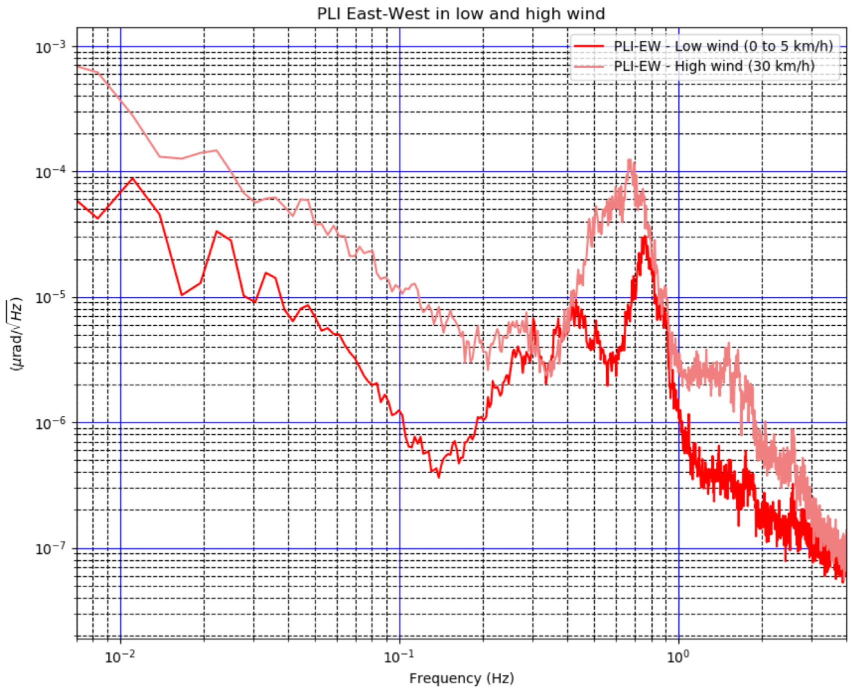
Data from August 23rd
Only sub-set of data in the interesting times
01:00-03:00 UTC
08:00-10:00 UTC

Although not very uniform in wind speed

Effect of the wind: on PLI

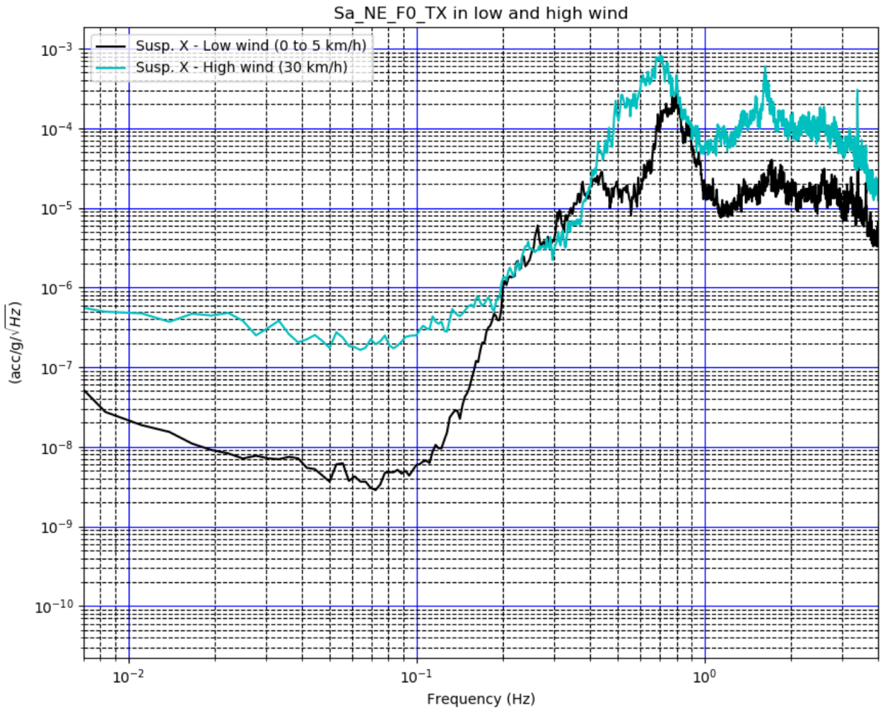


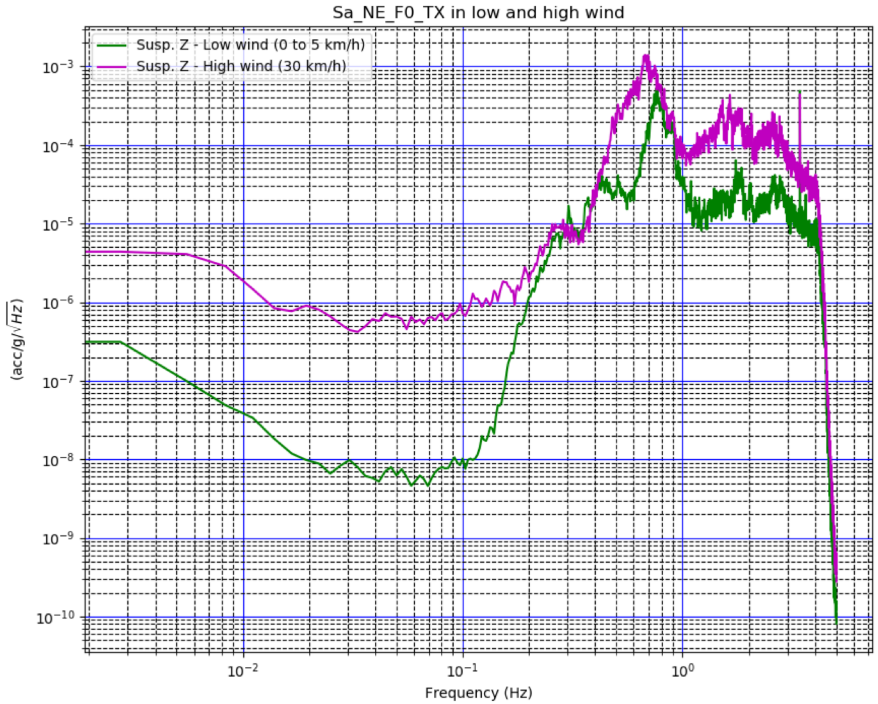




- NS coordinate, aligned as the laser beam and the Napoli's tiltmeter
- EW coordinate, orthogonal to NS

