

THE CALIBRATION OF THE PRECISION LASER INCLINOMETER

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The calibration methods of the two-coordinate Precision Laser Inclinometer (PLI) are presented. For the inclinometer studied sample, the calibration coefficients of (630 ± 70) and (531 ± 66) $\mu\text{rad/V}$ have been determined by two independent methods.

Представлены методы калибровки двухкоординатного прецизионного лазерного инклинометра. Для инклинометра найдены калибровочные коэффициенты (630 ± 70) и (531 ± 66) мкрад/В, полученные двумя независимыми методами.

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INTRODUCTION

The Precision Laser Inclinometer (PLI) represents a new type of sensor that is able to measure the slope of a surface in an angular interval of angles (from 0.01 to 100 μrad) and in a frequency range of (10 μHz –1 Hz) [1–3].

The principal feature of the new inclinometer is the precision that can reach by last estimates $5 \cdot 10^{-9}$ rad [2]. The inclinometer is essentially a new kind of a two-coordinate angular seismograph for surface waves with the ability to determine the direction of the wave.

For the high-precision implementation of the inclinometer, a controlled detector calibration is necessary. The article presents the method of inclinometer calibration and describes its verification by the special measurement procedure.

THE PRECISION LASER INCLINOMETER OPERATION PRINCIPAL

In the inclinometer, the gravity vector (GV) is used as a stable reference direction that is guaranteed by significant and stable Earth mass. Outside factors altering the GV direction are mainly linked to solar and lunar influences [4]. The GV-direction change at daily basis is $7.8 \cdot 10^{-8}$ rad for lunar and $3 \cdot 10^{-8}$ rad for solar effects. For a short period of one hour the GV-stability estimate could be better than 10^{-9} rad.

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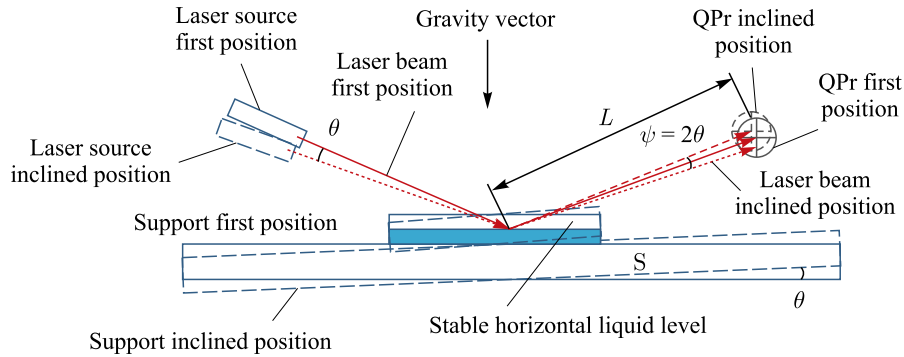


Fig. 1. The angle $\psi = 2\theta$ is the slope of the laser ray in the precision laser inclinometer when its basement S is inclined by the angle θ

The GV stability has an important consequence — the stability of the horizontal surface of liquid.

The working principle of the inclinometer is illustrated by Fig. 1.

The vessel with liquid is positioned on a massive base S. On the base are also fixed: the laser source and the sensitive photoreceiver (the Quadrant Photoreceiver (QPr)). To detect the tilt angle θ of the base S (in case of ground motion), one uses the *reflection* of the laser ray at the surface of the liquid in the vessel.

As this surface is always horizontal, the reflected laser ray is deviated by the angle ψ that is twice bigger than the angle θ of the base S inclination: $\psi = 2\theta$. It is linked to the QPr inclination with respect to its primary location at the angle θ and — due to horizontality of the liquid's surface — with the laser-ray angular deviation θ . The laser ray is turned by 2θ relative to the QPr.

The ray angular bias $\psi = 2\theta$ is detected by the quadrant photoreceiver. With the known laser spot displacement Δx^1 on the QPr and the known distance L between the liquid's surface and the QPr, one determines the angle $\psi = \Delta x/L$ and, respectively, the inclination angle of the inclinometer base S:

$$\theta = \frac{\Delta x}{2L}. \tag{1}$$

THE PRECISION LASER INCLINOMETER

Figures 2 and 3 represent the scheme of the precision laser inclinometer.

