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Accuracy Test of Laser Tracker under Condition of Air Turbulence

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Abstract. Laser tracking for interior industrial metrology is discussed. In this work, the effects of air turbulence on the angle of laser wave propagation is analyzed in the absence of the effects associated with other meteorological parameters (pressure, humidity) and particulate pollutants (dust, smoke). This analysis establishes the effectiveness of laser tracking under turbulent air conditions and quantification of deviations in the angular and linear accuracy from those provided by the manufacturer. An experimental setup and associated measurement method to determine the turbulence structure coefficient are described. It was found that turbulent air conditions resulted in a radical decrease in measurement accuracy. The reduction in accuracy was evidenced by a decrease in power and an increase in standard deviation of the laser beam, as well as a decline in the angle and distance measurement precision. The experimental measurements show a high correlation to predicted values.

Keywords: laser station, industrial surveying, large scale-metrology, random propagation of laser beam.

Conference topic: Technologies of geodesy and cadastre.

Introduction

The aim of this work was to examine the effect of air turbulence on metrology engineering measurements (Franceschini 2014; Peggs *et al.* 2009; Zobrist *et al.* 2007) which can occur in the factory halls. The experiments were conducted with a Leica AT402 laser tracker, which, according to the manufacturer specifications, provides an accuracy of 0.01 mm for distance measurements up to 320 m. This research was performed in a manufacturing plant modernizing rail vehicles (PESA Bydgoszcz SA) in Poland.

Measurements were made in the varnish and drying room for specific components of rail vehicles. Two test stations were constructed. The first station consisted of a tracker and an integrated portable computer. The second contained the tracker, red-ring reflector (RRR), and coherent radiometer, which also were connected to the computer. The distance between stations was 37.5 m. All measurements were performed for both natural and turbulent conditions in the paint room. With the help of a tracker, the beam coordinates in the prism’s XY plane were determined. At the same time, radiometer measurements recorded changes in the laser beam power. From these measurements, it was possible to calculate the predicted position of the laser beam and compare it with the values measured by the tracker.

The phenomenon of air turbulence

In the literature, air movement is compared to the course of a viscous liquid in a thin tube. In contrast to air, the current picture can be considered a liquid separated into circulation streams which have not mix. This is laminar motion, that is, one in which there are no intermixing streams, and the speed at any point is constant or changes are regulated.

In atmospheric air movement, the velocity of air molecules at each designated point is constantly changing in magnitude and direction. These are random and disordered changes in the air molecules’ velocities. This phenomenon can be observed in streams of smoke coming out of industrial hall chimneys. Motion of the particles is so-called turbulent motion, characterized by random changes in speed and air molecules that are vigorously stirred.

When a laser beam propagates through a turbulent atmosphere, it experiences random fluctuations in the refractive index. The fluctuations are due to turbulent eddies caused by stochastic variations of the temperature. In practice, it is difficult to sufficiently control the composition of the air in optical instruments to achieve high accuracy. Under realistic medium conditions, light propagation depends on the concentration of inhomogeneity centers, which changes dynamically along the direction of propagation (Kolmogorow 1978). Laser surveying in an uncontrolled atmosphere requires accurate formulas describing refraction as a function of air perturbation. Due to heterogeneity, the coefficient of refraction, which is the main parameter describing the optical properties of the medium, depends on the position vector r and can be expressed as (Kwiecień 1989):

$$N(\overrightarrow{r}) = N_0 + N_1(\overrightarrow{r}), \tag{1}$$

where $N_0 = \langle N(\vec{r}) \rangle \cong 1$ is the constant refraction coefficient for a homogeneous medium and depends on temperature, pressure, and the humidity of air and $N_1(\vec{r})$ is the correction accounting for the variation in the refraction coefficient due to turbulence; the angled brackets < > indicate the statistical mean (expected value). Systematic refraction is characterized by regular, slow (longer than three minutes) changes, and these variations overlap random fluctuation caused by air turbulence.

