Observation of the 2D Earth surface angular deformations by the Moon and Sun with the Precision Laser Inclinometer

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(JINR and CERN)

Presented by M. Lyablin

CLIC WORKSHOP2017

To the Precision Laser Inclinometer Creation History

- **2008**: The first prototype R&D's; determination of the conditions for the high precision registration of an Earth surface angular oscillations
- **2012**: Russian Federation State Patent on the Precision Laser Inclinometer
- **2013-2014**: The experiments with the PLI prototypes in an air media
- **2015:** The creation of the vacuumed PLI prototype; experiments in the TT1 at CERN
- **2016:** The creation of an automated interferometric calibration of the Professional PLI

The Reports on the CLIC Workshops 2014-2015-2016

- **2014:** The presentation of the method
- **2015:** The registration by the PLI of the microseismic oscillations at the thermostabilized conditions
- **2016:** The comparison of an Earths quakes PLI measurements data with the Hydrostatic Level System data

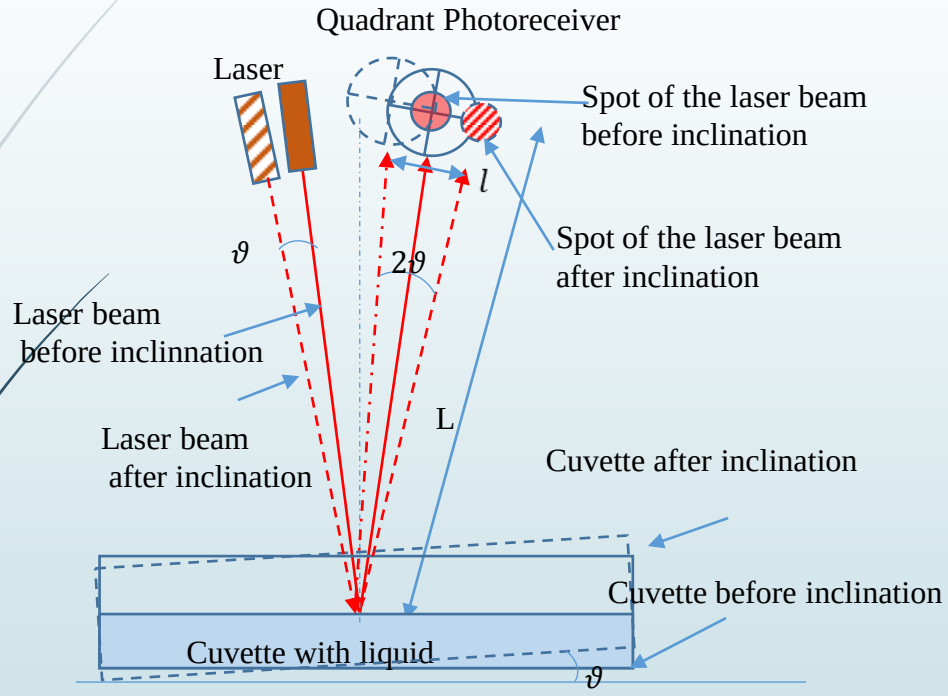
The Creation of the Professional Precision Laser Inclinometer

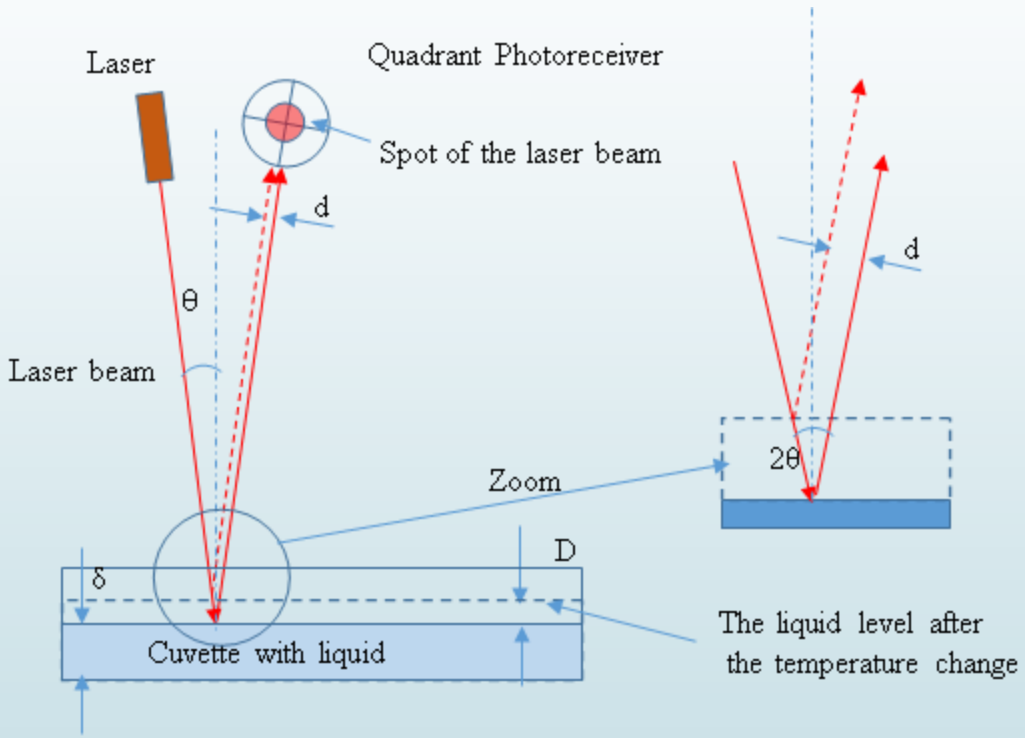
The Stabilizing and Service Systems are to be developed

1. The temperature stabilization of the PLI sensitive element,
2. An automated system for an accounting of the angular noise movement of the laser ray ,
3. The determination of the top edge of the PLI frequency diapason,
4. An automated system for two coordinates angular calibration,
5. The stabilization of the parameters of the registering ADC,
6. The production of the service code for the PLI,
7. The design study of the PLI and the creation of shop drawings,
8. Manufacturing of the PLI in the DLNP Workshop.

The temperature stabilization of the concrete floor in the CERN Transport Tunnel #1

The Laser ray space location changing in function of working liquid temperature variation





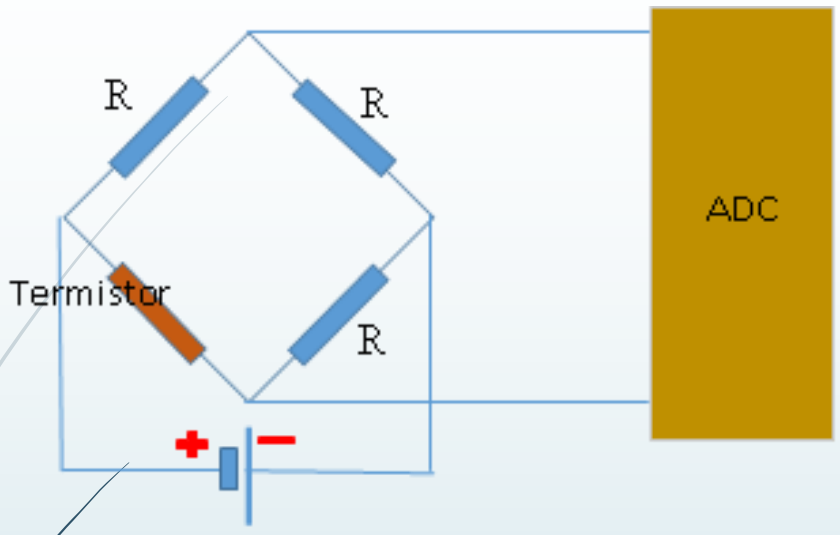
$$D = \delta\,\beta\Delta T, d = 2\theta D = 2\theta\delta\,\beta\Delta T,\ \vartheta = \frac{\theta\delta\,\beta\Delta T}{L},\quad \Delta T = \frac{L\vartheta}{\theta\delta\,\beta}$$

For L=0.5m, $\vartheta = 10^{-9}$ rad, $\beta = 6\cdot10^{-4}$ $^0C^{-1}$,

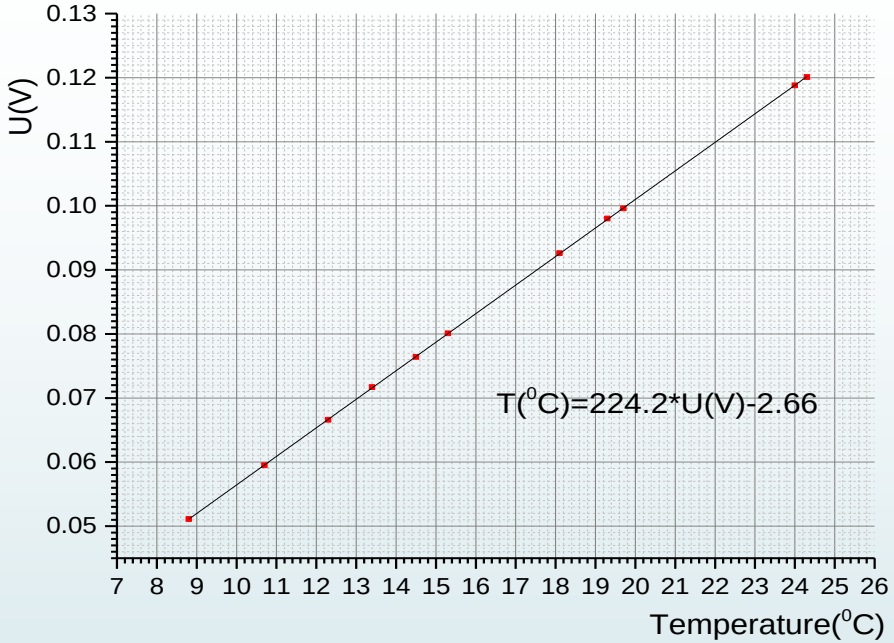
$\theta = 2.5\cdot10^{-2}$rad, $\delta = 4\cdot10^{-3}$m we obtain $\Delta T = 8.3\cdot10^{-3}\,^0C$.

The temperature stabilization on the level of **$8.3\cdot10^{-3}\,^0C$** for the day long period by the active thermostatic methods is currently impossible.

