Two-wave laser displacement meter

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Abstract. A two-wave laser displacement meter based on Michelson interferometer has been developed for measurements at an unknown temperature profile at the measurement trace. The requirements for meteorological parameters support during displacement measurements using the offered laser interferometer are less strict compared to using an one-wave interferometer. The article describes the optical schematic of the device. The results for the measurements of the developed laser interferometer for realization of the displacement unit within the limits of 60 m are presented. The weather condition influence on measurements was estimated. The application of pseudorandom displacement of the interferometer’s reference arm with accumulation made possible the reflector position resolution down to 0.01 μm at the stoped-displacement mode, and down to 0.05 μm at the displacement mode. It was shown that such resolution allows to measure displacements at trace up to 60 m with inaccuracies less than 10 μm at the temperature profile amplitude up to 1 °C.

1. Introduction

Devices for measuring distances in the optical wave range include laser distance meters and interferometers. These devices are very widely used in geodesy [1, 2]. They are used for measuring distances to artificial satellites of the Earth and to the Moon, for determining coordinates in aerial photography and marine geodesy, for precision linear measurements in various tasks of applied geodesy and metrology.

Geodesic interferometry of the optical range is the most precise method of measuring distances (about tens of meters) and their changes, which has a micron accuracy [3‒5]. Geodesic interferometry has recently become particularly important due to the need to create bases of the highest accuracy for metrological certification of linear measuring instruments, in particular laser and radio distance meters, as well as for precision measurements for geophysical purposes (studying the deformations of the earth's crust for the purpose of predicting earthquakes, etc.).

In all electronic methods of measuring distances, without exception, the primary role is played by taking into account the influence of the environment in which electromagnetic waves propagate. The accuracy of the interference measurements of the displacements depends on the phase velocity of the electromagnetic wave propagation along the measuring path. In the atmosphere, this speed is affected by temperature, atmospheric pressure, relative humidity, and the gas composition of the atmospheric air. To determine the refractive index accurately, information about weather parameters along the measuring base is required, which is a very difficult task to obtain. The meteorological method or the method of direct measurements of meteorological parameters in a sufficiently large number of points is used, for example, on measuring base of the State
Primary special standard of the unit of length GET 199–2018. Along the measuring line there are 32 temperature sensors, as well as pressure, humidity and carbon dioxide meters.

To simplify the requirements for measuring and maintaining meteorological parameters on the measuring measuring base, a two-wave laser interferometer was developed for measurements with a fractional resolution of the interference fringe count at an unknown temperature profile on the measuring base.

2. Two-wave dispersion method

The two-wave dispersion method [1, 2, 6] of displacement measurements allows measurements at an unknown temperature profile on the measuring base, but at the same time the requirements for the accuracy of optical path measurements are increased. The idea of the method is to determine the refractive index through the difference in the count of the interference fringes for two different wavelengths on the path. The method requires measurements of displacements with a resolution of less than one interference fringe.

The analytical expression for the corrected distance in the two-wave method is represented by the relation [6]

$$D = S - A\Delta S - B < \frac{e}{T} > D_0,$$

(1)

Where $S = D < n >$ – optical path (distance traveled by radiation in the atmosphere), $< n >$ – the average integral index of refraction on the trace, $A = \frac{n_0 - 1}{\Delta n_0}$ – constant coefficients for the two given wavelengths $\lambda_1$ and $\lambda_2$, $n_0$ is the refractive index of air under standard conditions (at $T_0 = 273.15$ K, $P_0 = 101.325$ kPa, $e = 0$ mmHg, 0.0375% CO$_2$) for the wavelength for which $< n >$ is calculated, $\Delta n_0 = < n_{01} > - < n_{02} >, \Delta S$ – difference of optical paths, $B = \Delta \mu_0 (A - A_e)$— constant coefficients for the two given wavelengths $\lambda_1$ and $\lambda_2$, $\mu_0$ – is the refractive index of water vapor under standard conditions for the wavelength for which $< n >$ is calculated, $\Delta \mu_0$ – the difference between the values of $\mu_0$ for $\lambda_1$ and $\lambda_2$, $A_e = \frac{\mu_0 - 1}{\Delta \mu_0}$ – constant coefficients for the two given wavelengths $\lambda_1$ and $\lambda_2$, $< \frac{e}{T} >$ – the average value of the ratio of humidity (partial pressure of water vapor) and temperature along the measuring base, determined by the results of temperature and humidity measurements at the ends of the line, $D_0$ – is an approximate value of the measured distance that needs to be known about four orders of magnitude less accurately than $< n >$.

