Professional Precision Laser inclinometer: the noise origins and data processing

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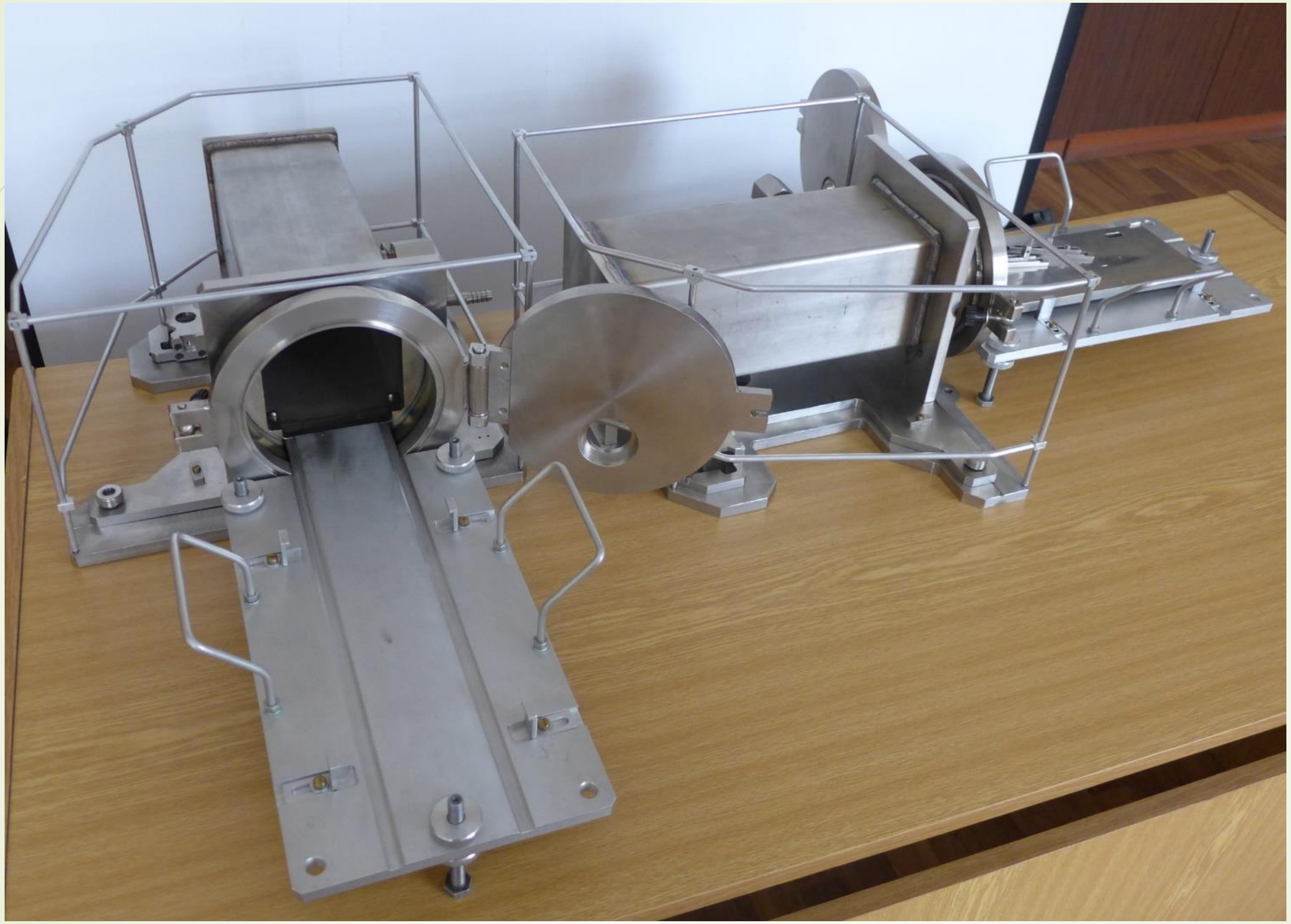
NEW TRENDS IN HIGH-ENRGY PHYSICS 2018

The Professional Precision Laser Inclinometer (PPLI)



January 2017

The first units of Professional PLI have been manufactured and assembled in JINR
for the wide research program on the registration of Earth surface angular oscillations.

Commissioning of the PPLI in CERN in the Transport Tunnel #1 (TT1)

October 2017

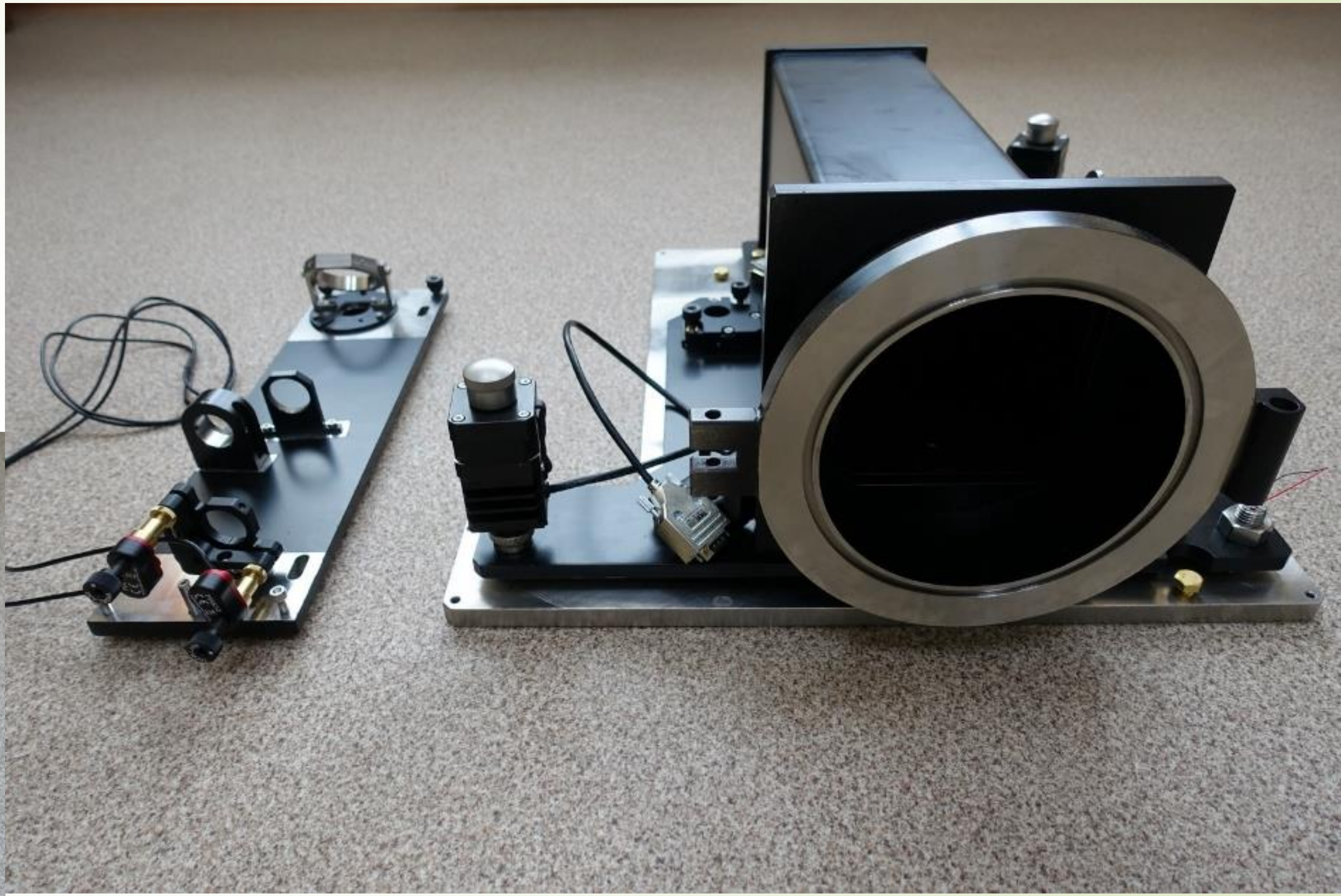
Nowadays the first PPLI is commissioned in TT1 with full remote control operation mode.

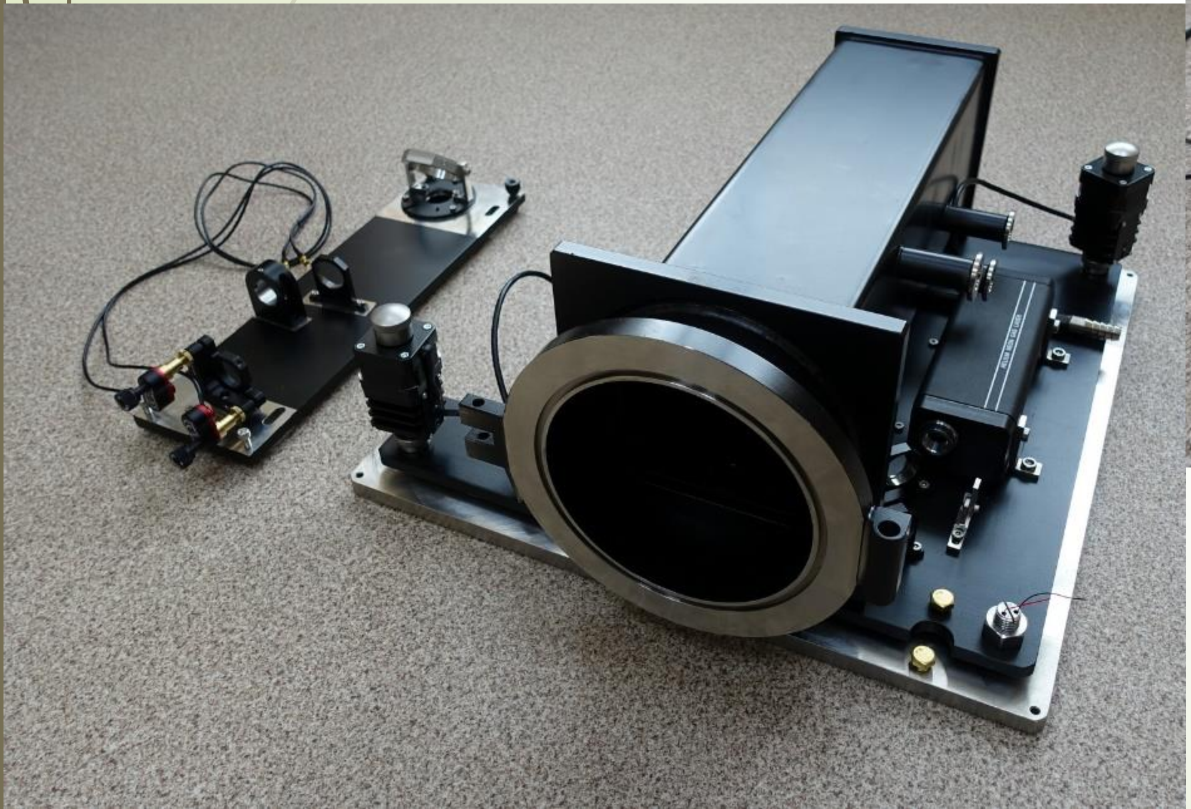
In PPLI the following questions are solved:

- remote control and adjustment of the instrument,
- automatic calibration of the instrument,
- processing and monitoring of the angular inclination of the Earth's surface.