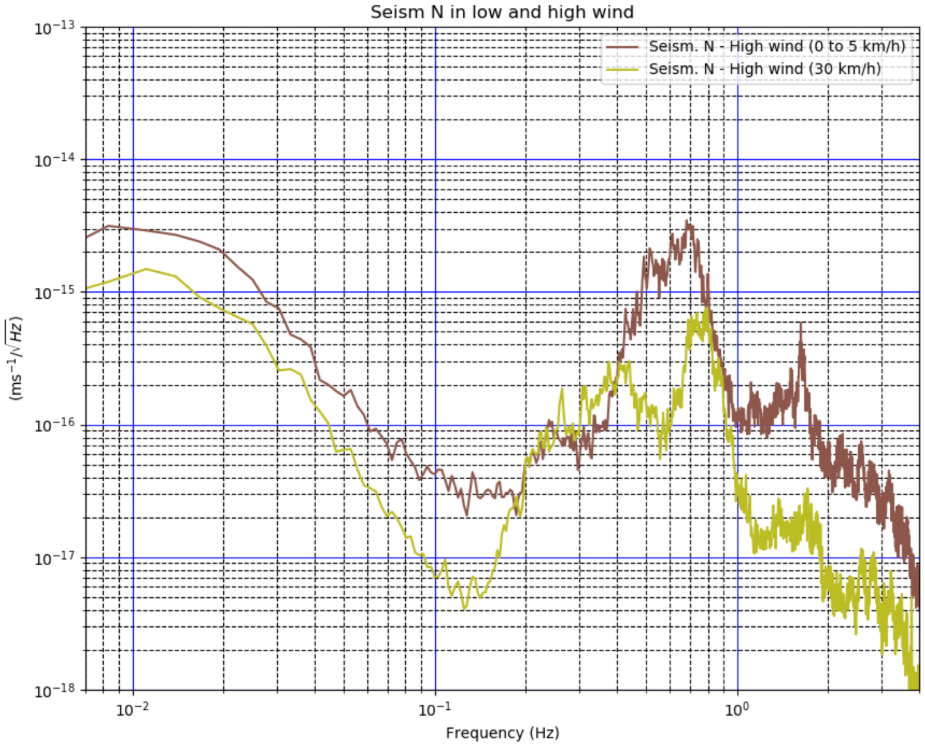
Effect of the wind: on Suspension

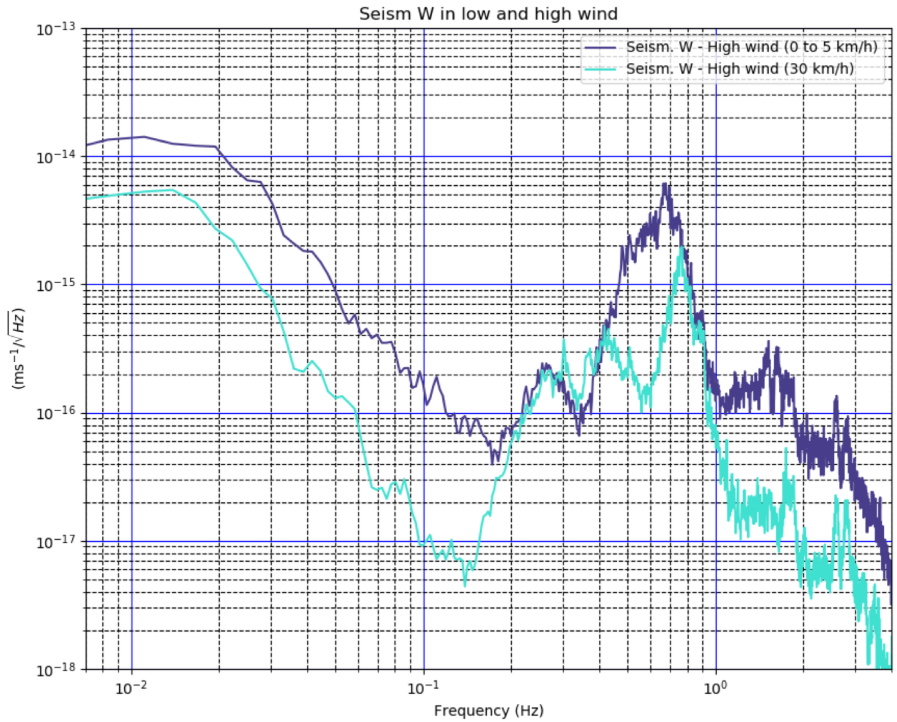




TX and TZ directions

Effect of the wind: on Seismometer

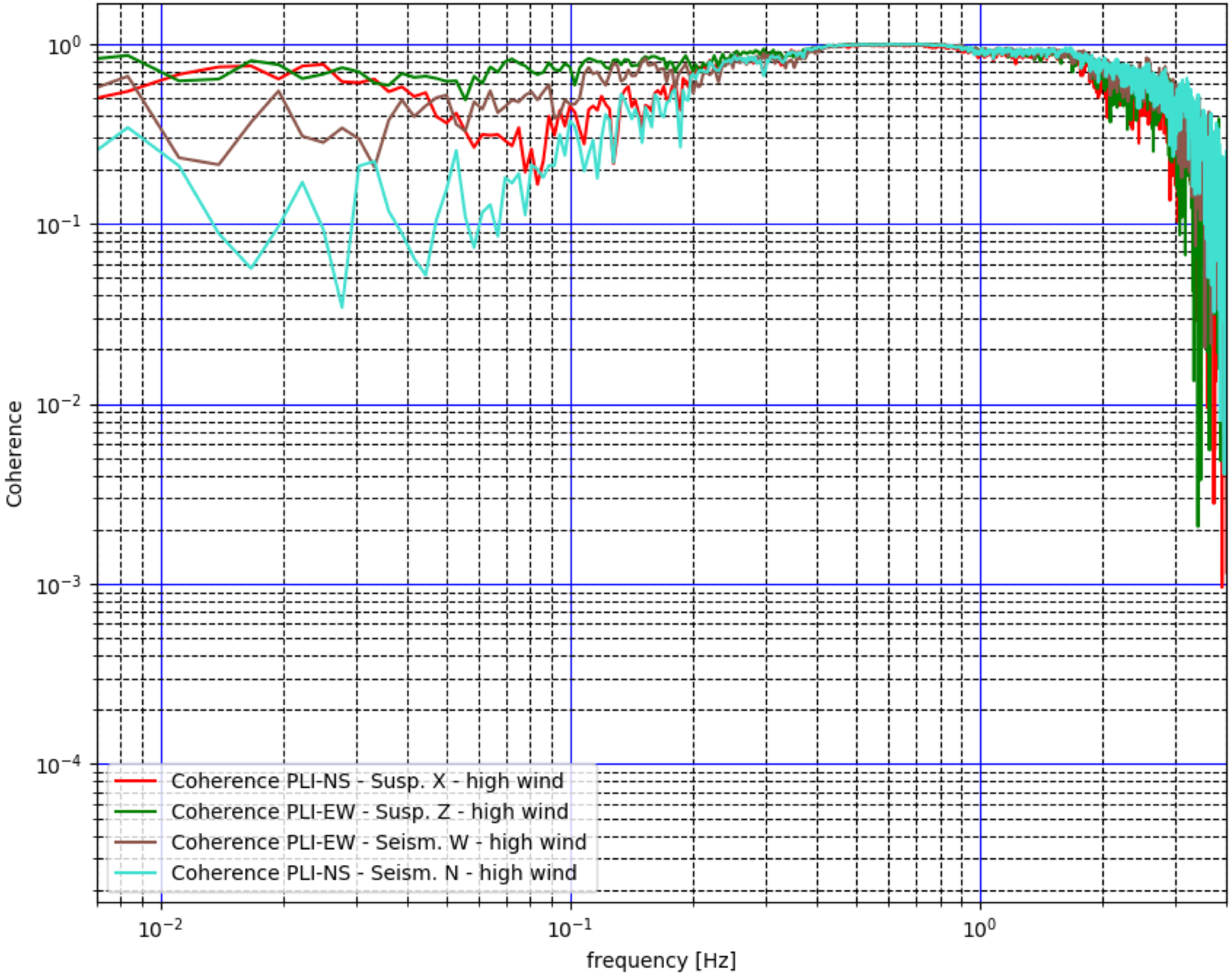




N and W directions

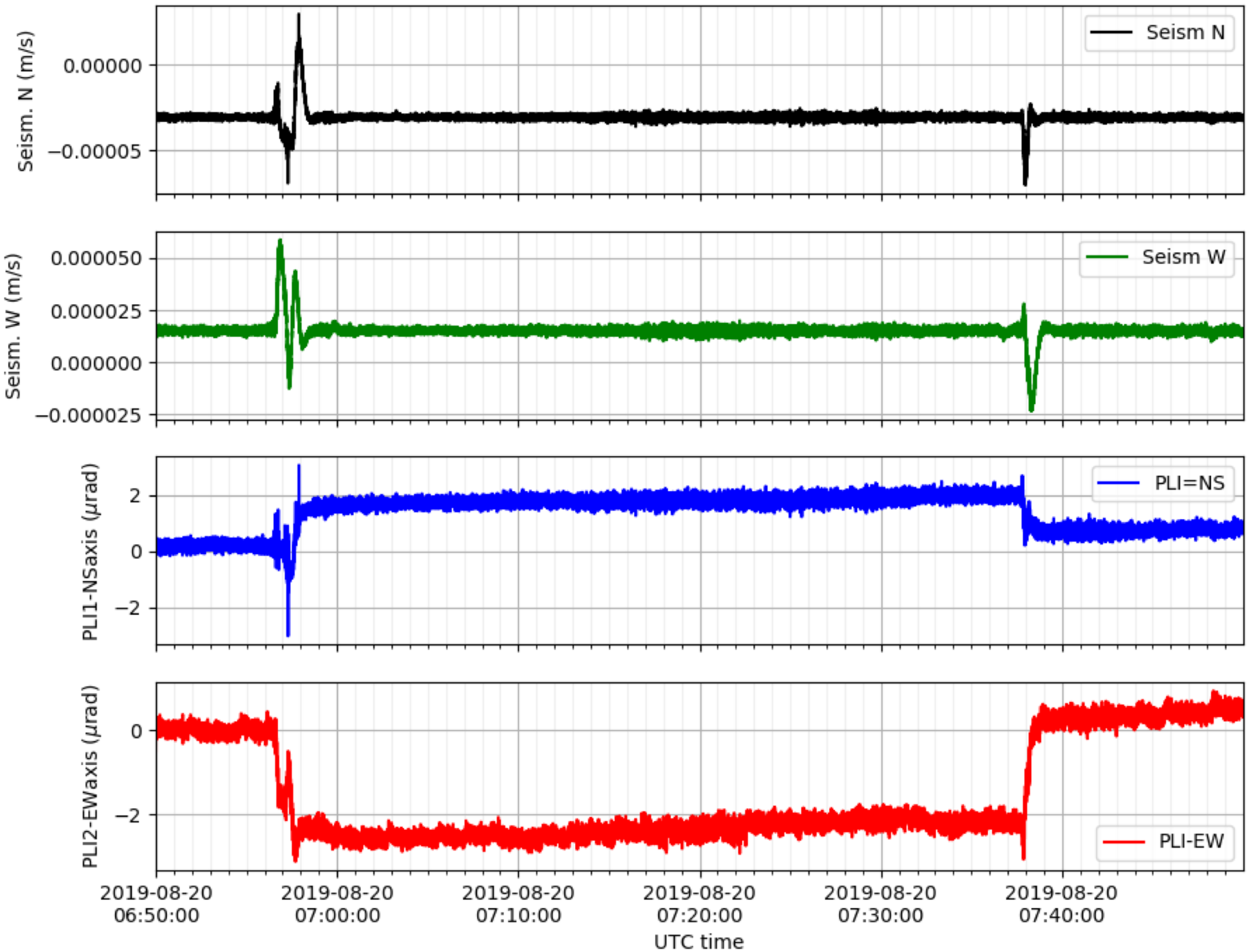
Effect of the wind: Coherence

Best coherence PLI-Suspensions
Non uniformity of wind speed affects the coherence