$S$, $A$ and $B$ are taken for the same wavelength (for $\lambda_1$ or for $\lambda_2$). Therefore, the corrected distance is obtained from the results of measurements of two quantities: the optical path $S$ at any of the two wavelengths and the difference in the optical paths $\Delta S$ for these two wavelengths.

The calculated data for estimating the required accuracy of measuring the difference in optical paths for the wavelengths $\lambda_1 = 532$ nm and $\lambda_2 = 1064$ nm are shown in table 1.

Using the formula for indirect measurements, we estimate the required accuracy of measuring the difference in optical paths

$$\delta_{\Delta S} = \frac{D}{A} \sqrt{\delta_{< n >}^2 - \left(\frac{B}{T}\right)^2 \delta_e^2}.$$

(2)

The non-excluded systematic error in measuring the travel length on the measuring base of up to 60 m should be no more than 10 $\mu$m. Therefore

$$\delta_{< n >} = \frac{10^{-10} - 6m}{60 m} = 0.167 \cdot 10^{-6}.$$

We will make the calculation taking the air humidity of 50% and the temperature of 25 $^\circ$C. The partial pressure of water vapor under these conditions of 11.88 mmHg. With an error of measurement of moisture in point 2%, we get

$$\delta_e = 11.88 \cdot \frac{2}{100} = 0.2376 \text{ (mmHg)}.$$
Table 1. The calculated data for estimating the required accuracy of measuring the difference in optical paths.

| Parameter name                                                                 | Parameter designation | Parameter value       |
|--------------------------------------------------------------------------------|-----------------------|-----------------------|
| Standard refractive index of air for the wavelength $\lambda_1 = 532$ nm       | $n_{01}$              | 1.000293526           |
| Standard refractive index of air for the wavelength $\lambda_1 = 1064$ nm     | $n_{02}$              | 1.00028907            |
| Coefficient                                                                    | $A_1$                 | 65.87                 |
| Coefficient                                                                    | $A_2$                 | 64.87                 |
| Refractive index of water vapor under standard conditions for the wavelength $\lambda_1 = 532$ nm | $\mu_{01} - 1$        | 15.995·10^{-6}        |
| Refractive index of water vapor under standard conditions for the wavelength $\lambda_1 = 1064$ nm | $\mu_{02} - 1$        | 16.52·10^{-6}         |
| The difference in the refractive indices of water vapor under standard conditions | $\Delta \mu_0$        | 0.525·10^{-6}         |
| Coefficient                                                                    | $A_{e1}$              | 30.47                 |
| Coefficient                                                                    | $A_{e2}$              | 31.47                 |
| Coefficient                                                                    | $B_1$                 | 18.585·10^{-6}        |
| Coefficient                                                                    | $B_2$                 | 17.535·10^{-6}        |

Table 2. The calculated values of the component errors of the length measurements by a two-wave laser interferometer.