All the components of the laser inclinometer are fixed on a massive basement plate S. The laser irradiation is formed by the collimator to a ray with diameter $D = 2$ cm and sent to Mirror 1 (top view, Fig. 2). Mirror 1 (side view, Fig. 3) directs the beam to the vessel with a liquid, partly reflects from the liquid's surface and returns backwards. To increase the sensitivity, a long focus lens $f = 1000$ mm is used. The laser ray passes twice this lens and is focused on $f/2$ distance to a spot of diameter $d = 100 \mu\text{m}$ on the surface of the QPr. For

¹ Δx is determined by the QPr displacement with micrometric screw to the position when the signals from photoreceivers of the QPr will again be equal.

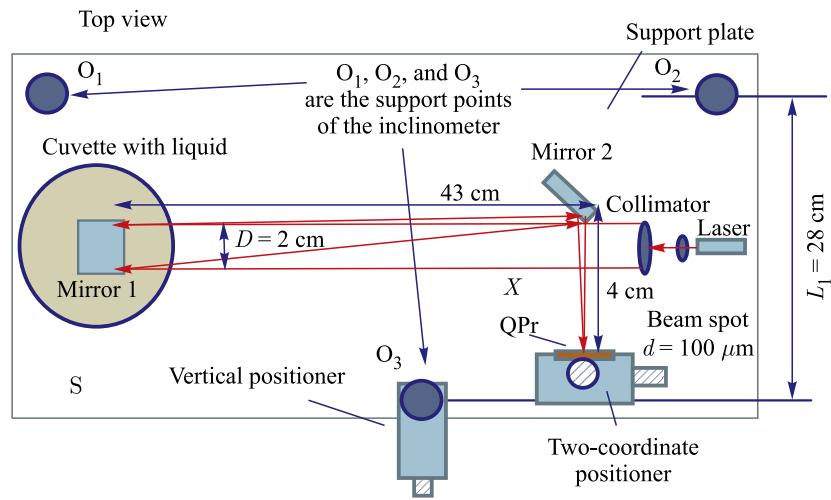


Fig. 2. The precision laser inclinometer (top view)

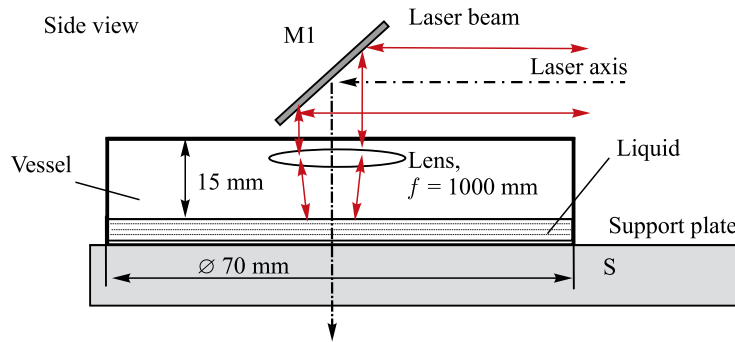


Fig. 3. The precision laser inclinometer (side view)

the registration convenience the laser ray moves back at the small angle $\approx 1^\circ$ with respect to the previous direction. Mirror 2 (Fig. 2) directs the beam on the QPr. The QPr is mounted on a two-coordinate positioner, which serves to position the crosshair of the QPr on the laser-ray axis and for calibration verification (see below).

The base S has three support points: O_1 , O_2 are located at the base edges and O_3 is in the middle. Under the support point O_3 a vertical positioner is installed to perform the calibration. The base S rotates relatively to the O_1O_2 axis. The design of the inclinometer supports does not foresee a calibration by rotation of the base S around the axis perpendicular to the O_1O_2 line.

The inclinometer operates as follows:

- when the base S is inclined (due to angular motion of the Earth surface), the angular displacement of the ray reflected from the liquid's surface occurs;

- it biases by the distance Δx the laser spot on the QPr;
- the QPr signals feed the ADC LA-I24 [5] and are recorded on the PC;
- after processing of the accumulated data, the time dependence of base inclination angle is calculated.

The key element in the data processing is the calibration of the inclinometer — the determination of the dependence between the QPr signals and the tilt of the inclinometer base.

THE ANGULAR CALIBRATION OF THE PRECISION LASER INCLINOMETER

During the calibration, the inclinometer base S is turned by the known angle θ_k and then the signal U_k from the QPr is measured and the calibration coefficient K_k is determined:

$$\theta_k = K_k U_k. \quad (2)$$

The linear dependence of the QPr signals on the calibration inclination is supposed. It is justified by the relatively small value of $\Delta x_k \cong 10 \mu\text{m}$ of the laser spot displacement (caused by the tilt of the base S during the calibration) with respect to the spot diameter $d = 100 \mu\text{m}$ on the QPr: $\Delta x_k \ll d$ [6].