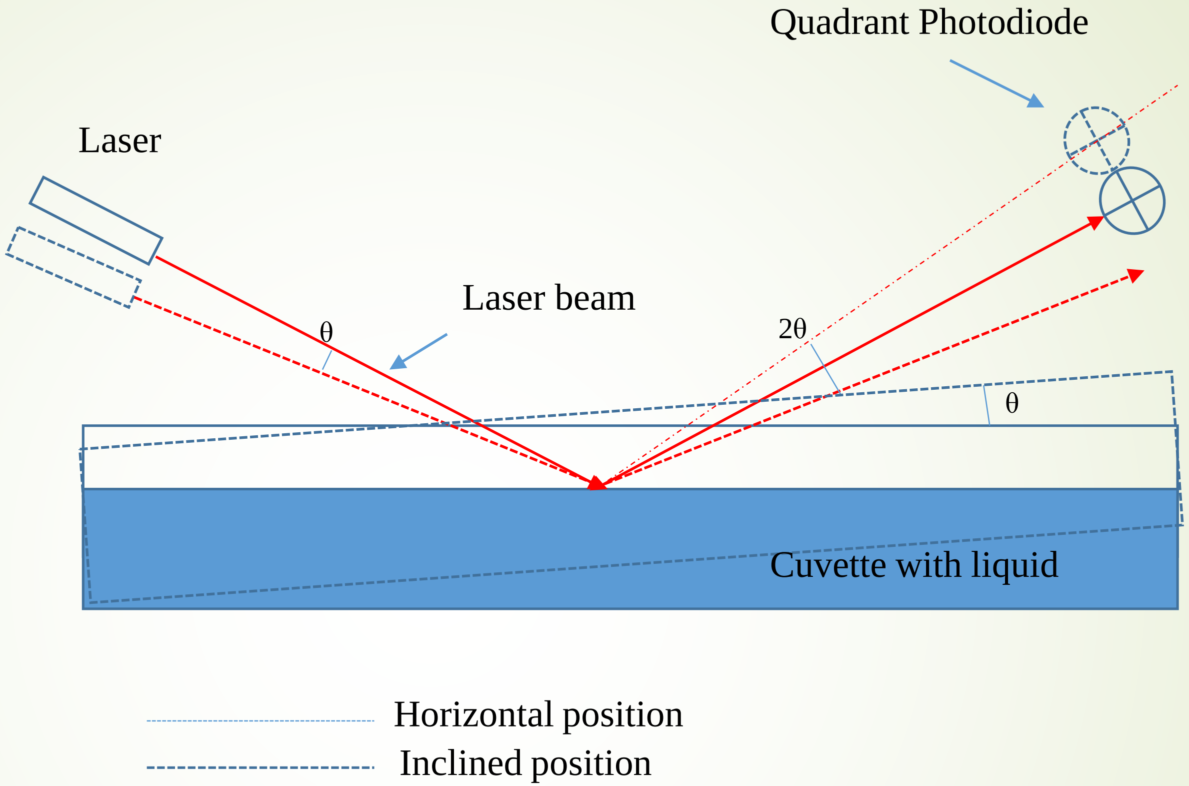
Professional Precision Laser Inclinometer (Stage 2)

May 2018



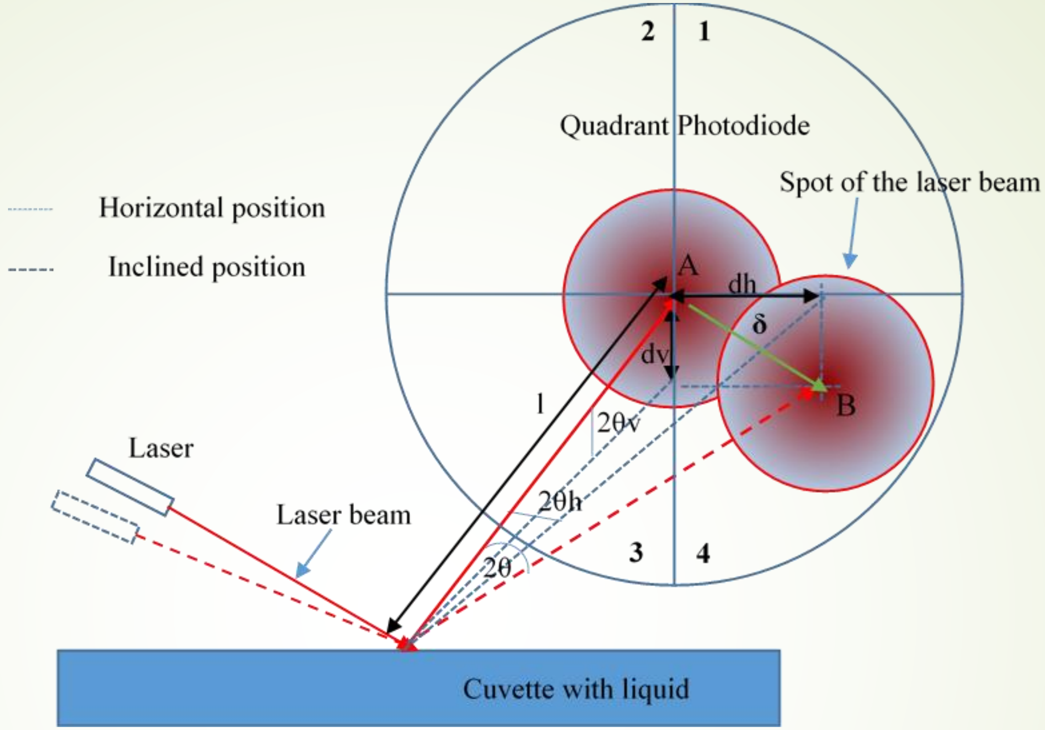


The operating principle of precision laser inclinometer



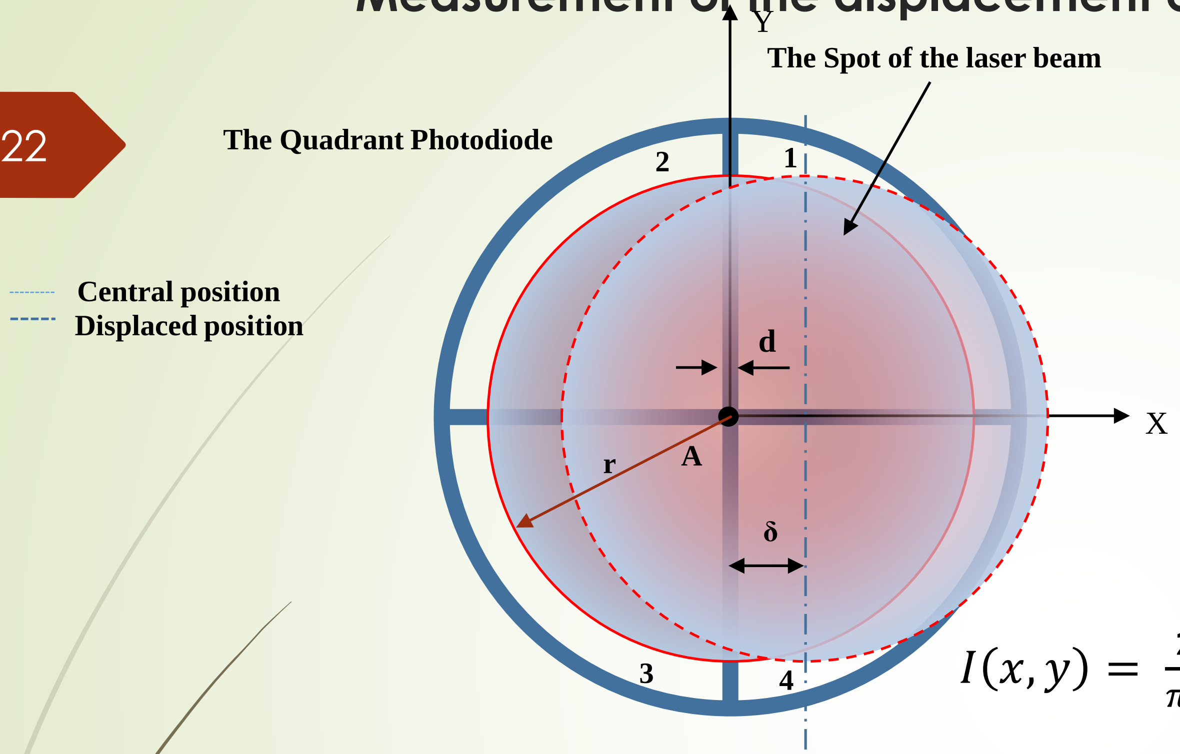
- The laser beam reflects from the liquid surface.
- The reflected beam is registered by a position-sensitive quadrant photodetector.
- When the cuvette is tilted by an angle ***θ***, due to the horizontal nature of the liquid surface, the reflected beam changes its angular position by ***2θ***.
- The spot of the reflected laser beam changes its position on the quadrant photodetector.