The Precision temperature measurement by the thermistor



The temperature measurement scheme by the thermistor in Winston-bridge chain

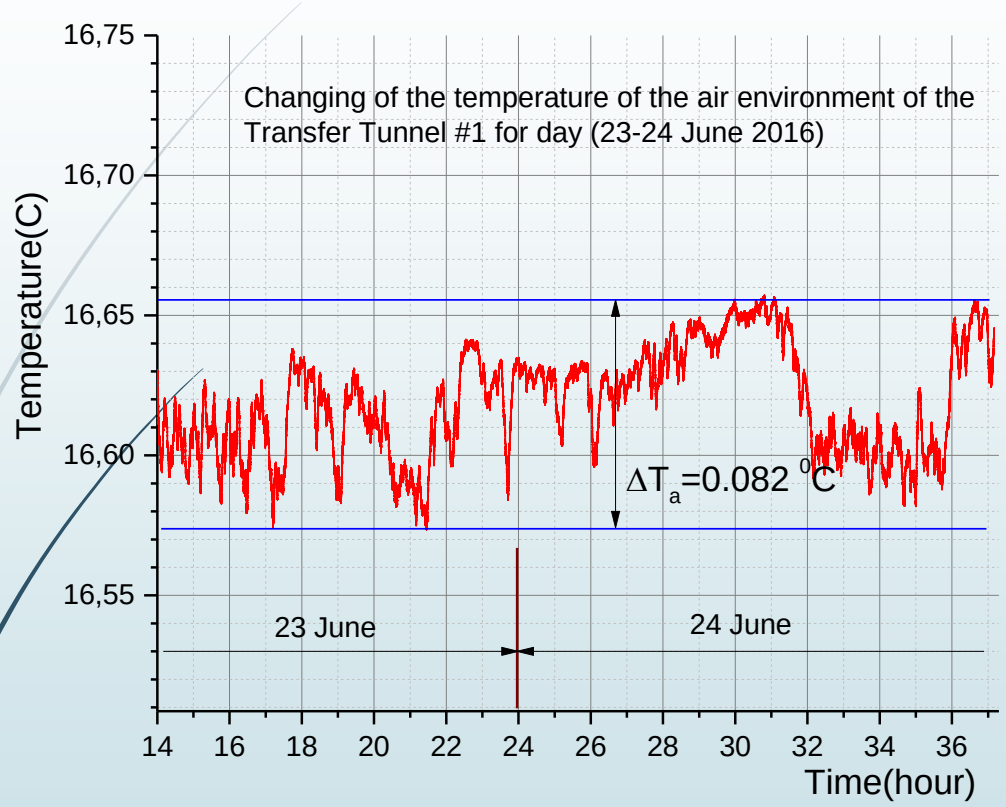


The thermistor signal in function of the outside temperature

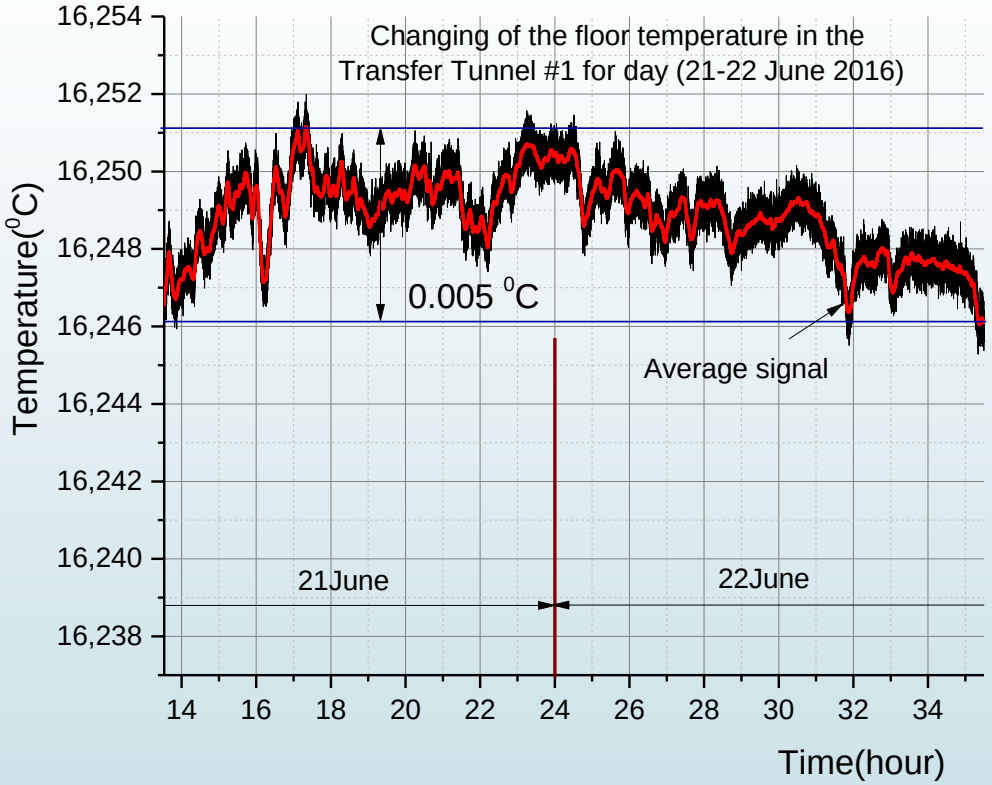
The temperature measurement in **[9 ^{0}C; 24 ^{0}C]** range.
After the fitting the σ_{rms} for experimental temperature points deviation from the linearity was **$0.77\cdot10^{-4}$ ^{0}C** and respectively for thermistor experimental points one gets **$0.78\cdot10^{-4}$ V**.

$$T(^0C)=224.2U(V)-2.66$$

The measurement of the temperature stability of an air media and of the concrete floor in the Transport Tunnel #1



The day long temperature variation in the air media of Transport Tunnel #1 for 23 ÷24 June 2016



The day long temperature variation in the concrete floor of Transport Tunnel #1 for 21 ÷22 June 2016

The local result

- To reach a day long (or more) measurement precision of **10^{-9} rad** one needs the temperature stabilizing of the **8 10^{-3} ^{0}C.**
- By the tested thermistor we have experimentally measured the day long temperature variation of an air media and of the floor in the **CERN Transport Tunnel #1**

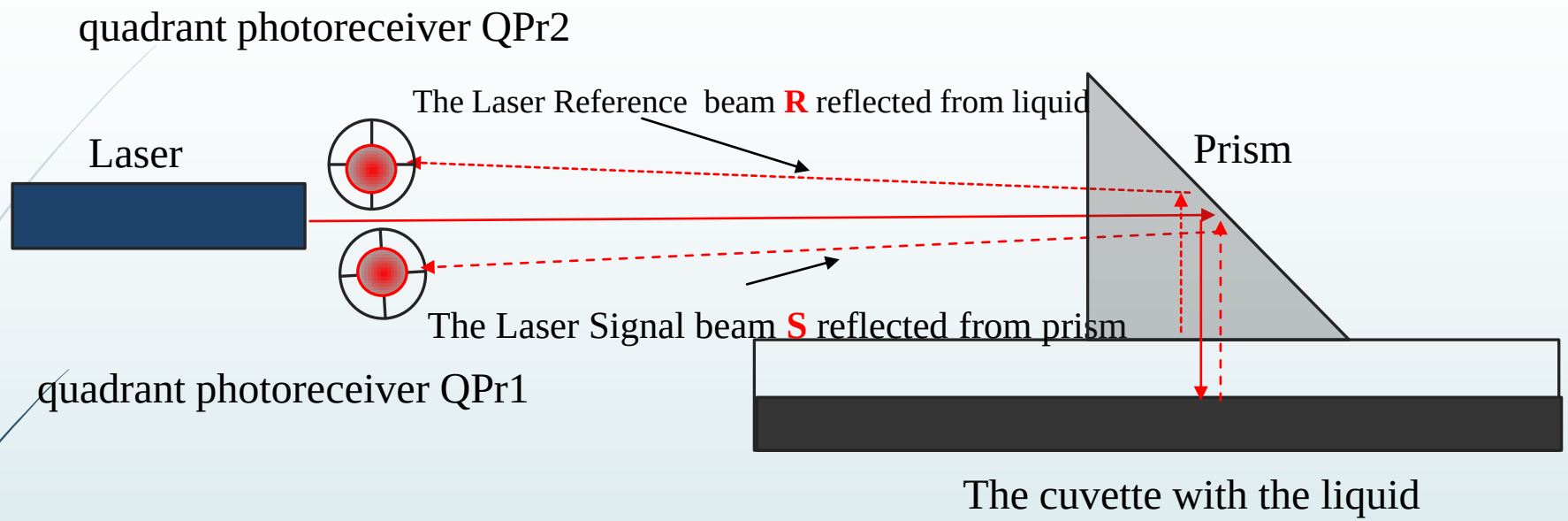
To be concrete:

- For the air media we obtained **8.2 10^{-2} ^{0}C**
- For the concrete floor we obtained **5.0 10^{-3} ^{0}C.**
- When using for the PLI the temperature stability of the **concrete floor** the high sensitivity range is getting wider and to be specific becomes [**10^{-6}Hz;1Hz**]; This achievement allows to detect in two angular coordinates the phenomenon of an Earth surface angular deformations by the Moon and Sun with the relative resolution **0.01** **(In the LHC location area)**.

The compensation of the noise origin laser ray oscillations in the Precision Laser Inclinometer

- The first measurement PLI data have developed on a **few microradian** level the noise signals with duration a few hours and longer. The further investigations have shown: the main reason for event observed is the noise origin laser beam axis angular oscillations
- Application of an active stabilization improves to the level of **10^{-7} rad** the space location stability of the laser irradiation direction

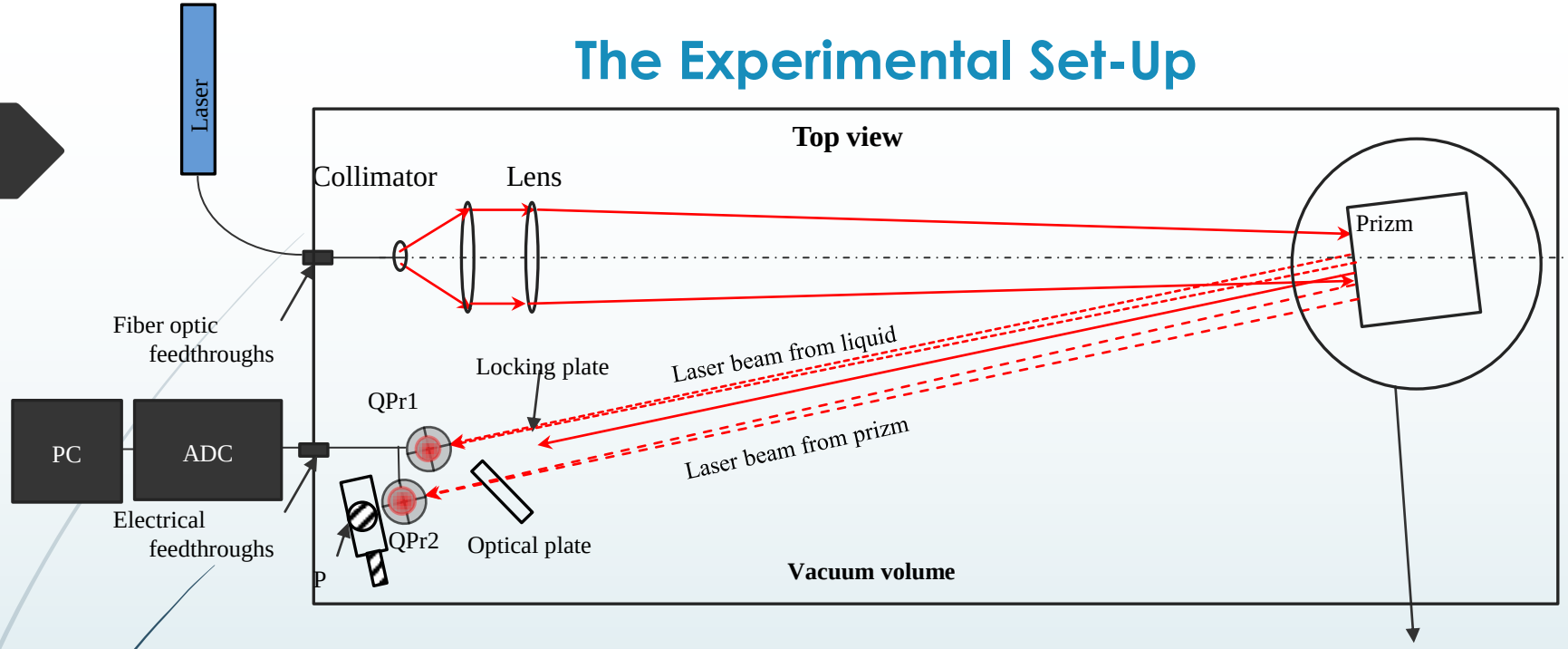
The system for compensation of laser ray angular movement in the Precision Laser Inclinometer

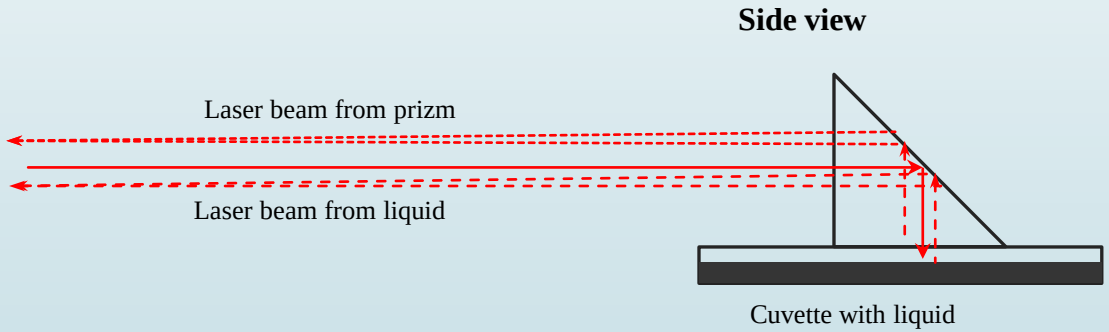


The registration of the noise origin laser ray angular oscillations in the PLI with the help of laser reference ray reflected from the deflecting Prism

- By use of the about similar space location of the signal **S** and of the reference **R** rays let from the registered signal **S** from the **QPR1** subtract the reference signal **R** from the **QPR2**.
- In result we get the signal for the Earth surface slope free from the noise of laser ray angular oscillations.

