High precision fiber interferometric interrogation of tiltmeters for applications in geophysics and in industry

Han Cheng SEAT

seat@laas.fr
H.Seat@aquitaine-electronique.fr

R. Briand
M. Cattoen, F. Lizion, O. Bernal

Consortium ANR LINES & FUI MIRZA

Summary

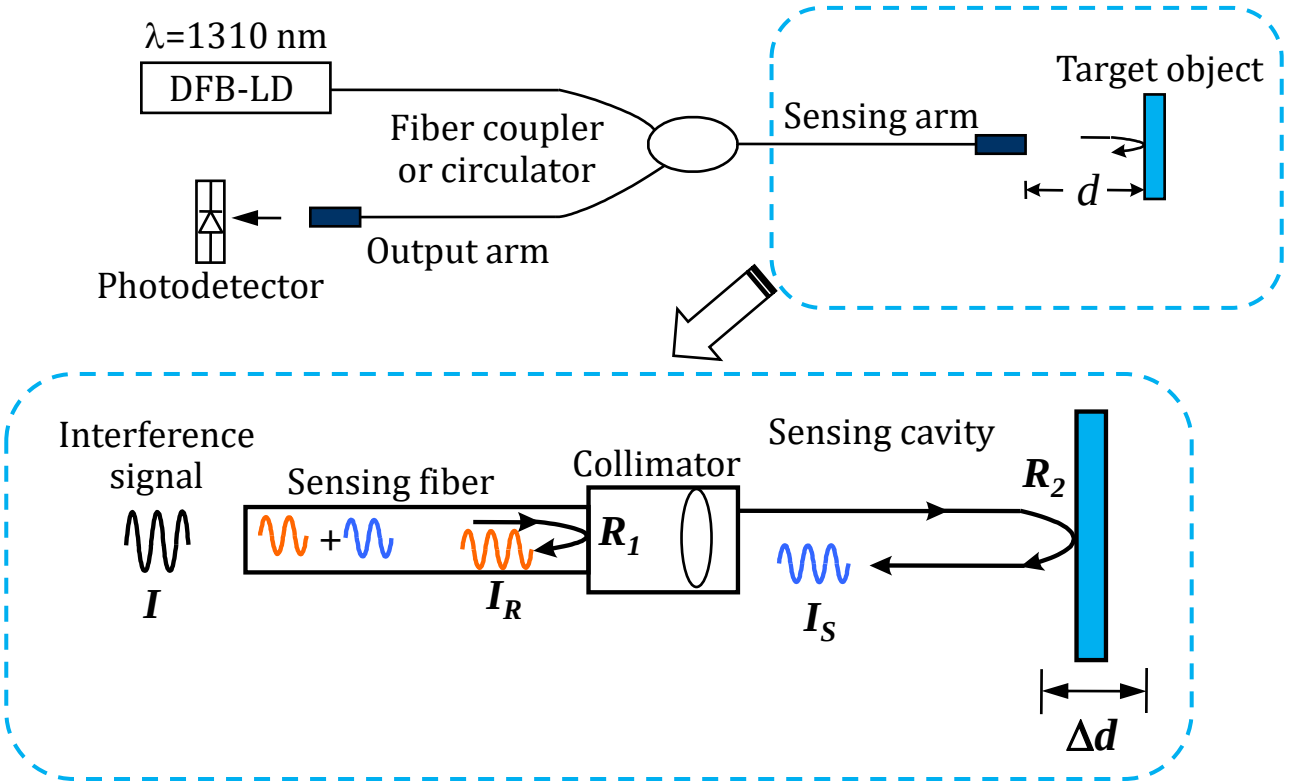
I. **Extrinsic fiber Fabry-Perot interferometer (EFFPI) development for displacement measurements**
   - Operating principles
   - Performance

II. **Fiber interferometric borehole tiltmeter (fiBT)**

III. **Fiber interferometric long-baseline hydrostatic leveling sensor (fiHLS)**

IV. **Conclusions & Perspectives**

I. EFFPI for displacements : Operating principles



$$I = I_R + I_S + 2\sqrt{I_R I_S}\cos(\Delta\theta) \quad \Rightarrow \quad V = V_0 + V_m \cos(\Delta\theta)$$

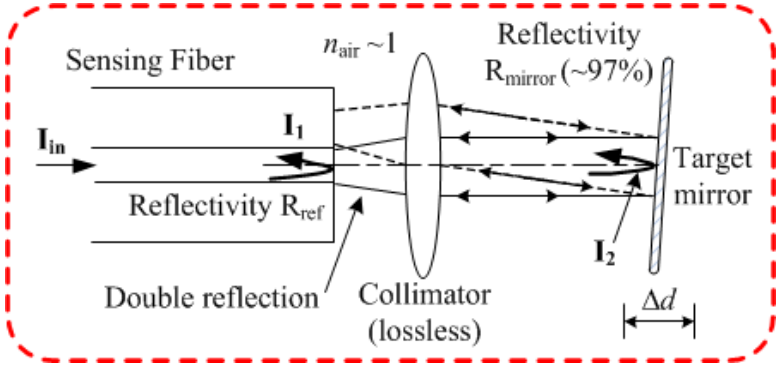
$$\Delta\theta = \frac{4p\pi n}{\lambda}\Delta d$$

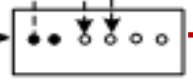
$\Delta\theta$ calculated modulo π ⇒ directional ambiguities

p = number of reflections

I. EFFPI for displacements : Operating principles

- **Experimental schematic**





DFB-LD + ISO

LD Driver + TEC

$f_1 + f_2$

Dual modulation circuit

Control in

Trigger

PD

1x2 FC

SF

C

T

$d + \Delta d$

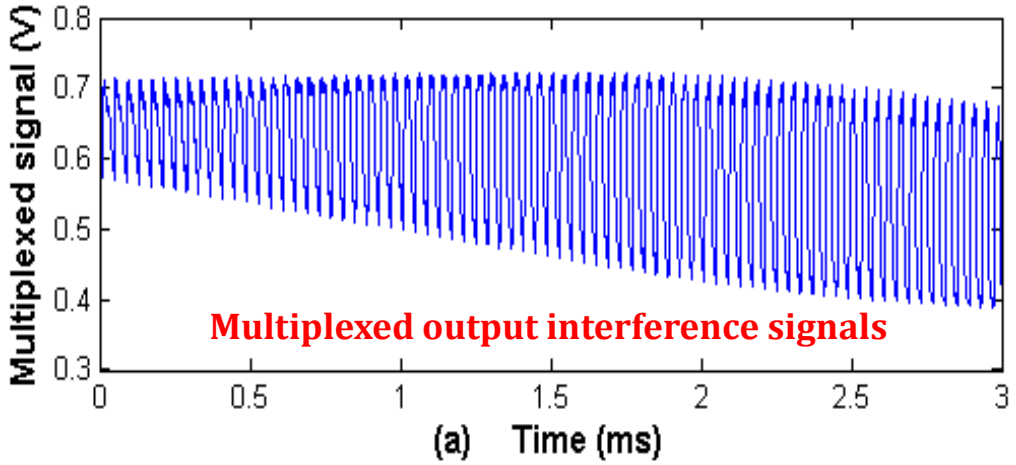
USB2

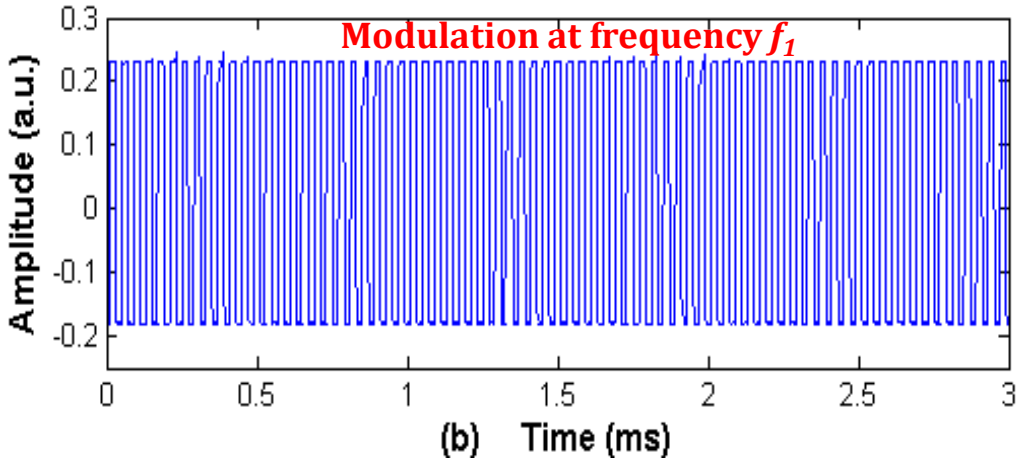
Quasi-realtime signal demodulation

DAQ Unit

I. EFFPI for displacements: Operating principles

- **Modulation scheme to obtain quadrature interference signals**





Quadrature

$$\Delta\theta = 4\pi nd\left(\frac{\Delta\lambda}{\lambda^2}\right) = \frac{\pi}{2}$$

