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Original paper

Analysis of development tendencies of metrological technologies to control rangefinders of an electronic distance measurement instruments

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Abstract: The article analyses the development of metrological control technologies for electronic distance measurement rangefinders to determine their main characteristic of accuracy – the root mean square error of distance measurement. It is established that the current reference linear bases are reliable and serve as the main means of transmitting a unit of length from the standards to the working means of measuring length. The article describes the existing linear reference bases and specifies their accuracy and disadvantages. It is concluded that the disadvantages of linear reference bases are deprived of the reference linear bases built in special laboratories. They use distances measured by the differential method with laser interferometers as reference distances. The application of such technology allowed to automate the processes of measurements and calculations. There is development of fibre-optic linear bases, in which optical fibres of known length are used as model lines. The article offers a new technical solution – a combination of fiber-optic and interference linear bases, which allows to qualitatively improve the system of metrological support of laser rangefinders. This is achieved by having a fiber-optic unit, which allows you to create baselines of increased length, while ensuring small dimensions of the baseline, and relative interference base, which provides high accuracy of linear measurements and does not require calibration of the base with a precision rangefinder, which eliminates several difficulties associated with changes in the refractive index, makes measurements independent of the wavelength of the radiation source and almost independent of the ambient temperature.

Keywords: calibration, rangefinder, electronic distance measurement, reference linear station, root mean square error of distance measurement

1. Introduction

In the conditions of modern geodetic production, a considerable volume of linear measurements is carried out by means of laser measuring tapes, electronic distance measurements (EDM) or by rangefinders of the special geodetic equipment (Malik et al., 2020; Tereshchuk et al., 2021). The use of such devices significantly increases productivity, makes it possible to automate the processing of field measurement results.

To obtain reliable results of distance measurements, it is necessary to perform metrological control of electronic rangefinders in general and EDM rangefinders in particular. Like any other measuring tools, EDMs are subject to metrological control, the main purpose of which is to assess the compliance of the actual metrological characteristics of the device with the specified ones. This article considers the reproduction technology of the main metrological characteristics of the EDM rangefinder - the root mean square error of distance measurement.

Taking into account that rangefinder and angular gauge of the EDM are independent parts the following regulatory documents were used for their verification: (GOST 19223-90, 1991) – to verify the rangefinder, (MPU164/01-2003, 2003) – to verify the angular gauge.

According to these documents, the metrological control of EDM rangefinders is carried out on reference linear stations (RLS). RLS consists of reference (model) lines of different length measured with high accuracy and fixed on the ground by centers that are laid in places with the most favorable topographic and hydrogeological conditions (Fig. 1) (RTM 68-8.12-85, 1985).

a)

b)

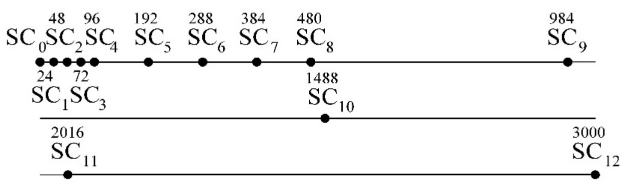

Fig. 1. Field reference linear station (a) and the suggested centers' (SC) location scheme (b)

General length, number of intervals and their length are set taking into account the purpose, accuracy and operating range controlled by the EDM rangefinders. The classification of stations by accuracy is given in the Table 1.

Table 1. Classification of RLS by accuracy by RTM 68-8.12-85 (1985)

No.	Station name and category	Error in determining the length of the intervals (mm)
1	Reference station of the 0 category	(0.1–0.3) 10^{-6} D
2	Reference station of the 1st category	(0.3–0.5) 10^{-6} D
3	Reference station of the 2nd category	(1–1.5) 10^{-6} D
4	Reference station of the 3rd category	(3–4) 10^{-6} D

Considerable national and international experience suggests that RLS is a reliable means of transmitting a unit of length from references to the working means of measuring length and almost fully meet the modern requirements of metrological control of EDM rangefinders (Yorczik, 1986; Kupko et al., 2004; Trevogo et al., 2011; Ellis et al., 2013; Janssen and Watson, 2014).