The Experimental Set-Up

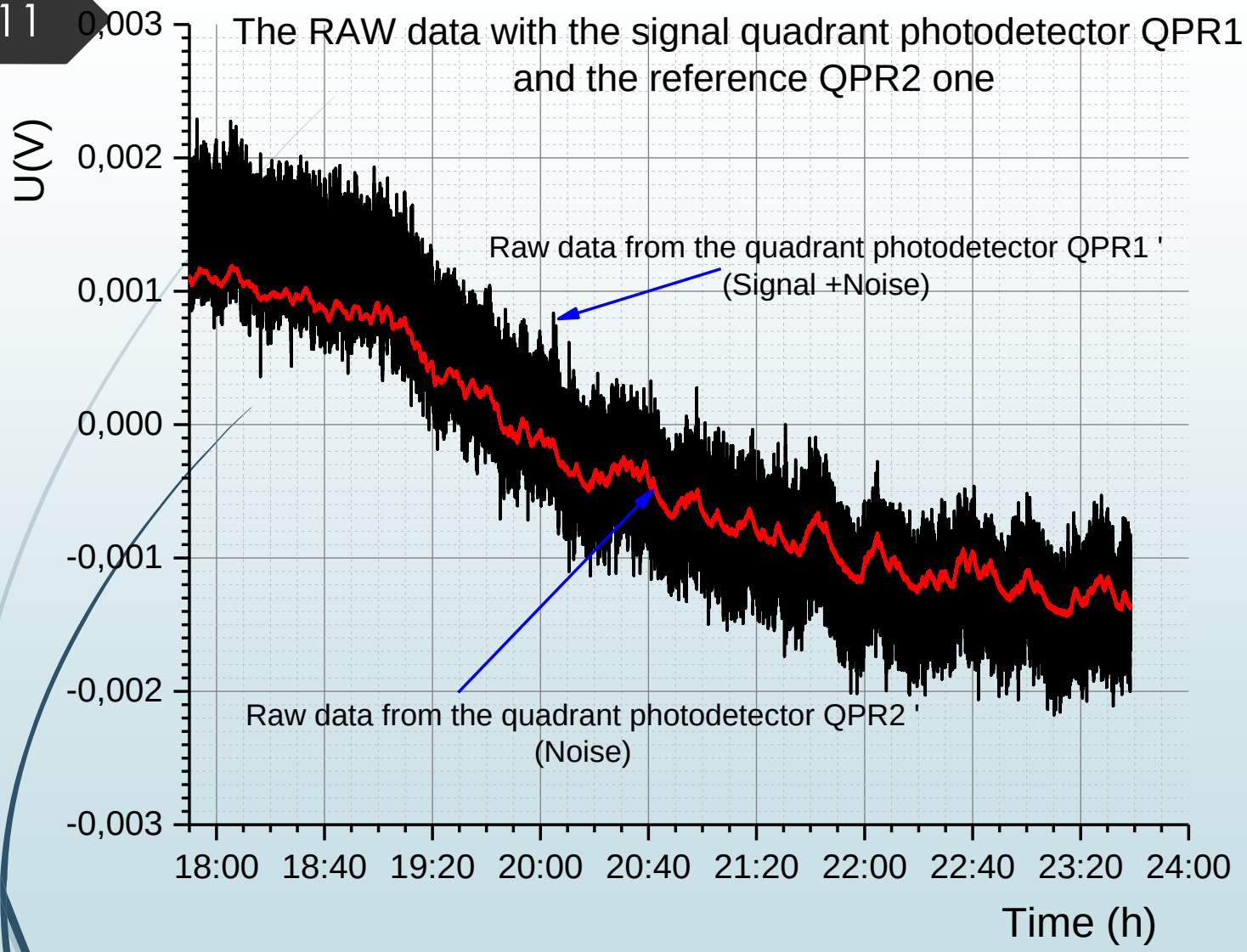




The Precision Laser Inclinometer with the possibility to compensate the laser ray angular movement of a noise origin

- In the experiment there were used the following time parameters: one measurement duration was **0.1sec**, the observation period was **6 hour** long

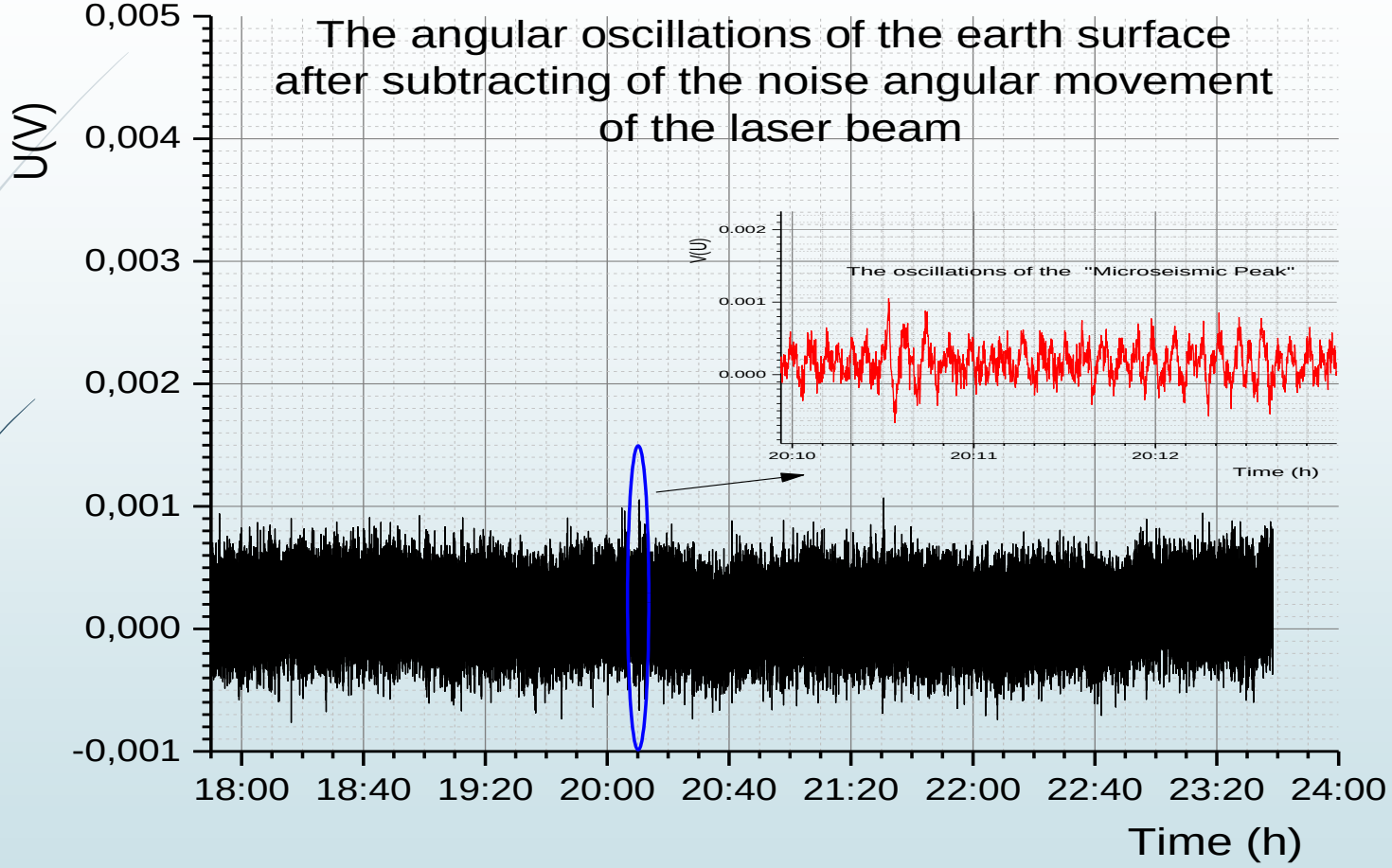
The Results of Measurements (A)



The laser ray spot displacement in one direction on the surface of the photoreceivers QPR1 and QPR2

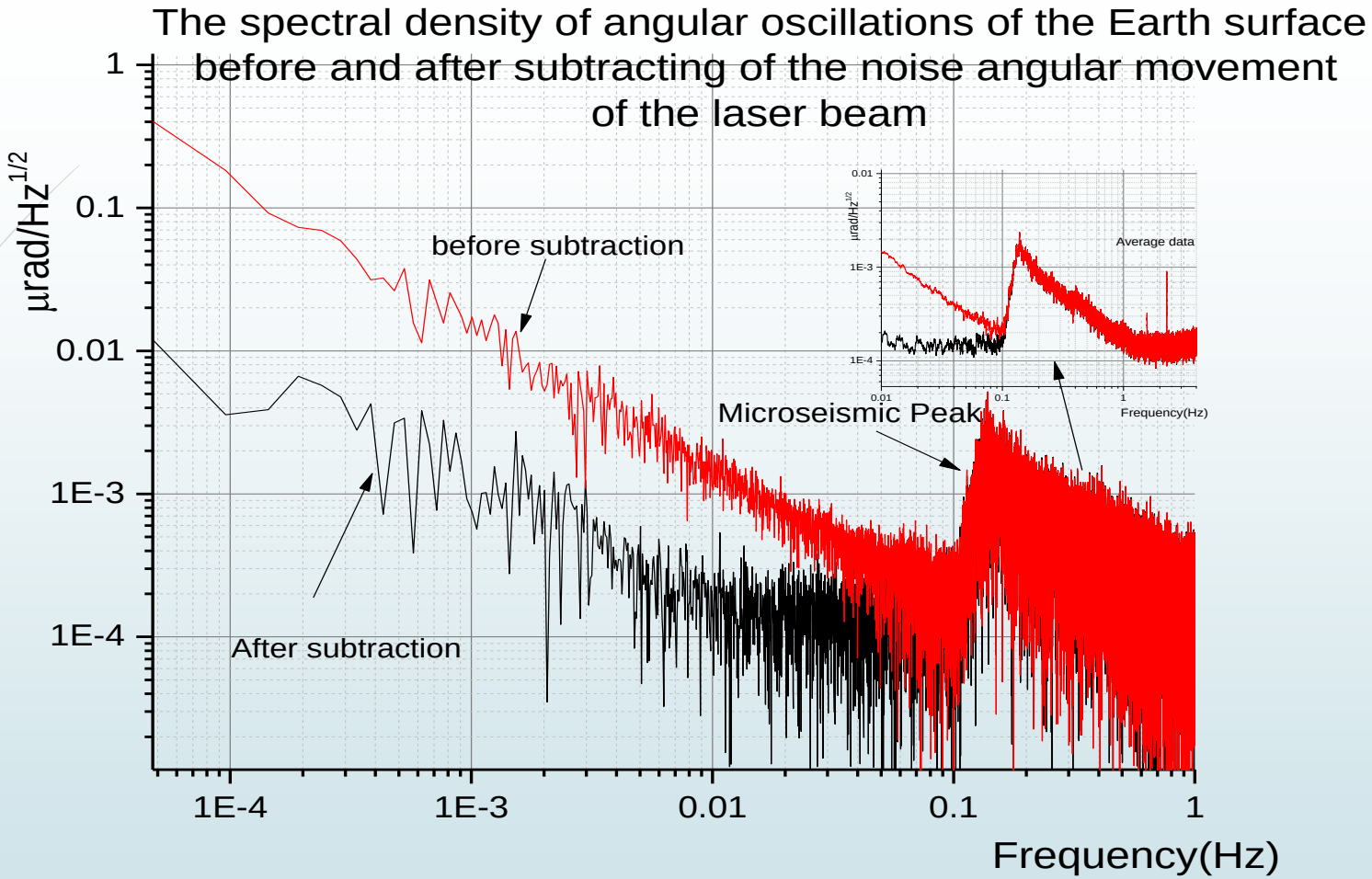
- As one may see the correlation of the Signal ray angular displacement and of the Laser Reference ray angular displacement has been observed.

The Results of Measurements(B)



- After the above indicated procedure the laser ray angular movement of a noise origin was suppressed significantly

The Results of Measurements (C)



The spectral density of the Earth surface angular oscillations of the signal ray: before and after subtraction of laser ray movement of a noise origin

- The significant– by the factor **30** x – reduction of the laser ray angular movement of a noise origin has been achieved in the **[5 10^{-5}Hz; 10^{-1} Hz]** frequency range. It is to be mentioned that in the frequency interval of **[510^{-5}Hz; 10^{-4} Hz]** the noise components have been reduced to level of **10^{-8} rad/Hz$^{1/2}$**

The determination of the maximal frequency for registration by the Precision Laser Inclinometer of the Earth surface angular oscillations

- When registering of the Earth surface angular oscillations of the seismic origin we stable observe the periodic seismic activity, - the so called “Micro seismic Peak” in **[0.1Hz;0.5Hz]** band .
- This peak is one of the most high frequency periodic phenomenon. The higher frequency periodic oscillations of the Earth surface have-as a rule-an industrial origin : vacuum pipes operating, traffic etc.
- The maximal frequency of the Earth surface angular oscillations achievable for registration by the Precision laser inclinometer has been determined.