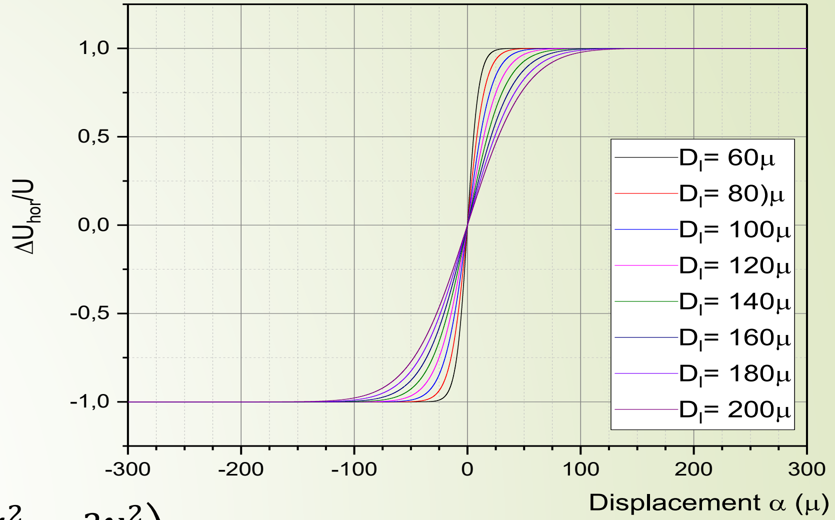
The principle of registration by the PLI



- $\Delta U_{ver} = (U_1 + U_2) - (U_3 + U_4)$ $\Delta U_{hor} = (U_1 + U_4) - (U_2 + U_3)$
- Under the condition that the displacement $\boldsymbol{\delta}$ is small $\boldsymbol{\delta \ll r}$,where **r**-radius of the laser beam.
- $2\theta_{hor} = \frac{\delta_{hor}}{l}$ $2\theta_{ver} = \frac{\delta_{ver}}{l}$; $\theta_{hor} = K_{hor}\Delta U_{hor}$; $\theta_{ver} = K_{ver}\Delta U_{ver}$.
- Using the preliminary determined calibration coefficients K_{hor} and K_{ver}, we determine the signal from the quadrant photodetector in radians.

Measurement of the displacement of the laser beam by the quadrant photodetector



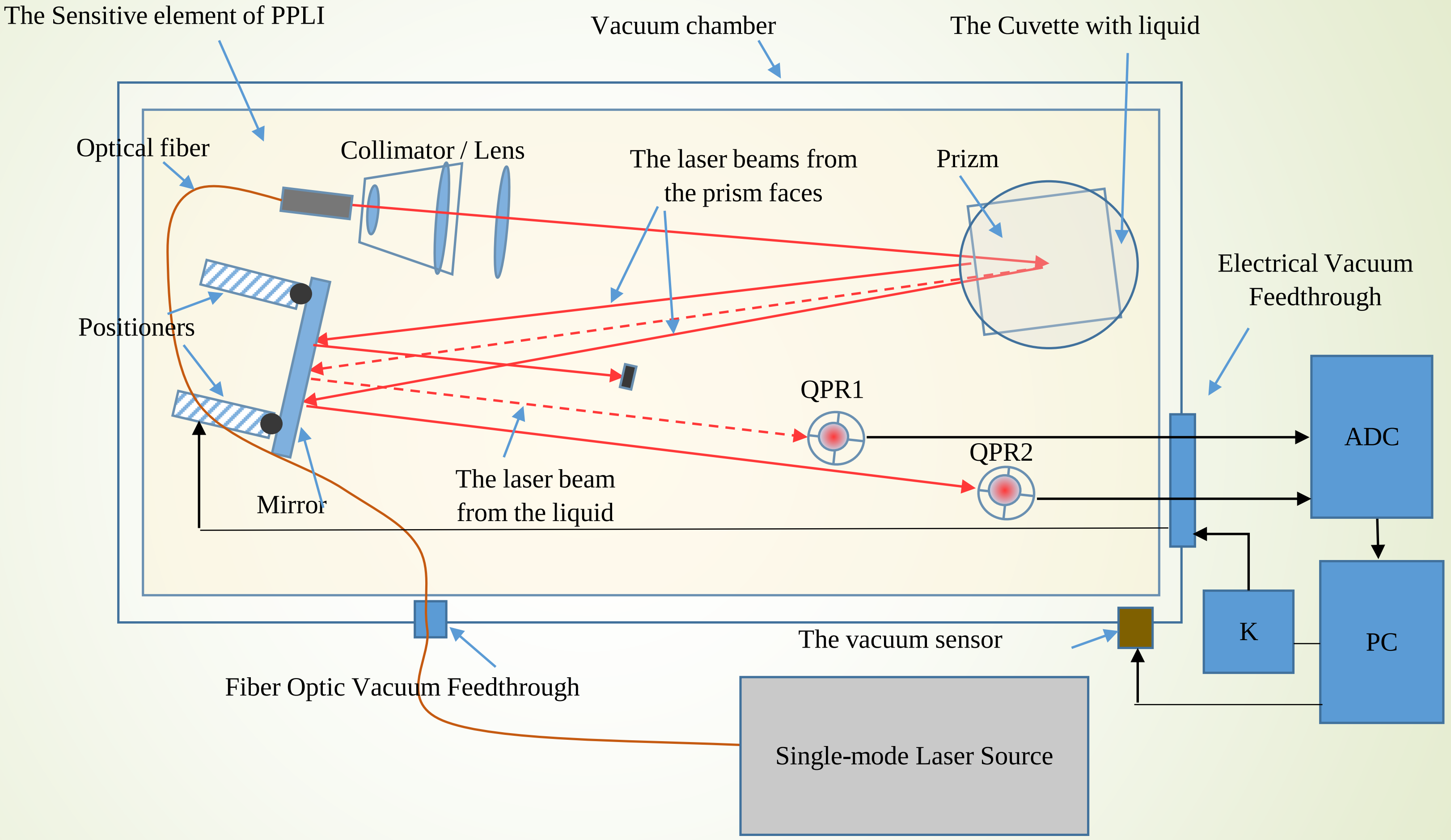


$$I(x,y) = \frac{2P}{\pi r^2} exp(-\left(\frac{2x^2}{r^2} + \frac{2y^2}{r^2}\right))$$

$$\frac{\Delta U_{\text{hor}}}{U} = \frac{(U_2+U_3)-(U_1+U_4)}{U_1+U_2+U_3+U_4} = \frac{\Delta P_{\text{hor}}}{P} = \frac{\text{erf}\left(\frac{(a-d)\sqrt{2}}{r_0}\right) + \text{erf}\left(\frac{(a+d)\sqrt{2}}{r_0}\right)}{2\text{erf}\left(\frac{w\sqrt{2}}{r_0}\right) + \text{erf}\left(\frac{(a-d)\sqrt{2}}{r_0}\right) - \text{erf}\left(\frac{(a+d)\sqrt{2}}{r_0}\right)}$$

- Increasing of the diameter **2r** of the laser beam, the range of the linear laser spot shifts is increasing .
- At **d = 30μ**, the optimal diameter of the laser beam is **2r = 100μ**
- The range of linear displacements with a possible nonlinearity of **1% is 13μ**, which is equivalent to **13μrad** of the slope of the earth's surface

Scheme of the Professional Precision Laser Inclinometer



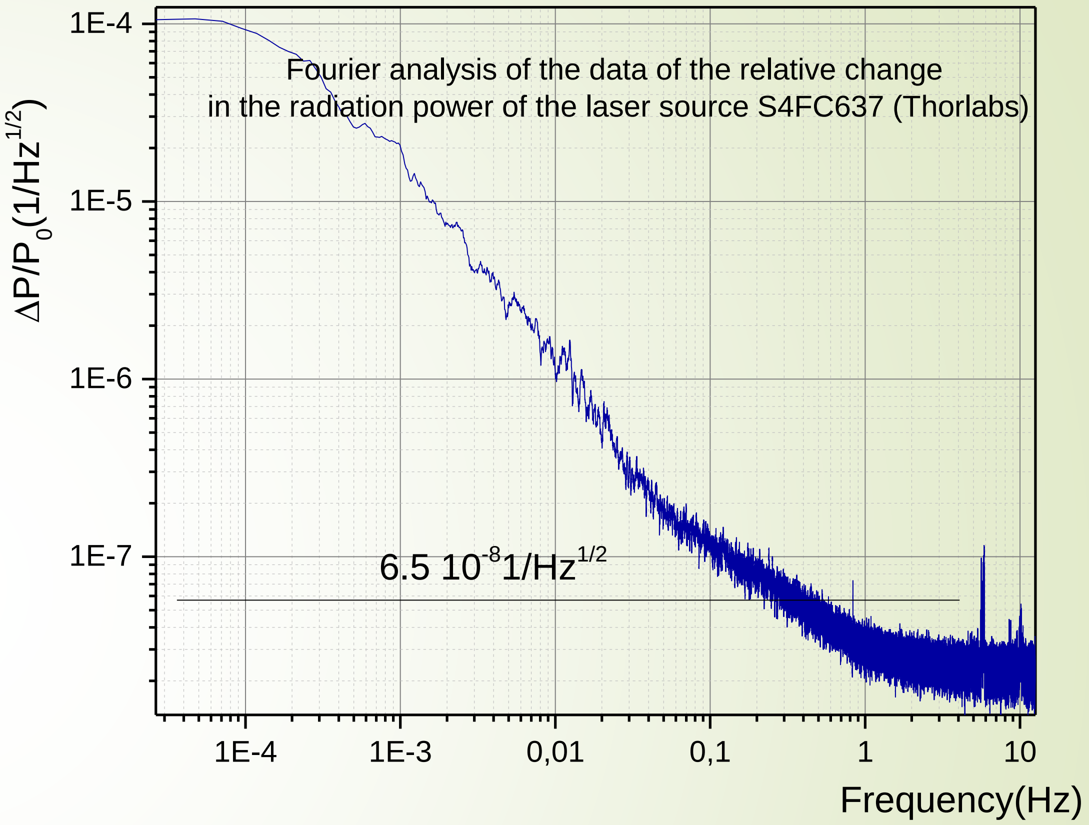
- The laser beam reflected from liquid is directed to the photodetector **QPR1**.
- The reference beam reflected from the prism surface is directed to **QPR2** and used for the registration of the noise wandering of laser beam.