Field procedures for testing EDM rangefinders are described in an international standard ISO 17123-4:2012 (ISO 17123-4:2012, 2012). In Barković et al. (2016) and Ježko and Sokol (2018) described the testing processes of the EDM rangefinder at the RLS of the Faculty of Geodesy of the University of Zagreb and at the Hungarian national comparison base Gödöllö, respectively, which were conducted in accordance with the international standard ISO 17123-4: 2012. The testing process consisted in ascertaining that the empirical values of the standard deviations of the distance measurements correspond to the values specified in the manufacturer's specifications. The article Solarić et al. (2008) describes the measurement of the baseline of Zagreb RLS using GPS devices. Differences between distances measured with two pairs of GPS and a precise EDM were determined. The difference between the distances thus determined was 0.1 mm at 100 m, 0.3 mm at 500 m, and 0.1 mm at 1000 m. For Zagreb RLS, the standard deviations of distances measured with a precise EDM and further corrected were 2–55 µm; the standard deviations of distances between RLS supports ranged from 32 to 44 µm (Zrinjski et al., 2019). It is concluded that the greatest source of uncertainties in electro-optical distance measurements is not in the EDM rangefinders, but in the atmosphere (Zrinjski et al., 2019). A paper Inal et al. (2008) describes the scaling RLS of Selcuk University in Konya (Turkey) using GPS. The RMS errors of the distances determined by the GPS range from $\pm(0.20 \div 0.60)$ mm. The disadvantage of the described methods is the need to measure and take into account the parameters of the atmosphere, as well as the lack of possibility to calibrate the reference instruments on this RLS.

2. Controlling the metrological characteristics of the distance measuring unit EDM at RLS in Ukraine

It is common knowledge that root mean square error of electronic rangefinders is calculated using the formula:

$$m_D = a + b \cdot 10^{-6} D, \tag{1}$$

where a is a parameter characterizing RLS constant component that is independent from the distance, b is a parameter characterizing RLS component dependent on distance D taken in millimeters.

Until recently, metrological control of light rangefinders was performed in Ukraine complying with (GOST 19223-90, 1991). RLS of EDM distance measurement on a reference line is determined using the formula (GOST 19223-90, 1991):

$$\widetilde{m}_D = \sqrt{\frac{\sum_{i=1}^{n} (\Delta_i)^2}{n}}, \tag{2}$$

where Δ is the difference between the result of line measurement in each reception and its reference value, n is the number of measurement receptions.

To determine compliance with the lower limit of accuracy of EDM distance measurements of, it is necessary to perform at least 4 receptions of measuring several short reference lines, including the shortest, which corresponds to the lower limit of the range of distance measurement of EDM. The test results were considered positive if the following condition was met for each line:

$$\widetilde{m}_D \leq m_D, \tag{3}$$

where m_D is calculated using the formula (1).

Control of compliance of the upper limit of accuracy of EDM distance measurements is carried out by measurement by 10 receptions of lines, the length of which can differ from the upper limit of a range of distance measurement by a particular EDM no more than on 10%. RLS of such distance measurement is calculated using the formula (GOST 19223-90, 1991):

$$\widetilde{m}_{D_l} = \sqrt{\frac{\sum_{i=1}^{10} (D_i - \bar{D})^2}{9}}, \tag{4}$$

where $\bar{D} = \frac{1}{10} \sum_{i=1}^{10} D_i$, D_i is the distance measurement result by i reception.

Given formula (4), it appears that the maximum distance that can be measured by EDM may not be the reference. It is clear that in the case of using a reference line, the RLS of its measurement by a particular EDM should be determined by formula (2). In any case, the condition must be met (3).

Since March 30, 2020 a new regulatory document concerning metrological and technical requirements for theodolites and electronic total stations has been introduced in Ukraine. According to this document, the experimental constant component of the rangefinder block of the EDM is calculated using the formula:

$$\widetilde{a} = \sqrt{\frac{\sum_{i=1}^{n} (D_i - D_i^{ms})^2}{\chi^2_\alpha(\nu)}}, \tag{5}$$

where D_i is distances measured by the EDM in mm; D_i^{ms} is reference values of distances up to 100 m long, taken in mm; ν is the number of degrees of freedom that equals the number of distances measured n_α; $\chi_\alpha^2(\nu)$ is distribution coefficient χ^2 chosen from available tables according to significance level and the number of degrees of freedom $\nu = n_\alpha$.

RLS experimental variable component of EDM rangefinder block is calculated using the formula (6):

$$\widetilde{b} = \max\left[\frac{\left|D_i - D_i^{ms}\right| - t_\alpha(\nu)\cdot\widetilde{a}}{t_b(\nu)\cdot D_i^{ms}}\right]\cdot 10^6\ m, \tag{6}$$

where D_i^{ms} reference values of distances up to 100 m long, taken in mm, $t_\alpha(\nu)$ is Student's distribution coefficient determined from the tables according to confidence level $P = 1 - \alpha = 0.95$ and the number of degrees of freedom, is Student's t-distribution coefficient determined from the tables according to confidence level $P = 1 - \alpha = 0.95$ and the number of degrees of freedom $\nu = n_b$, n_b is the total number of measured distances up to 100 m long.