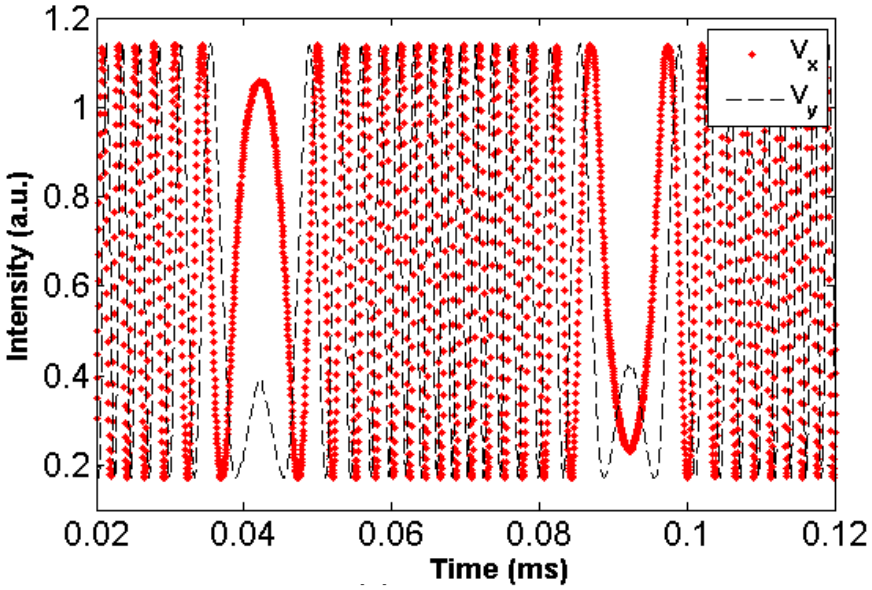
$$\boxed{\frac{\Delta\lambda}{\lambda^2} = \frac{1}{8nd}}$$ **Phase condition**

$$V_x = V_{0x} + V_{mx}\cos(\theta)$$ ***X*-component**

$$V_y = V_{0y} + V_{my}\sin(\theta)$$ ***Y*-component**

I. EFFPI for displacements: Operating principles

- **Generating quadrature interference signals ⇒ target direction**

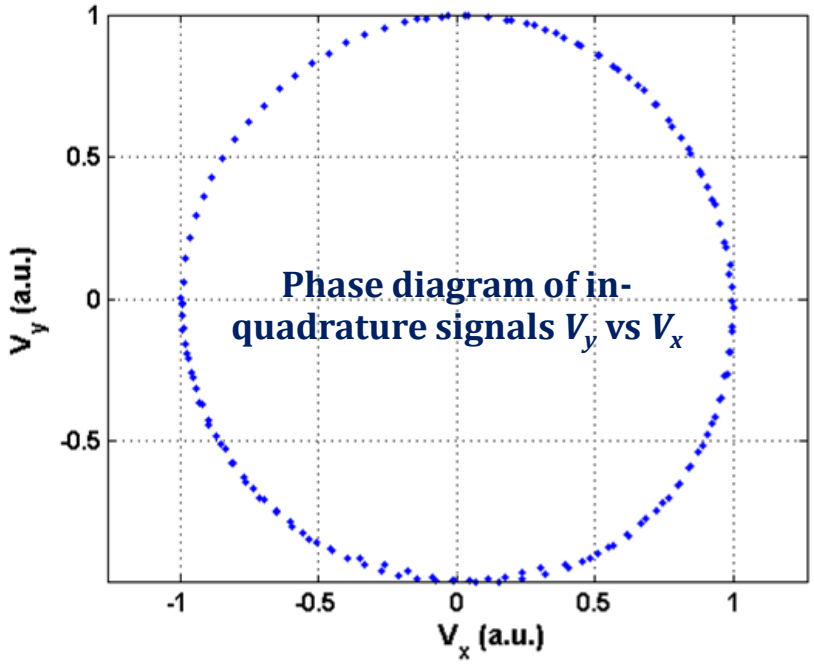


In-quadrature signals V_y and V_x for mobile target

$$V_x = V_{0x} + V_{mx}\cos(\theta)$$

$$V_y = V_{0y} + V_{my}\sin(\theta)$$

Quadrature condition



1 interference fringe ⇒ $\Delta d = \dfrac{\lambda}{4n}$

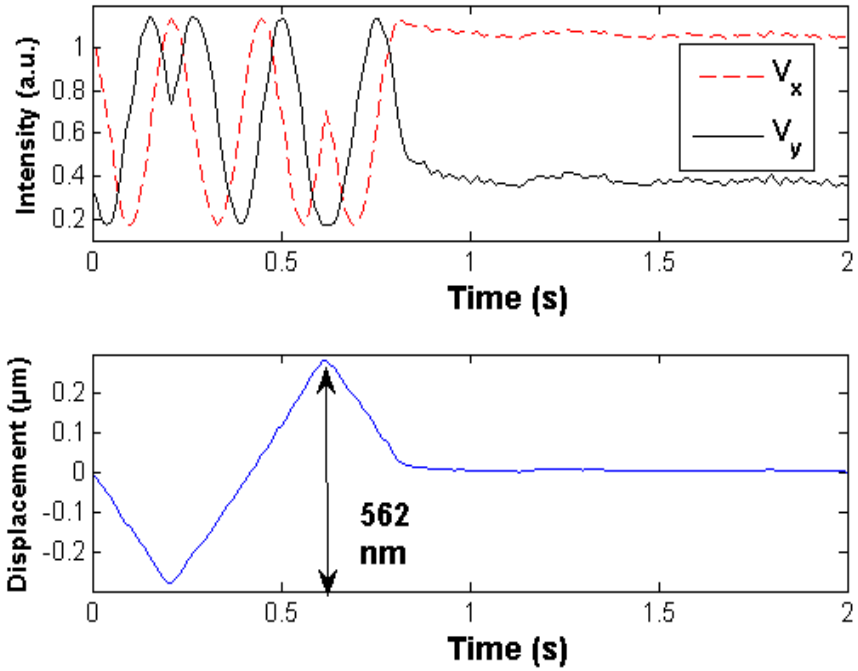
Modulation f_1 at 25 kHz & d ~25 mm

- $\Delta i(t)$ ~0.48 mA ⇒ $\Delta\lambda$ ~4.3 pm

I. EFFPI for displacements: Operating principles

- **"Reference displacement" ⇒ weak (< λ/4) and quasi-static displacement or stationary target**

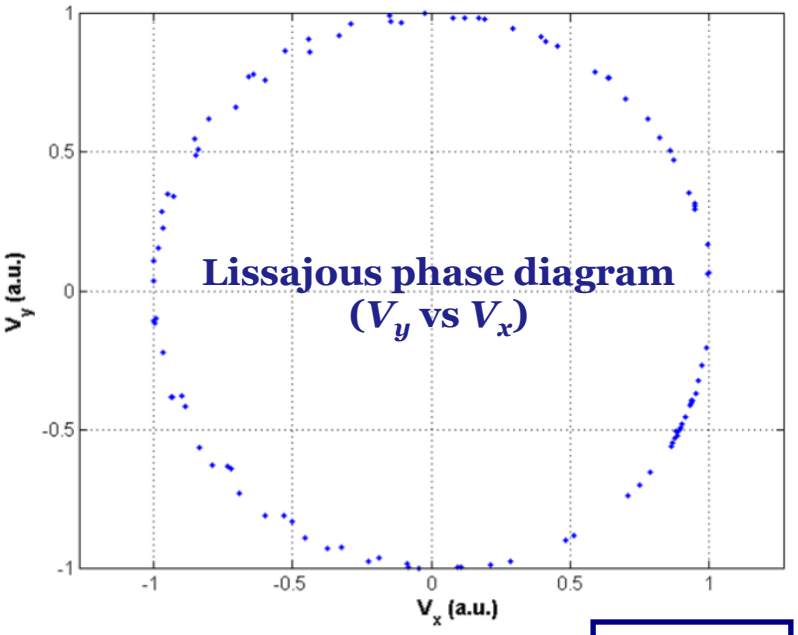
Demodulated V_y and V_x in quadrature



Phase condition

$$\frac{\Delta\lambda}{\lambda^2} \geq \frac{1}{2nd}$$

Reference displacement



1 interference fringe ⇒

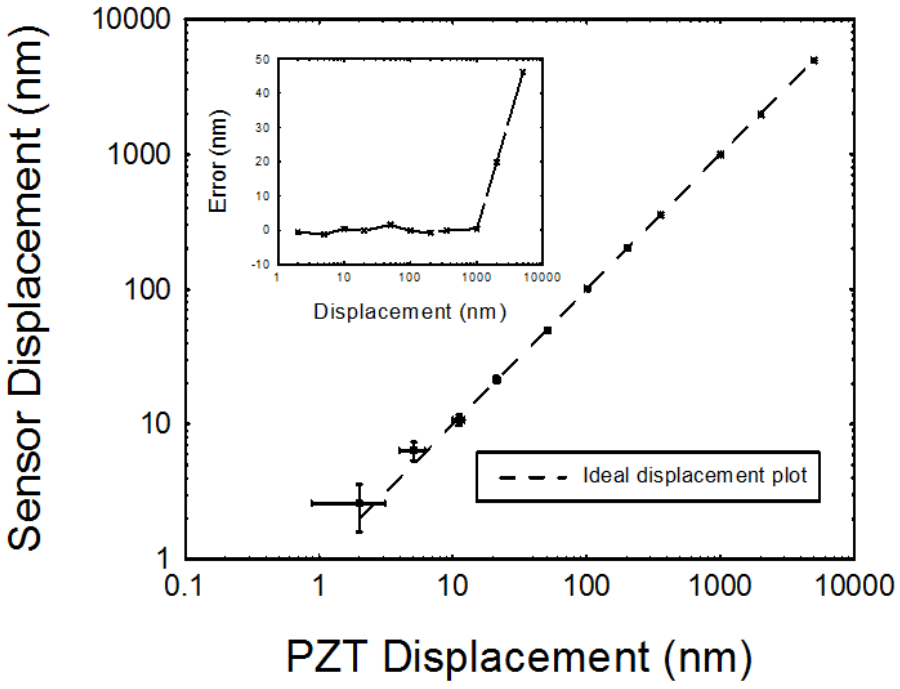
$$\Delta d = \frac{\lambda}{4n}$$

Modulation f_2 at ~1 Hz (d ~25 mm)

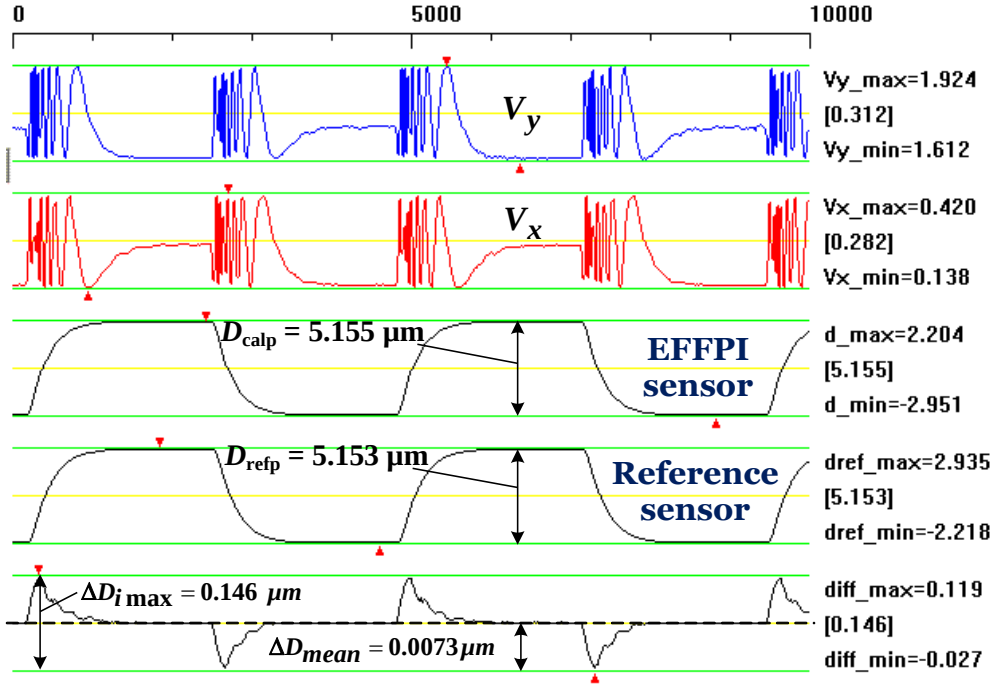
- $\Delta i(t)$ ~1.94 mA ⇒ $\Delta\lambda$ ~17.19 pm