Noise of the PLI: amplitude noise of the laser source

ΔP/P0

The relative change in the radiation powerΔP/P0

Time(h)

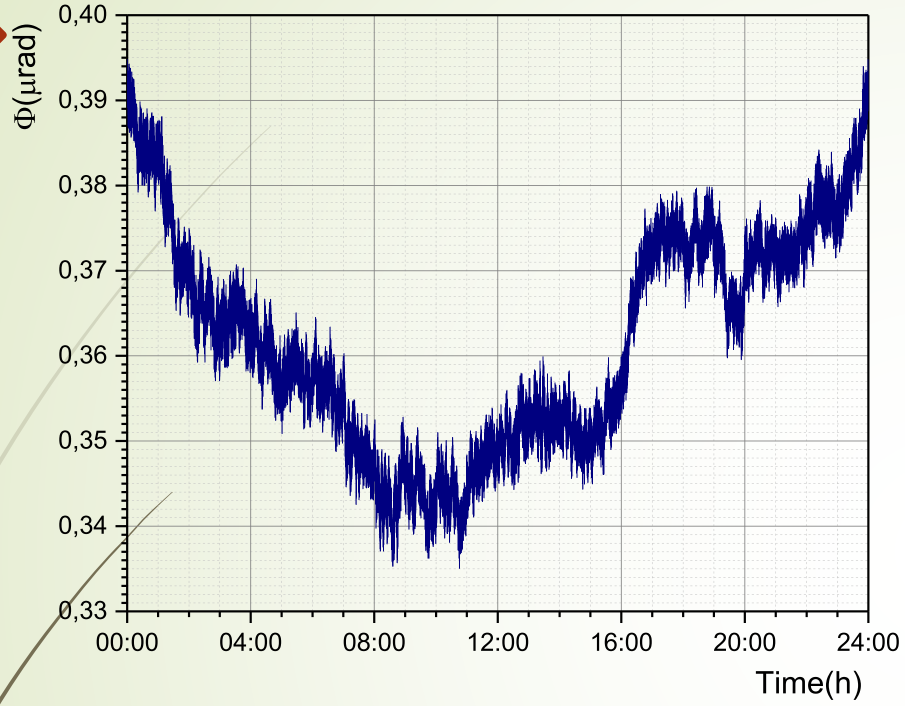


The power relative change $\frac{\Delta P}{P_0}$ of the laser source S1FC637 (Thorlabs) over a period of 12 hours

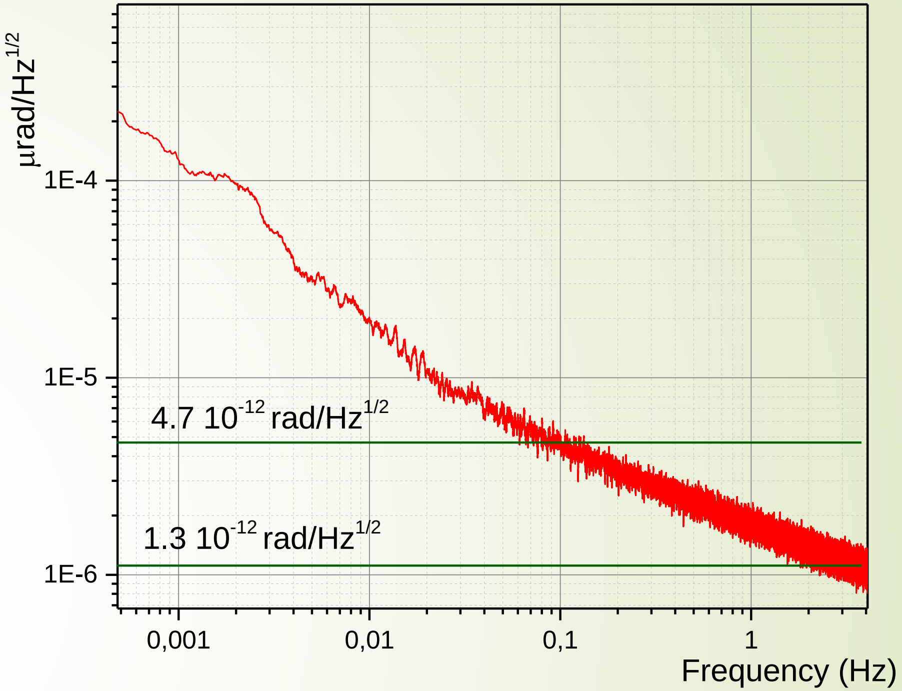
Fourier analysis of the power variation $\frac{\Delta P}{P_0}$ of the laser source S1FC637 (Thorlabs)

- The relative amplitude noise varies within $\frac{\Delta P}{P_0}$ = **1.7 10^{-3}** for the period of **12 hours**
- In the frequency range **0.1 – 4 Hz** the noise spectral density is **6.5 10^{-8} 1/$Hz^{1/2}$**

The noise of the angular wandering of the laser beam



Angular wandering of laser beam in vacuum from the laser source S1FC637 with fiber optic output



Fourier analysis of the angular wandering of laser beam

- The amplitude of angular changes of the laser beam is **0.06 µrad** per day.
- In the frequency range **[0.1Hz; 4Hz]**, the noise spectral density changes from **4.3 10^{-12} rad/$Hz^{1/2}$** up to **1.3 10^{-12} rad/$Hz^{1/2}$ (mean 3 10^{-12}rad/$Hz^{1/2}$)**.

Clearing of laser signal of amplitude and angular noise

- We use dimensionless signals from the signal beam and from reference beam as follows

$$S_{ver} = \frac{\Delta U_{ver}}{U} = \frac{(U_1 + U_2) - (U_3 + U_4)}{U_1 + U_2 + U_3 + U_4} \quad S_{hor} = \frac{\Delta U_{ver}}{U} = \frac{(U_1 + U_4) - (U_2 + U_3)}{U_1 + U_2 + U_3 + U_4}$$

$$R_{ver} = \frac{\Delta \bar{U}_{ver}}{\bar{U}} = \frac{(\bar{U}_1 + \bar{U}_2) - (\bar{U}_3 + \bar{U}_4)}{\bar{U}_1 + \bar{U}_2 + \bar{U}_3 + \bar{U}_4} \quad R_{hor} = \frac{\Delta \bar{U}_{hor}}{\bar{U}} = \frac{(\bar{U}_1 + \bar{U}_4) - (\bar{U}_2 + \bar{U}_3)}{\bar{U}_1 + \bar{U}_2 + \bar{U}_3 + \bar{U}_4}$$

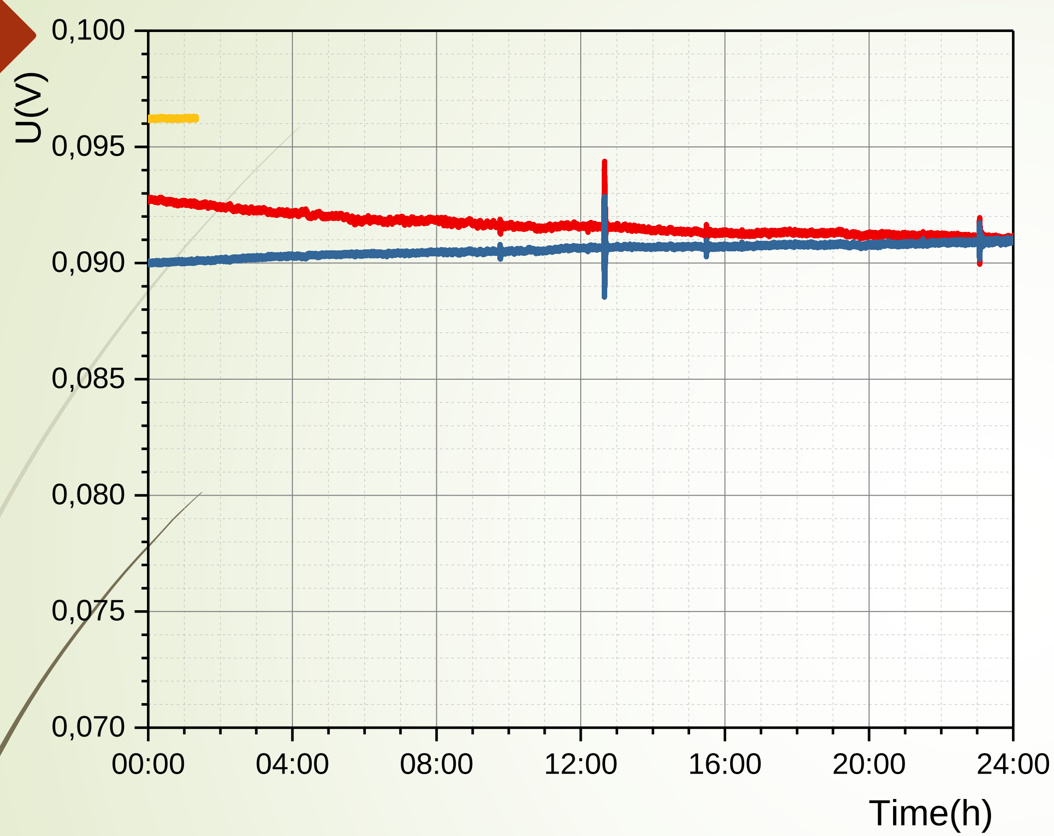
- The calibration coefficients

$$k_{hor} = \frac{\Delta\theta_{hor}}{\Delta S_{hor}} \; ; \quad k_{ver} = \frac{\Delta\theta_{ver}}{\Delta S_{ver}}$$

- The complete processing consists in subtraction of noise of the angular wander of the laser beam R_{ver} R_{hor} from the signals S_{ver}; S_{hor} with the multiplication of the result by the calibration coefficients k_{hor} , k_{hor}

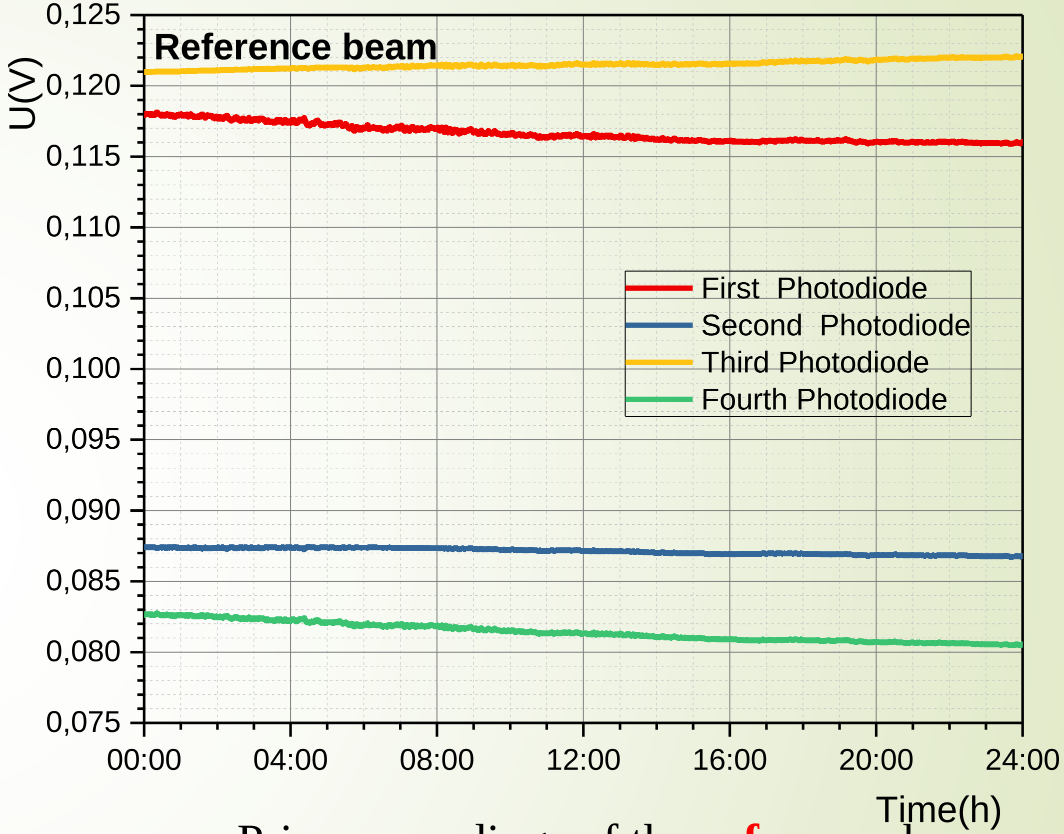
$$\theta_{ver} = (S_{ver} - R_{ver})K_{ver}; \; \theta_{hor} = (S_{hor} - R_{hor})K_{hor}$$