Given $\left|D_i - D_i^{ms}\right| - t_a \cdot \widetilde{a} \leq 0$ then $\widetilde{b} = 0$ (Metrology, 2020), as a result of metrological control, the main metrological characteristic, which is experimental RLS of distance measuring using EDM rangefinder, is obtained in the form of:

$$\widetilde{m}_D = \widetilde{a} + \widetilde{b}\cdot 10^{-6} D. \tag{7}$$

According to the corresponding coefficient values in equation (7) the EDM rangefinder is given an accuracy class: highly accurate, accurate or technical (Metrology, 2020).

Formula (5) is obtained under the condition (Voitenko, 2003), which corresponds to the lower limit of the interval a-estimation:

$$\gamma\cdot\widetilde{a}' \leq a, \tag{8}$$

where γ is a coefficient calculated using the formula (Voitenko, 2003):

$$\gamma = \sqrt{\frac{n}{\chi^2}} \tag{9}$$

and experimental RLB of determining the constant in the general case as the point estimation equals:

$$\widetilde{a}' = \sqrt{\frac{\sum\limits_{i=1}^{n}\left(D_i - D_i^{ms}\right)^2}{n}}. \tag{10}$$

Therefore, the product (9) on (10) according to the right-hand side of inequality (8) allows to obtain formula (5).

In formula (6) for distances more than 100 m from the error module $\left|D_i - D_i^{ms}\right|$ the error is removed $t_a(\nu)\cdot\widetilde{a}$ of the determination of the experimental value of the constant component obtained for distances up to 100 m, and due to division by $t_b(\nu)$ and by D_i^{ms} from the error go to the experimental value of the variable component of the UPC measurement of distances, which is expressed in millimeters per 1 kilometer of the measured length. And the greatest value for the measured distances is chosen.

In Ukraine, regulatory documents on the methods for metrological testing of EDM rangefinders are being currently developed.

It should be noted that there are the shortcomings typical of RLB. As noted in (Trevogo et al., 2007), in Ukraine it is advisable to have at least 1–2 RLB of the 2nd category per region. So far in Ukraine about 10 RLSs are created and operated, which, considering EDM's wide application in geodetic practice, can be insufficient for their periodic calibration. The task of bringing the number of RLSs to the desired density is complicated by a number of negative factors:

- the organization of such stations and their maintenance is rather labor-consuming and expensive process, and their remoteness from settlements negatively influences preservation of such points and time of calibration;
- impossibility (complexity) of measurements during adverse weather conditions (rain, snow, strong wind);
- the need to use additional equipment to account for errors due to external conditions to measure lines larger than 2 km;
- economic inefficiency of calibration of 1–2 ĹDMs;
- possibility (convenience) of measurements only in daylight, which significantly reduces the calibration time (especially in winter), and accordingly the number of EDMs subject to metrological control;
- impossibility of automation of technological operations.

3. Results of the improvement of the EDM rangefinder accuracy control methods

3.1. Laboratory methods for testing EDM rangefinders

Deprived of some of the above negative factors, RLSs are installed in special laboratories at state metrological services, metrological services of geodetic instrument manufacturers or universities. For example, a linear station was placed in the laboratory of the Czech Technical University in Prague (Fig. 2) (Braun et al., 2014). Measurements of the length between the baseline points were performed using a precision instrument with a standard deviation of 0.02 mm (Štroner et al., 2018).

Placing a linear station in the laboratory has some advantages over on-site ones, in particular: the ability to perform calibrations regardless of weather conditions, time of day and season; a slight difference in temperature and pressure along the entire station, which can usually be neglected; maintenance, control of reference distances, calibration of devices is performed without going to the testing area, which significantly increases the economic efficiency of control. The disadvantages include the complexity of the structure and the small length of such stations, which is 20–100 m.

a) b)

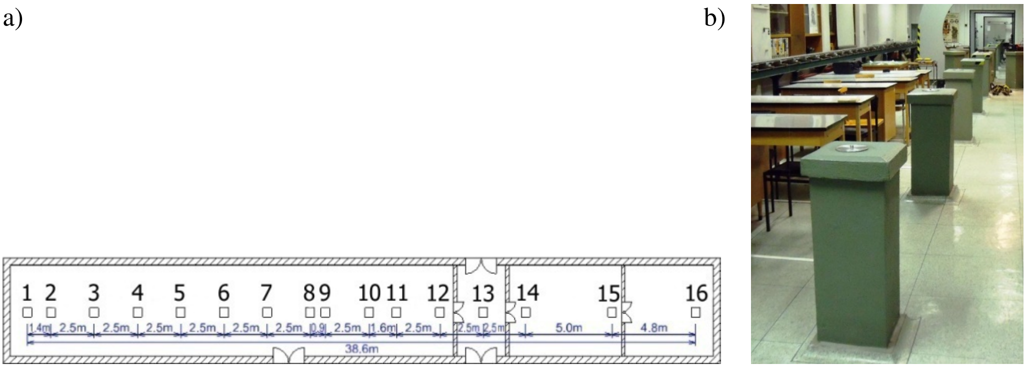

Fig. 2. A linear station of the laboratory of the Czech Technical University: general scheme of a laboratory station (a) and station centers with forced centering devices (b)