| Error components                                                                 | Error    | Component of the length measurement error |
|---------------------------------------------------------------------------------|----------|------------------------------------------|
| 1. The instrumental error $\Theta_i$                                           | 4.4 μm   |                                          |
| Uncertainty of the laser radiation frequency                                    | $\leq 10^{-9}$ | $\leq 0.06$ μm                             |
| Measurement error of the optical path difference $\Theta_S$                    | 150 nm   | 4.38 μm                                   |
| 2. The influence of the weather conditions of the environment $\Theta_{en}$    |          | 2.1 μm                                    |
| Temperature                                                                     | 0.1 °C   | $<10^{-8}$                                 |
| Humidity                                                                        | 2% RH    | $1.7·10^{-8}$                              |
| CO$_2$ concentration                                                             | 10 %     | $7·10^{-9}$                                |
| Accuracy of the dispersion formula                                              | $2.3·10^{-8}$ | $2.3·10^{-8}$                              |
| 3. Imperfection of the geometry of the movement of the angle reflector on the measuring ruler of the reference measuring base $\Theta_b$ |          |                                          |
| According to the upper estimate for the reference measuring base of FSUE VNIIFTRI | 5.5 μm   | 5.5 μm                                    |
\[ \delta_{AS} = \frac{60}{65.87} \sqrt{(0.167 \cdot 10^{-6})^2 - \left(\frac{18.585 \cdot 10^{-6}}{298}\right)^2 \cdot (0.2376)^2} = 152 \text{ nm}. \]

Thus, in order to ensure the measurement error of the 60-meter-long measuring base of ±10 μm, it is necessary to measure the difference in optical paths for rays of 532 nm and 1064 nm with an error of less than 150 nm.

The calculated values of the component errors of the length measurements by a two-wave laser interferometer are given in Table 2.

The non-excluded systematic error of measuring the travel length by a two-wave laser interferometer is equal to

\[ \Theta = K \cdot \sqrt{\theta_i^2 + \theta_n^2 + \theta_b^2}, \quad (3) \]

where \( K = 1.1 \) with a confidence probability of \( P = 0.95. \)

The non-excluded systematic error of the displacement measurement by a two-wave laser interferometer on the VNIIFTRI measuring base is estimated at \( \Theta = 8.2 \mu m. \)

3. Design features of a two-wave laser interferometer

A two-wave laser displacement meter based on the Michelson interferometer was developed to solve the problem of measuring displacements at an unknown temperature profile on the measurement measuring base [7]. The optical scheme of a two-wave interferometer is shown in Figure 1.

\[ \text{Figure 1. Optical scheme of a two-wave interferometer.} \]

The laser interferometer consists of a laser radiation generation unit containing a highly stable laser emitter (1) based on Nd:YVO₄ laser emitting at two wavelengths of 532 nm and 1064 nm. The laser generation frequency at a wavelength of 532 nm is stabilized by an iodine cell [8]. The polarization of radiation at a wavelength of 532 nm is linear, vertical, and at a wavelength of 1064 nm – linear, at an angle of 45°. Next are prism (2), quarter-wave phase plate (3) (532 nm), beam expander (4), polarizing
cube (5), non-polarizing beam splitter (6). Splitter (6) divides the light beam into a beam p1 that enters on the retroreflector of the reference arm of the interferometer (7), and a beam p2 that enters on the phase plate $\lambda/4$ (532 nm and 1064 nm) (9) and periscope (10). The retroreflector of the measuring arm of the interferometer (large retro-reflector) (11) is placed on a carriage moving along the measuring track. The interfered beams fall on the spectral beam divider (12) and the receiving device, which includes polarizing beam splitters (13), (14) and four photodetectors PD1–PD4. An electronic computing unit processes Photodiode signals. The diagram of the electronic computing unit of a two-wave laser interferometer is shown in figure 2.

![Diagram](image)

**Figure 2.** Diagram of the electronic computing unit of a two-wave laser interferometer.

The PSF1-PSF4 photo signal formers corrected the levels of the electrical signals in order to keep them within the limits necessary for discrimination of the electrical signals received at the output of the photodetectors. The signal is adjusted by changing the gain and shift for each channel using digital potentiometers. The adjustment can be performed both in manual and automatic mode. The device contains 4 channels for processing signals coming from four photodetectors.

The photosignal processing and fringes counting units PPFCU1–PPFCU2 are used for automatically determining the direction of counting and counting the number of interference fringes, taking into account the direction of movement of the retro-reflector in the measuring arm of the interferometer, and transmitting data on the number of counted interference fringes to a personal computer PC via the USB interface.