The theory of the influence of atmospheric turbulence on propagation of electromagnetic waves has been extensively discussed (Alim *et al.* 2010; Chiba 1971; Pemha, Ngo Nyobe 2011; Strohbehn 1978; Tatarsky 1971; Zunino *et al.* 2015). Turbulence is a random process described by stochastic parameters. Accounting for the random changes in velocity (i.e., its value and direction) of each particle in the medium is a complicated issue, and a complete statistical or stochastic analysis is impossible.

Atmospheric factors affecting the accuracy of measurements in enclosed areas of production halls

Poor air conditions cause difficulty in laser measurements laser in closed production facilities. Measurements in industrial halls are carried out in a specific environment shaped by many factors related to the production technology in use.

The existence of temperature gradients in the atmosphere leads to laser beam scattering (Frehlich 2000; Webb, Jones 2004; Weiss 2002), resulting in a systematic change in the refractive coefficient N_0 along the path of propagation. Variation in N_0 in closed rooms can be connected to the following causes:

- daily changes in temperature caused by the production process,
- seasonal changes of temperature outside industrial buildings,
- heat emitted by various machines used in production,
- central heating,
- cold conditioned air coming out of the cooling devices,
- turbulence through “drafts” in the open,
- mismatched air vents to ventilate and condition the room causing the formation of the so-called dead zones, (i.e., those in which there is no air exchange and zones where speed limits are exceeded, the temperature and humidity),
- leaky and broken windows in the halls of industrial causing thermal gradients,
- changes in air density which depends on its temperature, humidity and pressure,
- dust from the production of data elements or substances,
- fumes and exhaust gas extracted by motor vehicles that are in the production plant,
- inadequate or poorly executed ventilation system,
- large amounts air pollutants emitted by the equipment and apparatuses,
- uninsulated parts of machinery and equipment, where the process uses heat or harmful substances in the form of vapors, gases or dusts (Galetto *et al.* 2009; Holejko 1981; Kwiecień 1982, 1985a, 1985b, 1986, 1989; Kwiecień, Żak 1990).

Angular and linear deviations of the laser beam

Assuming the output of the laser beam is focused and has a diameter D_0 and that its size determines the direction of radiation, the equation determining where the radiation will fall to zero as a result of the divergence of the diameter D at a distance L will be:

$$D = [(2.9\frac{\lambda L}{D_0})^2 + \left(\frac{2\lambda L}{\pi R_0}\right)^2\Bigg]^{\frac{1}{2}}, \qquad (2)$$

where: $R_0 = k^{-\frac{6}{5}} C_N^{-\frac{6}{5}} L^{-\frac{3}{5}}$ is the coherence radius of the wave, L is the propagation distance of the laser beam, and $k = \sqrt{k_x^2 + k_y^2 + k_z^2}$ in the range of $-\frac{2\pi}{L_0} < k < \frac{2\pi}{l_0}$ turbulence. The parameter k is described as the greatest distance at which fluctuations in the refractive coefficient are correlated, and is an internal scale that describes the smallest eddies of turbulence.

The value of parameter C_N^2 characterizes the various stages of turbulences (Wilfert, Dordowa 2009):

– $C_n \sim 10^{-8}$ m$^{-1/3}$ – weak turbulence,
– $C_n \sim 10^{-8}$ m$^{-1/3}$ – moderate turbulence,
– $C_n \sim 10^{-7}$ m$^{-1/3}$ – strong turbulence.

If the diameter D is smaller than the internal l_0 scale turbulence along the propagation path, the following equation for the angular root mean square deviation of the laser beam at any point in propagation path can be written as:

$$\left\langle \delta^2 \right\rangle = 5.726\, C_N^2\, l\, D^{-\frac{1}{3}}, \tag{3}$$

where: C_N^2 is a structural constant refractive coefficient that acts as a measure of beam fluctuations. Details on deriving this equation can be found in (Kwiecień 1989; Wei, Ma 2010).

However, the total root mean square deviation of the arrival angle at the end of path L will be:

$$\left\langle \theta^2 \right\rangle = \left\langle \delta^2 \right\rangle \frac{L}{l}, \tag{4}$$

where: $\frac{L}{l}$ is the number of elementary segments.