Funny effects: 20 August

Every Tuesday for 30 minutes a strange effect



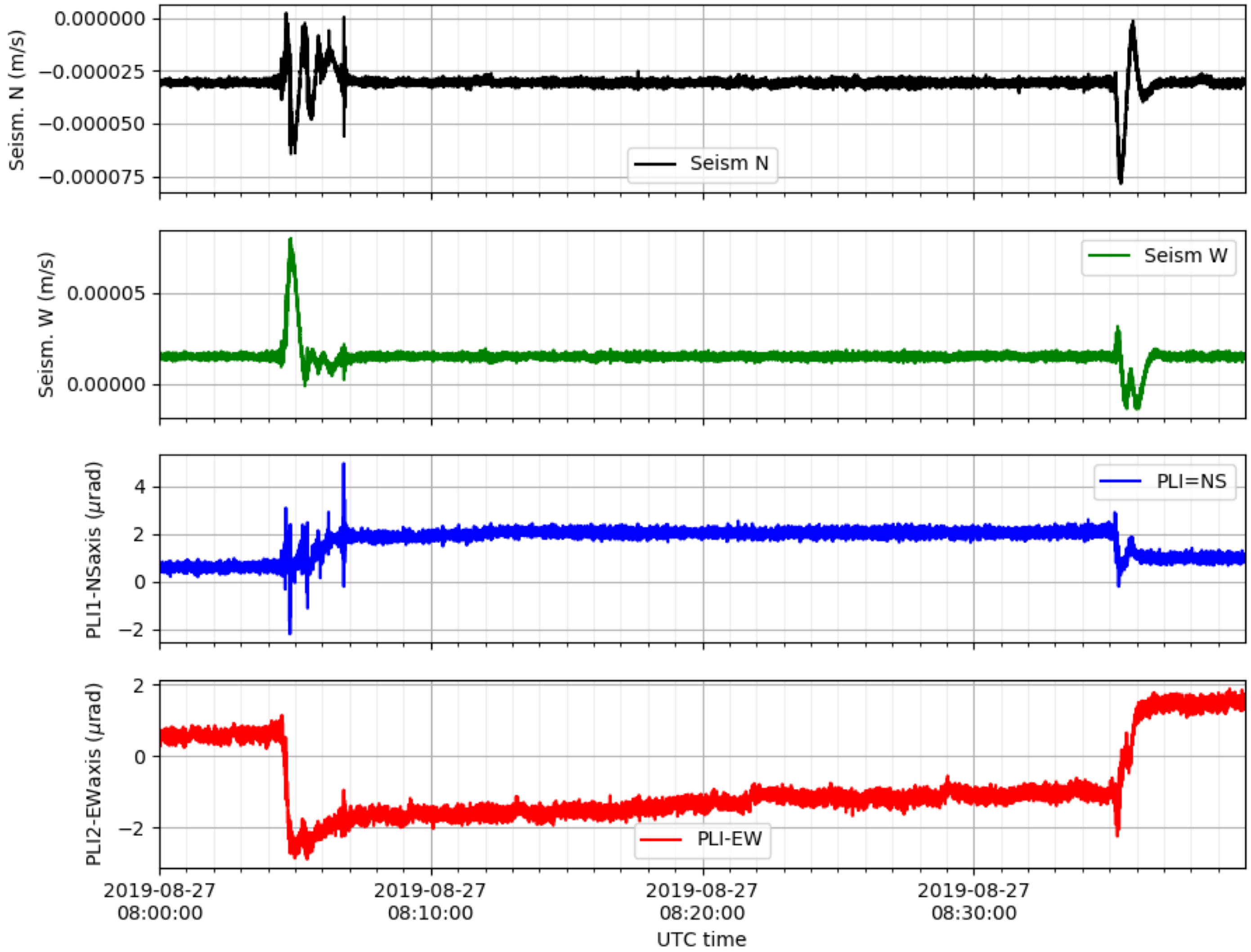
Observation
of a structure
in speed from
seismometer

~1.7 μrad offset
during ~ 30 minutes
around 08:56 CEST

~2.6 μrad offset
during ~ 30 minutes
Back to ~ 0.6 mrad
At 09:37 CEST

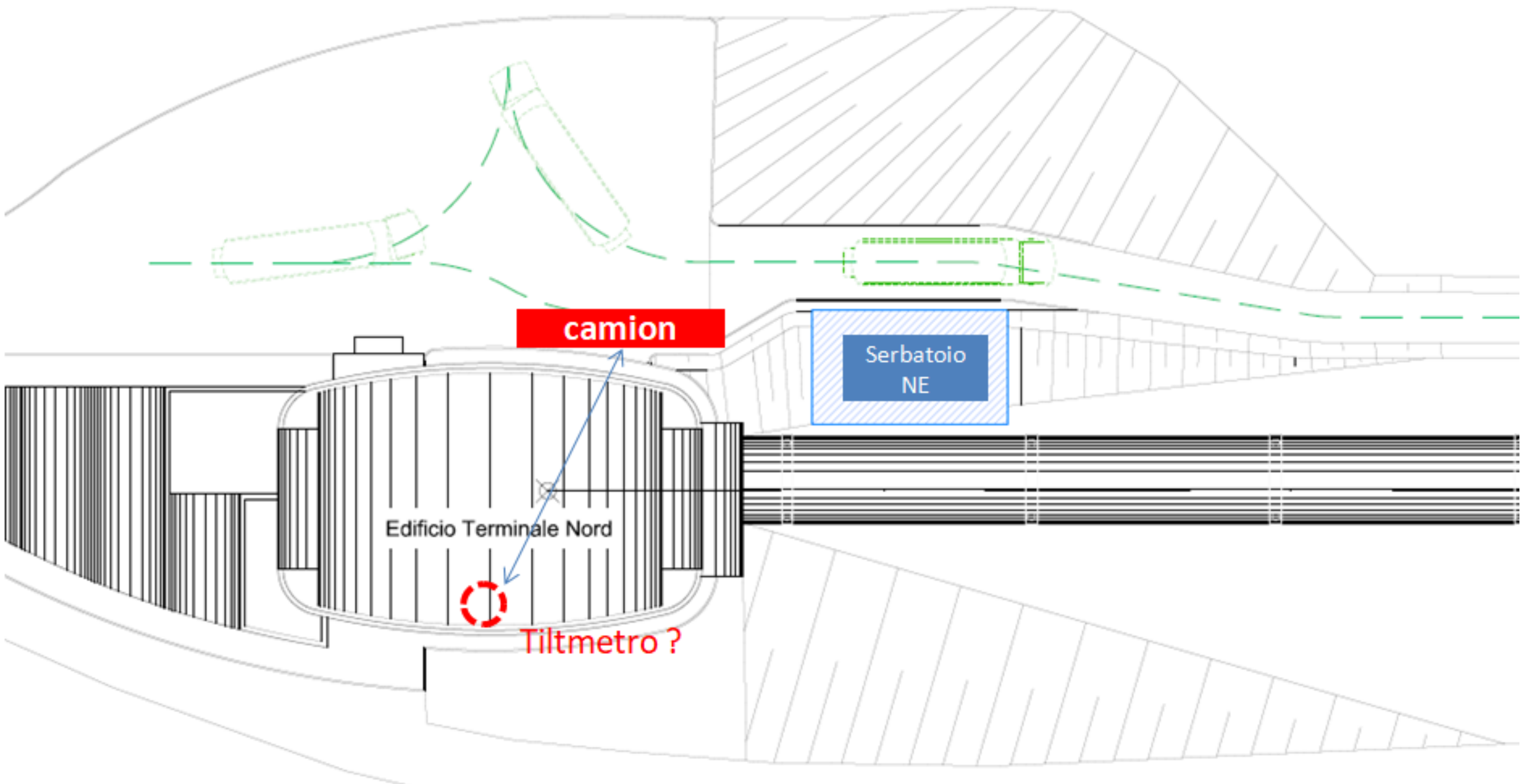
Funny effects: 27 August

Every Tuesday for 30 minutes a strange effect



Observation of the same phenomena

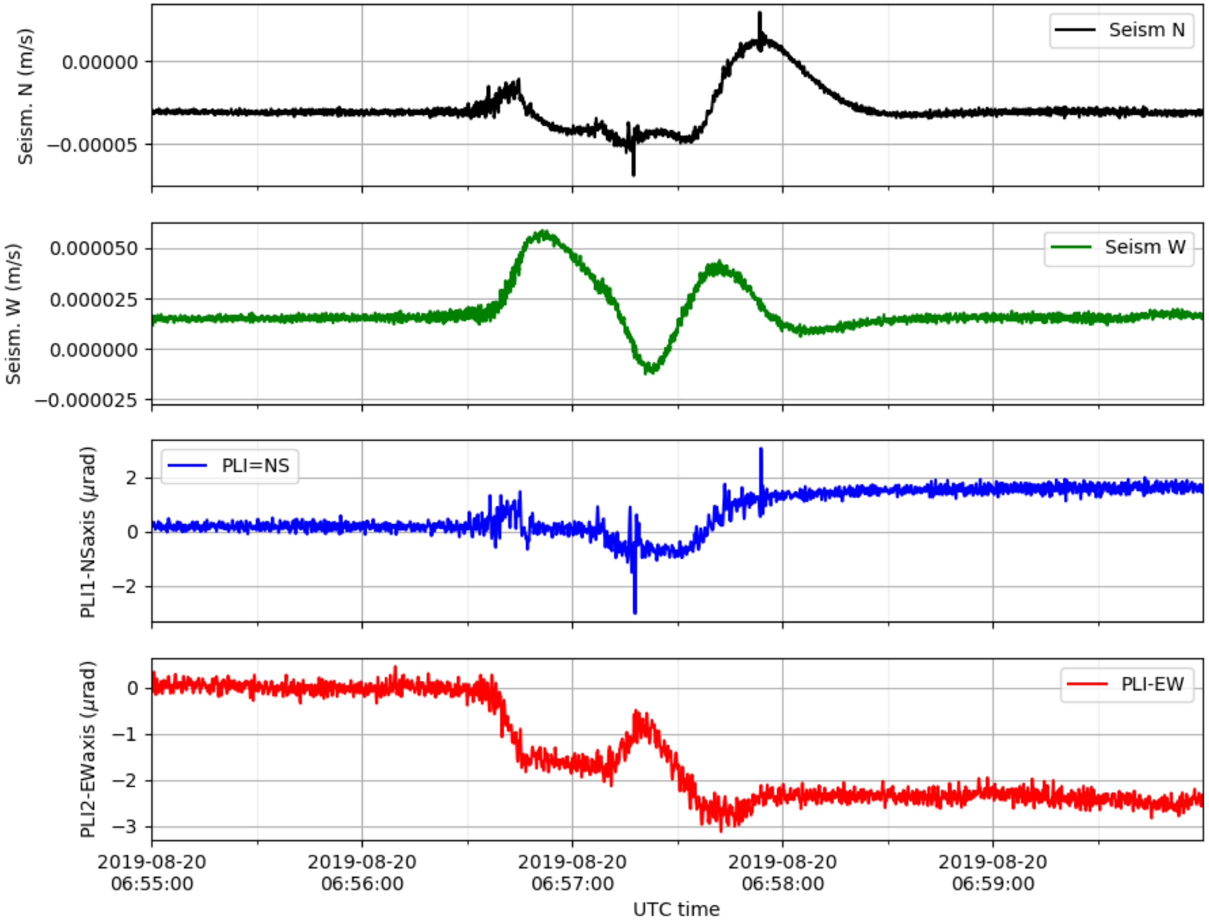
More maneuvering back and forth?