The system for collecting meteorological parameters of the SCMP consists of temperature sensors TS1, TS2, located at the ends of the optical path, a humidity sensor HS, a pressure sensor PS, a carbon dioxide concentration sensor SCO2. Figure 3 shows a two-wave laser interferometer.
The principle of operation of the developed interferometer is as follows. The linearly polarized radiation of laser (1) passes through the prism (2), which is used to correct the direction of the beam. With the help of a quarter-wave phase plate (532 nm), it is converted into radiation with circular polarization (532 nm). Further, the light beam with the help of the beam expander (4) increases in diameter to ensure the necessary amount of diffraction divergence of the beam. Passes through the polarizing cube (5), oriented at an angle of 45° to the horizontal. The non-polarizing beam splitter (6) divides the beam into two beams, each of which contains a radiation component with s- and p-polarization. One beam is directed to a small retro-reflector (7), the other to a large retro-reflector (11). To ensure the possibility of registering the count of interference fringes for two wavelengths, a phase plate $\lambda/4$ (532 nm and 1064 nm) (9) is installed in the measuring arm of the interferometer, which provides a phase shift nearly $\pi/2$ between the radiation components with s- and p-polarization. The light beam propagating in the measuring arm of the interferometer, after reflection from the large retro-reflector through the periscope (10), again enters the non-polarizing beam splitter (6), where it interferes with the light beam coming from the small retroreflector. Further, using the spectral beam divider (12), the interfered beams are divided into two beams – 1064 nm and 532 nm. After the polarization separation of the interfering beams by the beam splitters (13), (14), four photodiodes PD1-FD4 register four interferograms, two for each wavelength, shifted in phase. The reverse count of the interference fringes makes it possible to register the alternating displacement and find the average displacement value with a resolution of up to a fraction of the fringes.

At the end of the small retroreflector there is a device that creates displacements by the amount of deformation of the piezoelectric element – a piezoactuator (8). The piezoactuator is excited in the frequency band from 10 to 150 Hz with an amplitude of 2–3 laser wavelengths. The displacement measurements are read from 100 to 10,000 times, which makes it possible to obtain values with fractional values from the interference fringe count when processing the measurement results during accumulation. With pseudorandom excitation, this movement will also be pseudorandom. As a result,
the RMS of displacement measurements decreases by $\sim \sqrt{N}$ counts, which allows us to obtain a resolution for measuring displacements up to $10^{-4}\lambda$, and the RMS of displacement measurements from $10^{-2}\lambda$ to $2 \cdot 10^{-1}\lambda$.

4. Experimental test results of a two-wave laser interferometer

During the tests of the two-wave laser interferometer, the following results were obtained, presented in table 3 and figure 4.

Table 3. Test results of a two-wave laser interferometer.

| No | Name of the metrological characteristic | Measured value |
|----|----------------------------------------|----------------|
| 1  | The RMS of a series of $N$ measurements of the initial position of the carriage | 0.04 $\mu$m |
| 2  | The RMS of a series of $N$ measurements of the final position of the carriage | 0.08 $\mu$m |
| 3  | The RMS of measuring the length of the segment | 2.5 $\mu$m |
| 4  | Optical path difference for two wavelengths 532 nm and 1064 nm | maximum value 4 $\mu$m |

The results obtained showed that the resolution of the position of the reflector up to 0.01 $\mu$m is provided during the complete movement, and up to 0.05 $\mu$m during the movement.

5. Conclusion

In the course of the work, a two-wave laser interferometer was developed and manufactured. The tests carried out on the device showed that the both channels results have a random component of the error that meets the requirements for the conversion of the refractive index, then the interferometer can be used at an unknown temperature profile.
It is shown that the use of a two-wave interferometer reduces the measurement error of displacements at an unknown temperature profile along the measuring base. These allows the developed interferometer to be used as a reference carrier when comparing length standards and measuring base after additional studies. The use of pseudorandom movement of the reference arm of the interferometer with accumulation made it possible to provide resolution of the position of the reflector at the completed movement up to 0.01 μm, and during the movement—up to 0.05 μm. It is shown that such a resolution allows measuring the movement on a measuring base up to 60 m with an error of less than 10 μm at a temperature profile amplitude of up to 1 °C instead of 0.1 °C.

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