Therefore:

$$\left\langle \theta^2 \right\rangle = 5.726\, C_N^2\, L\, D^{-\frac{1}{3}}. \tag{5}$$

Consider now the linear deviation p of the beam at the end of the propagation distance. This quantity can be defined as the derivative of angular changes along the propagation path multiplied by the distance from the point where the turbulence structure coefficient C_N to the receiver is determined, where the measurements are collected. Since the changes in the angle of propagation are small and their derivatives with respect to the path are statistically independent, the linear deviations are described by

$$p^2 = \int_0^l \left(L - l\right)^2 \left(\frac{d\theta}{dl}\right)^2 dl. \tag{6}$$

Assuming that $\left\langle d\theta \right\rangle$ is a linear function like in equation (3) follows:

$$\left\langle p^2 \right\rangle = \frac{1}{3} \left\langle \theta^2 \right\rangle L^2 \tag{7}$$

and with equation (5), yields:

$$\left\langle p^2 \right\rangle = 1.9\, L^3 C_N^2\, D^{-\frac{1}{3}}, \tag{8}$$

where: C_N^2 – is the value of structure coefficient which characterizes the various stages of turbulences; L – is the propagation distance, (i.e., the distance between transmitter and receiver); D – is the diameter of the laser beam; $p^2 = p_x^2 + p_y^2$ (p_x – deviation of beam position in the plane XY; p_y – deviation of beam position in the plane XY).

Test measurements of the influence of air turbulence on tracker laser survey

Recording of the time data was limited to three minutes based on the assumption stated in the introduction of this work. Systematic refraction, which has not been studied here, occurs after this period. The total number of measurements consisted of five independent tests for air turbulence. A laser beam with wavelength of 650 nm and a maximum average radiant power of 5 mW was emitted from a Tracker Leica AT402 which emerged from a telescope objective having an initial diameter of $D_0 = 1\,\text{mm}$ (Leica Geosystems 2015).

Linear deviations in the laser beam were measured at the end of the propagation path using a 1.5" Red-Ring Reflector in the "precise" measurement mode. The producer's inspection certificate in accordance with DIN 55350-18-4.2.2 specifies the following accuracy for this device: maximum deviation of distance measurement of +/–10 µm (standard deviation of single distance measurement σ = +/–5 µm/m) and resolution of 0.07 seconds arc of angle measurement (Hz and V).

In any case, after the test was recorded, laser beam power was measured at the end of the propagation path using a Coherent PowerMax-USB/RS model UV/VIS radiometer with a wavelength ranging from 325 nm to 1065 nm. Research was carried out in the room for painting and drying of large rail vehicles parts, where turbulent conditions exist. The drying room (Fig. 1) possesses a gate on each side (W1, W2) which were raised and lowered for the experiment. The first research station was constructed near gate W1, and the second located near gate W2.

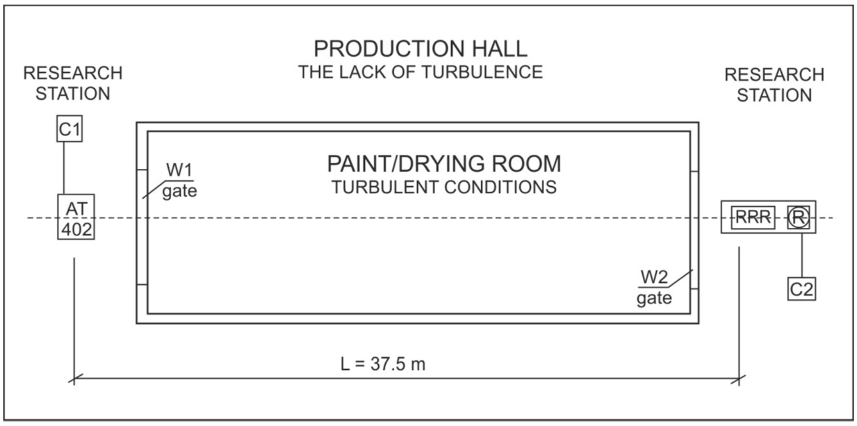

Fig. 1. Scheme of measurement experiment (AT402 Leica Tracker, C1 – Computer no. 1, C2 – Computer no. 2, RRR – Prism, R – Radiometer, W1 – Gate no. 1, W2 – Gate no. 2) (Source: own work)