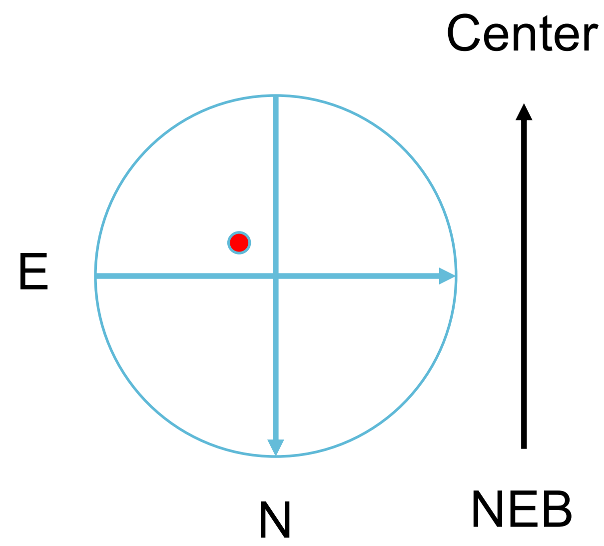


Nitrogen filling
Credit: A. Pasqualetti (picture), F. Ricci (hint)

Funny effects: start of it

Presence of a structure with different inclinations



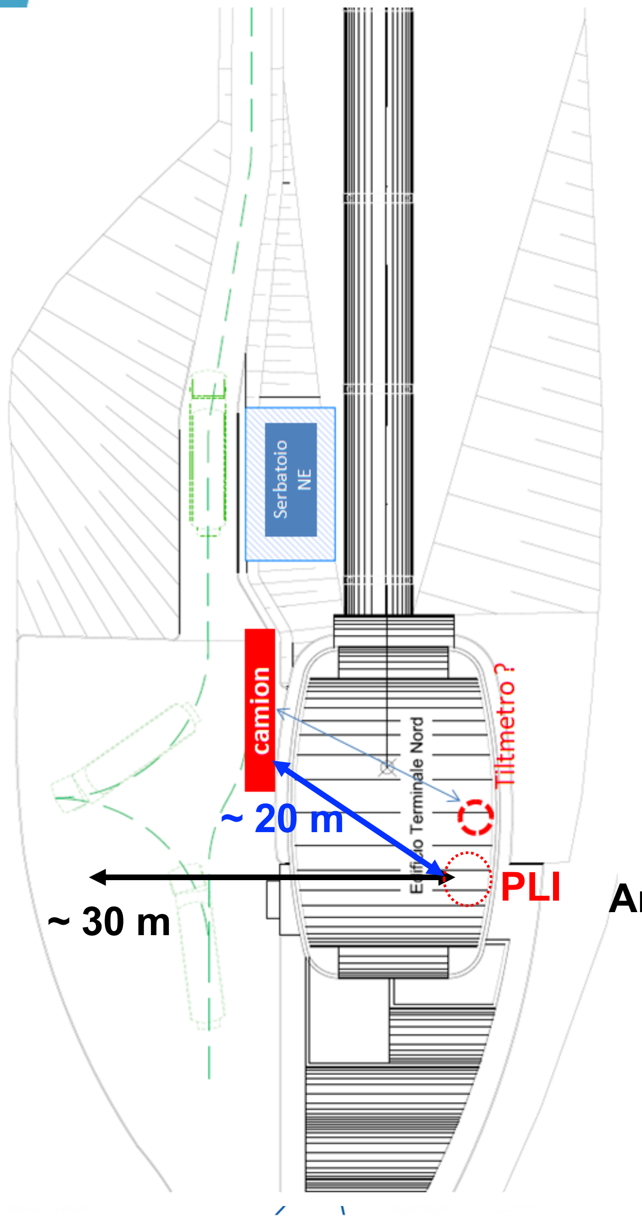


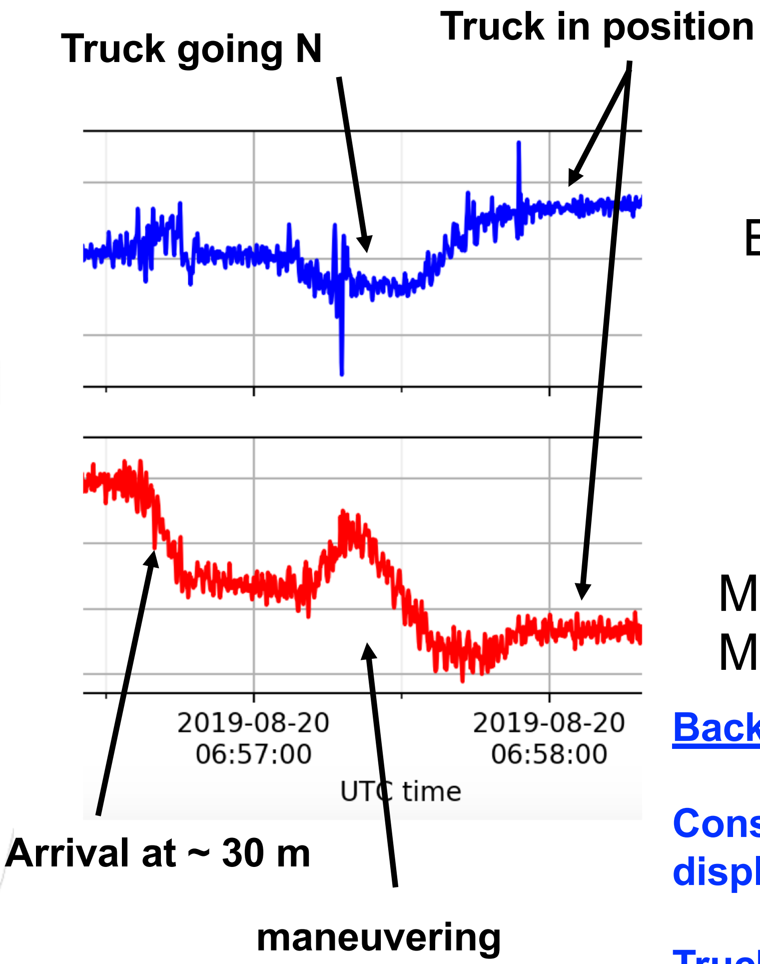
Max 1.7 μrad offset S
Max 2.6 μrad offset E

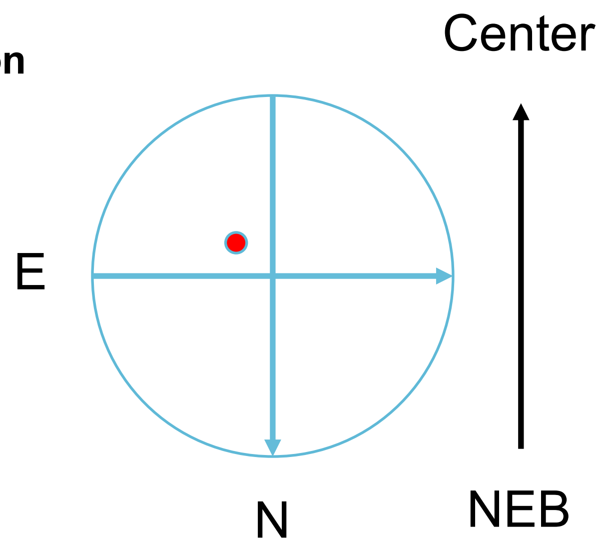
Max ~ 3.1 μrad in top left quadrant

Funny effects: the LN_2 tank truck

Presence of a structure with different inclinations at arrival







Max 1.7 μrad offset S
Max 2.6 μrad offset E

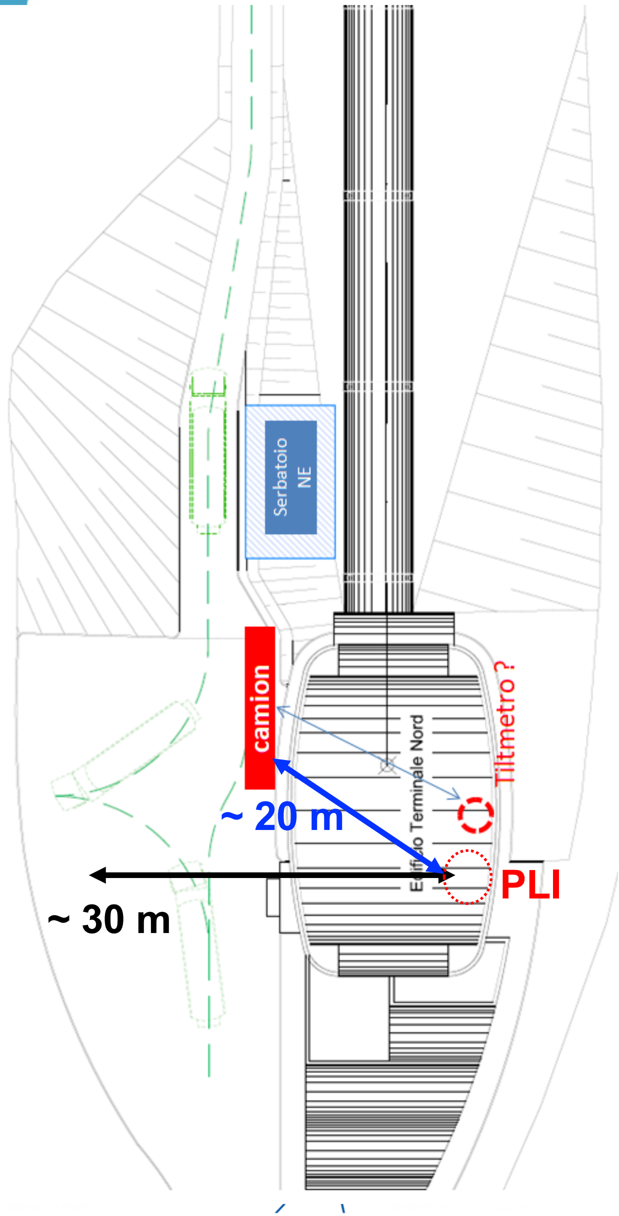
Back of the envelop calculation

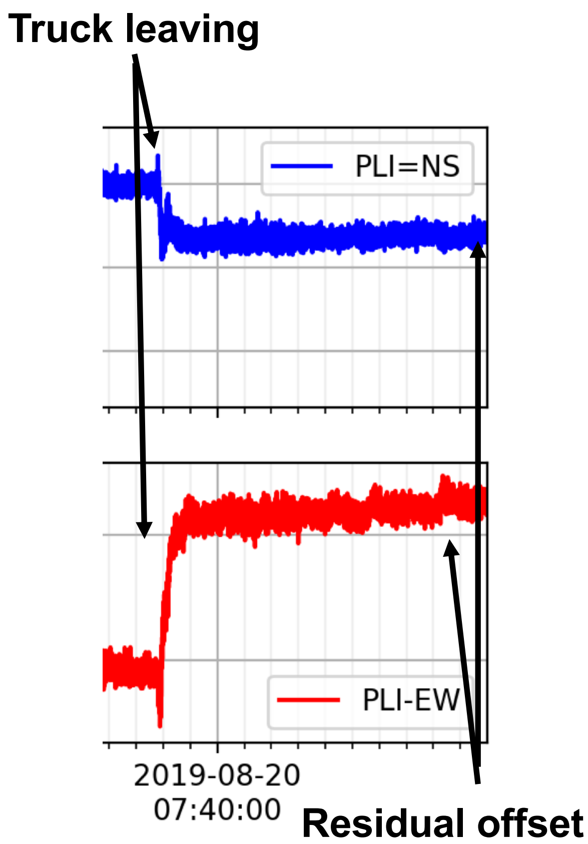
Consistent ~ 60 μm vertical displacement measurement