I. EFFPI performance: static & dynamic displacements

- **Displacement calibration against reference piezo-electric transducer**



Step displacement against reference PZT



Dynamic displacement against PZT at 10 Hz

Quasi-static performance

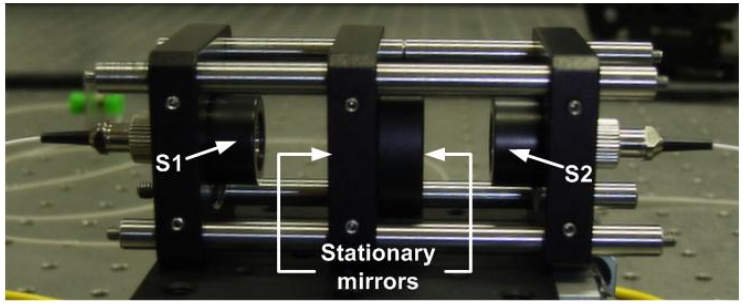
- range: 2 nm – >10 mm (limited by PZT linearity)
- precision < 1.5 nm (0.03%)
- max velocity ~4 mm/s

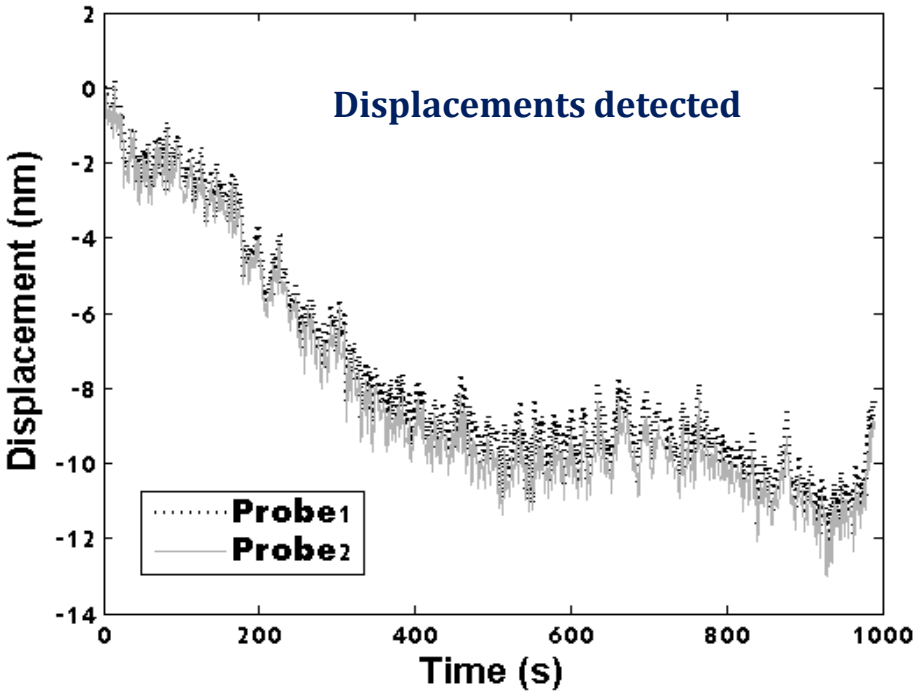
Dynamic performance

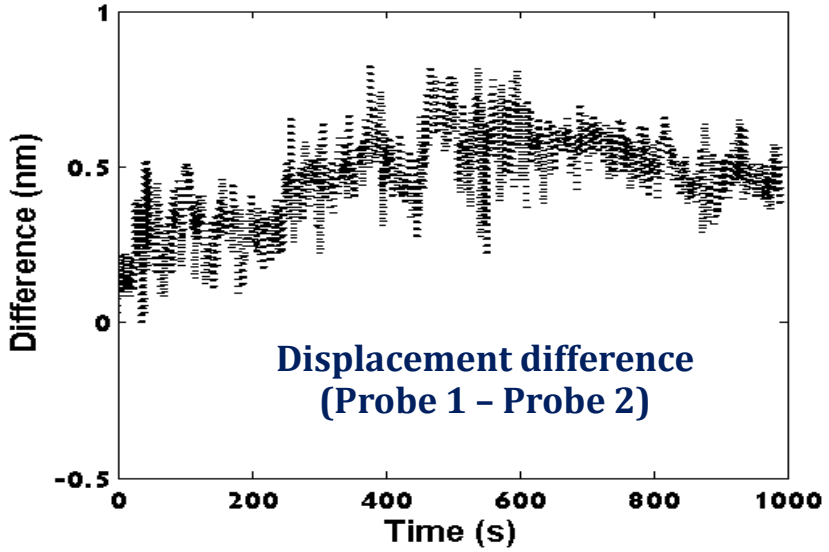
- EFFPI amplitude ~5.155 µm (c.f. 5.153 µm reference)
- difference ~2 nm (0.04%)
- bandwidth 10^{-3} – 500 Hz

I. EFFPI performance: drift & stability

- **Drift & stability characterization with differential probes**





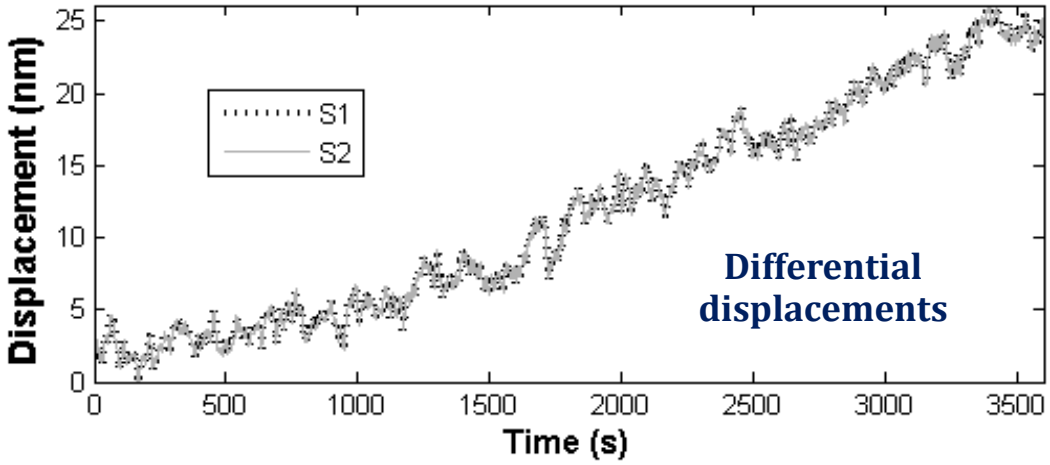


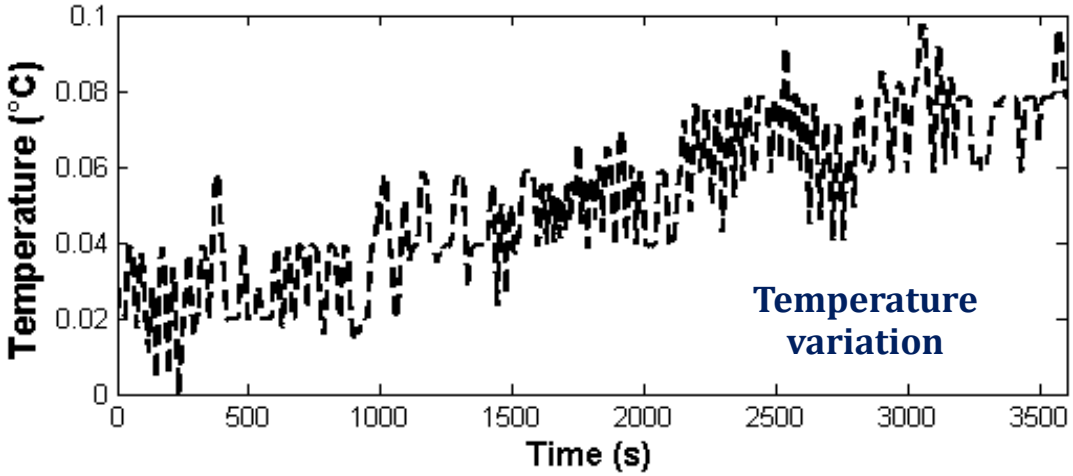
Differential sensor configuration

- Probe 1 and Probe 2 displacements ~14 nm
- 16.5 mins of data extracted at 1 kHz
- Difference
  - max: < 1 nm
  - min: ~0.15 nm
- Possible causes: external vibrations, temperature-induced perturbations, wavelength variations