A slightly different principle underlies the work of the laboratory for EDM -calibration at Leica Geosystems company and Ghent University, Belgium (Reischmann, 2010; De Wulf et al., 2011) is shown in Figure 3.

a) b)

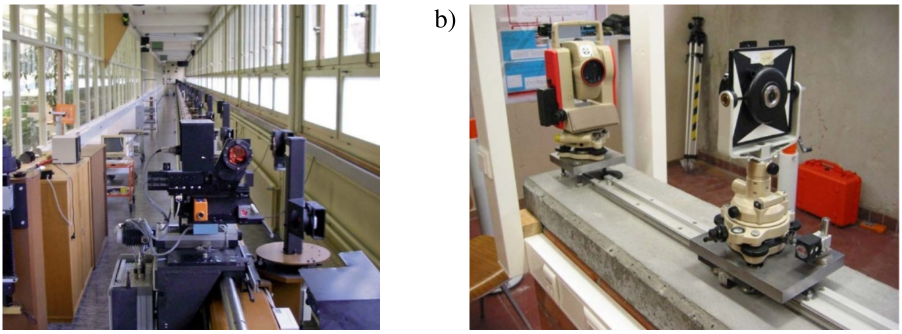

Fig. 3. EDM-calibration laboratory: at Leica Geosystems company (a) and at Ghent University (Belgium) (b)

Table 2 shows the calibration and measurement capabilities of the Leica Geosystems EDM calibration laboratory according to the Swiss Accreditation Service, which accredits Leica Geosystems calibration laboratories every five years (Swiss Accreditation Service SAS, 2020).

Table 2. Calibration and measurement capability of Leica Geosystems company laboratory

Distance measurement method	Measurement range	Measurement conditions	Best measurement capability	Remarks
Distance (to prism)	60 m	Laboratory	±0.16 mm	Measurement of linearity deviations
	120 m		±0.26 mm	
Distance (non prism)	60 m		±0.17 mm	
	120 m		±0.26 mm	

The length of calibration bench of Ghent University is 20 m. The authors in (De Wulf et al., 2011) expect to obtain a measurement accuracy better than 0.1 mm using interferometry.

RLS laboratories (Fig. 4) consist of a rigid base 1 and a guide 2 fixed on it, on which a movable carriage 3 with two oppositely directed reflectors 4, 5 is installed. Planes 6, 7, where EDM 8 and laser interferometer 9, respectively are fixed, are installed at the opposite ends of the station.

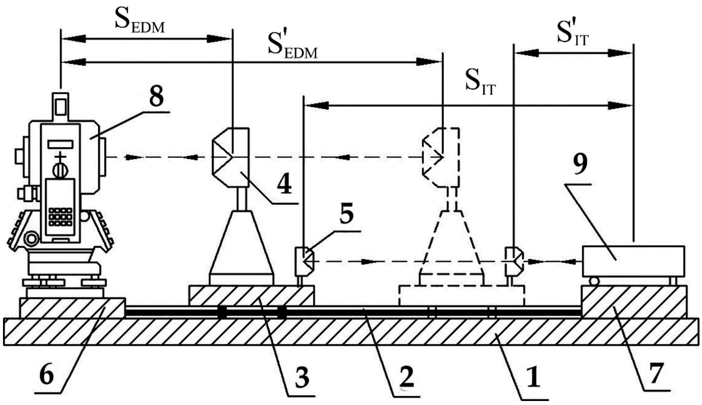

Fig. 4. Functional scheme of an interferometric laboratory station

The method of control presupposes measuring the same values of horizontal movements of the carriage with reflectors using EDM and laser interferometer, and the measurement error is determined through the formula:

$$\delta = \left(S'_{EDM} - S_{EDM}\right) - \left(S_{IT} - S'_{IT}\right), \tag{11}$$

where δ is the error of EDM -measurement of the reflector movement; S_{EDM}, S_{IT} are distances measured by EDM and laser interferometer, respectively, for the initial position of the carriage with a reflector; S'_{EDM}, S'_{IT} are distances measured by EDM and laser interferometer after the carriage with the reflector was moved.