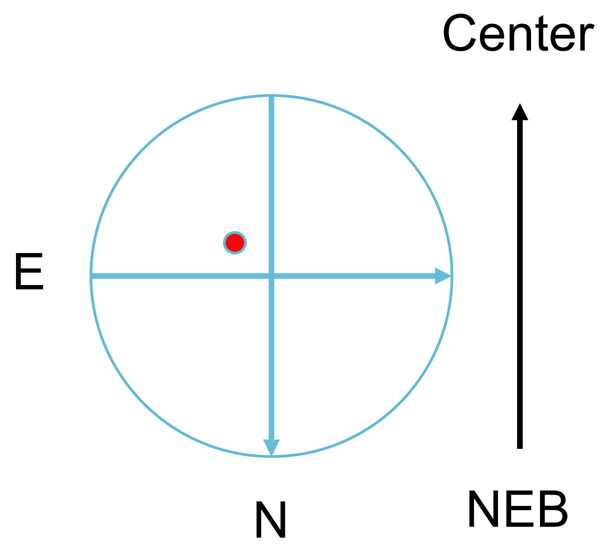
Truck probably ~ 30 tons

Funny effects: the LN_2 tank truck

Presence of a structure with different inclinations at arrival







Max 1.7 μrad offset S
Max 2.6 μrad offset E

Back of the envelop calculation

Residual vert displacement due to tank filled?

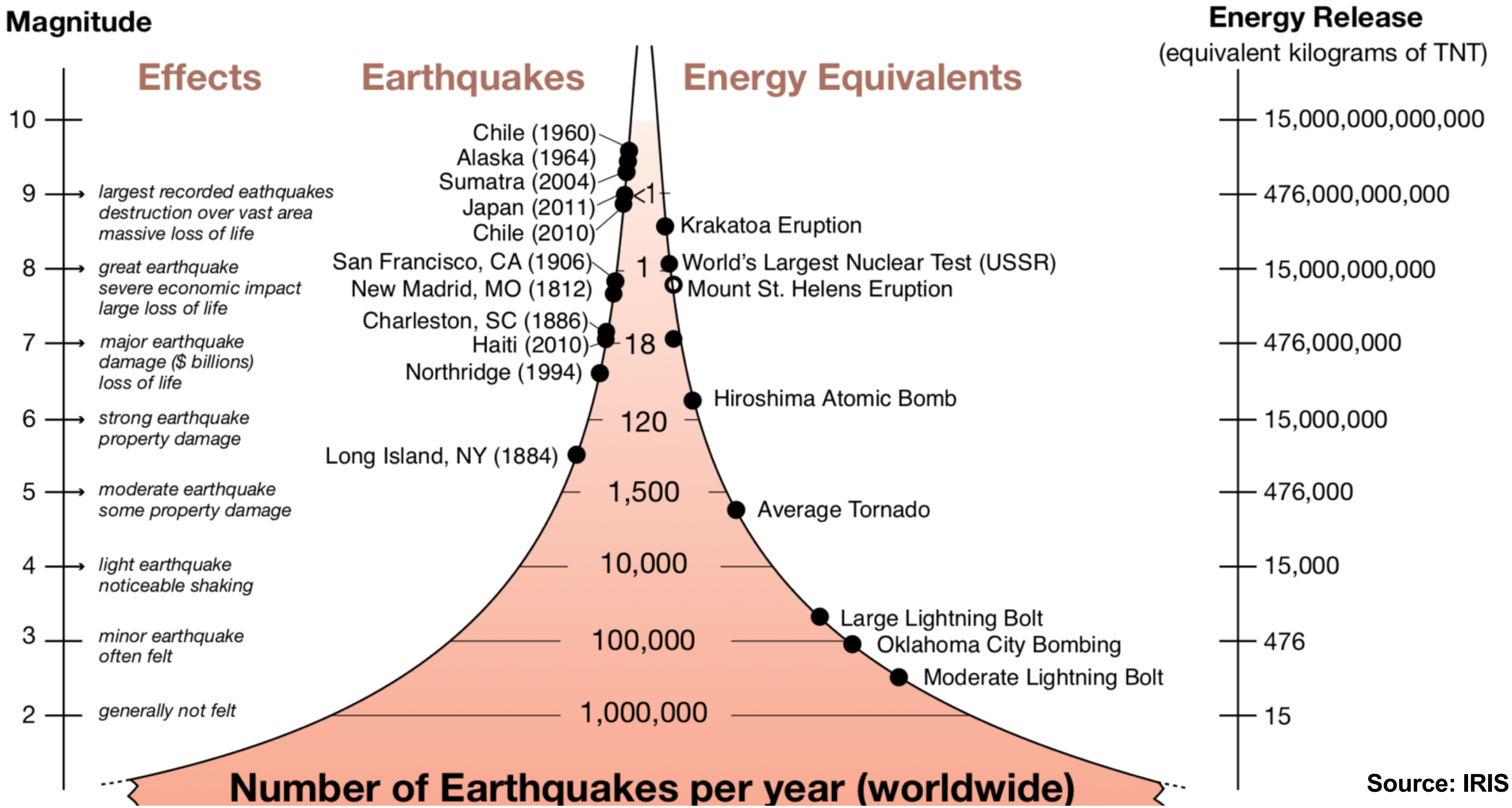
VERY PRELIMINARY

Experience in Virgo: summary

- We are happy that the instrument was setup in four hours and after few minutes was able to take data
  - Immediate clear coherence with suspensions sensors at micro-seismic peak
- We do not have perfect coherence at low frequency
  - Exploring if that is due to position of PLI on a different floor, far from the tower
  - Installation of the second PLI next to the tower
- Dream: installing the PLI in the vacuum volume and on the suspension

Before drawing conclusions:

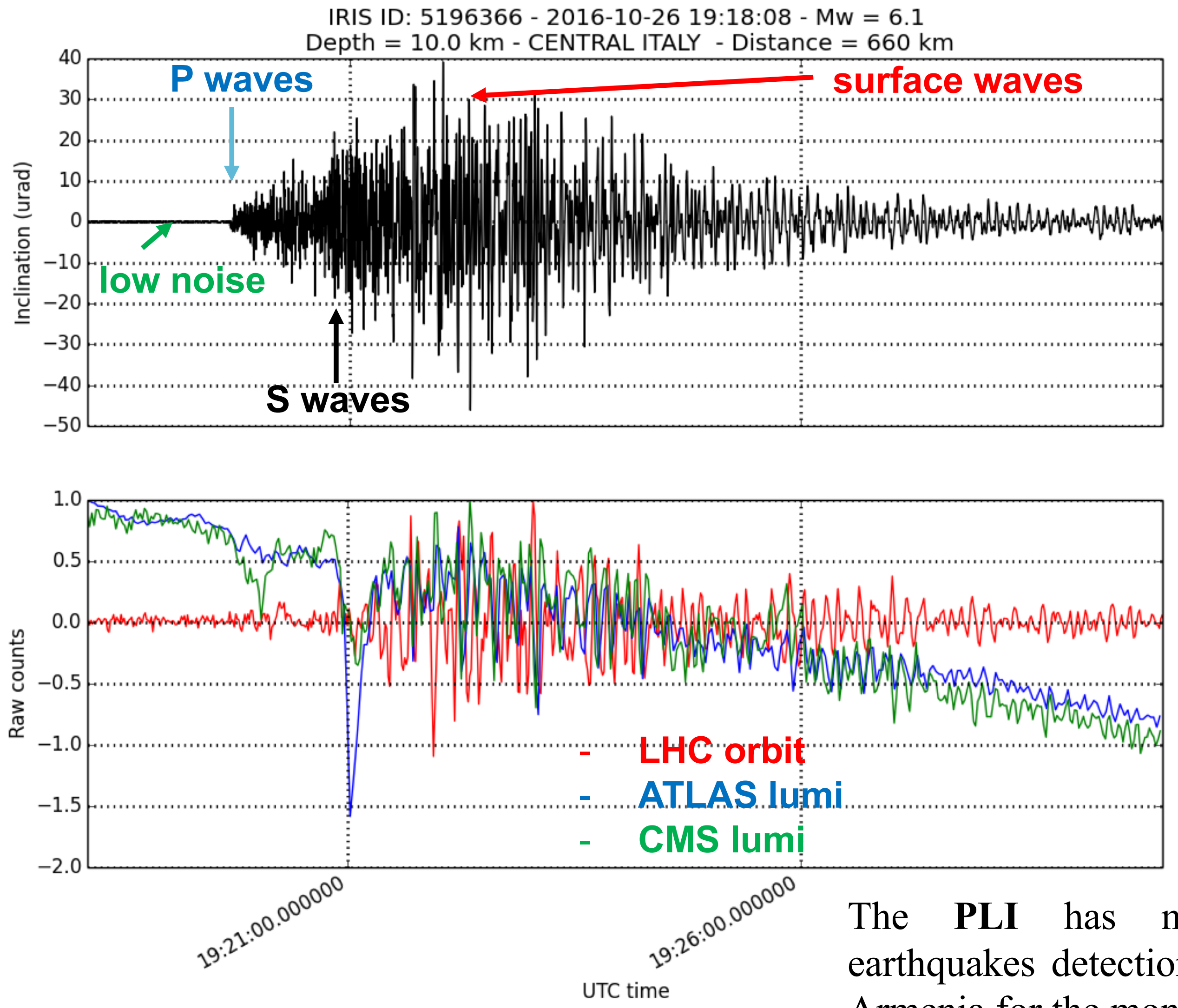
brief discussion of EEW research and how this is also relevant for Virgo and the dream



Earthquakes are always happening somewhere.