I. EFFPI performance: temperature sensitivity

- **Temperature sensitivity: equivalent displacement**



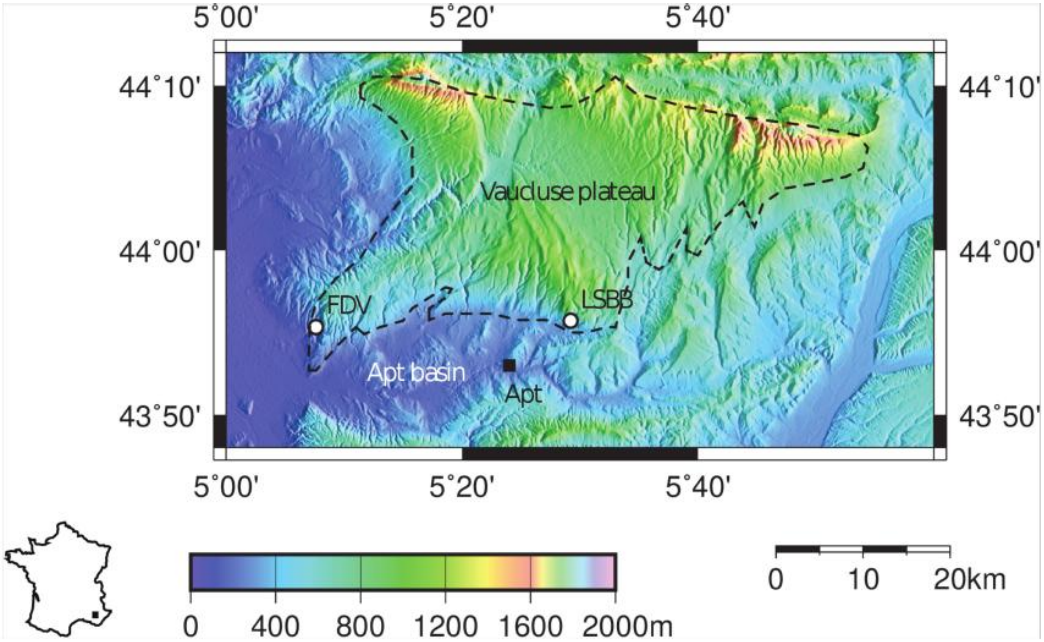


Differential configuration in controlled temperature chamber

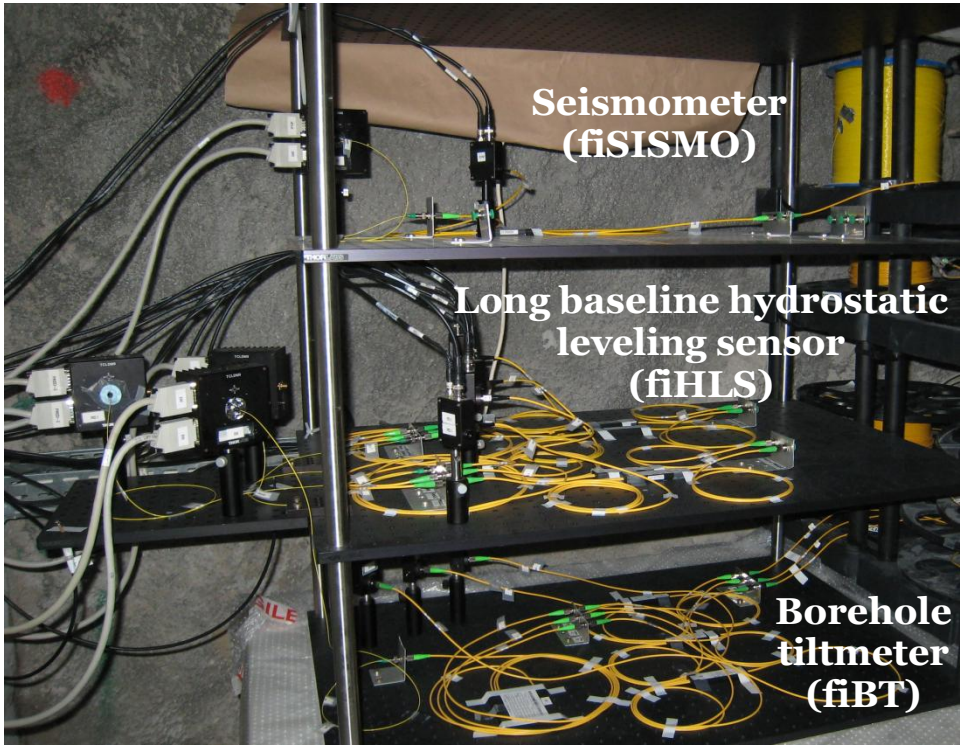
- relative temperature increase over ~1 hr period (~ 0.1 ° C)
- temperature variation by independent sensor (AD592 temperature sensor: 3.9 mV/° C)
- Probe1 & Probe2 displacements ~25.82 nm
- thermal expansion of steel cage system ~25.6 nm (stainless steel 410 ~10.5 µm/m/° C)

II. Applications in Geophysics: field deployment

- **Development & installation of 3 instruments at LSBB test site since Feb 2012**



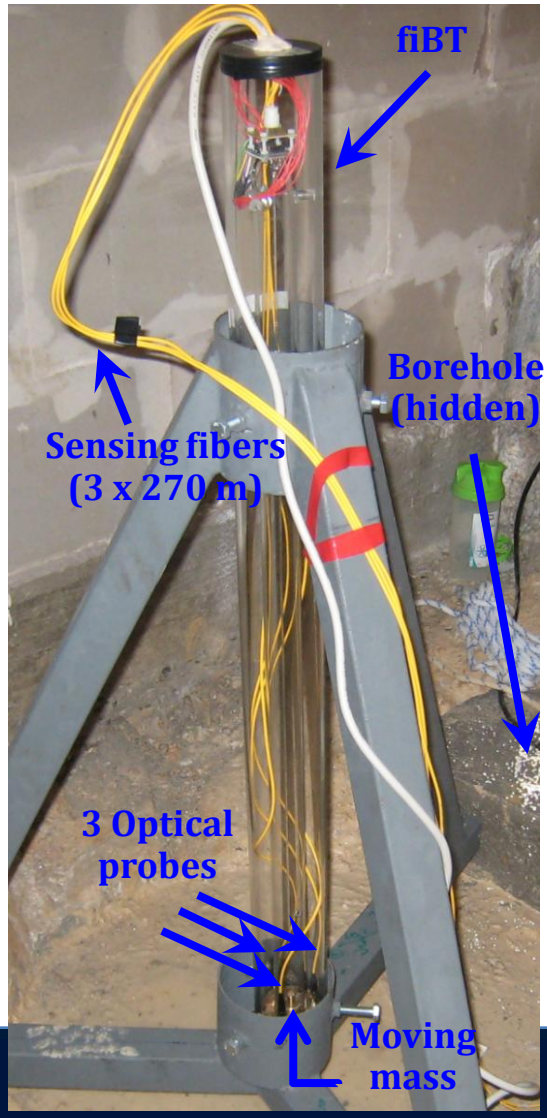
LSBB geo-location in the Vaucluse

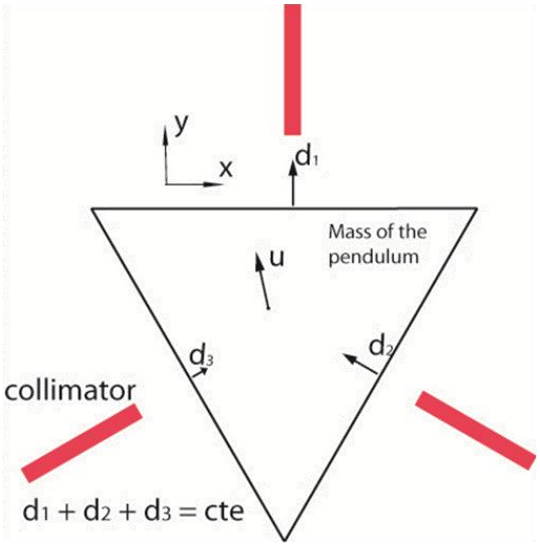


Components for seismometer (fiSISMO), bore-hole tiltmeter (fiBT) and long baseline hydrostatic levelling sensor (fiHLS)

II. Applications in Geophysics: fiBT

- **Fiber interferometric borehole tiltmeter (fiBT)**





Tri-axial measurement of displacements d_1, d_2 and d_3

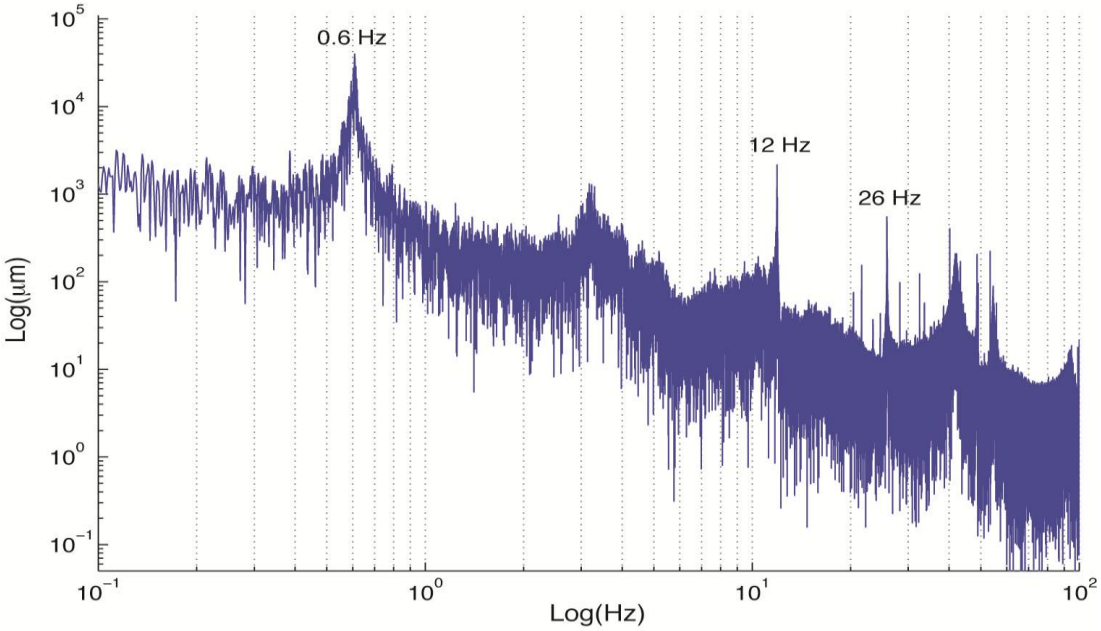
fiBT

- pendulumn principle
- tri-axial probes spaced 120° apart
- $d_1 + d_2 + d_3$ = constant
  - redundancy measurement
  - compensates common-mode "noise"
  - corrects for system drifts
- dynamic range ~ ±1 mm
- frequency domain: 10^{-2} – 10 Hz
- transfer to industry ongoing (FUI MIRZA project)