Measurements of turbulence structure coefficient

Radiometer measurements allowed to calculate the coefficient C_N according to formula (9):

$$C_N = \sqrt{\frac{\delta_I^{\,2}}{1,24 * 2\pi^{\frac{7}{6}} * \lambda^{-\frac{7}{6}} * L^{\frac{11}{6}}}}, \tag{9}$$

where: $\delta_I = \frac{\delta_M}{M}$; δ_I – standard deviations of laser beam intensity; δ_M – standard deviations of laser beam power [µW]; M – average power of laser beam [µW]; λ – laser wavelength [nm], λ = 628 nm; L – length of the propagation path of the laser beam [m].

The example of changes in the power of the laser beam with the stagnant air and turbulent conditions occurring in the paint room is presented in Fig. 2.

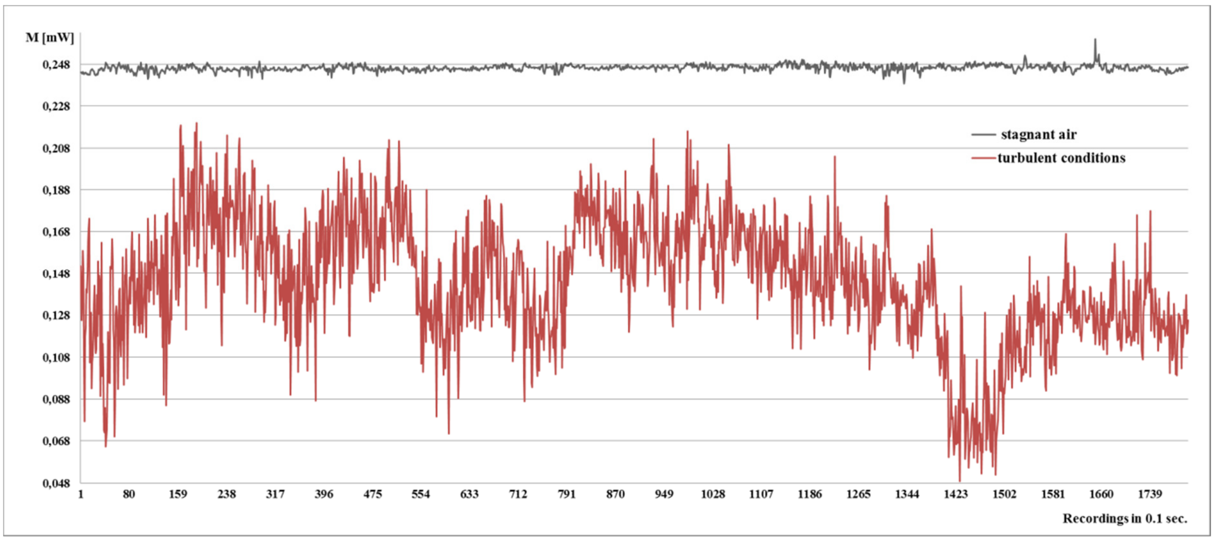

Fig. 2. Fluctuations of the laser beam power during the stagnant air and turbulent conditions for test 2 (Source: own work)

However, Table 1 shows the calculation results of the structure coefficient of turbulence C_N in different states of the air:

Table 1. The calculation results of the structure coefficient of turbulence C_N (Source: own work)

Test number	Turbulence conditions	Average beam power with standard deviation [mW]		Standard deviation of beam intensity [mW]	Turbulence structural coefficients [m$^{-1/3}$]
		$M \pm \delta_M$		$\delta_I = \frac{\delta_M}{M}$	$C_N = \sqrt{\frac{\delta_1^2}{1.24 \cdot 2\pi^{7/6} \cdot \lambda^{-7/6} \cdot L^{11/6}}}$
		M	δ_M	δ_I	C_{N_t}
1	Stagnant air	0.23	0.003	0.060	3.81 E-08
2		0.21	0.001	0.055	1.17 E-08
3	Turbulence air	0.14	0.030	0.051	6.27 E-07
4		0.20	0.040	0.044	5.85 E-07
5		0.21	0.030	0.046	4.18 E-07

Measurements of linear deviations of the laser beam

Measurements of the linear deviation of the laser beam were made in the XY coordinate plane of the prism, perpendicular to laser beam axis Z (Fig. 4). All measured coordinate values and standard deviations were saved in PolyWorks software.