Magnitude 2 and smaller earthquakes occur several hundred times a day world wide. Major earthquakes, greater than magnitude 7, happen more than once per month. "Great earthquakes", magnitude 8 and higher, occur about once a year.

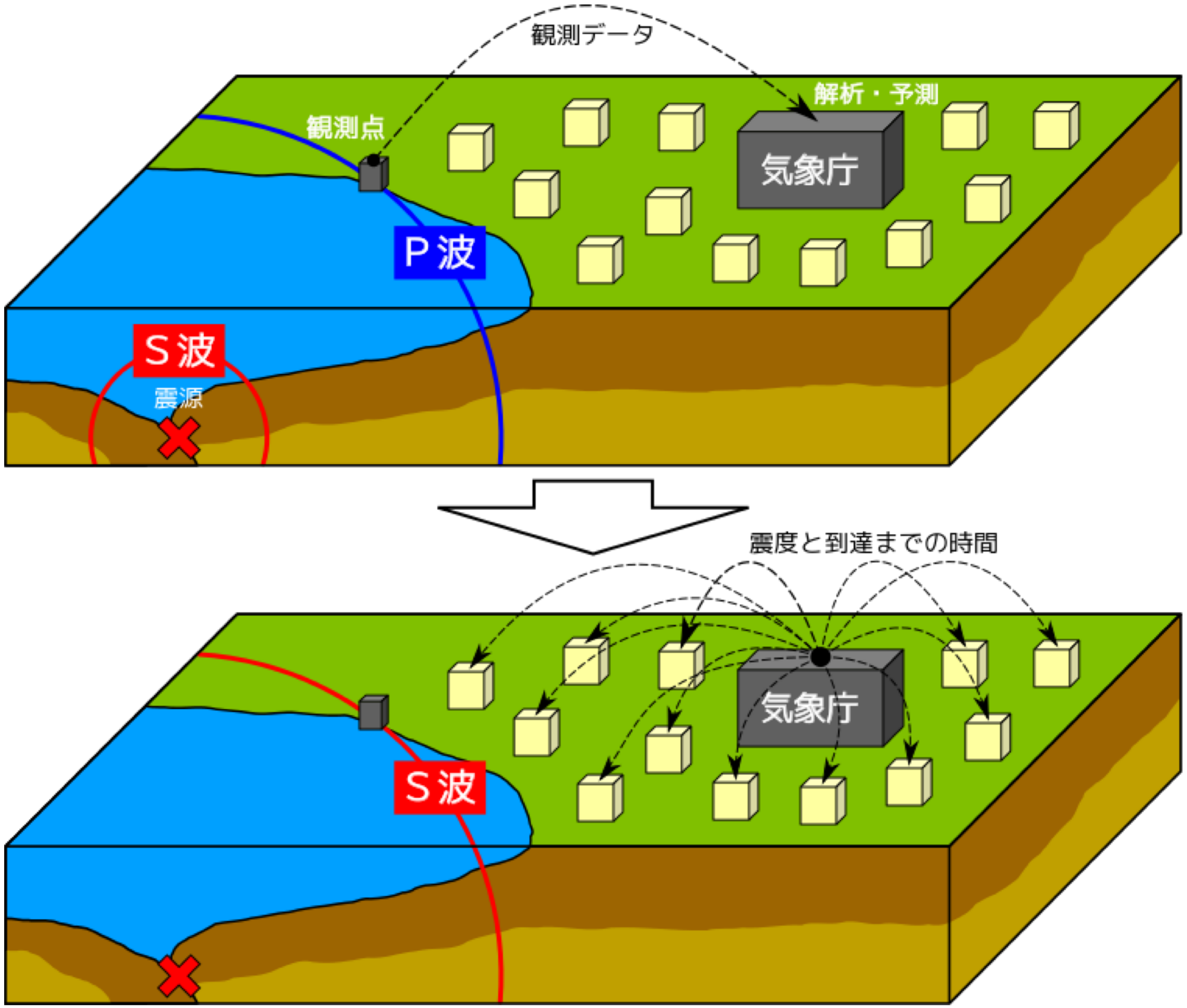
FAST EARTHQUAKES WARNING: single and multiple devices



The arrival of P waves allows to warn for the arrival of much stronger **S** and **surface waves**. The warning time depends on the distance from the epicenter. In Japan the majority of the earthquakes are originated in the sea, therefore it is possible to have from few seconds to minutes warning. Elsewhere most of the earthquakes are originated in populated areas, therefore any possibility of warning has to rely on extremely **low noise** and **high sensitivity** devices… like the **PLI**.

The **PLI** has multiple possible applications: earthquakes detection and warning (it is deployed in Armenia for the monitoring of seismic activity), active feedback for the stabilization of very sensitive devices, site protection, human activity detection, anomalies of Sun-Moon cycles and many others still to discover…

Japan Earthquakes early warning



Earthquake Early Warning in Japan: When two or more seismometers[1] detect P-waves (top image), the JMA immediately analyzes the readings and distributes the warning information to advanced users such as broadcasting stations and mobile phone companies, before the arrival of S-waves (bottom image).

Alerting system based on observations

- Prediction of earthquakes is probably impossible
  - The list of “precursors” is long and there is not a magic one, but rather the use of multiple indicators (electromagnetic effects, recent seismic activities, gas emissions, etc.)
- A network of PLIs can monitor a large geographical area: LHC ring or a specific seismically active area
  - As an example in Armenia there are 3-4 earthquakes/day, around active volcanic areas smaller earthquakes can be precursors of eruption (Vesuvius and Pozzuoli area, Etna)

Latest development for EEW systems: prompt gravity signals

- We started evaluating the capabilities of the PLI to detect prompt gravity signals
  - All started reading the article: Vallée, M et al. (2017) Observations and modeling of the elastogravity signals preceding direct seismic waves. Science 358:1164-1168. doi: 10.1126/science.aao0746
  - Looking at Tohoku Mw = 9.1 Earthquake in 2011, the authors managed to reconstruct prompt elasto-gravity signals travelling at speed of light, $3\ 10^5$ km/s to be compared with fast p-waves travelling at ~ 10 km/s
  - The signals from broadband seismometers have been compared to templates from modeling, showing that for smaller magnitude the instruments are not sensitive enough. The comparison with templates allow fast and precise magnitude evaluation
  - Several articles followed: for lower magnitude detection aim at 10^{-15} $1/\sqrt{Hz}$

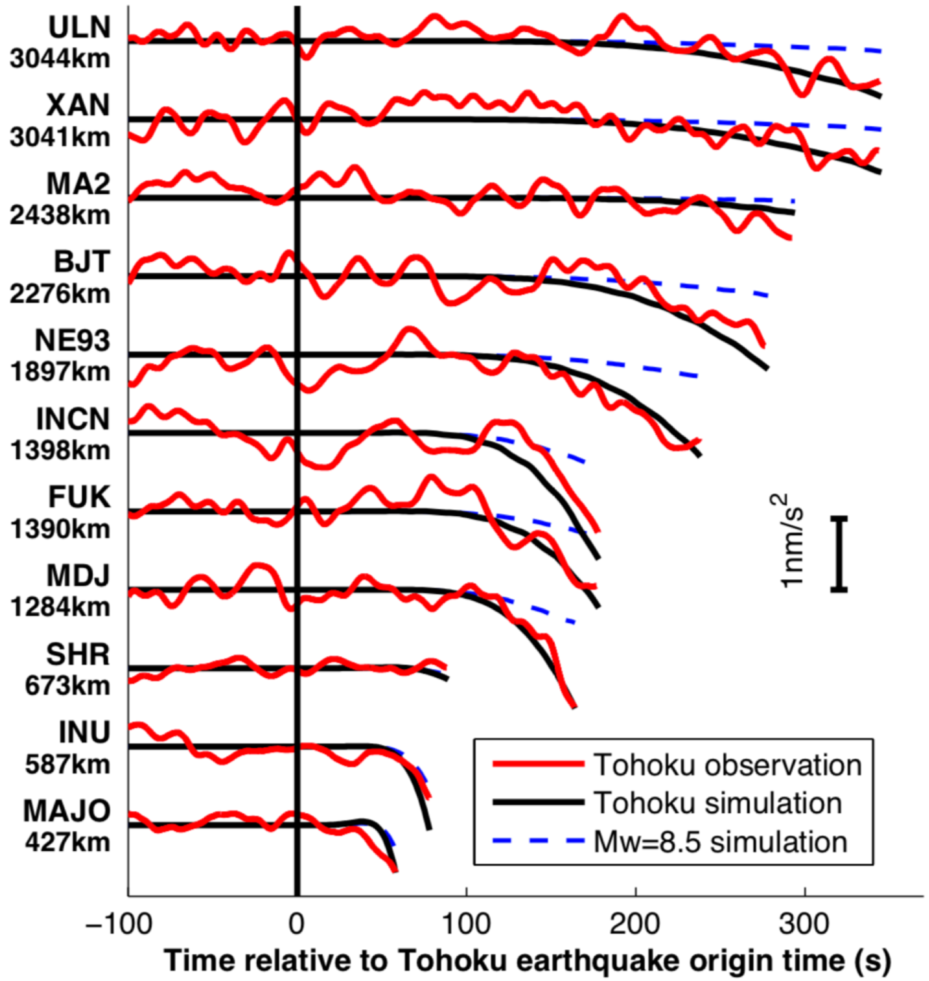


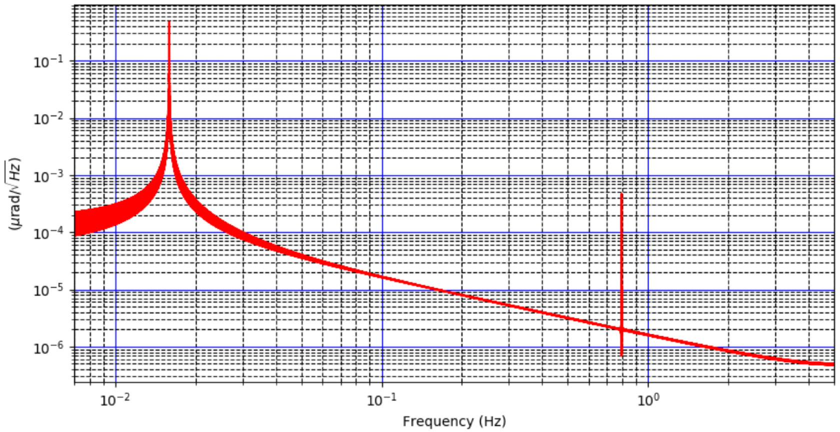
Figure 3: **Agreement between observed and modeled a_z^P signals, and influence of the earthquake magnitude**. Red (observed) and black (simulated) curves are in good agreement at all distances and azimuths from the Tohoku earthquake. The simulation for a fictitious $M_w = 8.5$ earthquake (dashed blue curve) shows large amplitude differences, directly illustrating the magnitude determination potential existing in these prompt elasto–gravity signals.