With the known distance L_1 (Fig. 2) between the O_1O_2 axis and the O_3 point and the calibration displacement Δx_k , one determines the calibration angle $\theta_k = \Delta x_k / L_1 = K_k U_k$.

One calculates the calibration coefficient K_k with the determined θ_k and measured U_k in accordance with (2):

$$K_k = \frac{\Delta x_k}{L_1 U_k}.$$

THE VERIFICATION OF THE INCLINOMETER'S ANGULAR CALIBRATION

Due to possible deformations of the floor under vertical positioner at the O_3 point (Fig. 2), the inclinometer base S during the calibration measurements may have some additional errors. To detect possible systematic errors during K_k determination, a special verification procedure is used.

For an independent verification of the angular calibration of an inclinometer let us displace the QPr with respect to laser beam spot on a certain Δx_{ver} value (Fig. 4) and determine the U_{ver} signal of the QPr that appeared due to the verification displacement.

The direction of the QPr displacement for the verification test coincides with the laser-ray movement direction during calibration. The turning of the basement S around the O_1O_2 axis displaces the laser ray horizontally. Consequently, in the same direction we biased the QPr when the test is executed.

As the distance L (Fig. 1) between the beam reflection point on the liquid's surface and the QPr is known, the "rotation angle" $\psi_{\text{ver}} = \Delta x_{\text{ver}} / L$ can be determined and, with (1), the verification "equivalent turn angle" $\theta_{\text{ver}} = \Delta x_{\text{ver}} / 2L$ is found. This is the tilt angle of the inclination base. Then, with (2), the verification value of the calibration coefficient is obtained:

$$K_{\text{ver}} = \frac{\theta_{\text{ver}}}{U_{\text{ver}}}. \quad (3)$$

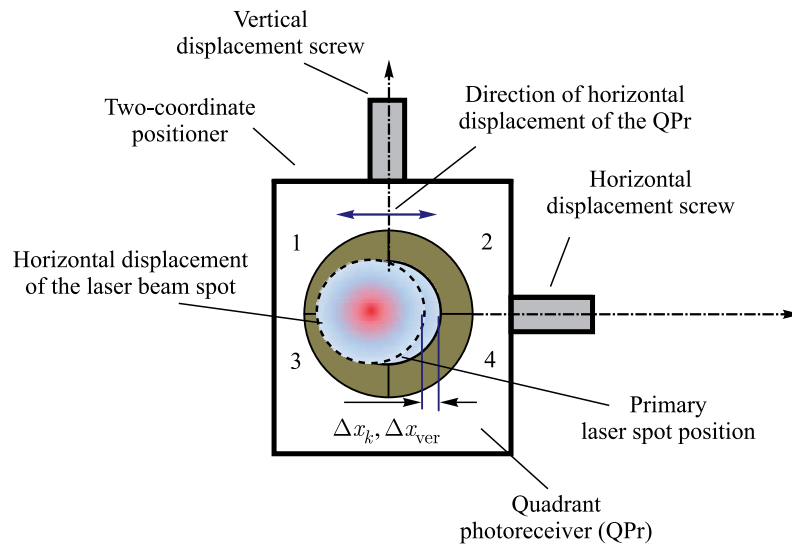


Fig. 4. The laser beam spot displacement on the quadrant photoreceiver during the calibration and the verification measurements

Figure 4 shows the laser beam spot verification displacement Δx_{ver} on the QPr. Out of four QPr signals U_1 , U_2 , U_3 , U_4 from the photosensor sections the difference signal is formed:

$$U_{\text{ver}} = (U_1 + U_3) - (U_2 + U_4).$$

During the calibration measurements the value U_k is defined similarly to U_{ver} :

$$U_k = (U_1 + U_3) - (U_2 + U_4).$$

The U_k , U_{ver} determine the value of the laser beam spot displacement at the calibration measurements and during its verification.

In other words, during the calibration the laser beam spot is displaced on the QPr as a result of calibration angle θ_k of the base S; but during the control we displace the QPr itself with respect to the laser beam spot on the known distance Δx_{ver} . The signals U_k and U_{ver} are recorded during the calibration and the test.