Signal processing in the PPLI – Stage 1



Primary readings of the **signal** beam

by quadrant photodetector **QPR1**

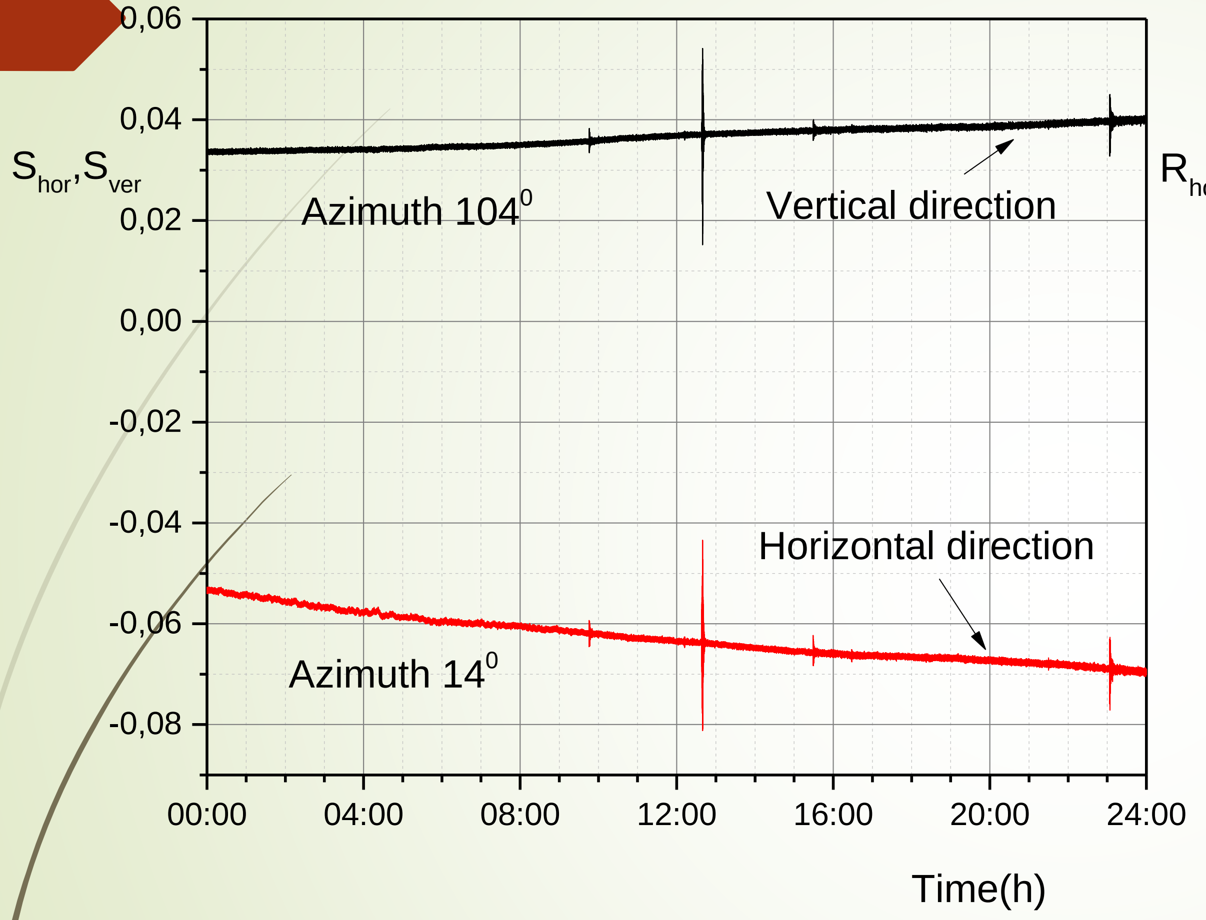


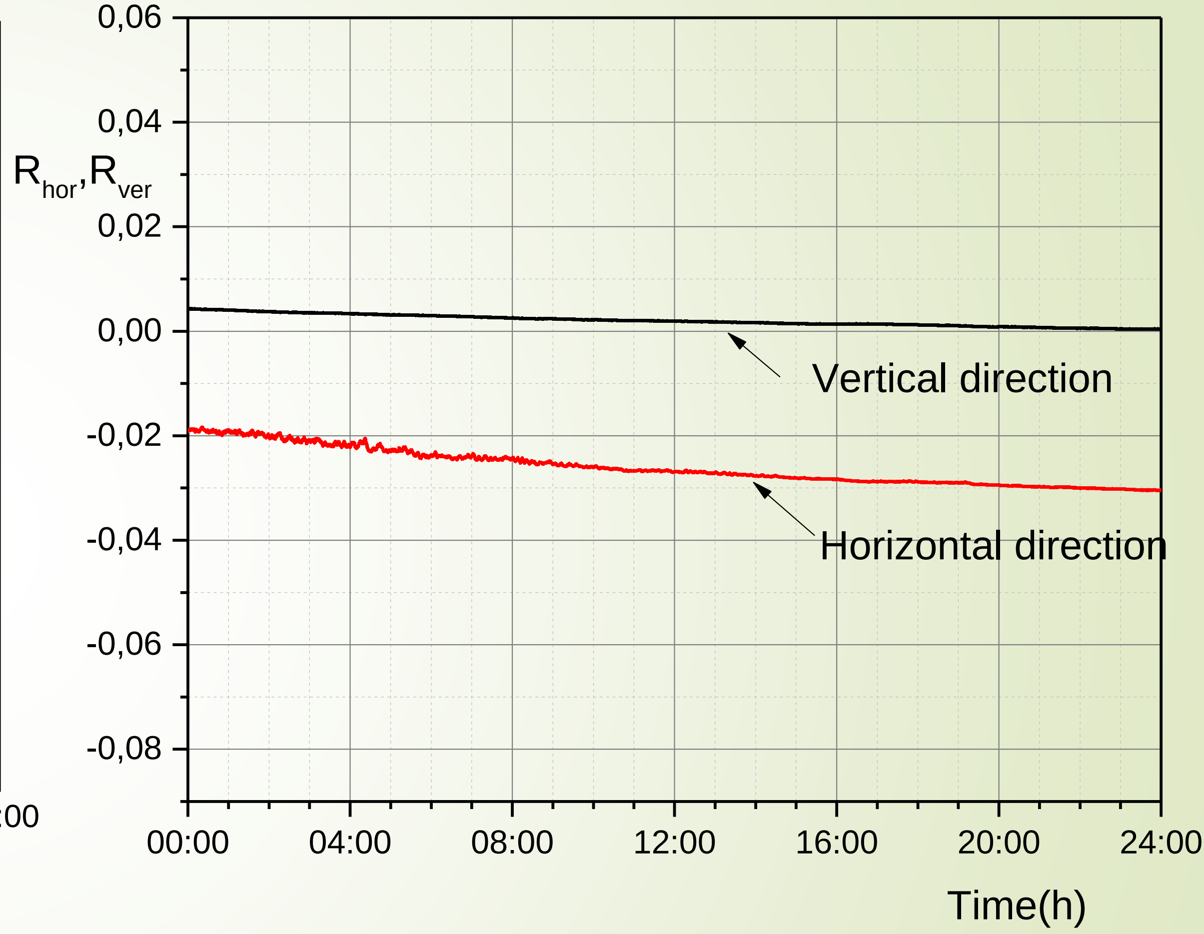
Primary readings of the **reference** beam

by quadrant photodetector **QPR2**

- At the first stage, we register the motion of the signal and reference beams on the **QPR1** and **QPR2**