Tri-axial fiBT

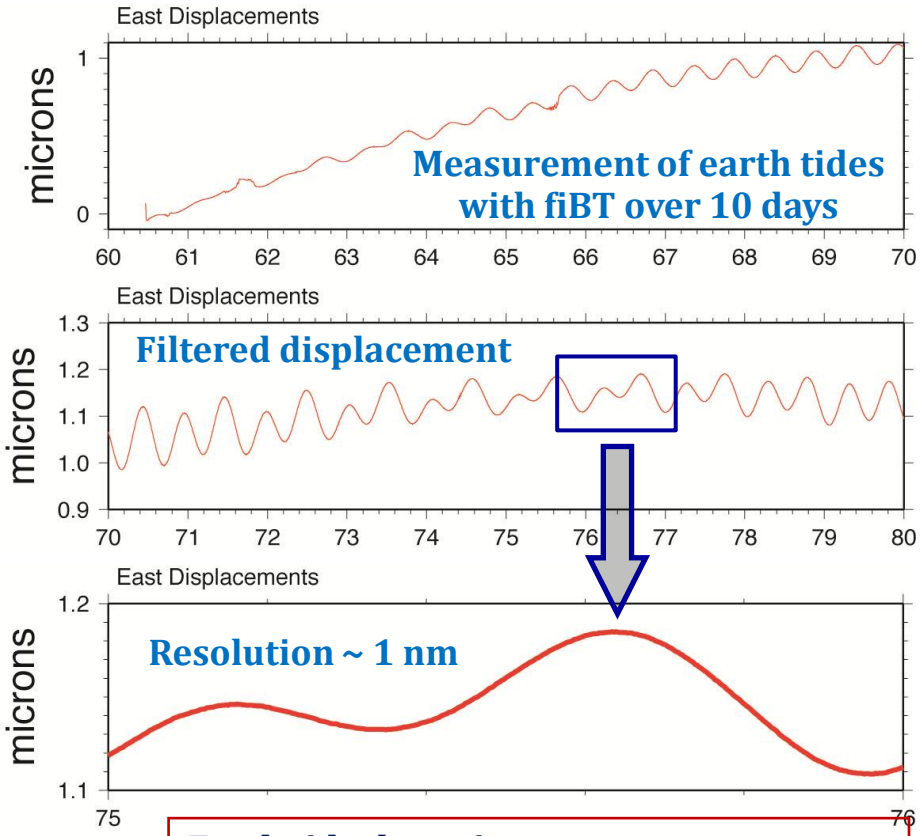
II. fiBT performance & Earth tide detection

- **fiBT frequence response from squarewave PZT excitation & Earth tide detection**



fiBT response

- 0.6 Hz frequency band denotes fundamental oscillating mode
- 12 Hz and 26 Hz bands indicate rod's vibration modes
- remaining frequency bands caused by parasitic movements

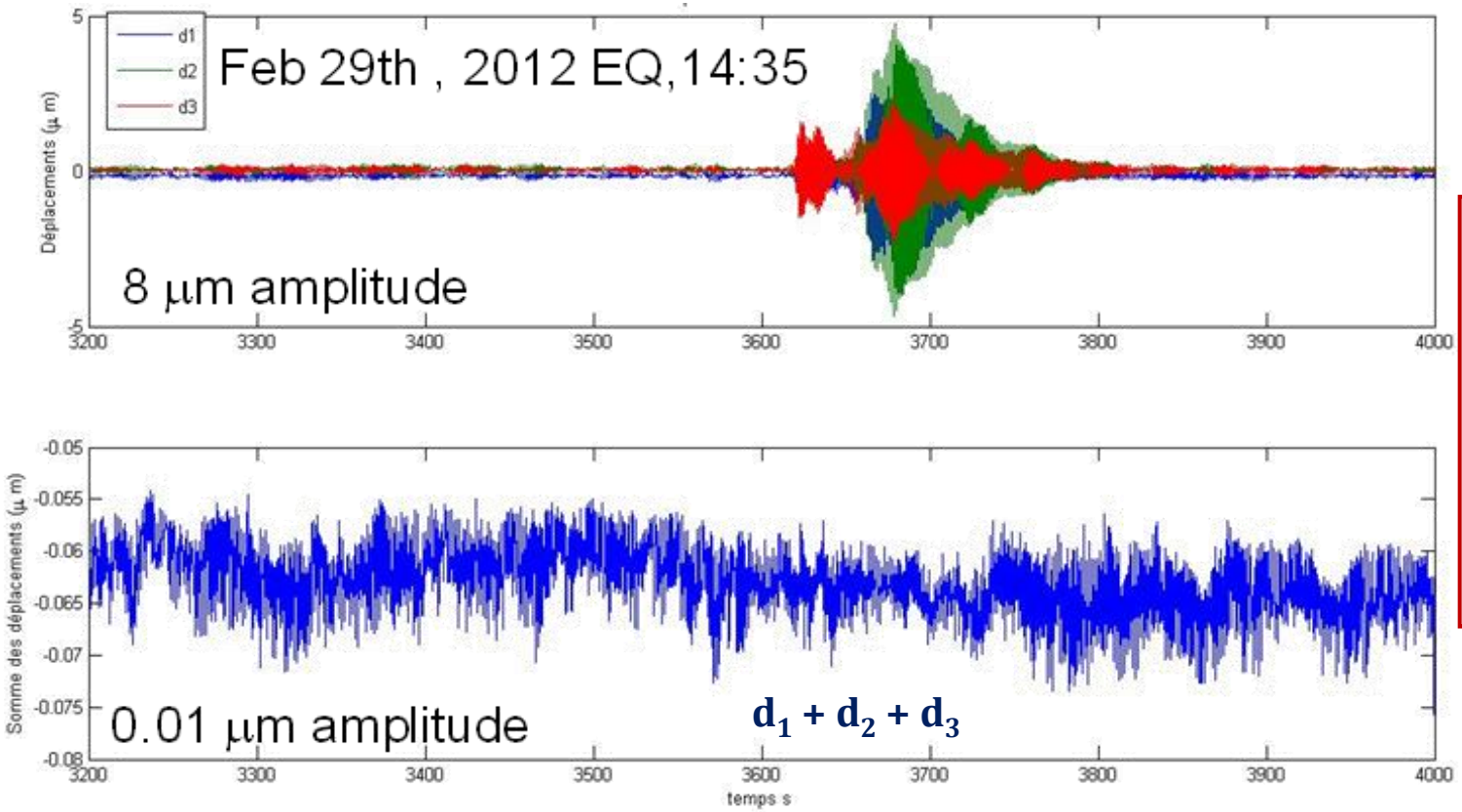


Earth tide detection

- 10 days observation of earth tides
- displacement resolution ~1 nm
- corresponding tilt resolution ~1 nrad

II. fiBT performance: redundancy capability

- **fiBT common-mode noise compensation: redundancy measurement**



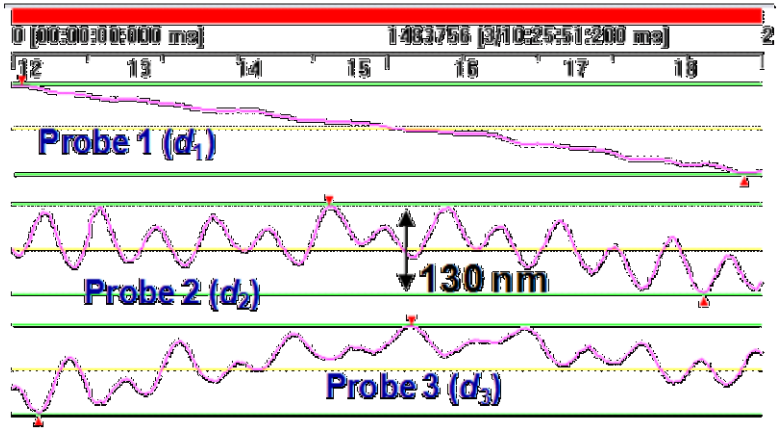
Redundancy performance

- M5.8 Japan earthquake on 29 Feb 2012
- sum of tri-axial displacements : $d_1 + d_2 + d_3$ = ~10 nm (offset)
- common-mode noise compensation: insensitive to pressure variations

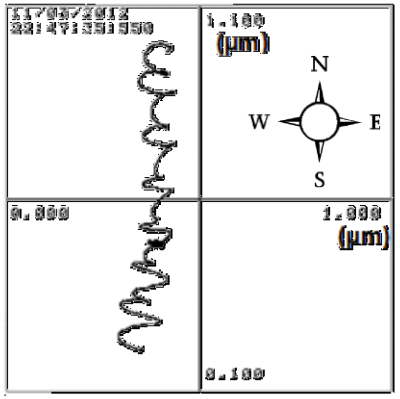
Evaluation of redundancy capability during remote earthquake

II. fiBT for Earthquake detection: 2D mapping

- **fiBT for 2D Earth deformation**



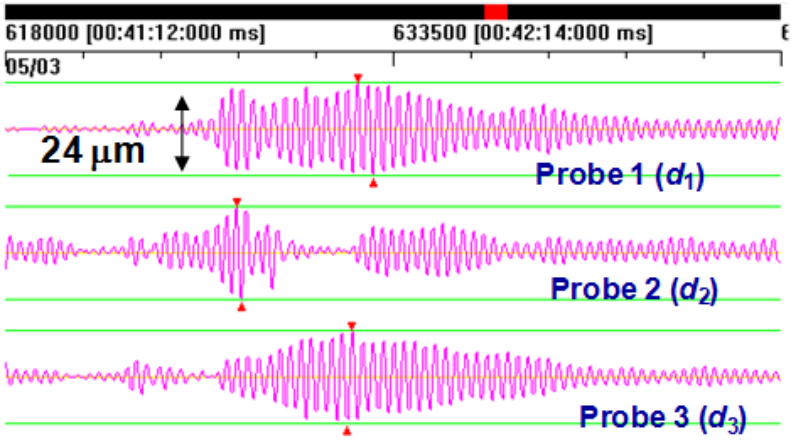
Oscillation of fiBT with earth tides



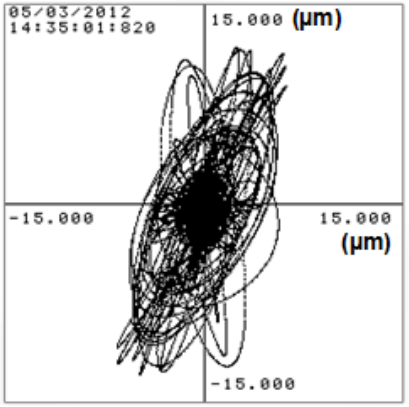
Natural oscillation

Earth tides

- 2-D observation
- orientation along N-S direction
- amplitudes ~80 – 130 nm (3-axis)



fiBT response to seismic activities (M 6.1 Argentina earthquake)