Data collection was carried out in the following order:

– Forty series measurements of the position XY at the end of the laser propagation path in normal atmospheric conditions (stagnant air and stable temperature) were made.
– Then, after removing the RRR reflector, the laser beam power was measured using the radiometer (recorded about 1800 results).
– Next, the two gates of the paint room were closed to raise the temperature inside to approx. 60°C (Fig. 3).
– When the gates were opened again, the measurement of XY beam position were taken during the turbulence caused by mixing the hot air overflow from the paint room and cooler external air.
– After removing the reflector, the fluctuations in laser power using a radiometer were measured again.

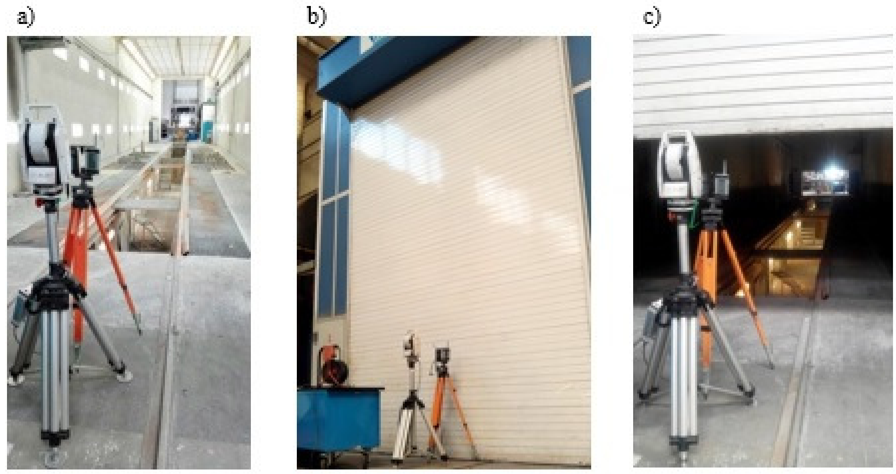

Fig. 3. Stages of research using tracker and radiometer. a) Measurements of laser beam position and power fluctuations in stagnant air. b) Heating paint room at the closed gate. c) Measurements of laser beam position and power fluctuations during air turbulence (Source: own work)

The procedure set described in stages 1 and 2 were repeated twice in stagnant air. However, the procedure described in stages 4 and 5 with turbulent air were repeated in three times.