Taking into account that the accuracy of distance measurements using a laser interferometer is 1 μm + 1 mm/km (Reischmann, 2010), and for the case when the difference between the distances measured by EDM is insignificant, the experimental root mean square error of the EDM rangefinder can be calculated using the formula:

$$\widetilde{m}_S = \frac{\widetilde{m}_\delta}{\sqrt{2}}, \tag{12}$$

where $\widetilde{m}_\delta$ can be calculated using formulas (2) or (5).

Due to the mechanism of positioning of the carriage with reflectors along the entire station, which is controlled from the control unit, the process of control operations takes place in automatic mode (Reischmann, 2010). The information from the laser interferometer and the EDM is transmitted to a personal computer, which contains software for processing the measurement results, which are stored in its memory and printed as a report on the metrological control of the EDM.

Interferometric laboratory stations are usually used to calibrate high-precision EDM s with a small range of distance measurements, which are used, for example, to install technical equipment in the specified position or to conduct experimental studies (Braun et al., 2015). This is due to the significantly limited measurement range of most laser interferometers, as well as the size of laboratories. In Braun et al. (2015) developed calibration procedures, including a special correction function, which resulted in a 50% reduction in the standard deviation. The standard deviation of distance measurements with the different EDM on the basis was 0.5 mm.

Hussein et al. (2020) describes the use of femtosecond laser pulses to calibrate EDM for a basis length of 58 m. The maximum accuracy of measuring the distances between fixed bases that make up the basis was 14 μm. The total EDM calibration error at a distance of 55 m was 324 μm. The disadvantage is that the EDM is not calibrated over the entire range of the instrument's operating length.

The authors Kolomiets and Podostroets (2014) proposed a laboratory method of metrological control of EDMs, which is based on the law of reflection of light from a flat mirror. With the help of a system of mirrors, a reference base line of zigzag shape is created – a mirror linear base. Such a system may consist of sets of mirrors with different distances between them to "collect" the required distance from a set of adjustable mirrors (Fig. 5).

Obviously, if to direct the sighting tube EDM on the mirror, the laser beam, reflected from the mirror, will continue its way to the next mirror, etc. to the reflector and reflecting from it in the same way will get to the transceiver system of the device, the display of which will show the value of the measured distance. Comparing it with a reference, measured by a more accurate electronic rangefinder, three times more accurate than that controlled (Metrology, 2020), allows to determine the accuracy of a particular EDM using the formula (2) (Kolomiets and Podostroets, 2014). To install a EDM in the laboratory, a slide table of an autocollimation unit for verification of levels and theodolites (AUVLT) is used, which is a universal control bench equipment and is designed to determine and control the metrological characteristics of geodetic instruments, including the protractor part EDM (Kolomiets and Podostroets, 2014). AUVLT (Fig. 6) has a vertical rack 1, which houses the bracket 2 with the autocollimator 3, which reproduces the horizontal sighting beam with the help of the oil horizon. This part of the device is an autocollimation unit for verification of levels (AUVL).

On the opposite side of the rack 1 there is a bracket 4 with a subject rack 5, on which a geodetic instrument 6 is installed, the metrological characteristics of which are controlled. The subject table 6 can move in height and tilt to a given angle. In the upper part of the rack 1 there is a tilter 7, on which there are two autocollimators 8 and 9, which reproduce two coaxial horizontal sighting rays. Tilter 7 and autocollimators 8, 9 form an autocollimation unit for calibration of theodolites (AUCT). In the upper part of the tilter 7 there is an autocollimator 10 – for calibration of laser and optical devices of vertical

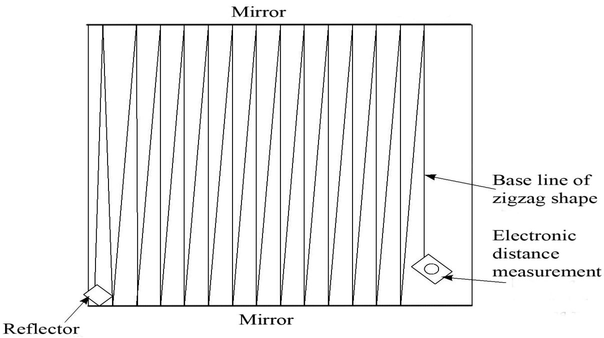

Fig. 5. General view of the mirror reference linear basis

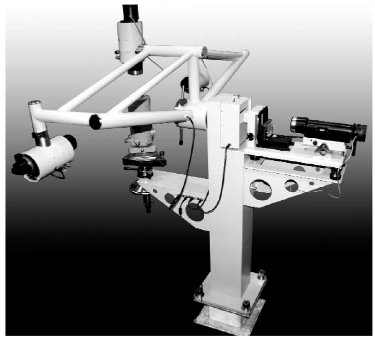

Fig. 6. Appearance of the AUVLT installation (Samoilenko et al., 2011)

design. The modernized AUVLT units have autocollimators equipped with photoelectric converters and equipped with computer programs to perform calculations of controlled metrological parameters (Samoilenko et al., 2011).