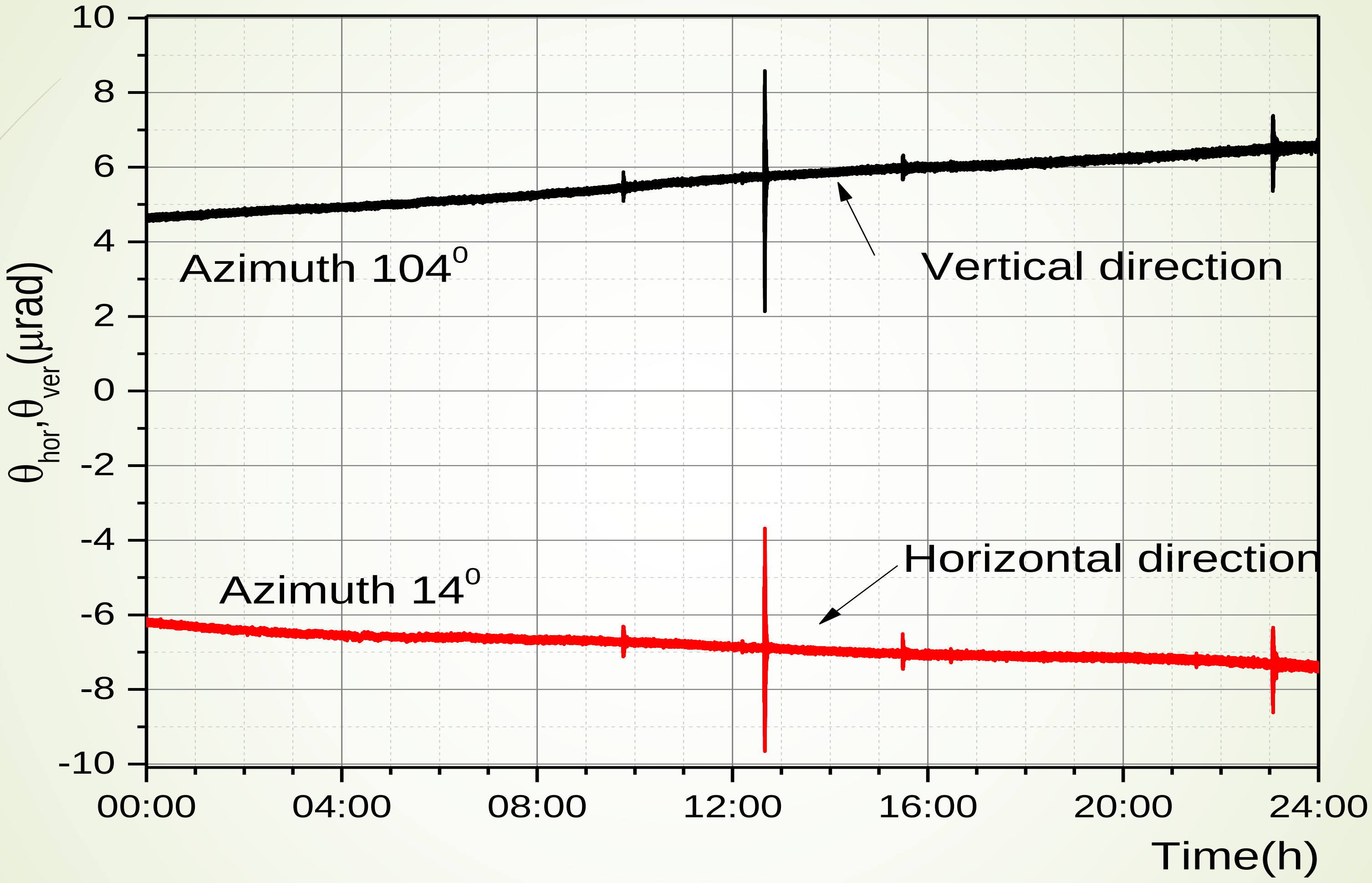
Signal processing in the PPLI – Stage 2





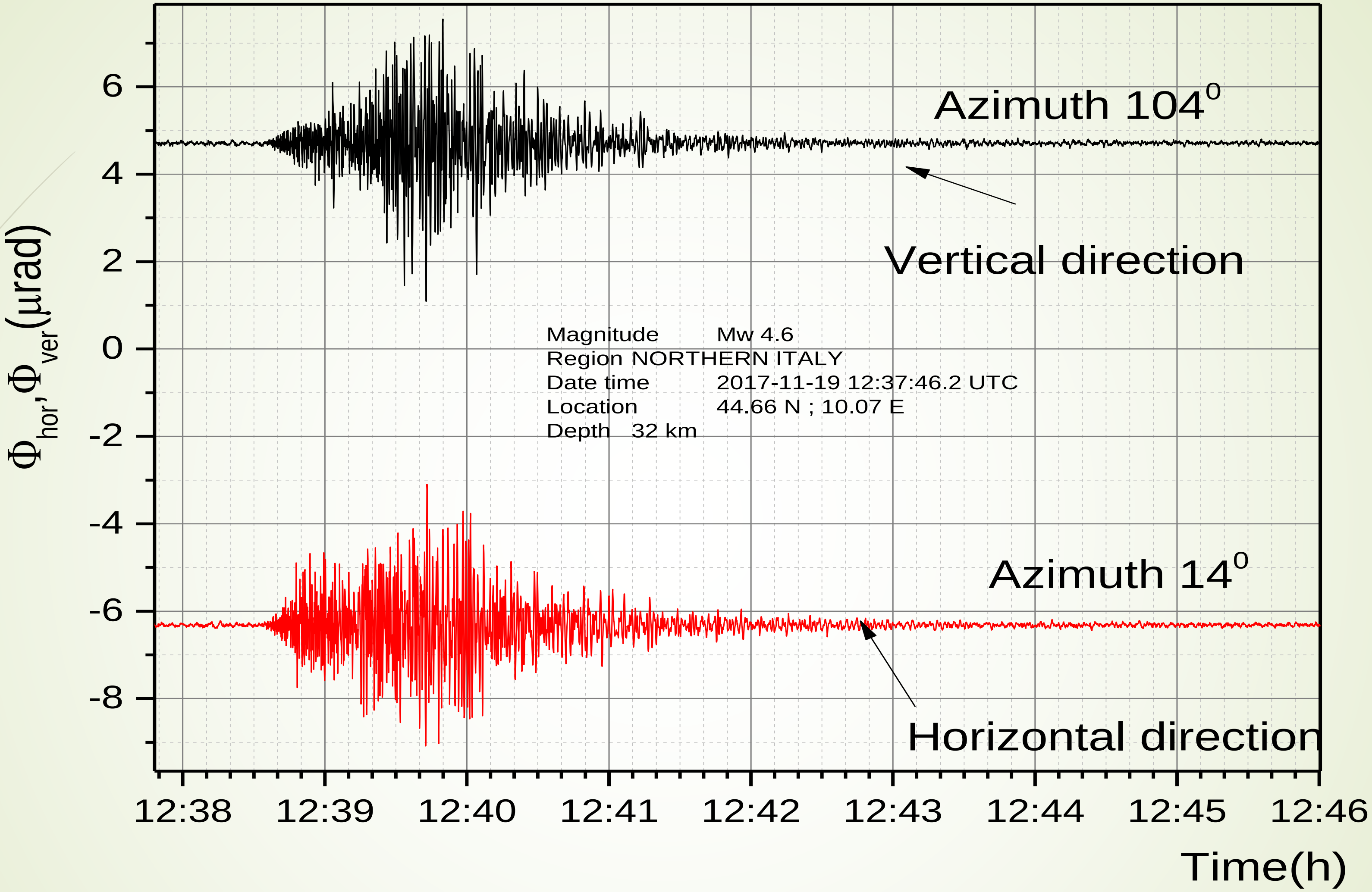
- Determination of dimensionless signals of the laser beam reflected from the surface of the liquid S_{ver}; S_{hor} and the noise of the angular wander of the laser beam R_{ver} ; R_{hor}

Signal processing in the PPLI – Stage 3



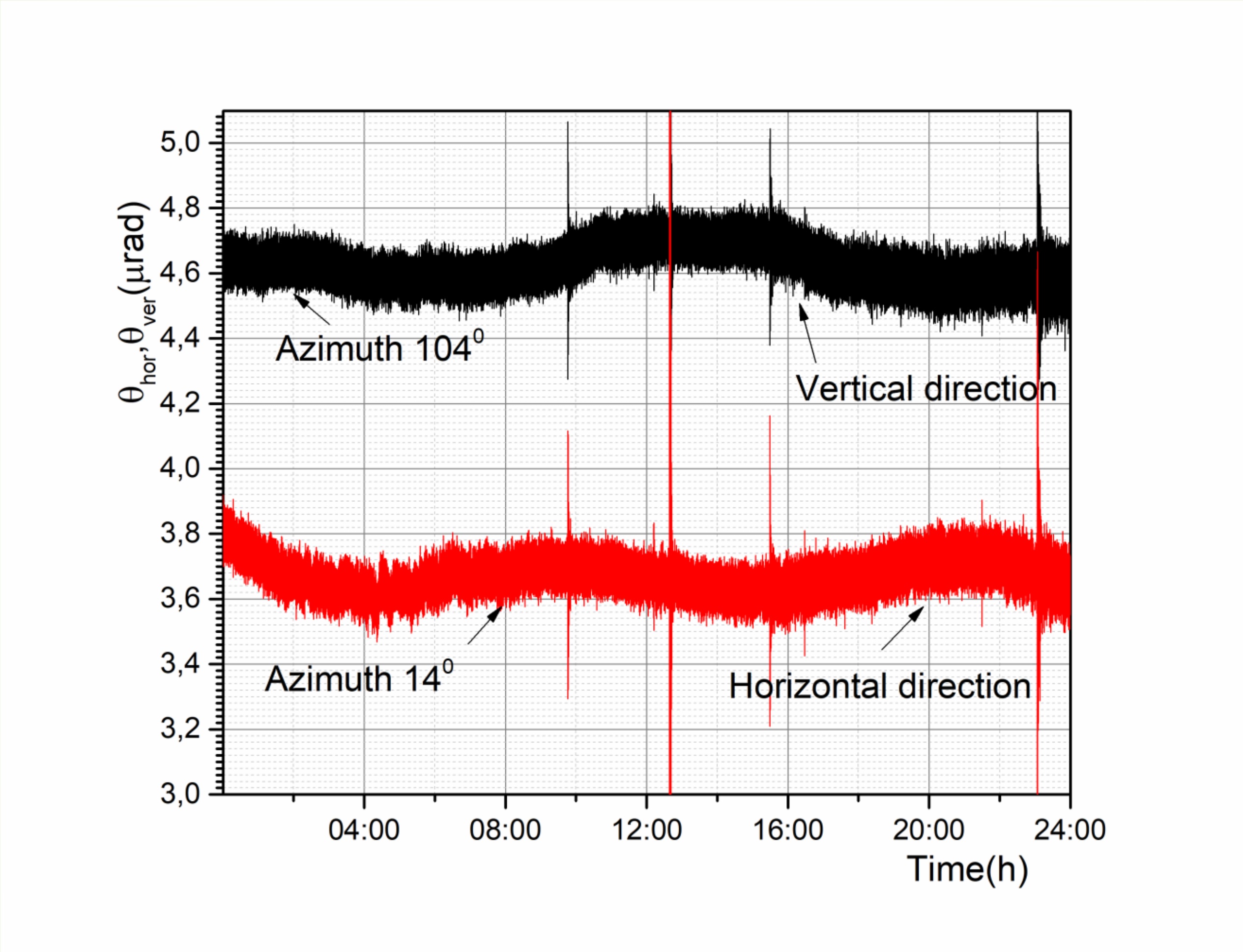
- The final result of the processing - Earth surface tilts in the vertical $\boldsymbol{\theta_{ver}}$ and horizontal $\boldsymbol{\theta_{hor}}$ planes