THE MEASUREMENT RESULTS

Angular Calibration of the Inclinometer. The inclinometer base S has been turned relative to the O_1O_2 axis by the angle $\theta_k = 5 \mu\text{m}/0.28 \text{ m} = (17.9 \pm 1.8) \mu\text{rad}$ by means of the micrometric screw of the vertical positioner (Fig. 2) with the known displacement $\delta_k = (5 \pm 0.5) \mu\text{m}$ (the passport precision of this vertical positioner is $\pm 1.5 \mu\text{m}$, but the set of nine independent shifts has been done and the accuracy $\pm 0.5 \mu\text{m}$ has been obtained by averaging of nine independent measurements). The up/down positioner displacements have been made with $\cong 40 \text{ s}$ interval. That is sufficient for the establishment of the horizontal level of the liquid's surface in the cuvette.

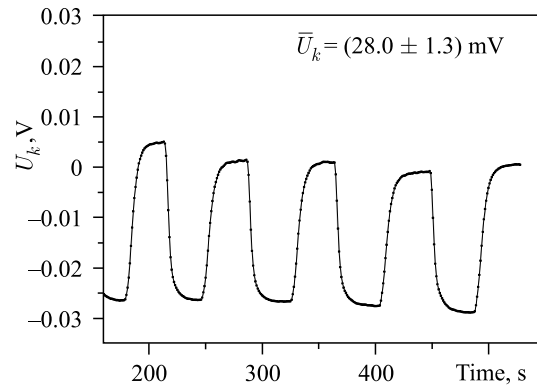


Fig. 5. The calibration signals U_k of the angular calibration of the inclinometer

Figure 5 gives the measurement data.

The nine displacements gave an average value for the signal of $\bar{U}_k = (28.0 \pm 1.3)$ mV. Using (2), one determines the calibration coefficient $K_k = (630 \pm 70)$ $\mu\text{rad/V}$.

Verification of Angular Calibration of the Inclinometer. The QPr has been displaced horizontally (Fig. 4) by $\Delta x_{\text{ver}} = (10 \pm 1)$ μm distance by the two coordinates positioned. The passport precision of the microscrew is ± 3 μm , but for determination of the QPr displacement the set of nine independent shifts has been done and the accuracy ± 1 μm has been obtained by averaging of nine independent measurements. The quadrant photoreceiver signals have been measured. The displacements of the positioner have been made at an $\cong 30$ s interval. That is sufficient for a stabilization of the QPr measurement results.

The measurement data are given in Fig. 6.

The ten test displacements gave the average signal $\bar{U}_{\text{ver}} = (18.8 \pm 1.3)$ mV.

Using Eq. (2), one determines the rotation angle that is equivalent to the displacement by the positioner $\theta_{\text{ver}} = \Delta x_{\text{ver}}/2L = (1 \pm 0.1) \cdot 10^{-5}$ rad, and with Eq. (3) one obtains the verification of the calibration coefficient $K_{\text{ver}} = (531 \pm 66)$ $\mu\text{rad/V}$.

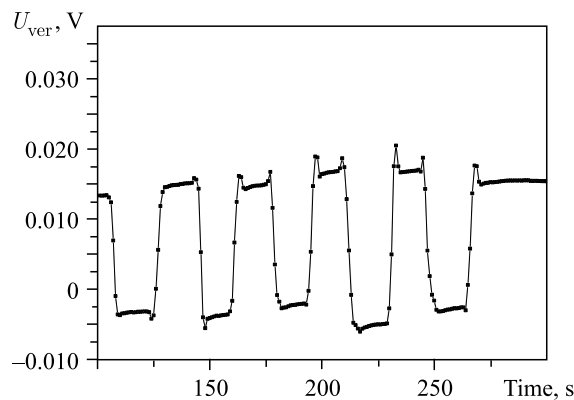


Fig. 6. The U_{ver} verification signals of the QPr for test of the angular calibration of the inclinometer

CONCLUSION

A calibration method for the precision laser inclinometer is proposed.

The calibration coefficient $K_k = (630 \pm 70) \mu\text{rad/V}$ has been measured for the known inclination angle of the inclinometer base.

By an independent method, using the known displacement of the quadrant photoreceiver relative to the stable laser beam, the calibration coefficient $K_{\text{ver}} = (531 \pm 66) \mu\text{rad/V}$ has been obtained.

Within the measurement, precision $K_k \approx K_{\text{ver}}$ shows the absence of significant systematic errors during the calibration.

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