The maximal frequency of the angular oscillation the Inclinometer is capable to register

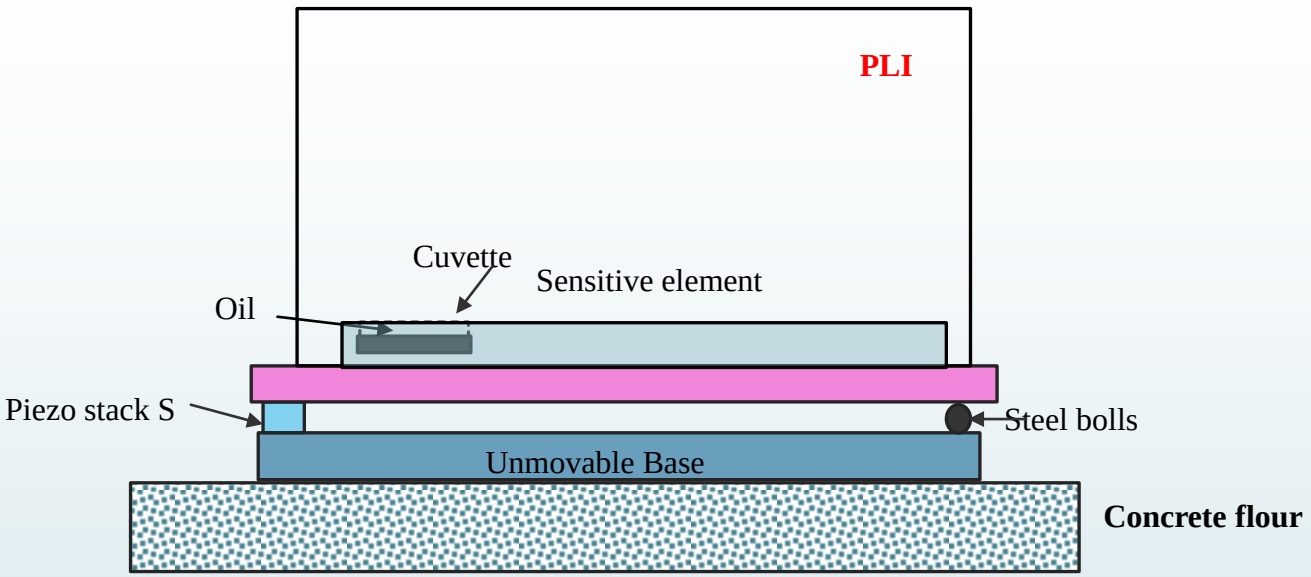
- The surface wave velocity in the thin layer of the liquid is given by the theoretic formula $\mathbf{V} = \sqrt{gd}$, where **g** is a free fall acceleration and **d**- thickness of layer of liquid.

- Velocity **V** does not depend on the frequency
- For the **4mm** thick liquid level the surface wave propagation speed is **19cm/sec**

- For **5cm** diameter of the liquid vessel the estimate for the expected maximal frequency to be registered by the PLI is $\frac{19cm/sec}{5cm} = 4Hz$

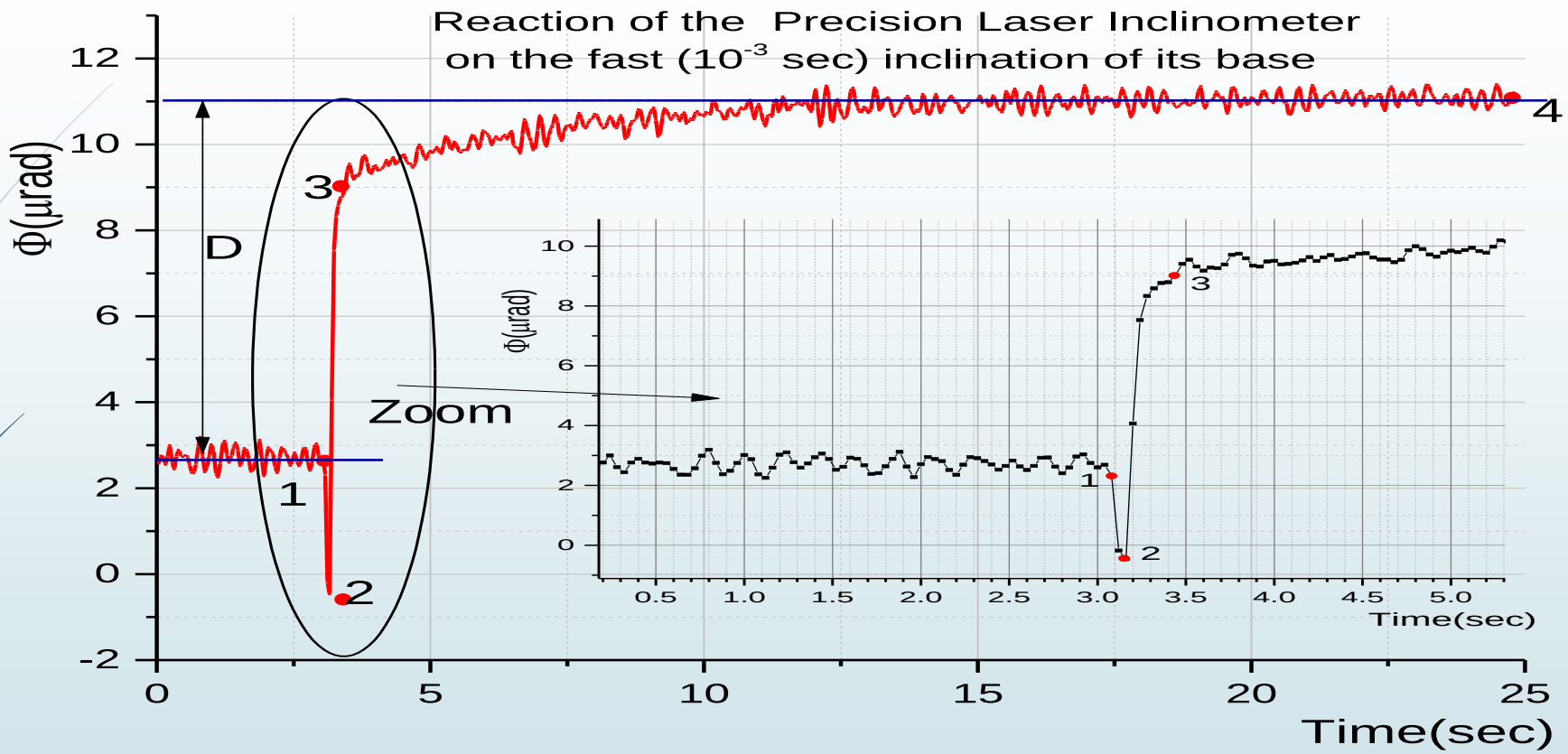
The Experiment

The experimental Set-up scheme for determining of the high frequency border of the PLI sensitivity interval



- The sensitive element –the cuvette with liquid –is located in the vacuum volume.
- As a liquid there was used an oil which has –preferably- the minimal evaporation in vacuum. The oil type **"I-20A"** also has been chosen with a condition to have a minimal cinematic viscosity **30 mm^2/sec** for **40^{0}C**. For the comparison we give the cinematic viscosity of the water at the same temperature **0.6 mm^2/sec**.
- On the piezo element **S** for the highly short time was applied the **50V** tension. For the period of the **10^{-3}sec** piezo element **S** had changed its length and lead to the platform inclination.

The experiment

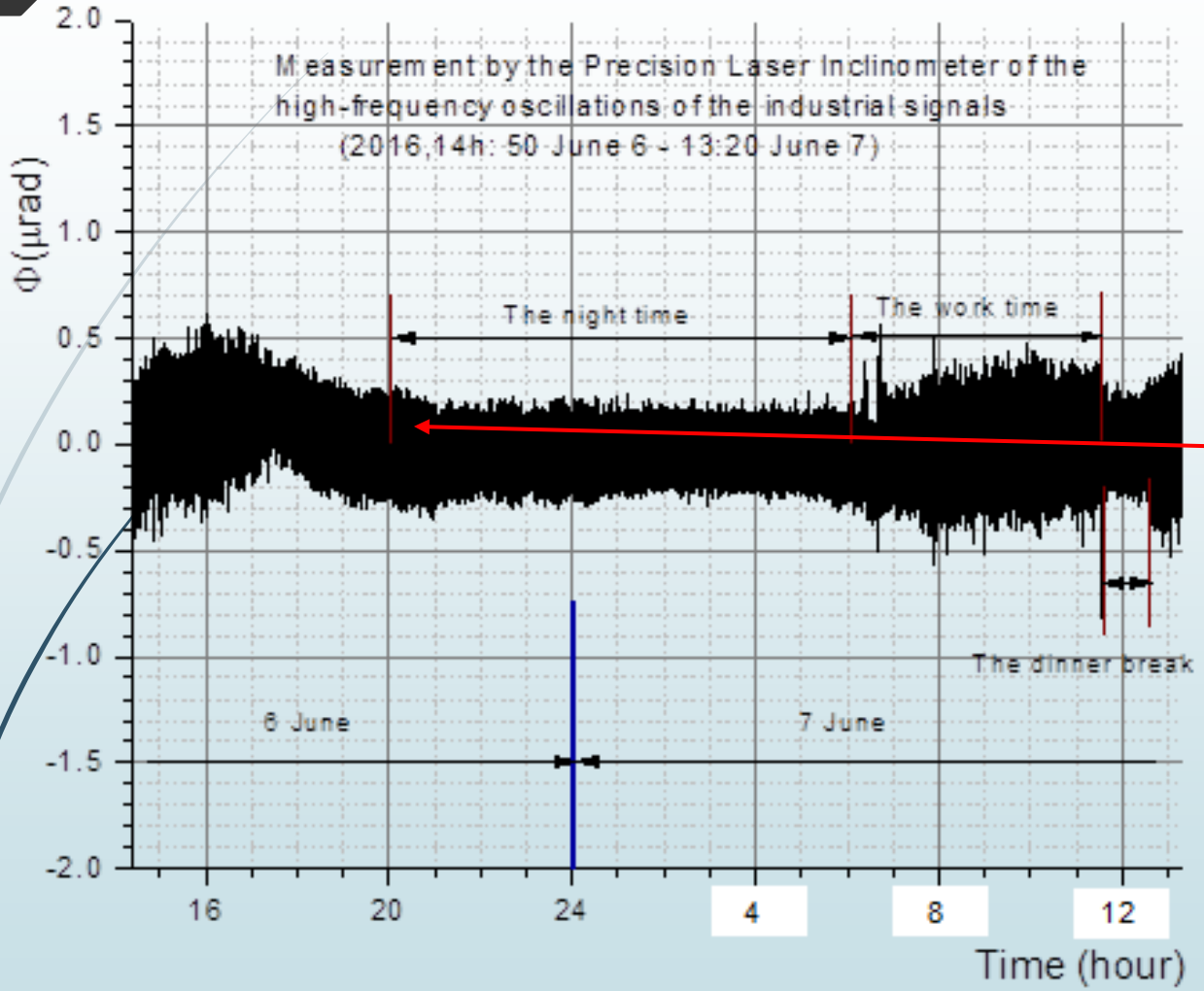


The phases of the inclinometer reacting on the fast inclination of its basement:

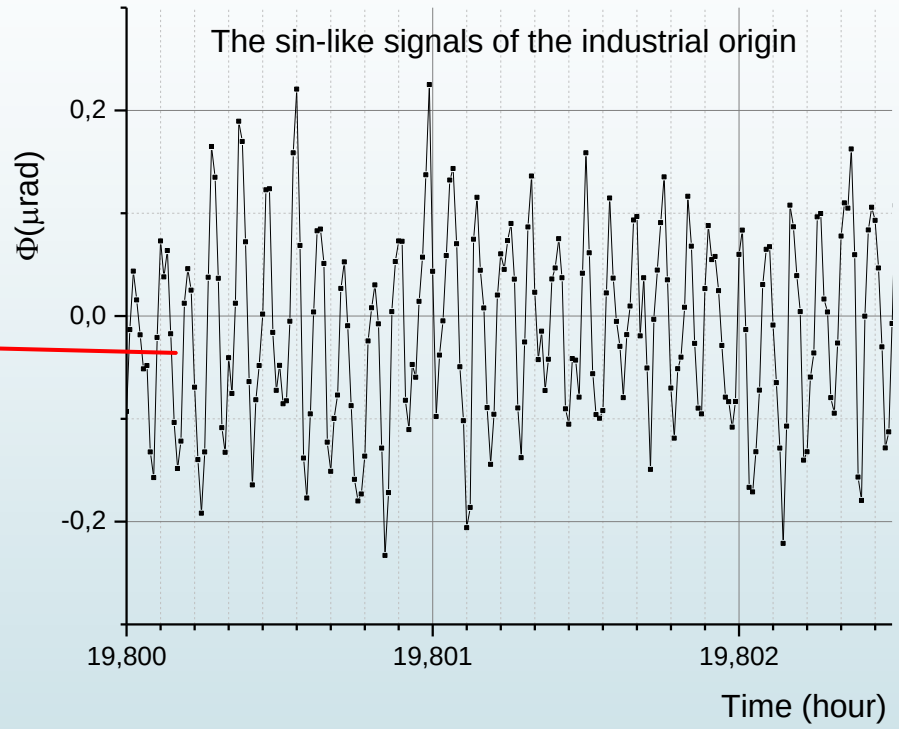
1. An inertial movement of the liquid in the inclination direction for **0.08sec** (between points **1-2**);
2. The reconstruction of the “horizontality” of the level of the liquid :

(2a) «fast» part, **0.24sec**, between **2** and **3** points; (2б) «slow» part, **20 sec** , between **3** and **4** points.