Reconstructed 2D movement

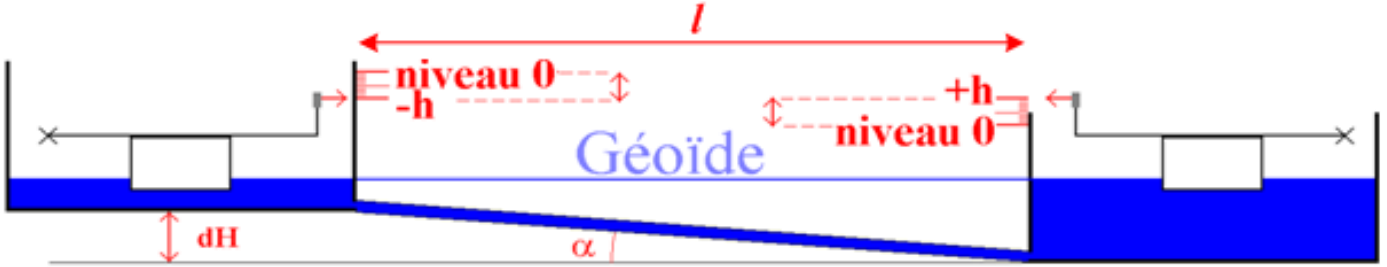
Earthquake detection

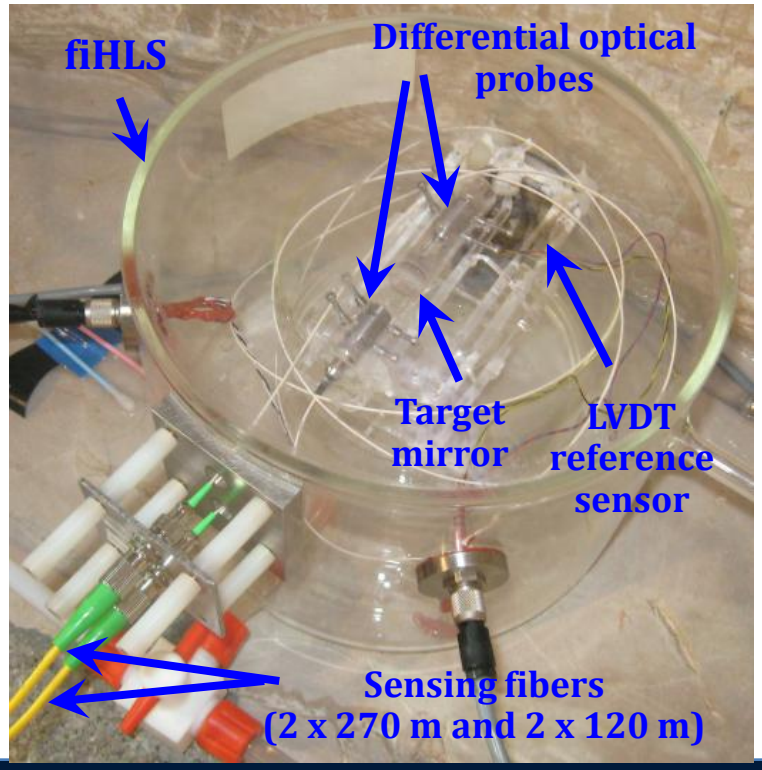
- Argentina earthquake 5 Mar 2012
- quake magnitude ~M6.1
- amplitudes ~15 – 24 µm (3-axis)

III. Applications in Geophysics: fiHLS

- **Fiber interferometric long-baseline hydrostatic leveling sensor (fiHLS)**

Long baseline hydrostatic inclinometer





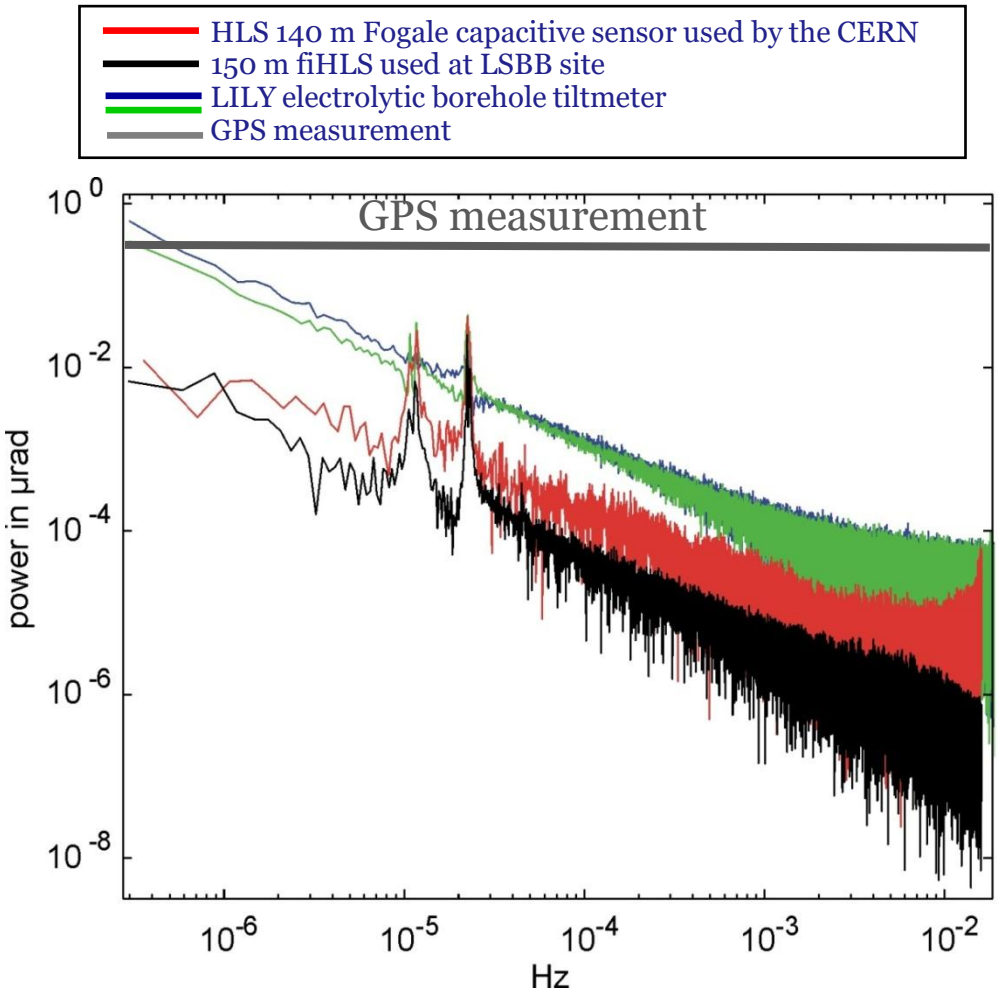
fiHLS performance

- liquid level variations ⇒ tilt (1 nrad ~ 1 mm/1000 km!)
- combined baseline 150 m
- tilt precision ~10^{-11} radians
- frequency domain: 10^{-5} – several Hz
- sensitive to earth tides, earthquakes, hydrological effects
- transfer to industry ongoing (FUI MIRZA project)

Differential fiHLS all-glass variant

III. fiHLS performance

- **fiHLS frequency response: comparison with HLS-Fogale, LILY tiltmeter, GPS**

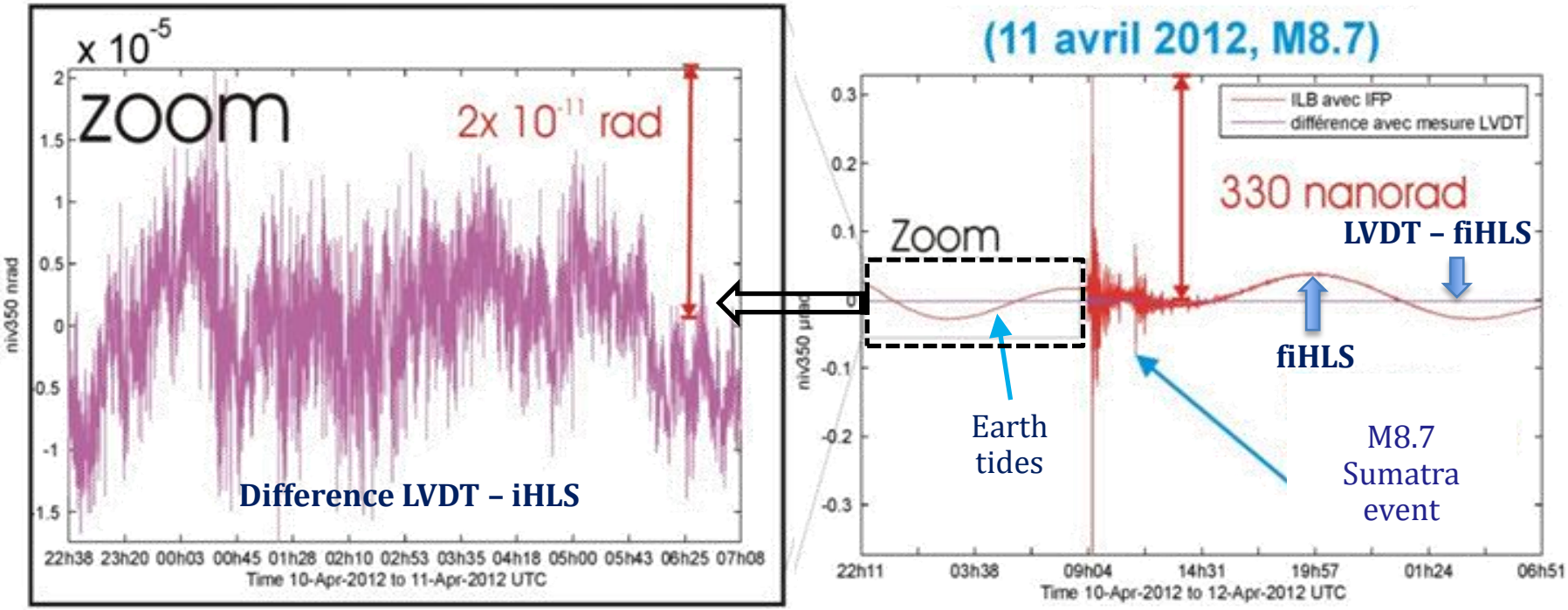


Summary of comparison

- frequency domain: 10^{-6} – 10^{-2} Hz
- from ~10^{-5} Hz
  - fiHLS ~10 times less noisy than HLS-Fogale
  - fiHLS >20 times better than LILY
- higher frequencies (from 10^{-2} Hz)
  - fiHLS ~100 times better than HLS-Fogale and LILY in precision
- fiHLS also less sensitive to atmospheric noise compared to GPS systems & LILY (local pressure variations)