EEW with PLI

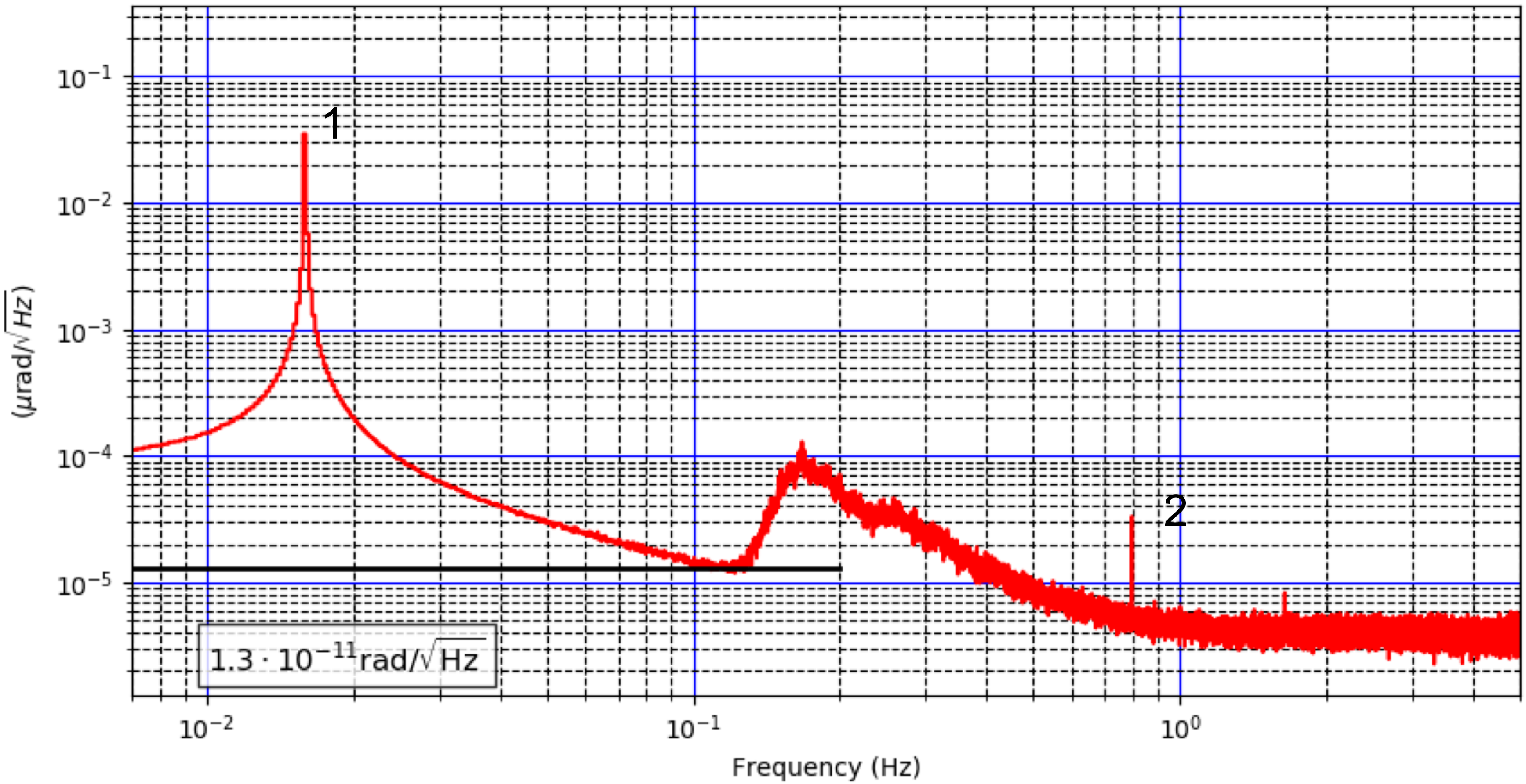
- We are investigating better our limits and trying to identify possible signals in the modest dataset we have for high magnitude Earthquakes (only 3 earthquake with Mw > 8 between 2015 and now)
- It needs a step further in sensitivity and in online detection capabilities possibly using machine learning and artificial neural networks

Further observations on sensitivity

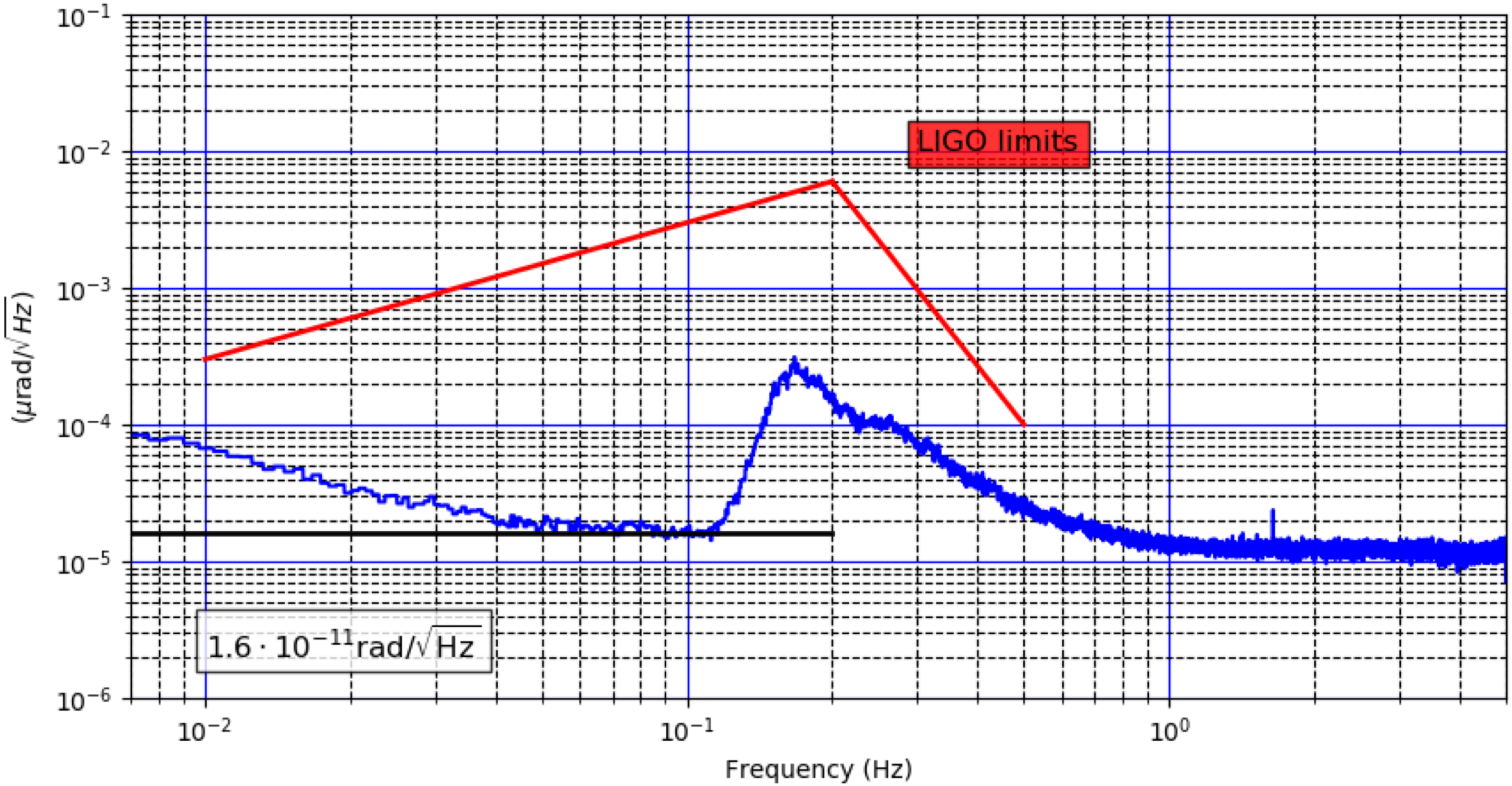
- A discussion is ongoing with Virgo colleagues on sensitivity and the normalization of DFT in frequency analysis
- To calibrate our normalization we summed the PLI signal over 24 hours to two known sinus in the same frequency range and with amplitude 10^{-6} and 10^{-9} at higher frequency