The registration by the Precision Laser Inclinometer of the high frequency signals of an industrial origin

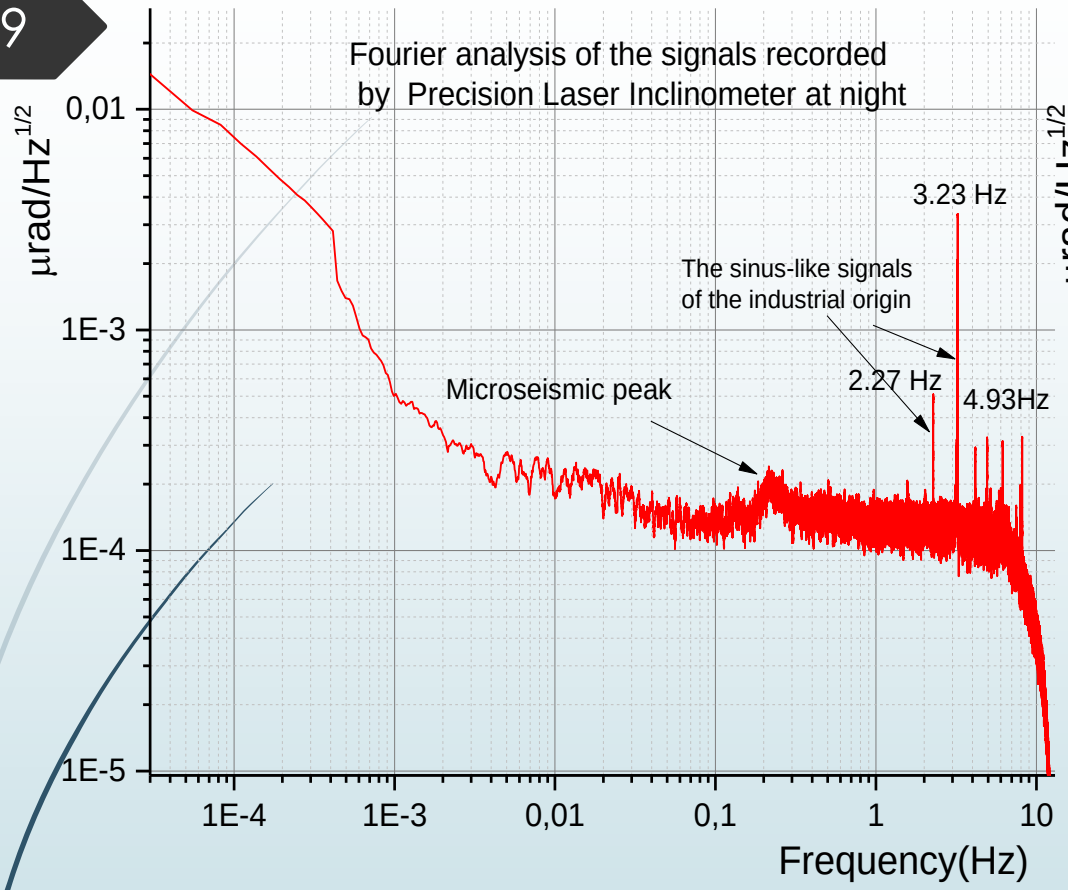


The PLI seismogram of the industrial noises registered for **one day duration**

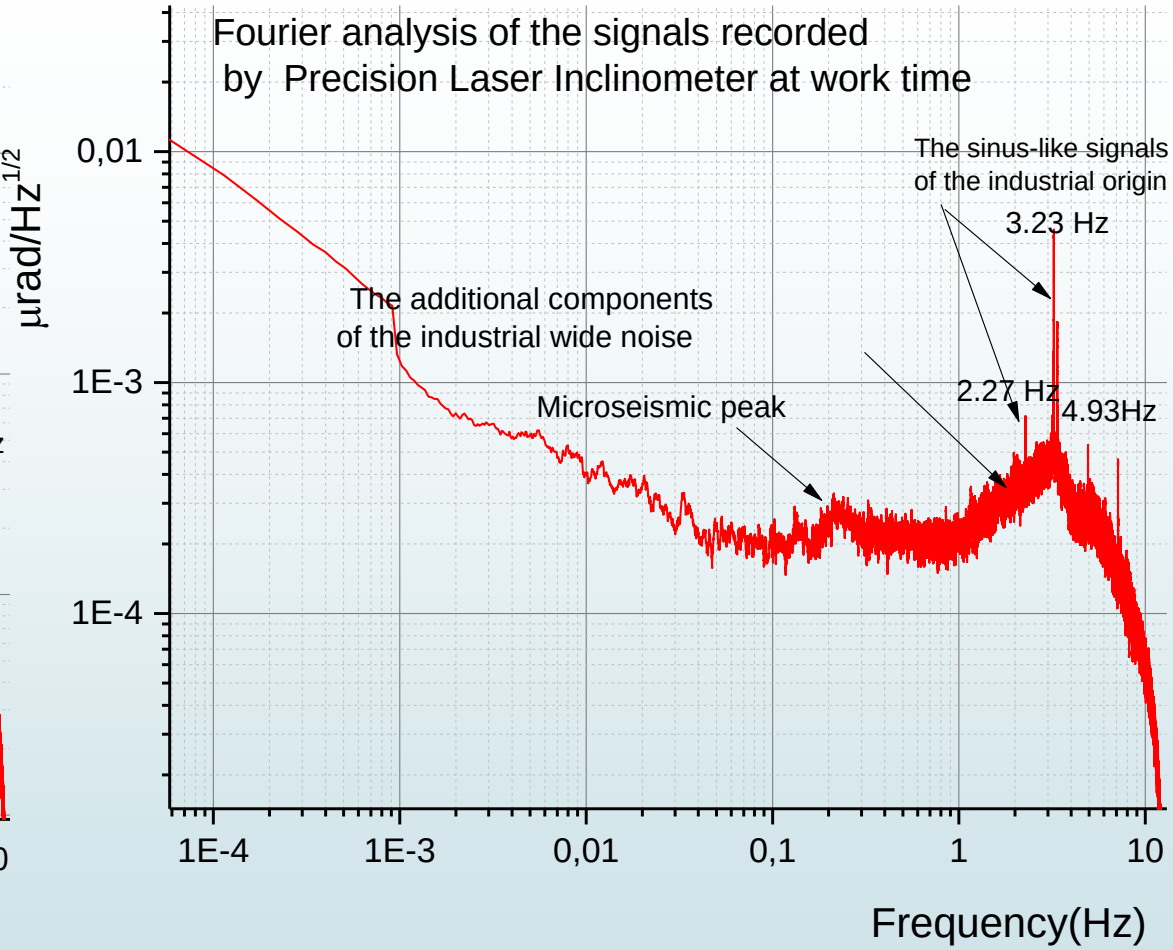


The registered sin –like signals of an industrial origin for **7sec**

The results of the Fourier analysis



The signals spectral density for the night time



The signals spectral density for the day time

The harmonic signals have been detected on the different frequencies. The dominating angular oscillation frequency for the Earth surface is **3.23 Hz**; the frequencies of **2.27Hz** and **4.93Hz** have also beenig observed.

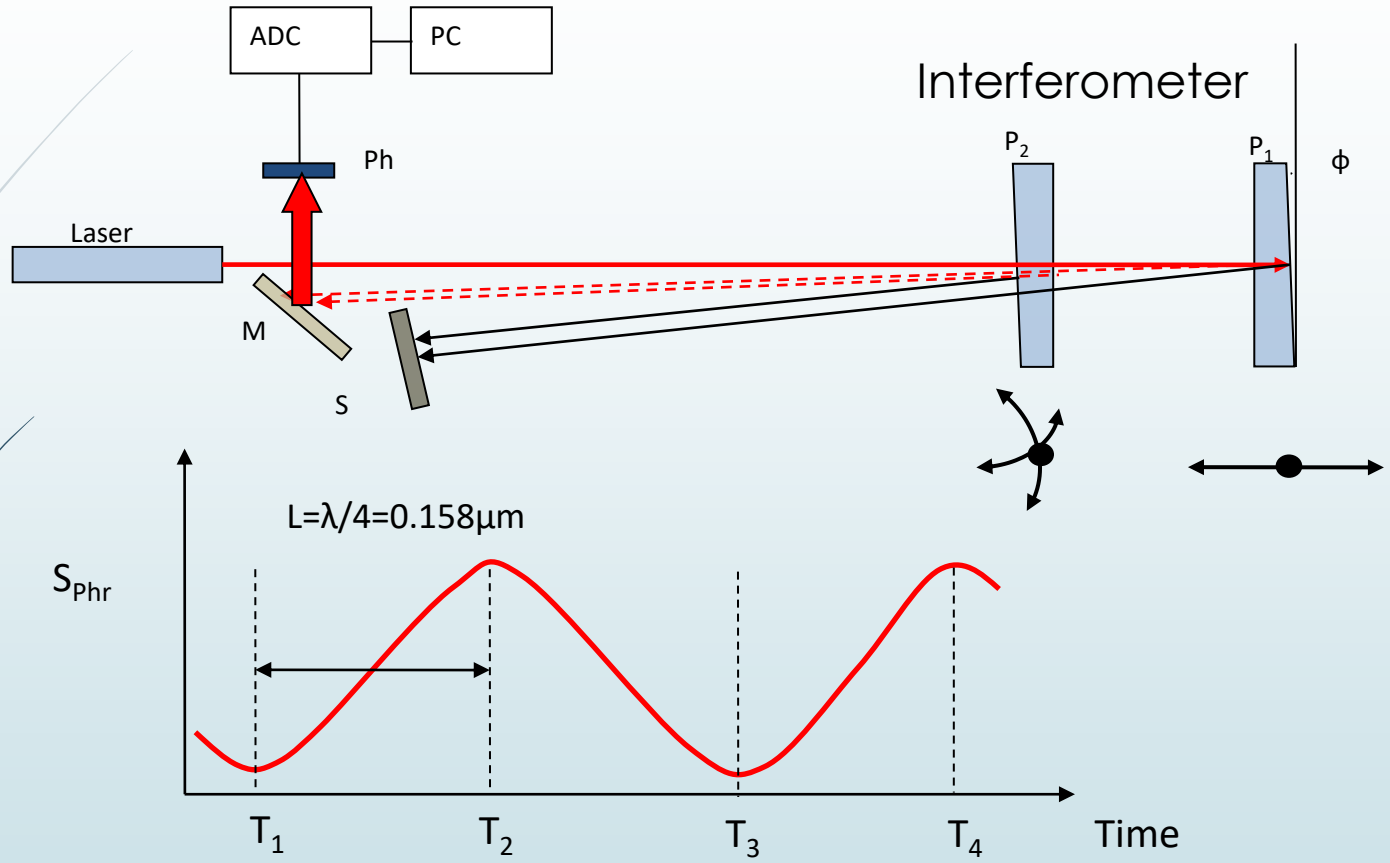
The local result

- The industrial oil **"I-20A"** has been used in the experiment at **16.2^{0}C** temperature in the vacuum conditions with **50mm** of cuvette diameter and **4mm** of the liquid depth . The upper border of **4Hz** was determined for the diapason of registrable frequency.
- The absence of the reflected waves on the surface of the liquid of the PLI has been proved experimentally, when fast inclination of the basement. It manifests the essential results: **the absence of the resonance effects in the PLI operation.**
- The narrow band signals of the Earth surface angular oscillations caused by the close working equipment have been registered; also the wide band industrial origin noise has been seen in the night and day observation periods.