III. fiHLS for Earth deformation

- **Sensitivity of fiHLS to Earthquakes**



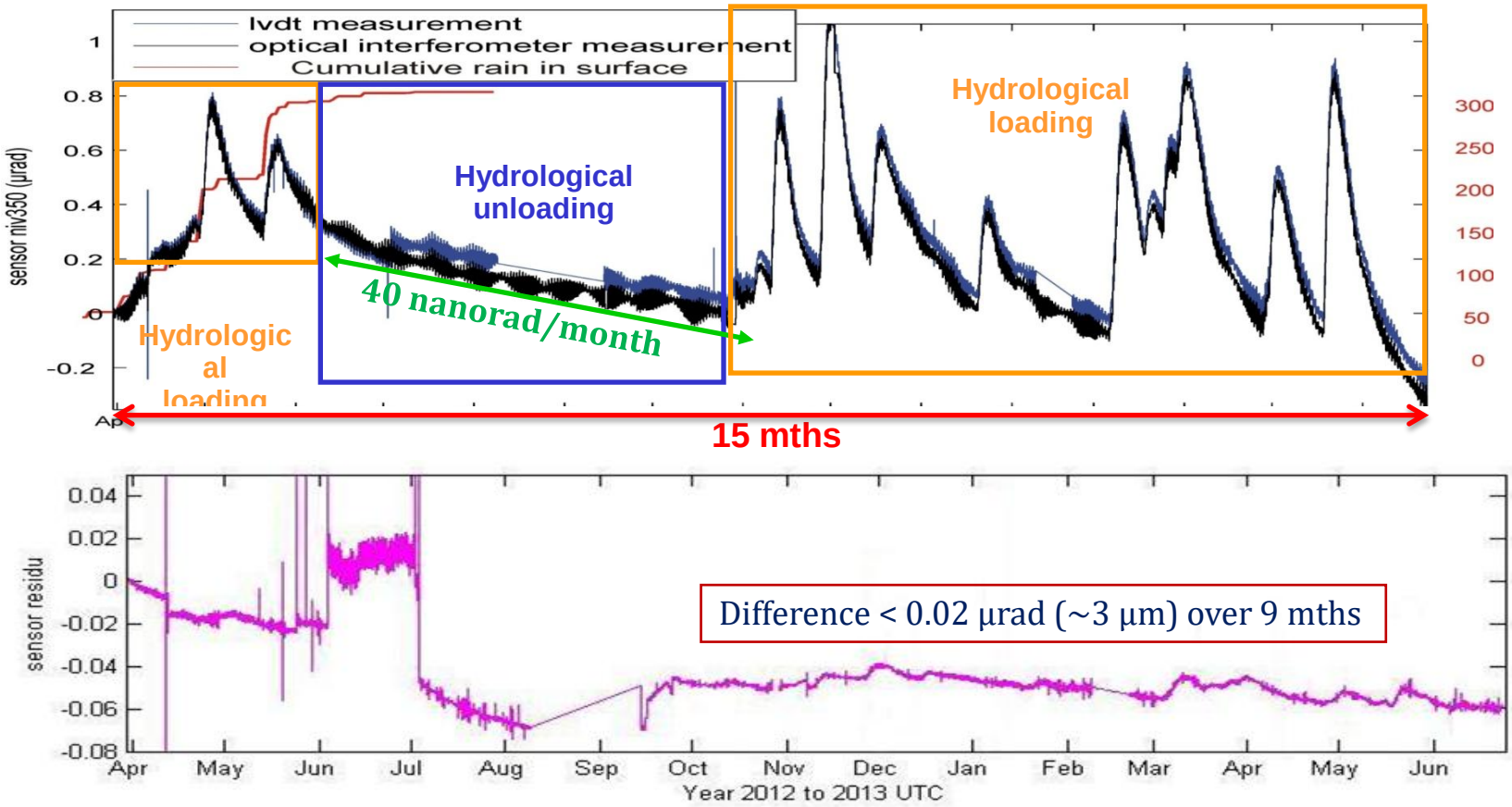
Earth tide and earthquake detection

- noise floor ~ 2 x 10^{-11} rad
- error < 0.2% before quake and ~3% during quake

III. fiHLS for hydrology

- **Sensitivity of fiHLS to precipitations (hydrological loading-unloading)**

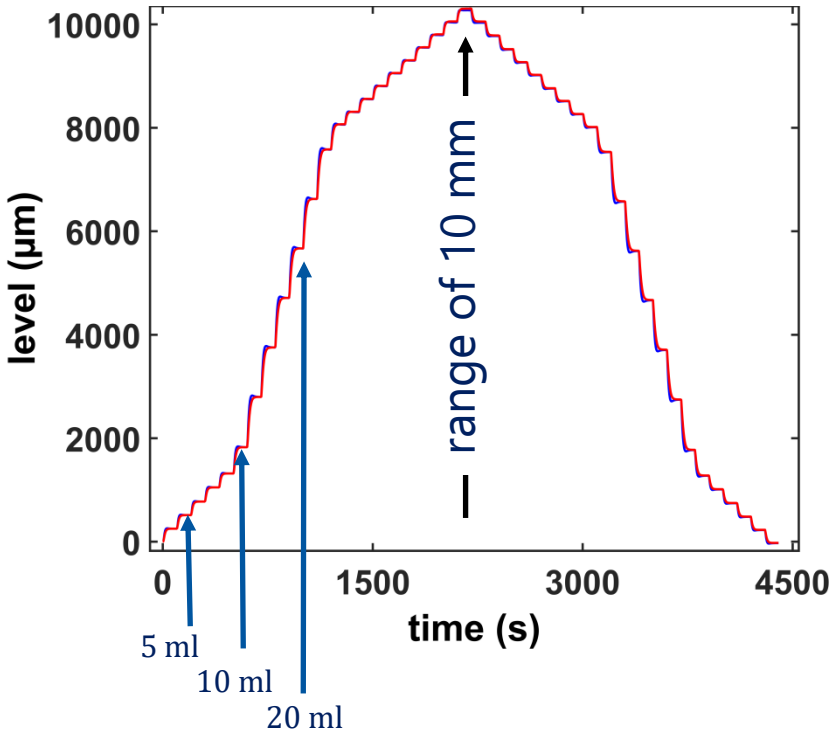
Detection of hydrological loading and unloading processes in test tunnel

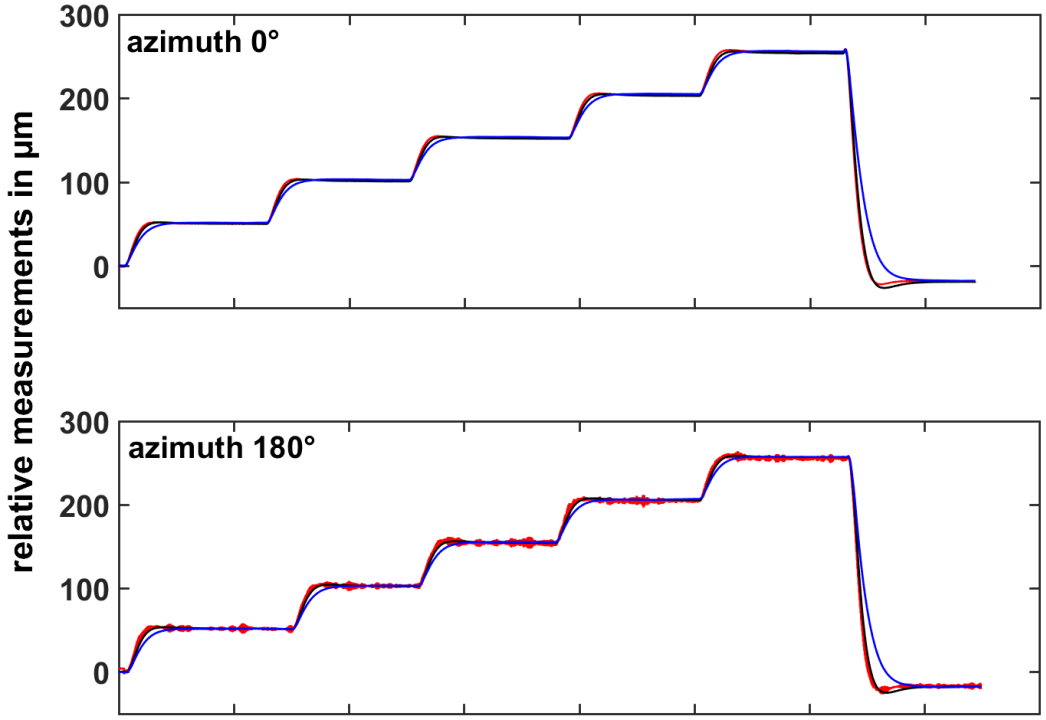


- **Reliability:** > 3 yrs continuous operation
- **Long-term stability:** max. drift ~40 nrad/mth

III. fiHLS for accelerator alignment at CERN

- **Characterization of fiHLS for CERN applications**





Range & linearity calibration

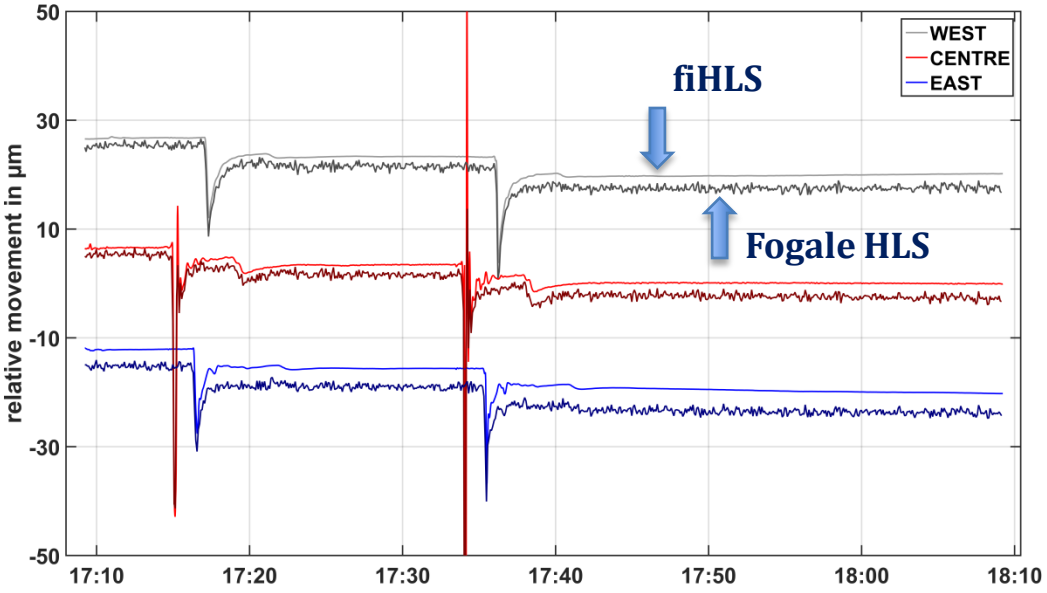
- 5 ml = 249 µm
- Repeatability & multiples within ±1 µm