PLI sensitivity + known sinus



Result on sensitivity: over 24 hours at CERN



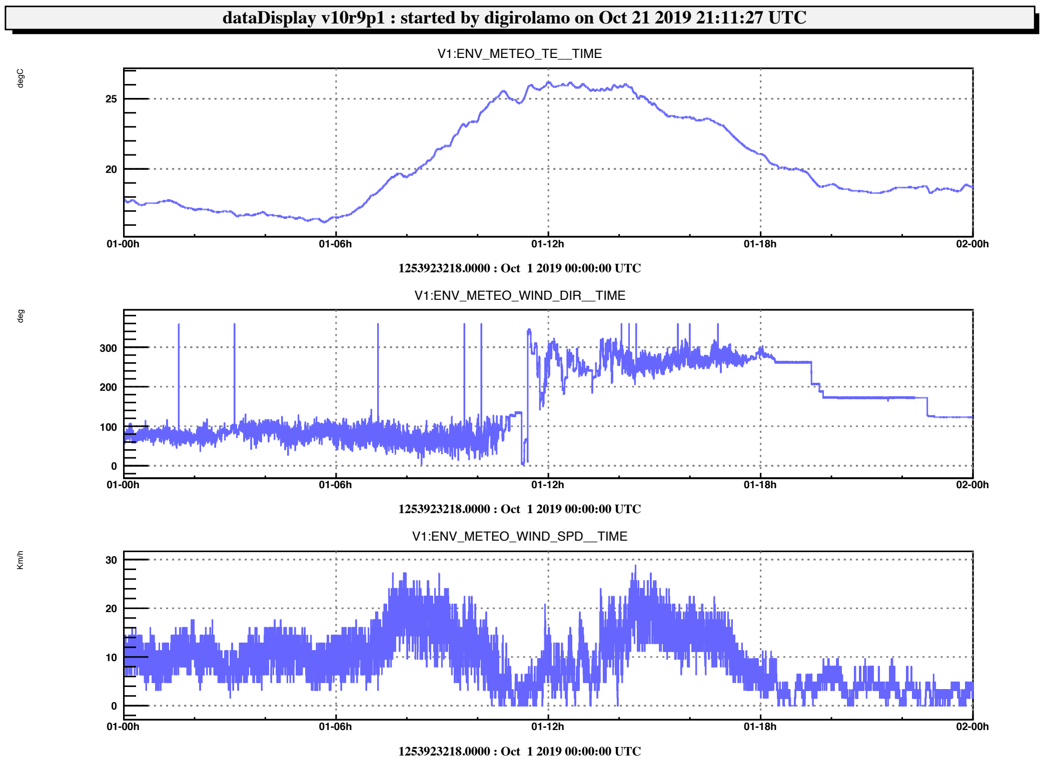
Virgo site is more "noisy"

- External temperature variations are high even in October: the ground deforms
- The sea is very near
- There is wind almost every day

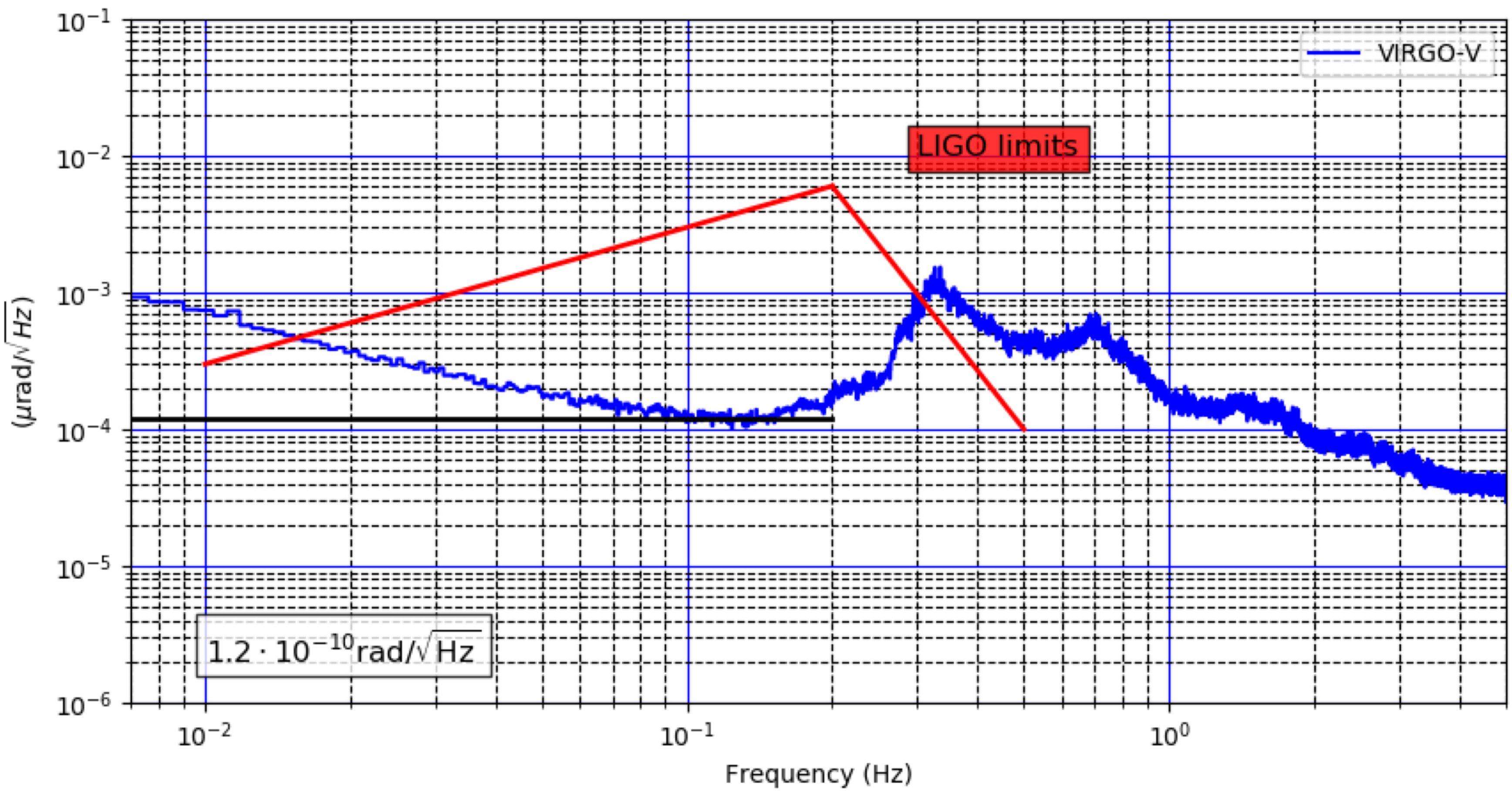
The PLI at CERN is located underground with a constant temperature within 0.1 C

We do see lake Geneva effects in windy days and of course the effect of seas and oceans, but nothing comparable to Tirreno at 15 km

There is no wind



Amplitude spectrum at Virgo

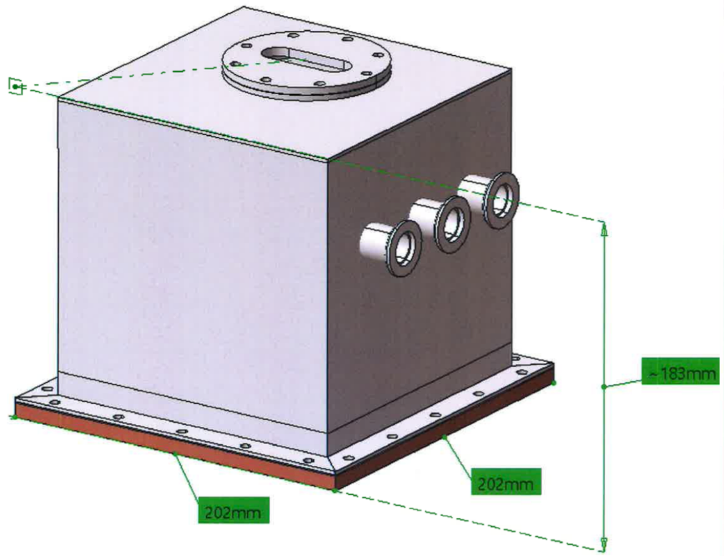


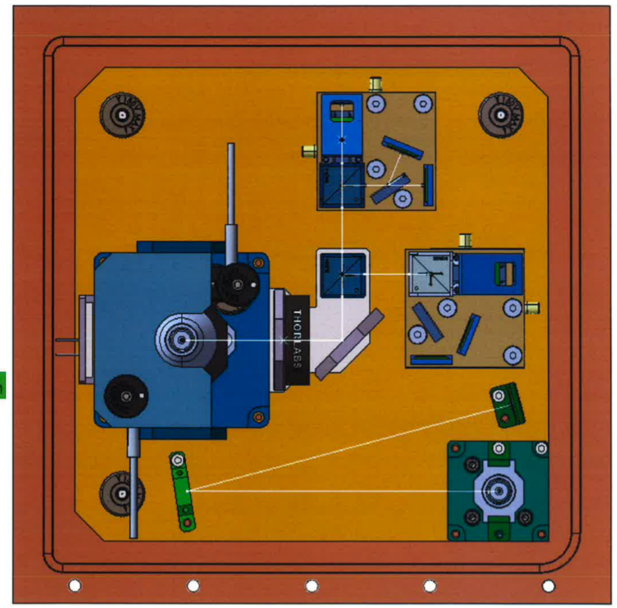
Next steps of our development

- Aiming at improving sensitivity for Virgo-like applications and for earthquake early warning systems
- Improve readout electronics to reduce number of readout channels (now 8 ADC channels) by doing on-board combination
- Reduce the size of the instrument
- The idea of CompactPLI is born, pending publication and patenting just few information here

The Compact PLI: two units being built now

- The new version is clearly more compact
- It makes use of a different approach to position sensitive detection that allows to decrease lenses focal length and beam spot diameter. Expected 1.4-1.6 times better sensitivity





Custom electronics for signal combination: better interfacing to standard DAQ systems and low consumption. Limits in frequency range to be studied: preference to enhance signal

Future developments

- Two main developments:
  - Usage in array of multiple devices for Newtonian Noise studies
  - Production of the compact device (sort of cube with edges length ~ 15-20 cm) aiming at possible deployment in Virgo vacuum volume and for a variety of studies (EEW)
- At CERN
  - PLIs will be deployed in LHC tunnel around CMS and ALICE
  - Studies for e+-e- colliders continuing
- Calibration measurements:
  - On top of on-board inclination calibration also periodic translational acceleration calibration: setup proposed in Pisa by Boschi, Cella, Frasconi, Gennai, Passuello, Ruggi et al, the usual suspects
  - Additional optical measurements inspired by Virgo to separate rotational and translational components of the angle: measuring reflected beam on focal plane and on image plane

Conclusions

- The PLI started being operational at CERN in 2015
- The PLI has been installed at Adv Virgo North End Building in August 2019
  - Looked at classical and funny effects
    - Earthquakes and Wind comparisons with other sensors are very instructive
    - Nitrogen truck weight measurements (coherence with suspensions signals under study)
- Lines of research:
  - Seismic noise studies for Virgo
  - Luminosity stability at accelerators
  - Earthquake Early Warning systems
  - Ground stability monitoring (landslides in Greece, iceberg movements, site protection, etc.)

Thank you