Thus, from the time of metrological control of EDM there is no need to remove it from the subject table to control a separate rangefinder or protractor units (Kolomiets and Podostroets, 2014). Therefore, the further direction of improving the metrological support of EDM is seen in the development of tools that will combine the procedure of control of protractor and distance measuring units of EDM in one procedure, which is performed in favorable laboratory conditions.

If 13 mirrors were needed to build according to the proposed scheme a 96-meter base (Kolomiets and Podostroets, 2014), then to build, for example, a 2 km base of such mirrors, it is necessary to have about 270, which is problematic. In addition, if in connection with the possible relocation of the laboratory to another room, with the dismantling and installation of AUVLT there will be no significant difficulties, but such a linear basis it will be necessary to create again.

During the certification of devices, in the framework of scientific research, it is of great interest to be able to assess the real accuracy of the remote control unit EDM over the entire range of working distances. For objective reasons, the construction of a field or laboratory linear basis according to the above given schemes is a difficult and sometimes impossible task.

3.2. EDM rangefinder accuracy control using optical fiber as a basis

There are existing devices for controlling the accuracy of the distance measuring unit EDM, in which the optical fiber is used as a basis. A fiber-optic basis is formed. The set of such lines makes a fiber-optic linear basis (FLB) (Vinogradov and Vorontsov, 2011; Burachek et al., 2014). Such devices are relatively small in size and make it possible to perform control measurements over long distances in the laboratory, thereby minimizing the influence of the external environment on the measurement results.

Figure 7 shows the design of a device for monitoring the metrological characteristics of the distance measuring unit EDM (Vinogradov and Vorontsov, 2011). The principle of operation of the device is as follows. The controlled EDM is fixed on the lifting table, then with the help of the lifting device the alignment of the telescope and the collimator tube is ensured, which is necessary for the exact hit of the laser beam on the prism of the focusing device. In the next step, the operator with the help of the screws of the total station connects the intersection of the grids of the threads of the device and the collimator tube, controlling the alignment through the eyepiece of the total station. After turning on the measurement mode, the laser beam EDM, passing through the nozzle tube on the lens, focuses on the end of the optical fiber. Then the signal passes through the optical fiber and returns from the other end to the lens of the device. Figure 8 shows a functional diagram for controlling the metrological characteristics of the distance measuring unit EDM, proposed by the authors in Burachek et al. (2014).

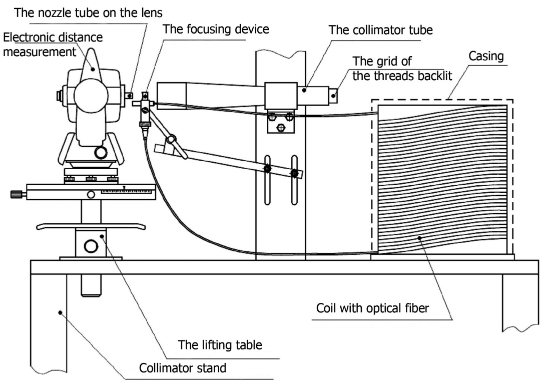

Fig. 7. Design of FLB for control of metrological characteristics of the distance measuring unit EDM (Vinogradov and Vorontsov, 2011)

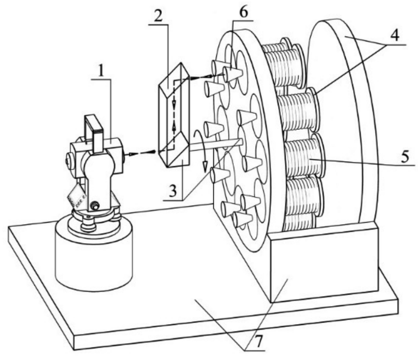

Fig. 8. The functional diagram for controlling the metrological characteristics of the distance measuring unit EDM (Burachek et al., 2014)

In the diagram (Fig. 8), the corresponding numbers indicate: 1 – EDM, 2 – light radiation switching unit, 3 – the mechanism of rotation and fixing of the switching unit, 4 – drum with a set of optical fibers, 5 – coil with optical fiber, 6 – input-output device of light radiation, 7 – the base of the device. At one end of the FLB devices of input-output of light radiation are fixed, by which the beam is focused on the end of the optical fiber. This can be, for example, a condenser lens, in the focal plane of which is the end of the optical fiber, or a focusing cone. A mirror coating is applied to the other end of the optical fiber. The switching unit with the mechanism of rotation and fixing directs light radiation to the optical fiber with the required length.