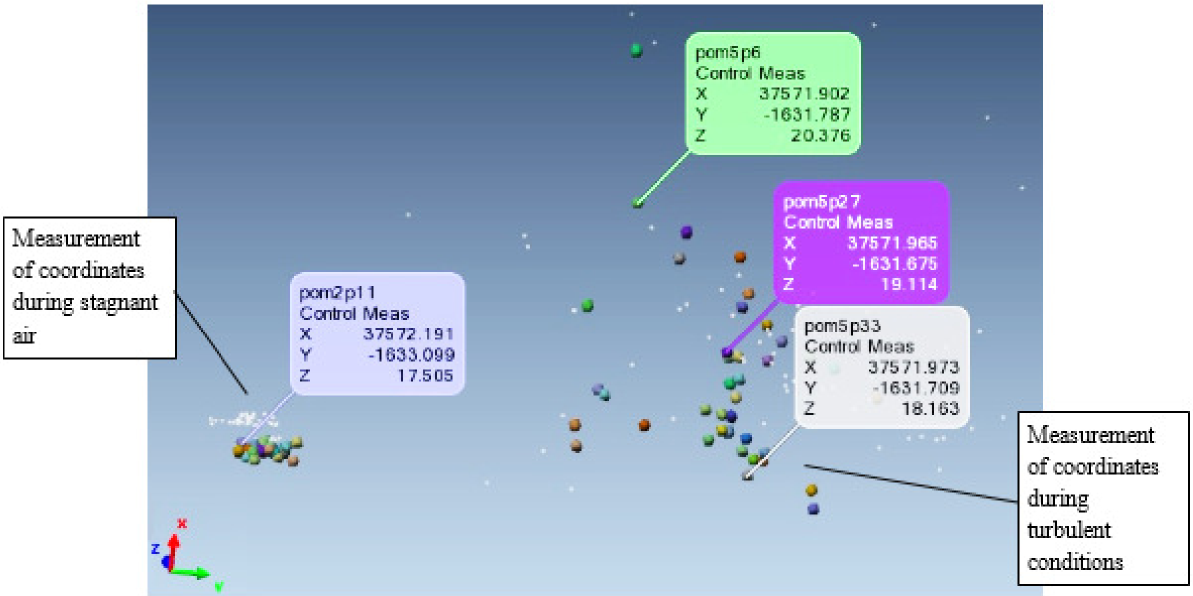

Fig. 4. Visualization of concentration and dispersion position points
in the PolyWorks software (Source: own work)

Figure 4 shows the dispersion of the registered coordinate values defining the position of the beam in the plane XY of the prism with the selected measurements during both natural conditions and turbulent. It can be seen that the coordinate values obtained in natural conditions have a small gap to each other, whereas those obtained in turbulent conditions show a large spread in beam position.

The graphs in Figures 5 and 6 show deviations in the X (vertical) and Y(horizontal) coordinates from their average values in the plane of the prism during stagnant air conditions (80 registered results) and turbulent conditions (120 registered results).

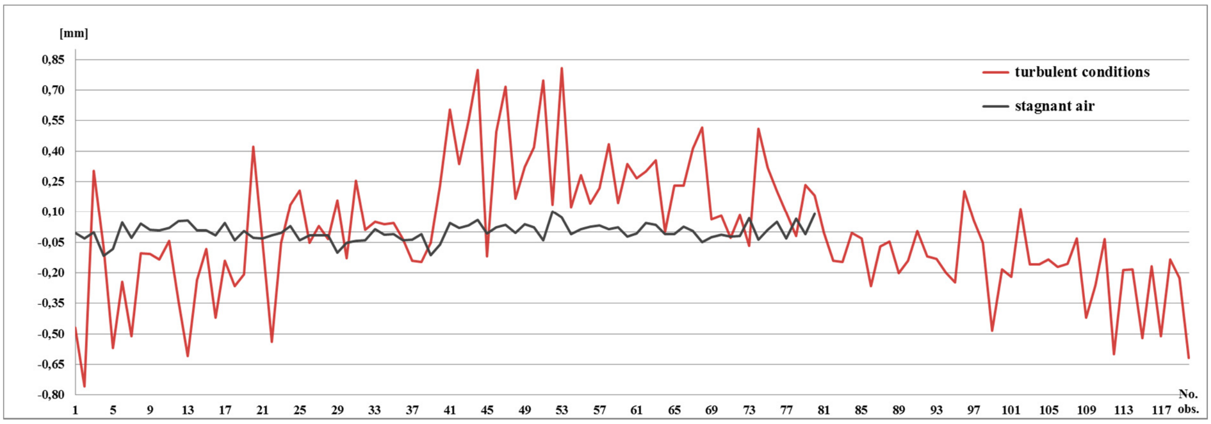

Fig. 5. Deviation of Y (horizontal) coordinate during stagnant air and turbulent conditions (Source: own work)

In Fig. 5, the deviations of the Y coordinate from the average value during stagnant air conditions are included in the range of –0.10 mm to +0.10 mm. During turbulent air conditions, these deviations are in the range of –0.76 mm to +0.81 mm. However, deviations of the X coordinate (Fig. 6) from the average value are included in the range of –0.10 mm to +0.13 mm during stagnant air conditions. During turbulent conditions, these values are in the range from –1.16 mm to +1.90 mm.