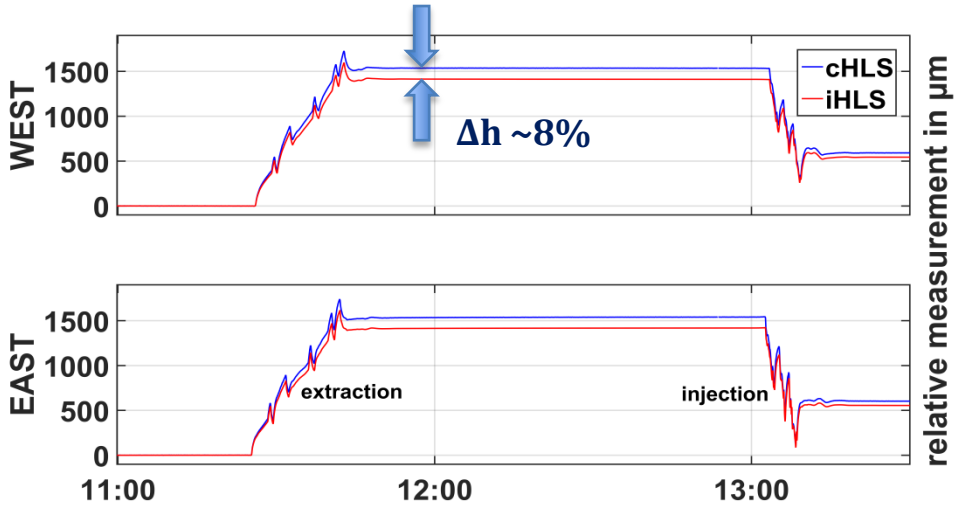
Inclination tolerance

- 3 sensor network with 2 horizontal & 1 inclined
- Tested at 4 azimuths
- Max. 1.3° injection and extraction of liquid

III. fiHLS for accelerator alignment at CERN

- **Characterization of fiHLS for CERN applications**





Sensitivity tests

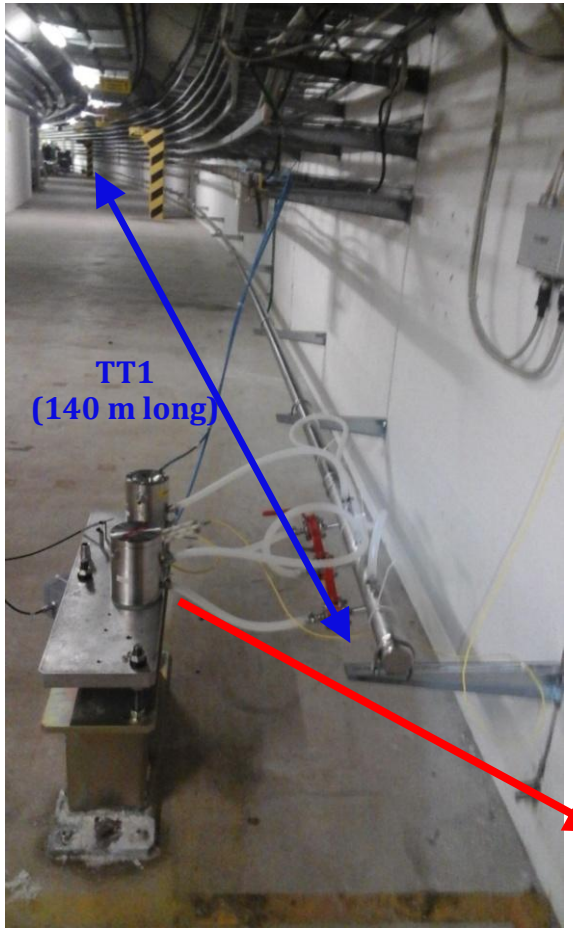
- Injection of 20 ml water
- Both sensor types see 3 m variation
- Shift in wavefront corresponds to position

Linearity tests

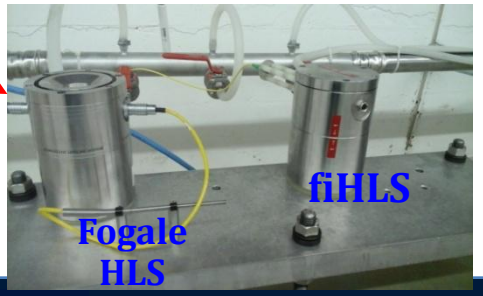
- Extraction and injection of water to main network
- Difference between both sensors ~8%
- Hypothesis: precision on liquid/oil RI in fiHLS

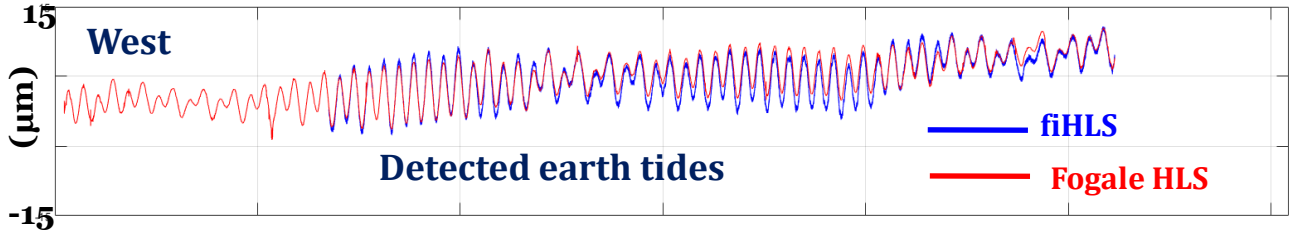
III. fiHLS for accelerator alignment at CERN

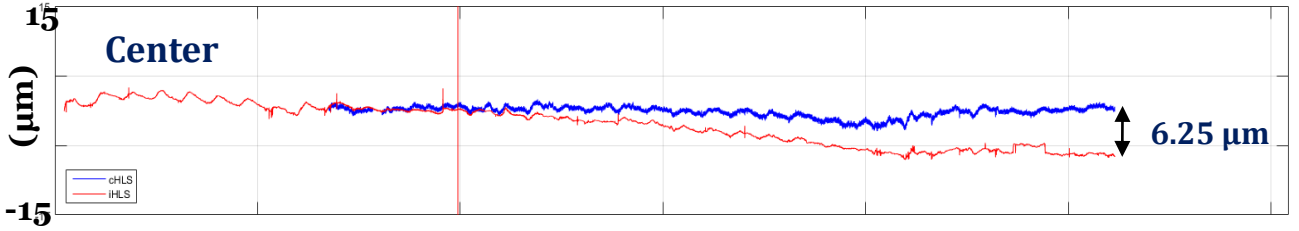
- **fiHLS for particle accelerator & collider alignment at CERN**



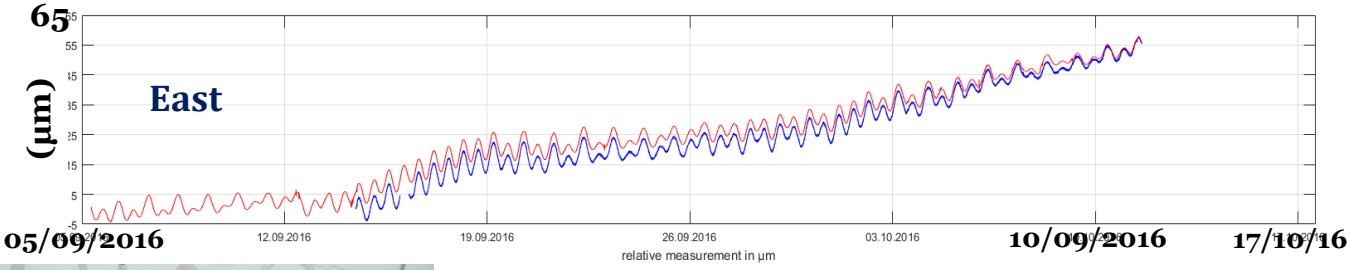
Evaluation of fiHLS at CERN's TT1 transfer tunnel







Comparison between iHLS-LINES and HLS-Fogale (stability)



Collider-accelerator alignment at CERN

- 3 fiHLS deployed at CERN
- continuous operation since July 2016
- high agreement between fiHLS and reference (Fogale HLS) measurements

IV. Conclusions & Perspectives

- EFFPI sensor development for geophysics and industry
  - Precision <2 nm over 10^{-3} – 500 Hz bandwidth
  - Dynamic range: 2 nm – >10 mm at 4 mm/s
  - Alignment tolerance >1.5° (double reflection, induced error < 10 nm)
  - Stability : < 1 nm error (differential configuration)
  - Temperature sensitivity: 25 – 50 nm/°C
- fiBT
  - Tilt resolution ~1 nrad over operating range: 10^{-2} – ~10 Hz & several mm's
  - Tri-axial ⇒ redundancy measurement (compensates temperature, pressure variation, etc)
  - Applications in near-field ground deformation, natural resource exploitation, volcanology, hydrology, etc
- fiHLS
  - Tilt resolution ~10^{-11} rad (150 m baseline) over operating range: ~10^{-4} – several Hz & several mm's
  - Differential configuration ⇒ common-mode "noise" compensation (pressure, temperature, etc)
  - Applications in far-field earthquake & Tsunami detection, hydrology, etc
- Perspectives & Future Work
  - Technology transfer & commercialization in progress
  - Laser wavelength locking to increase sensor resolution & dynamic
  - Absolute measurement of distance in progress