The principle of operation of the device is as follows. The operator turns on the EDM in the distance measurement mode, the transceiver of which emits a light signal that passes through the switching unit and focuses on the end of the optical fiber, travels the distance to its end, is reflected from the end with a mirror coating and returns to the EDM. Figure 9a shows the FLB scheme, which consists of three control baselines in length S_1,

S_2, S_3, one light-emitting input-output device (IOD) and two light dividers LD_1 and LD_2 (positions 1 and 2 in Fig. 9) – passive fiber-optic components designed to separate the light signal.

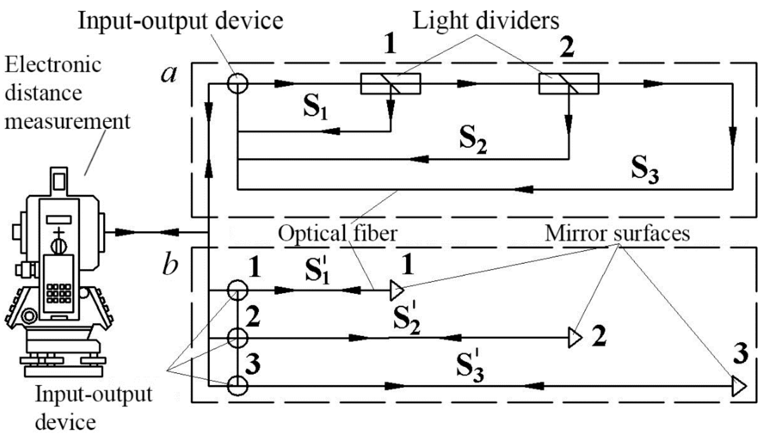

Fig. 9. FLB to control the accuracy of EDM: according to Vinogradov and Vorontsov (2011) (a) and according to Burachek et al. (2014) (b)

The laser beam of the remote control unit of the EDM, passing through one of the three base lines, returns to the lens of the device. The length of, for example, a line is equal to the path that the beam will travel in the direction IOD → LD_2 → IOD.

FLB, shown in Figure 9b, has optical fibers (length S'_1, S'_2, S'_3) and separate IOD. A mirror coating is applied to the ends of the optical fibers (in Fig. 9, b is marked as reflectors). The light beam passes through the optical fiber in the forward and reverse directions, and then registered by the photodetector of the EDM. As it is seen in Figure 9, the physical length of IOD is (Fig. 9a) greater than the length of the FLB (Fig. 9b) by an amount equal to $S_1 + S_2 + S_3$.

Assessment of the accuracy of control of metrological characteristics of the EDM distance measurement unit using fiber-optic length measurement was carried out in (Vinogradov, 2012). The error of distance measurement using fiber-optic components as a baseline was 2÷3 mm. The described scheme (Figs. 7 and 8) has a number of drawbacks. First, since the value of the measured distance directly depends on the wavelength of the radiation source, when determining the baseline lengths of fiber-optic lines with a precision laser rangefinder it is necessary to know its wavelength exactly, and before starting the EDM test it is necessary to determine the wavelength of each instrument and make a corresponding correction in the final result. Second, the refractive index of the quartz glass will change as the temperature of the optical fiber changes, both due to temperature changes and due to bending deformation caused by thermal expansion, which will also require making a corresponding correction to the measured distance. Third, this scheme does not allow us to determine the true baseline length, but only allows us to calculate the distance measurement error, which does not allow us to assess the accuracy of the EDM calibration. Also in Vinogradov (2012) the a priori accuracy of optical fiber length measurement with a laser rangefinder was calculated. It turned out that the measurement error is 0.005% of the length or 25 mm for 500 meters, which is a rather low accuracy.

3.3. Improvement of the method of controlling the metrological characteristics of the EDM rangefinder using a fiber-optic base

Taking into account the drawbacks of the described schemes, we propose a scheme of a universal laboratory linear base, which, on the one hand, can have compact dimensions and, at the same time, contain reference lines of great length, on the other hand, possess high measurement accuracy comparable with the interference one. High measurement accuracy is achieved by direct differential distance measurements, which is based on the use of a laser interferometer as a reference rangefinder and an optical fiber as a linear basis.

The authors of this paper in (Khomushko, 2018) proposed a functional scheme of fiber-optic interference linear basis for control of metrological characteristics of rangefinder EDM. The proposed laboratory reference linear basis is characterized by compact dimensions with control lines of increased length while maintaining high measurement accuracy. This result is achieved by combining fiber-optic and interference line bases, which allows to qualitatively improve the metrological support system of laser rangefinders. In this case, the fiber-optic base unit will allow setting the base lines of increased length, and the interference unit will provide high control accuracy without the need to determine the refractive index of the medium. To reduce the length of the FLB, and accordingly its dimensions, the authors proposed to combine the technical solutions of the above given schemes of FLB (Fig. 10). As can be seen from Figure 10, in the design of the FLB instead of light dividers there are switches installed – fiber-optic components that perform switching (redirection) of optical signals that pass from one fiber to another.