The high precision interferometric calibration of the Precision Laser Inclinometer

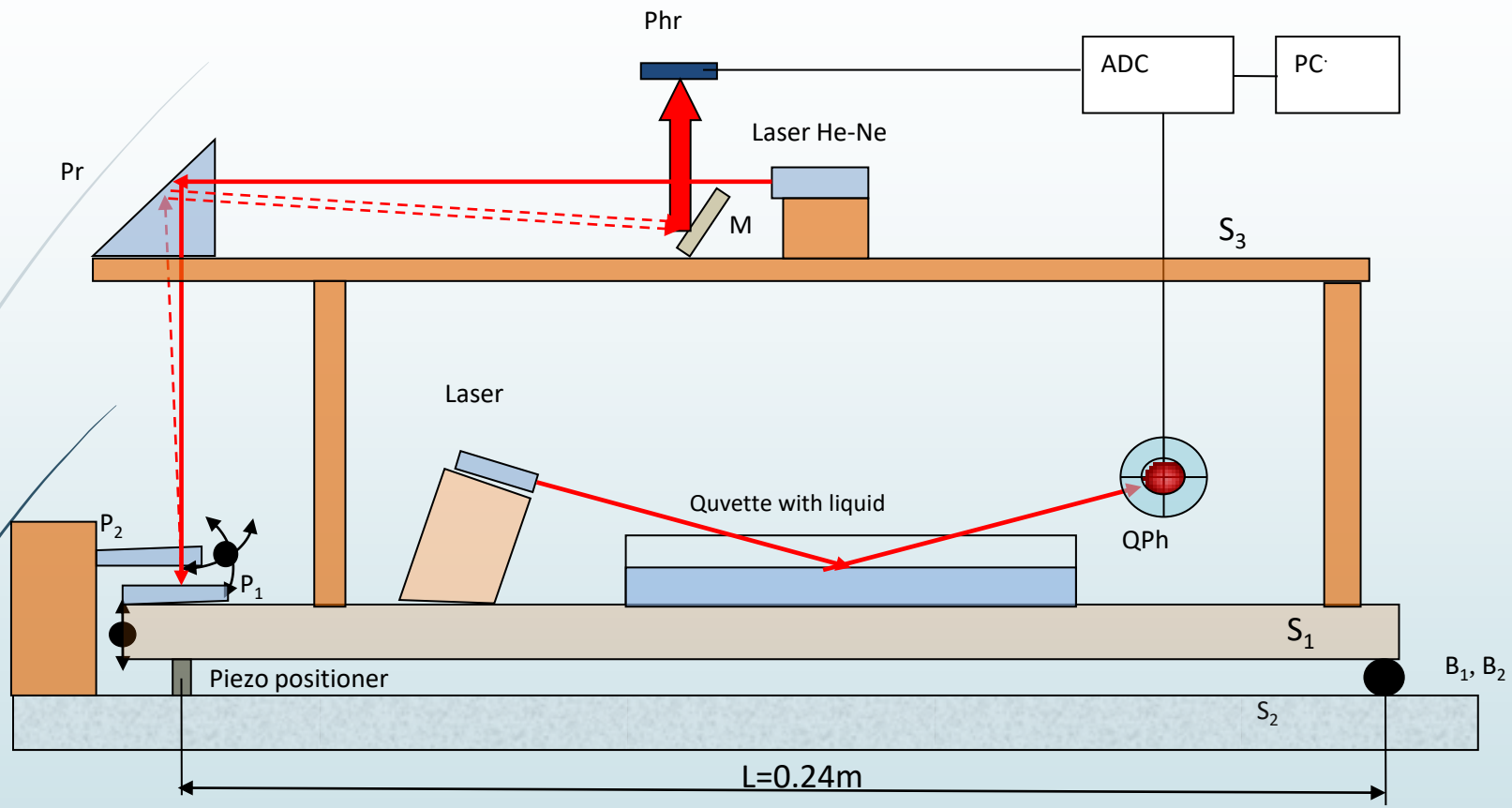
- For the effective use of the Precision Laser Inclinometer one needs to perform an automated precision calibration.
- Originally the "mechanical" calibration procedure was used with help of the vertical positioner.
- Its negative feathers are the following ones: unsatisfactory precision, the dependence from some external factors like temperature and pressure; absence of the possibility for the remount control measurements. All these circumstances have demanded the creation of the principally new calibration method.

The principle of the high precision INTERFEROMETRIC calibration of the Precision Laser Inclinometer (A)



- As a bases for the **INTERFEROMETRIC** measurement there was used the modified Fabri-Pero interferometer.

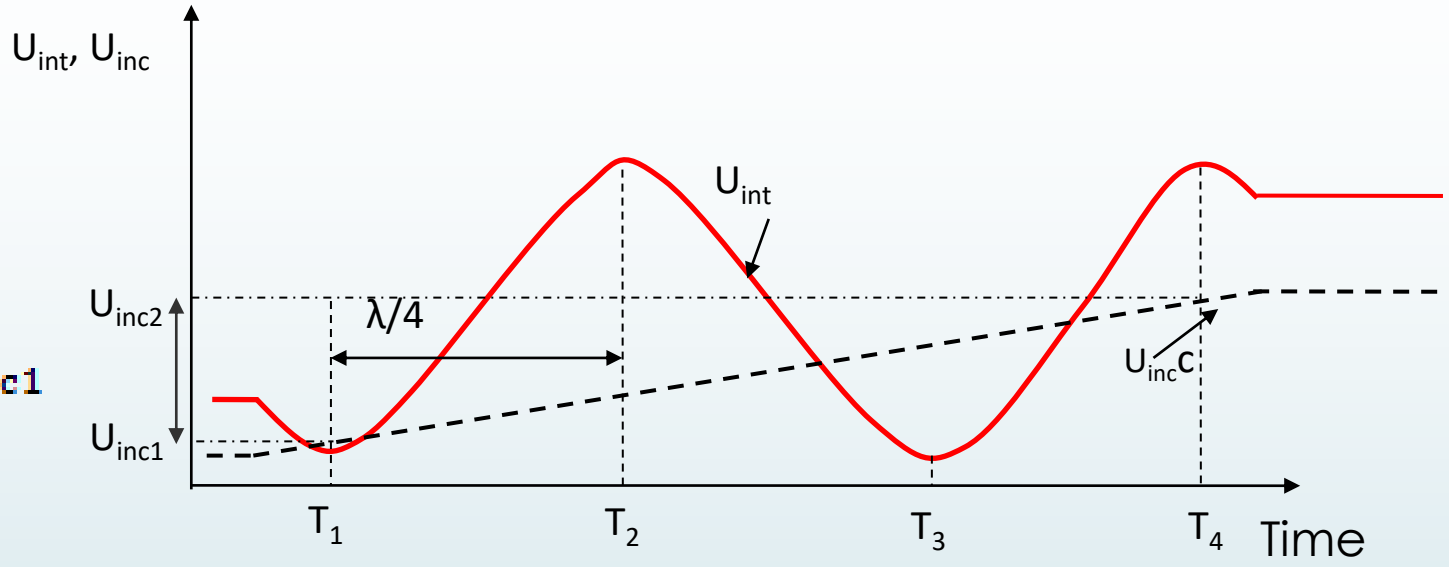
The principle of the high precision INTERFEROMETRIC calibration of the Precision Laser Inclinometer (B)



- The essential feature of the method: the **simultaneous measurements** of an interferometric picture **displacement** and of the **signal of the slope** of the Precision Laser Inclinometer appeared in the results of forced inclining of the platform of the PLI

The determination of the calibration coefficient $K = \frac{\theta}{\Delta U}$

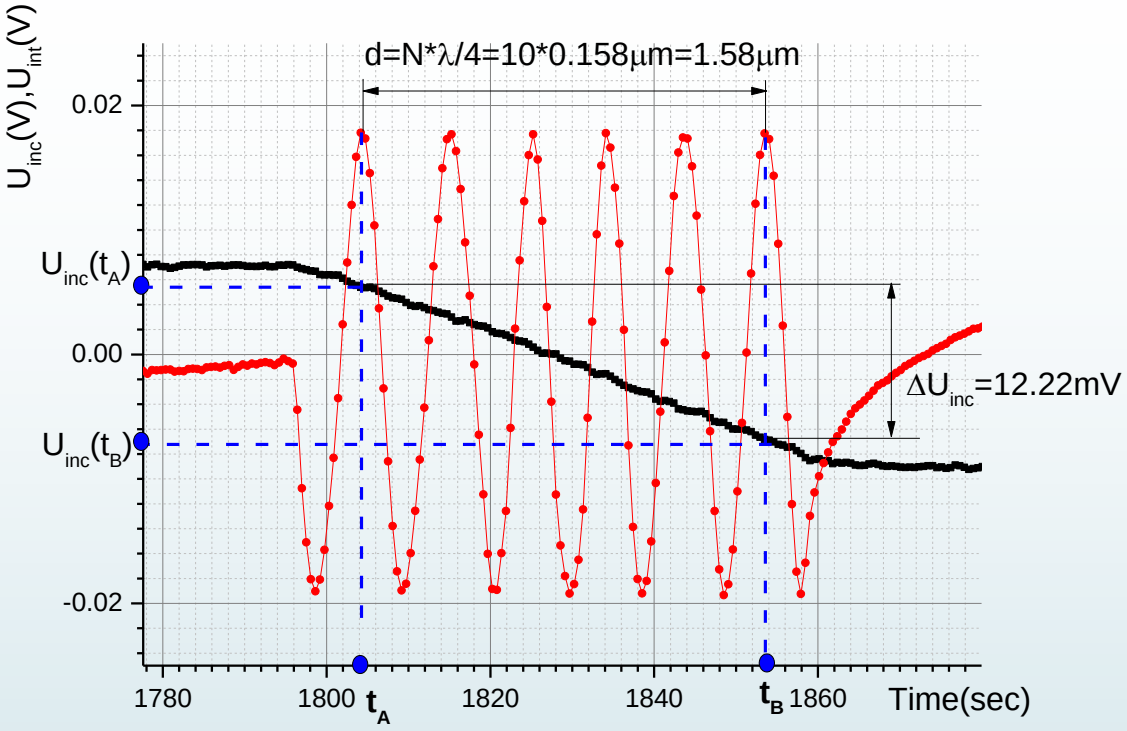
$$\Delta U = U_{inc2} - U_{inc1}$$



- First: Determination of the change **ΔU** of the interferometer signal corresponding to the angular displacement $\theta = \frac{\lambda}{4L}(N-1)$, where L - inclinometer base, N- number of the minima and maxima of the interference pattern.
- Second: the calibration coefficient **K** is being determined as a ratio of platform tilt angle **θ** to the "Volt" signal **ΔU** from the Precision Laser Inclinometer :