Registered microseismic signals: remote earthquakes



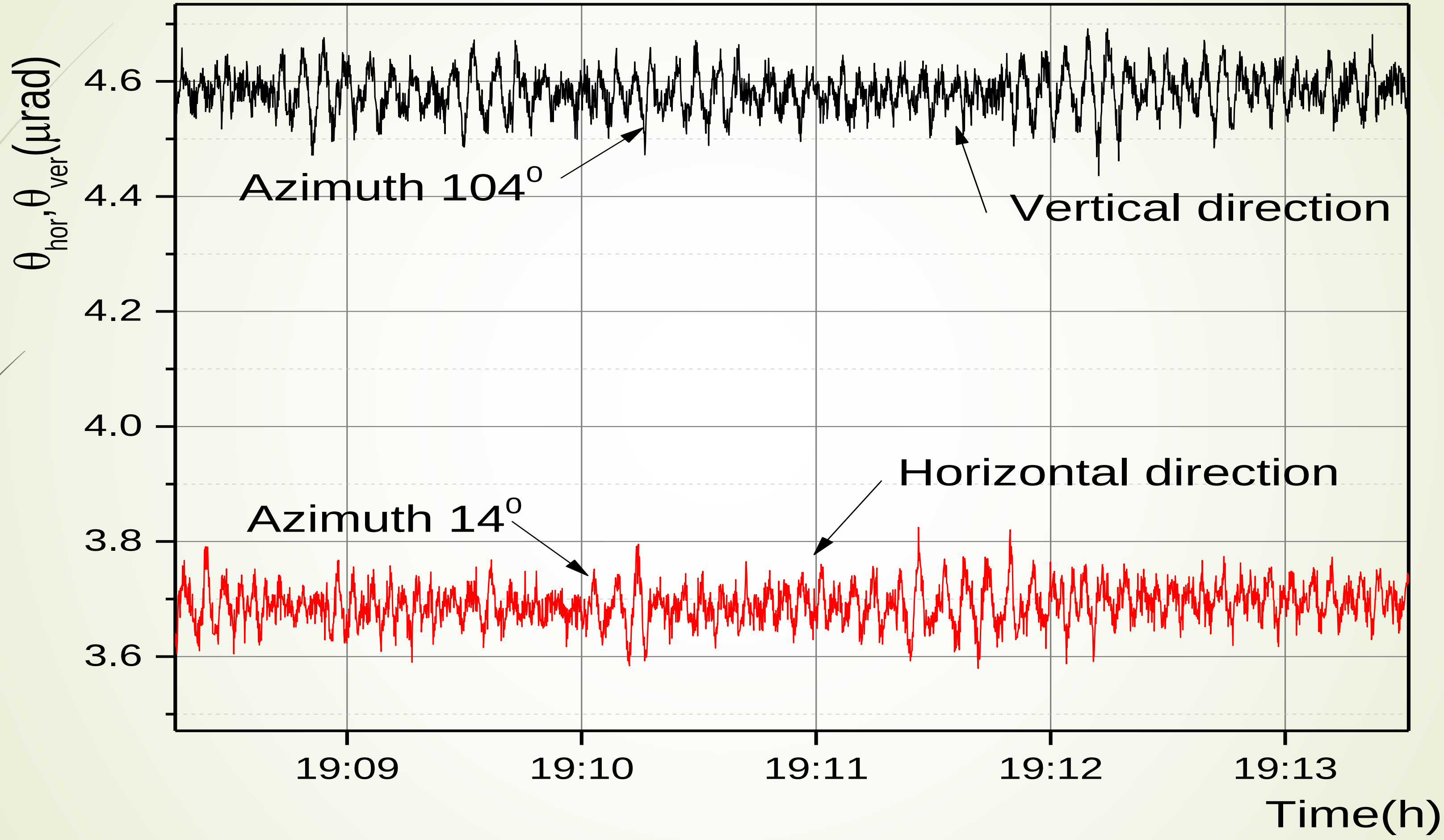
- Registration of the **4.8M** earthquake in Italy on **19 November 2017**

Registered microseismic signals: the angular slopes of the Earth's surface caused by the Moon and the Sun



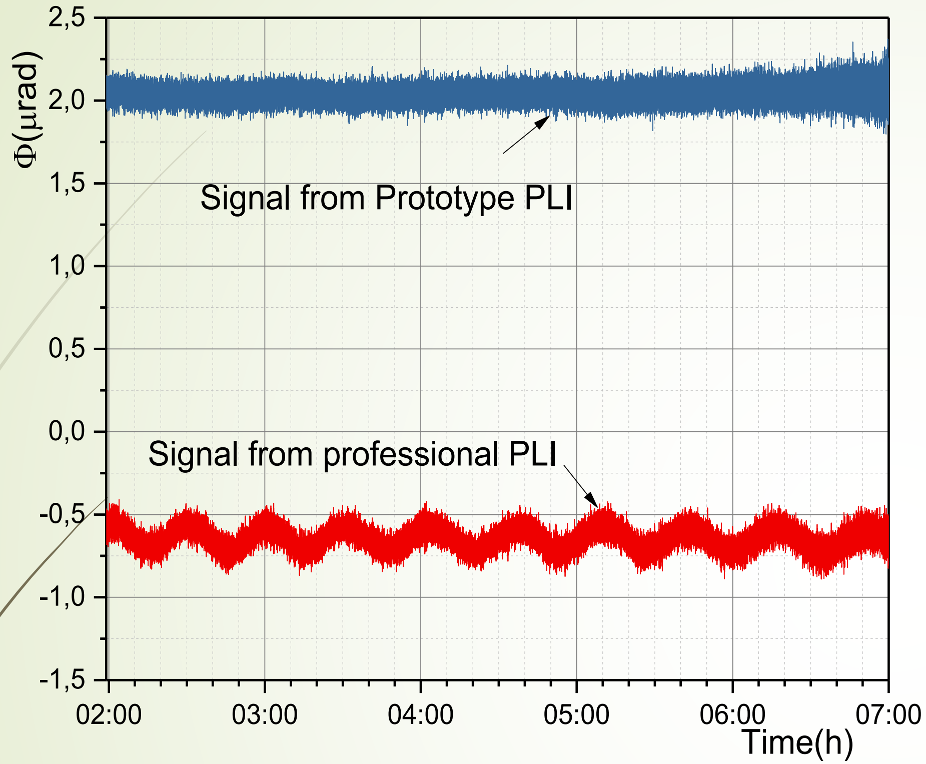
- There is a periodic **12 hour** signals of the inclination of the Earth's surface with an amplitude of **0.14μrad** in horizontal and **0.1 μrad** in vertical planes

Registered microseismic signals: "Microseismic Peak"

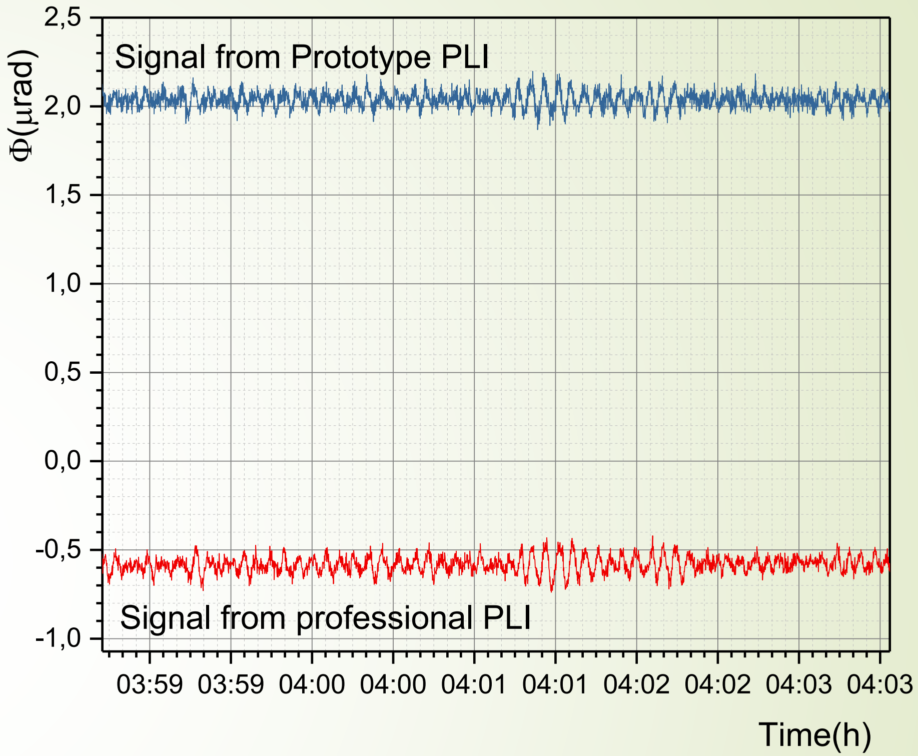


- Recording the periodic signal of the "Microseismic Peak"

Self-excited oscillation in the PLI and ways to minimize of their influence on the PLI data – Part 1



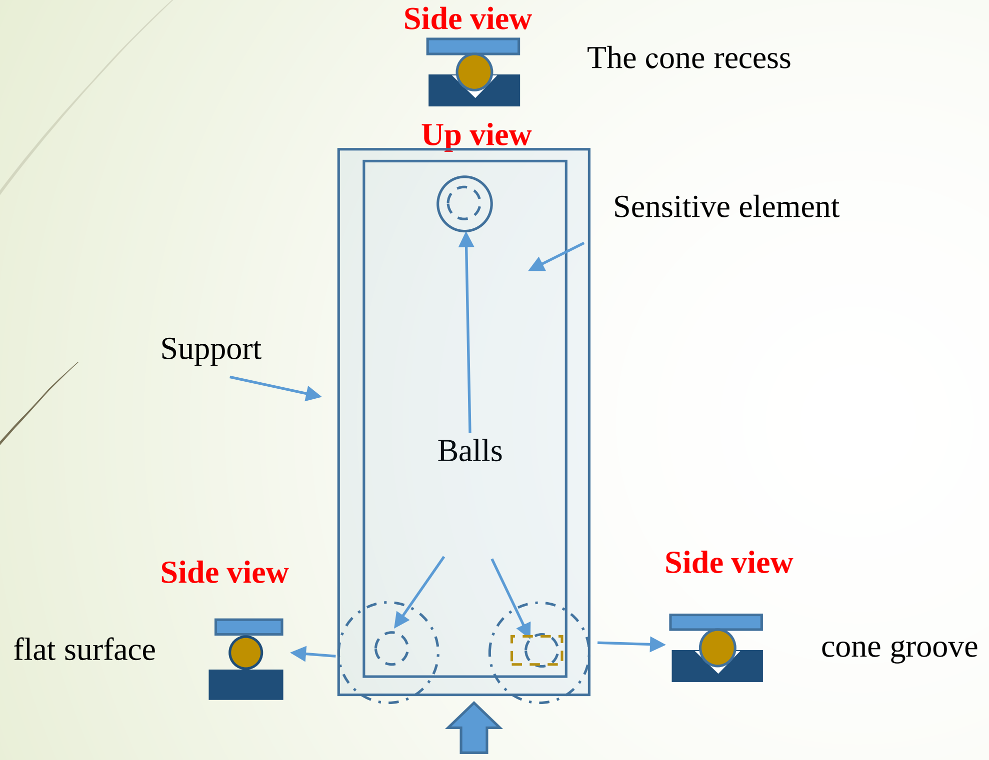
The auto-oscillation signal of the Professional PLI and the time-synchronized signal from the Prototype PLI

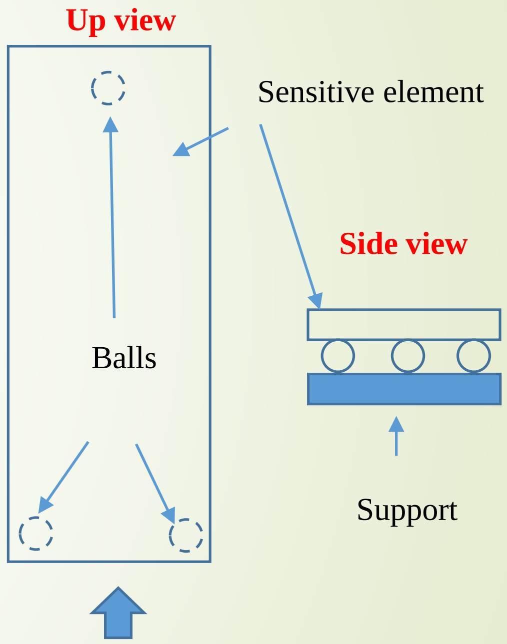


Coincidence of signals of the "Microseismic Peak" in the Professional and Prototype PLI

- There is a periodic (average period **of 32 min**) signal with an amplitude of **0.14 μrad,** which is absent in the simultaneously working Prototype PLI.
- At the same time, there is the amplitude and phase coincidence of the recording of oscillations of the “Microseismic Peak”.