The scheme of such FLB will be similar to the field: setting the signal switching to the desired reflectors, the light beam from the EDM will pass the base lines of different lengths (according to the measurement program) in the forward and reverse direction and recorded on the EDM photodetector. Given that the optical path length of the beam will be approximately 1.4 times greater than the running length of the optical fiber, to organize 5 km of the base will require about 3.5 km of optical fiber, which will be, for example, 7 coils (500 m of optical fiber) 0.50 m high and 0.30 m in diameter each.

The peculiarities of FLB include the fact that to determine the reference lengths of FLB with a precision light rangefinder it is necessary to accurately determine its wavelength, and before calibrating EDM it is necessary to determine the wavelength of its radiation and make the appropriate correction in the final result of the measured distance.

Therefore, in (Khomushko, 2018) it is proposed to combine interferometric measurements and the use of fiber-optic linear basis, which allows to abandon the measurement of EDM wavelength. To do this, Figure 4 shows a diagram of the interferometric laboratory base, attached to the plane 10 (Fig. 11), which houses the input devices 11 and output devices 12 of laser radiation from EDM 8 at the end of the optical fiber 13, which is placed on the coil 14.

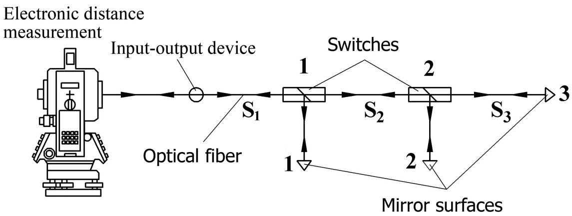

Fig. 10. Improved FLB circuit to control the accuracy of the rangefinder unit EDM

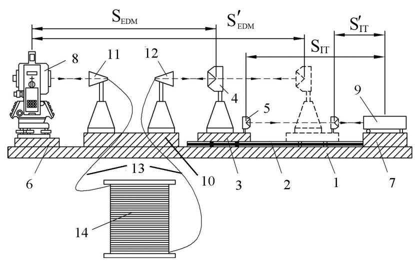

Fig. 11. To the functional scheme of fiber-optic interferometric basis

The method of control is to measure the same values of horizontal movements of the carriage with reflectors using EDM and laser interferometer, and the measurement error is determined according to formula (11). The experimental UPC of the EDM rangefinder can be calculated by formula (12). In this way, one can create a fiber-optic interferometric linear basis, if to use coils with optical fiber of different lengths, or use means of switching the optical signal, similar to the schemes shown in Figure 9 or Figure 10 (Khomushko, 2018).

4. Conclusions

Analyzing the current state of metrological control of electronic distance measurements rangefinders both in Ukraine and abroad, we can note the gradual transition from the use of field linear bases to laboratory measurements. This reduces the impact of external conditions on the measurement results, allows to partially automate the measurement process and creates a comfortable environment for test participants, which is important for ergonomic reasons. Joint use of laboratory linear bases and angular devices for calibration of rangefinder and angular units of EDMs has been initiated. However, field and laboratory methods have their disadvantages. The general disadvantage of field methods is the necessity to measure and take into account atmospheric parameters, and the absence of calibration of reference instruments at the calibration base. The general disadvantage of the laboratory methods is the complexity of construction and small length of such bases, which is 20–100 m.

Further development and improvement has received the use of fiber-optic linear bases, in which optical fibers of known length and calibration are used as sample lines by comparing the differences of distances measured by the electronic distance measurement with the differences of distances measured by the interferometer.

The article offers a technical solution – a combination of fiber-optic and interference linear bases, which allows to qualitatively improve the system of metrological support of laser rangefinders. This is achieved due to two main factors. Firstly, the presence of the fiber-optic unit makes it possible to organize the base lines of increased length, while ensuring small dimensions of the base line. Second, the basis of the proposed combined scheme is a relative interference base, which ensures high accuracy of linear measurements and does not require calibration of the base with a precision rangefinder, which eliminates a number of difficulties associated with changes in the refractive index, makes measurements independent of the wavelength of the radiation source and is virtually independent of the ambient temperature.

Author contributions

Conceptualization: V.B[1].; Methodology development: V.B[1]. and D.K.; Writing – original draft: D.K., S.K. and V.B[4].; Writing – review and editing: V.B[4]. and O.T.

Data availability statement

Source data (patent of Ukraine for the invention No. 116714) is freely available on the website of the organization State Enterprise "Ukrainian Intellectual Property Institute" (Ukrpatent): https://ukrpatent.org/en.

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