$$K = \frac{\theta}{\Delta U} = \frac{\lambda}{4L\Delta U}(N-1)$$

The experimental determination of the calibration coefficient



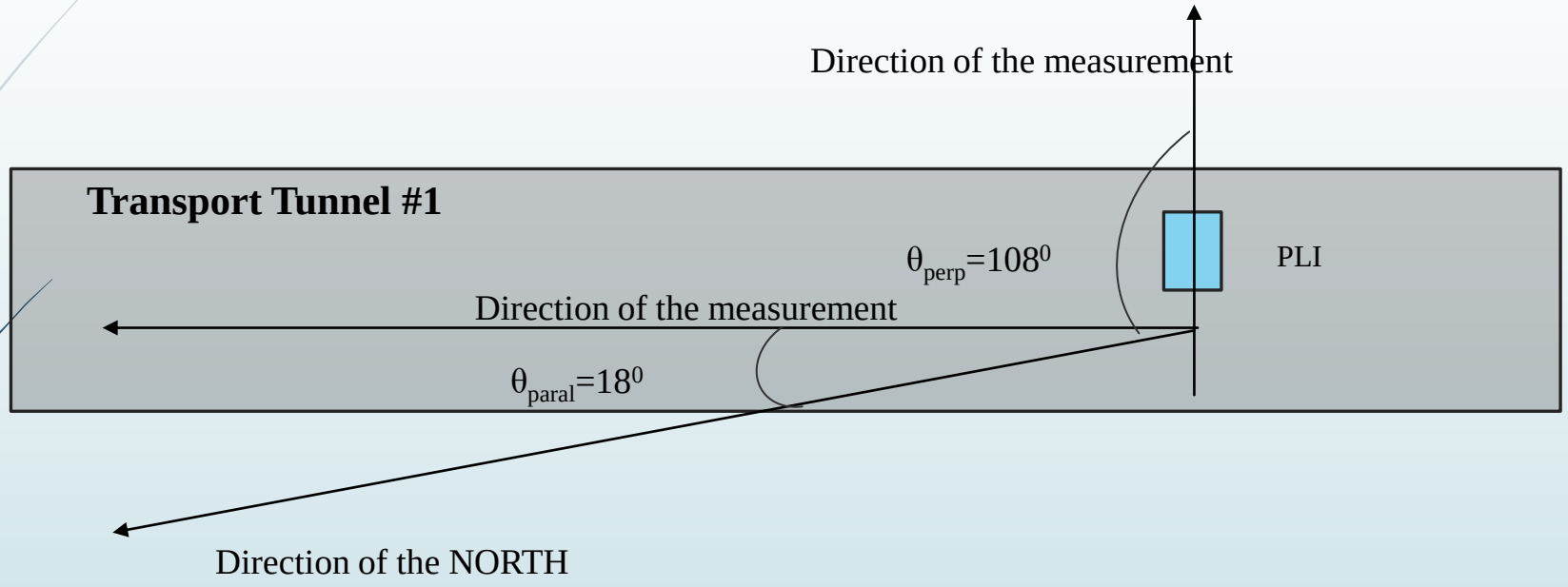
$$\theta = \frac{\lambda}{4L}(N-1)$$

- On the piezoelectric positioner was applied the growing tension in **0÷50 V** interval.
- The maximal vertical displacement of the support was **d=1.58±0.01μm** and it was corresponding to the calibration slope of the basement on the angle **θ=d/L=3.95±0.03 μrad**, where L=0.24m and is PLI basement length.
- This slope corresponds to the change of the signal **ΔU=12.22mV** from the inclinometer.
- Based on the **nine measurements** for $K = \frac{\theta}{\Delta U}$ one gets $\bar{K}$**= 322.5+1.9 μrad/V**.

The local result

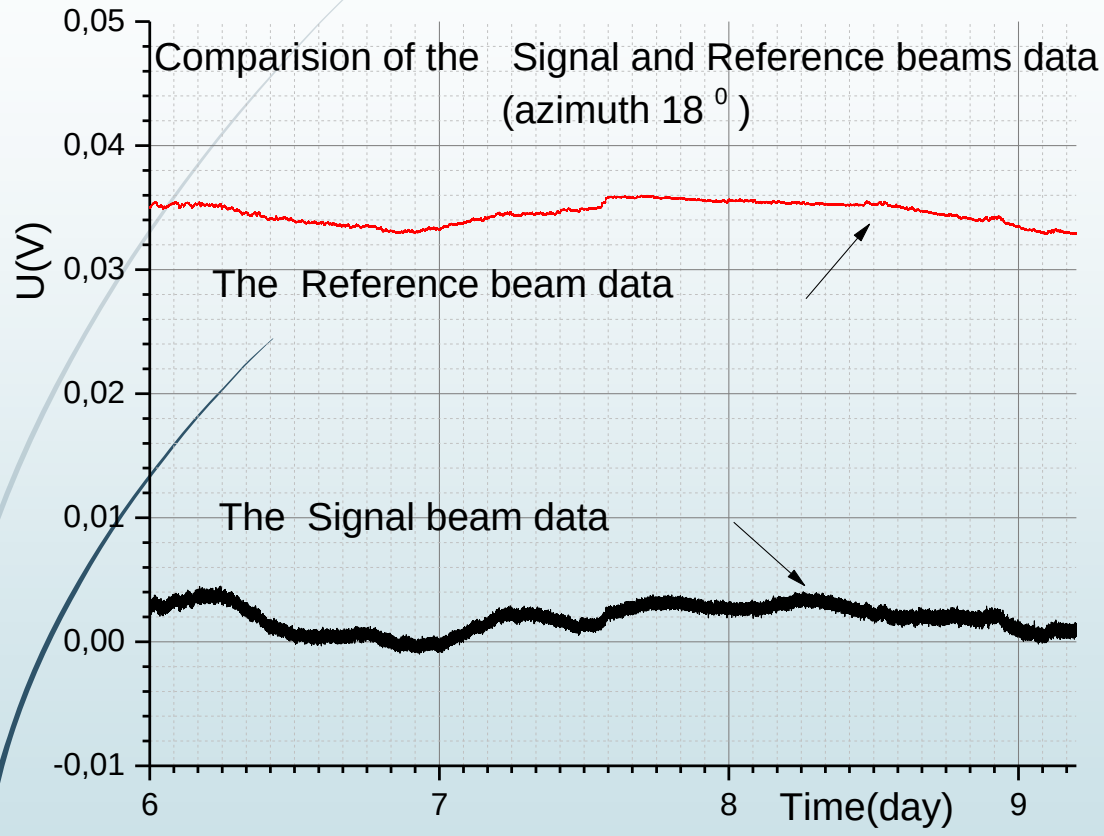
- There was proposed and realised an innovative method of the INTERFEROMETRIC calibration of the Precision Laser Inclinometer. The idea of the method is the SIMULTANEOUS measurement of the calibration slope (a) by the INTERFEROMETER and (b) by the INCLINOMETRE.
- The new automated calibration process has removed the systematic errors caused by temperature and pressure variations.
- In set of **nine** independent calibrating measurements there was determined the calibration coefficient $\bar{K}$**= 322.5+1.9 μrad/V**.
- Therelative precision of the calibration coefficient is **0.6 %**

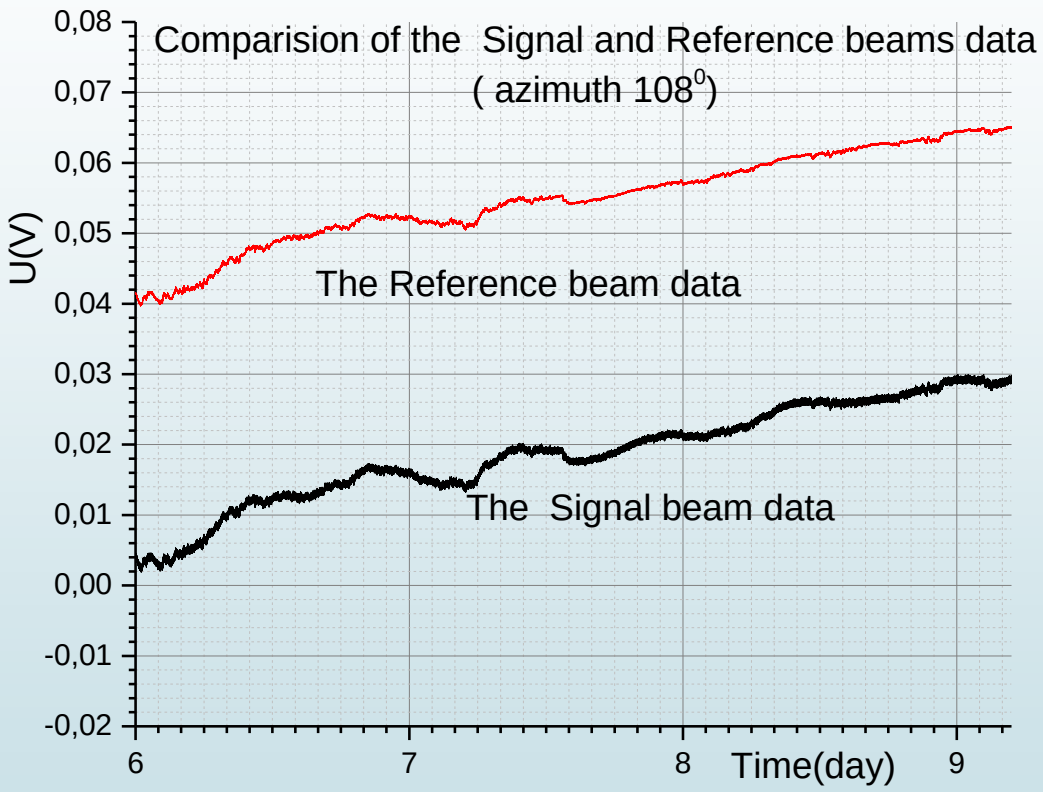
The location of the Precision Laser Inclinometer in the Transport Tunnel # 1



The PLI position during measurements in the TT1

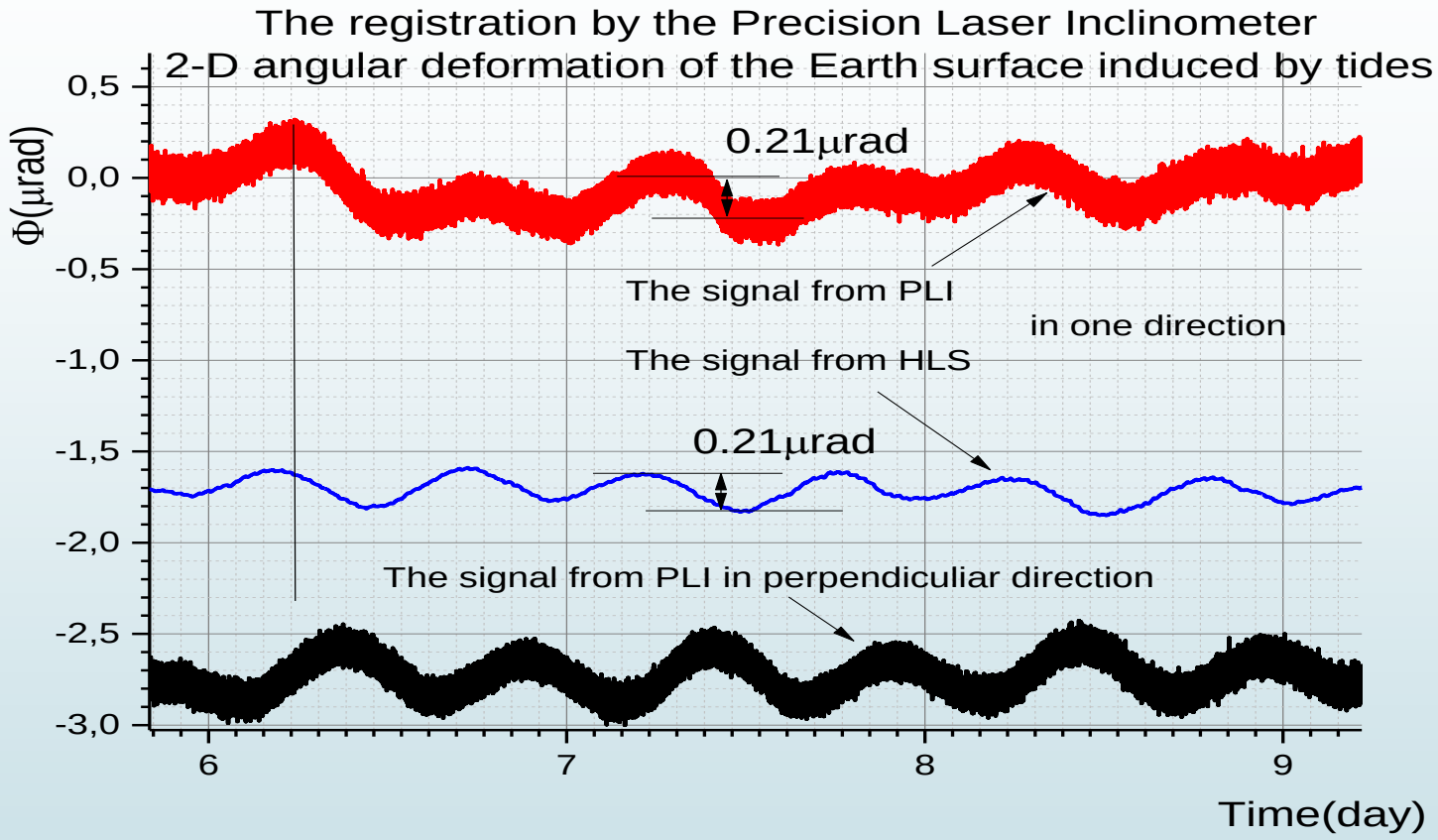
The registration of 2D angular inclinations of the Earth Surface caused by the influence of the Moon and Sun in the LHC location area