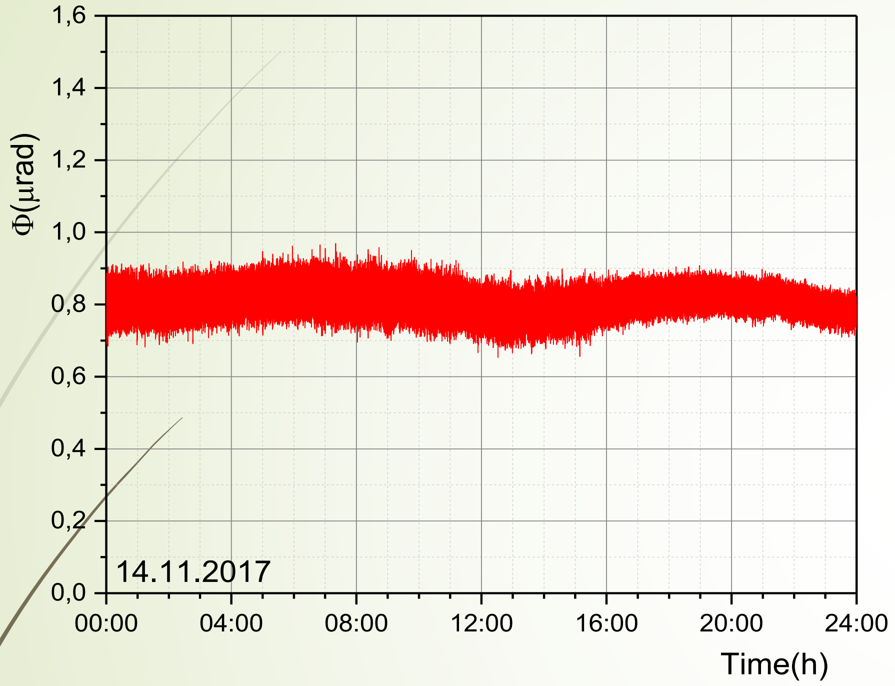
Self-excited oscillation in the PLI and ways to minimize of their influence on the PLI data – Part 2

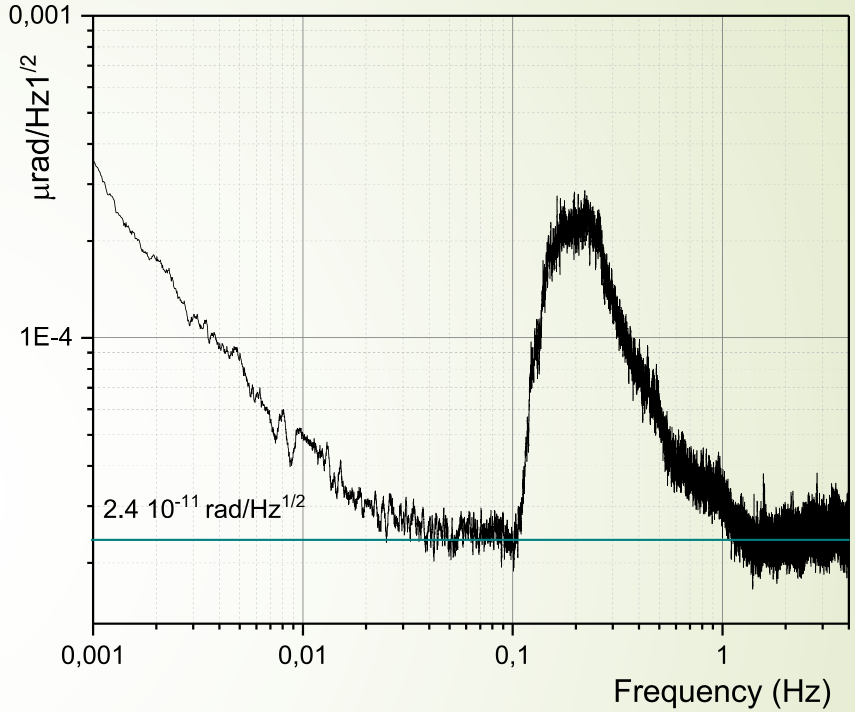




- Self-oscillation occurs in the points of the support of the sensitive element.
- There are no self-oscillations with the sensitive element mounted through the balls on the plane

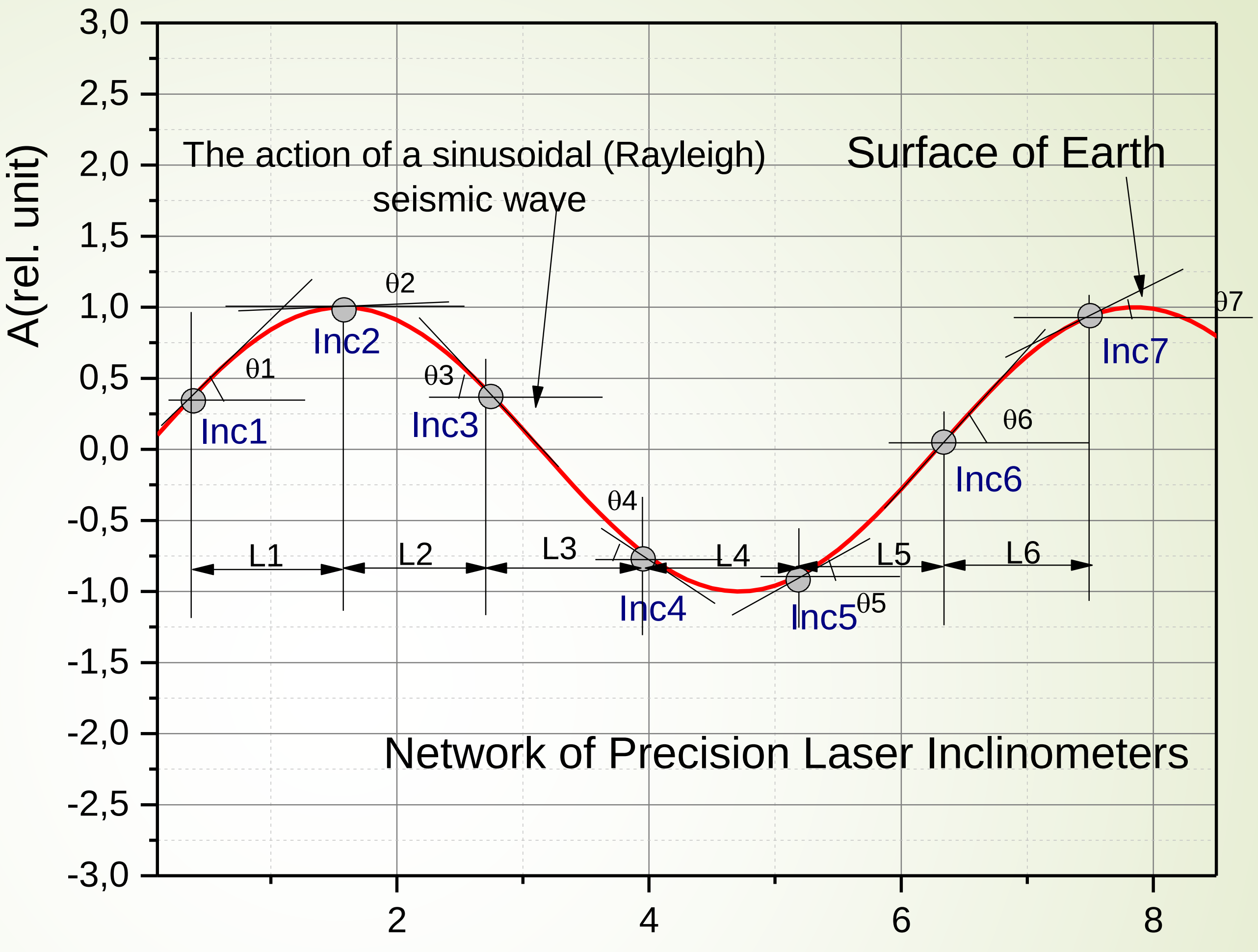
The achieved sensitivity of Professional Precision Laser Inclinometer





- The analysis of the measurements on November 14, 2017 with a relatively small level of the "Microseismic Peak" **(<0.1µrad)** shows:
- **The registered minimal microseismic oscillations is 2.4 10^{-11}rad/Hz$^{1/2}$**
- **The Instrumental noise is 3 10^{-12}rad/Hz$^{1/2}$**

Future Plans



- Using a distributed PLI network (**Inc1**, **Inc2**, … **Inc7**), one can visualize the passage of a Rayleigh wave on the Earth surface
- Knowing the distance between the Inclinometers **L1-L6** and the angles **θ1-θ7** recorded by these PLIs, it is possible to calculate the change in the height of seismic wave and, to determine the instantaneous Earth surface profile during the seismic waves propagation

Conclusion

- The results of testing of the new professional Precision Laser Inclinometer are presented
- Sensitivity of the PPLI has been increased and reached a level of **$2.4\ 10^{-11}$rad / Hz $^{1/2}$**
- Effective processing of daily measurement results with registration of microseismic phenomena are demonstrated
- The effect of self-oscillations in the support system of a sensitive element is detected. An effective way of neutralizing this effect is proposed.
- The creation of the PPLI's network will allow to determine the changes in the landscape of the Earth's surface under the collider. This information could be used by the feedback system to stabilize the colliders space focuses position. **It expectedly will increase the luminosity of the collider experiments.**