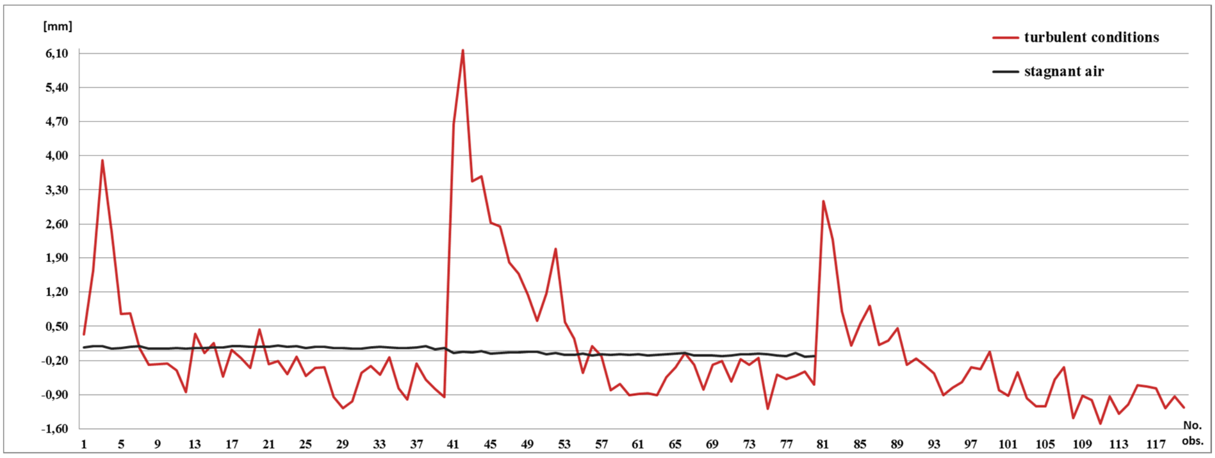

Fig. 6. Deviations of the X (vertical) coordinate during stagnant air and turbulent conditions (Source: own work)

Comparison of the measured deviations of the laser beam with the predicted

Comparison of the predicted and the measured resultant linear laser beam deviations is shown in Table 2. The predicted deviations of the laser beam, *p,* in the XY plane of the receiver were calculated using formula (8).

Table 2. The resultant of linear deviations of laser beam in the plane XY of the prism (Source: own work)

Test number	Conditions	Resultant of linear deviations of laser beam		
		Predicted deviations		Measured deviations
		p^2 [m^2]	+/– p [mm]	+/– p [mm]
1	Stagnant air	6.77E-10	0.03	0.05
2		6.36E-11	0.01	0.03
3	Turbulence	1.83E-07	0.43	0.68
4		1.59E-07	0.40	0.71
5		8.12E-08	0.28	0.45

The predicted linear deviations of the laser beam in stagnant air range from 0.01 mm to 0.03 mm, while the deviations measured using the tracker are between 0.03 mm and 0.05 mm. These results slightly exceed the manufacturer's declared permissible error of the device, which is 0.01 mm. The predicted linear deviations of the laser beam during strong air turbulence range from 0.28 mm to 0.43 mm, while the deviations measured by the tracker range from 0.45 mm to 0.71 mm.

Summary and conclusions

Test measurements have shown that it is possible to determine the size of the structure coefficient of turbulence (Cn) using a radiometer. Shown in Table 2 values of Cn during the stagnant air are in the range of $1.17 * 10^{-8}\ m^{-1/3}$ to $3.81 * 10^{-8}\ m^{-1/3}$, which indicates "weak turbulence" conditions. However, during turbulent conditions, Cn values are in the range of from $4.18 * 10^{-7}\ m^{-1/3}$ to $6.27 * 10^{-7}\ m^{-1/3}$, which corresponds to "strong turbulence".

The coordinates of the laser beam position in the plane of the prism XY have been measured during two states of air. The resultant deviations of the predicted and measured beam positions in the plane of the receiver show a high correlation and confirms the utility of laser tracker measurements to metrology. In contrast, the resultant beam deviations during turbulent conditions indicate a lack of usefulness tracker for metrology measurements.

This experiment proves that air turbulence has a significant impact on the accuracy of engineering metrology. It can be stated that Tracker Leica AT402 is not suitable for measurements during strong turbulence, which can occur on the factory hall. In adverse conditions, measurements should be halted, or if possible, the source of interference eliminated (e.g., stop the operation of the device emits high temperature). Manufacturers of laser trackers provide accuracy specifications relative to stable air conditions. In practice, however, there are many factors which affect the measurement accuracy of these devices.

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