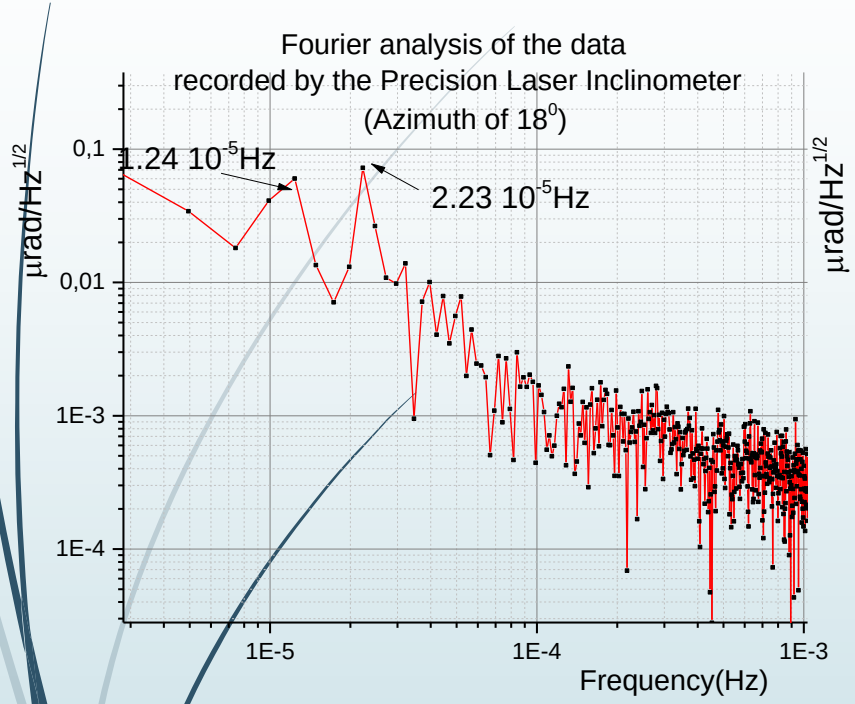
- The data of the **3-day (6÷9 May 2016)** long measurements of the signal and the reference beams in **TT1** in two mutually perpendicular vertical planes (azimuthes **18^0** and **118^0**)

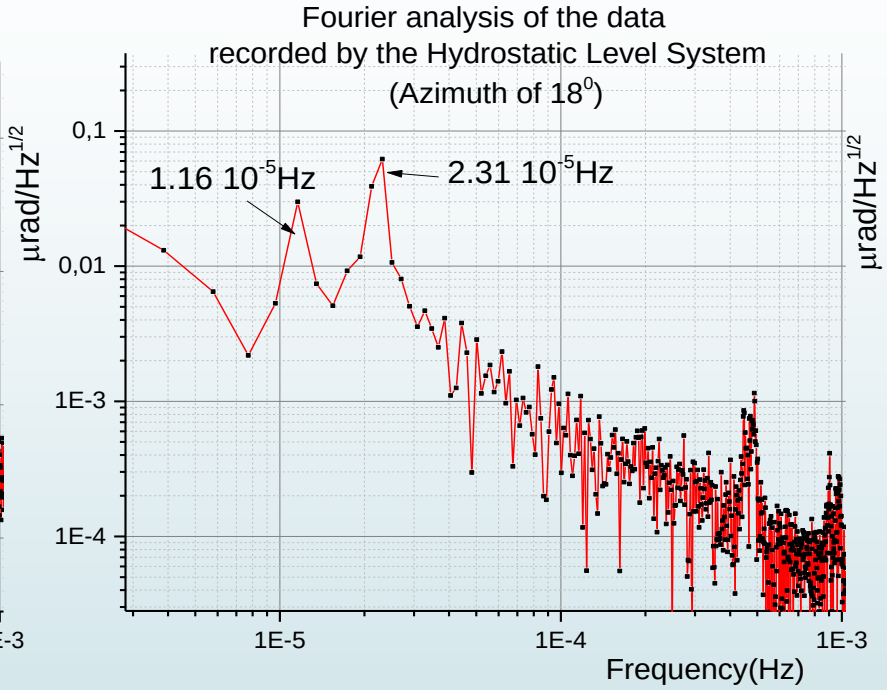
The Earth surface angular oscillations caused by the Moon and Sun and registered by the Hydrostatic Level System and by the Precision Laser Inclinometer in the LHC location area

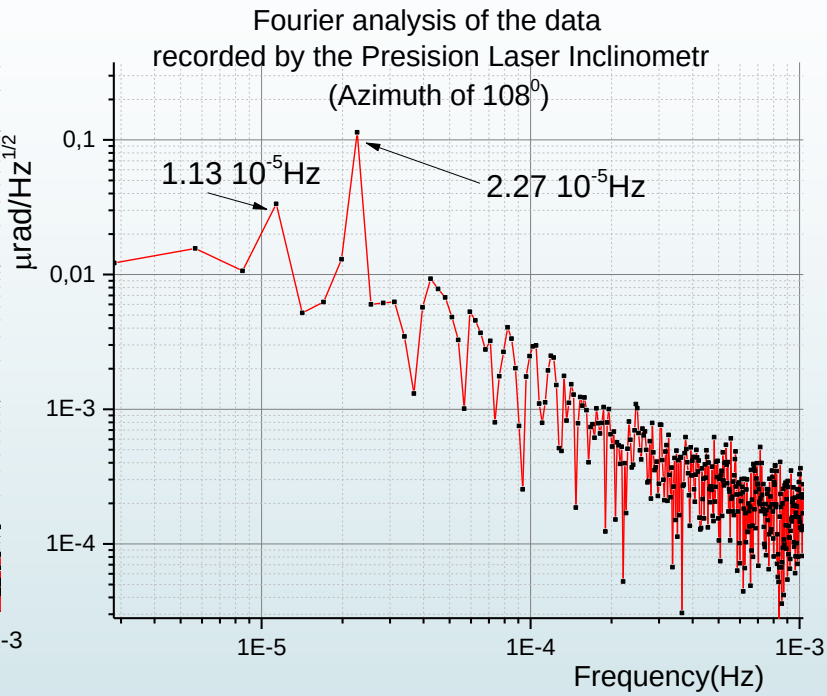


- Here is the comparison results: the phase coincidence of an Earth surface angular inclinations by the Moon and by the Sun registered by the **HLS** and **PLI** in **LHC** location area **(6÷9 May 2016)**

Fourier analysis of the HLS and PLI data







The known frequency of the tides on the Earth is **$2.2371 \cdot 10^{-5}$ Hz**
The rotation frequency of the Earth is **$1.1574 \cdot 10^{-5}$ Hz**

- Here is the comparison result one clearly observes the amplitude in the frequency coincidence of the Earth surface angular oscillations registered both by the HLS and PLI **in the LHC location area**.

The Main Results (A)

- The day long temperature variations of the rocky ground in the Transport Tunnel #1 is found on the level of **0.005 ^{0} C**. The idea to use the rocky ground temperature stability allowed to stabilize the PLI data on **~10^{-9} rad** level in the **[10^{-5}Hz;1Hz]** frequency band.
- The application of the methodic of the "reference laser ray" in the PLI operation decreased the noise origin laser beam angular oscillations by the factor **30 x** in the enlarged frequency band of **[5 ·10^{-5}Hz; 10^{-1} Hz]** ; essential that the noise level was decreased to **10^{-8} rad/Hz$^{1/2}$** in **[5 ·10^{-5}Hz; 10^{-4} Hz]** frequency interval.
- The use of a low viscosity oil has widened to **4Hz** the high frequency PLI diapason : it allowed one to register the Earth surface angular inclination of an industrial origin.
- An application of the innovative methodic we created of use of the interferometric calibration made possible to register the Earth surface angular oscillation with the relative angular precision of **0.6%**

The Main Results (B)

- The Precision Laser Inclinometer has registered the Earth surface angular oscillations induced by the Moon and Sun in two orthogonal planes **in the LHC location area** ,
- The PLI data coincide with HLS measurements results,
- The results achieved could hopefully be used for the seismic isolation of a large scale Physics research equipment.

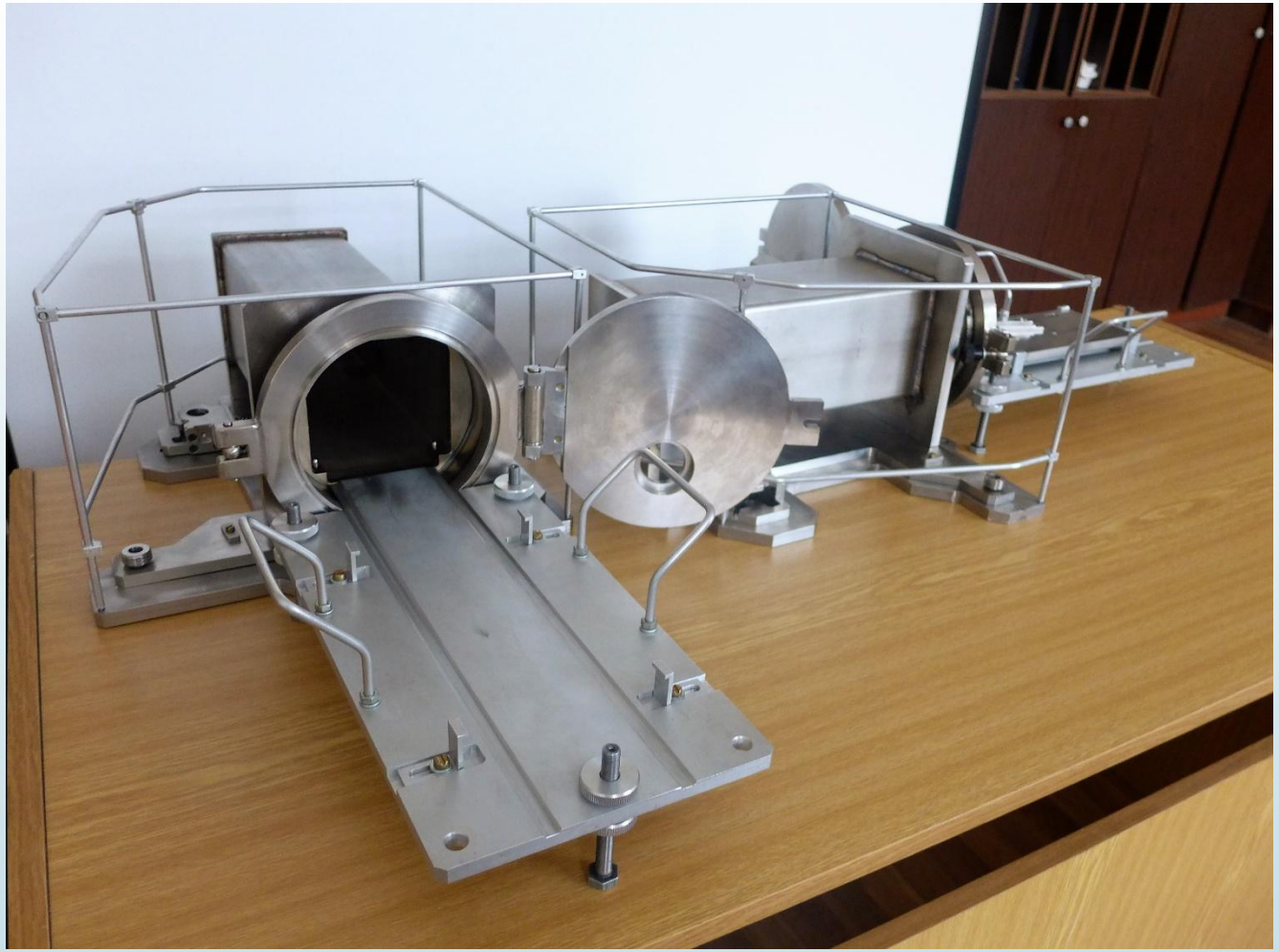
Acknowledgments :

- The PLI team commonly expresses its gratitude to P. Jenny for his supportive positive interest to our studies starting their early stages.
- Authors thank :

H. Mainaud Durand, V. Rude for presentation of the LHC data for comparison with PLI data, A. Herty for the help in our work in TT1 and V. Bednyakov for the stable interest and support.

- Dubna group thanks the scientific Fund BMBF (Germany) for the financial support of our investigation at the JINR (Dubna)

The Professional Precision Laser Inclinometer



January 2017

The Professional PLI samples have been assembled and prepared at JINR to wide research program of the Earth surface angular oscillations