Письма в ЭЧАЯ. 2015. Т. 12, № 2(193). С. 446–456

ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА. ЭКСПЕРИМЕНТ

THE LASER FIDUCIAL LINE MEASUREMENT PRECISION IN OPEN AIR MEDIA DETERMINED IN COMPARISON WITH LASER TRACKER AT-401

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The independent measurements by the newly proposed 50 m long Laser Fiducial Line (LFL) and by the Laser Tracker AT-401 were made at 16 and 34 m distances in an open air, and the LFL measurement precision was determined: 36 and 76 μm at 16 and 34 m distances, correspondingly.

Независимые измерения 50-метровой лазерной фидусиализированной линией (ЛФЛ) и лазер-трекером AT-401 на длинах 16 и 34 м в открытой воздушной среде определили точность измерения ЛФЛ: 36 и 76 мкм на длине 16 и 34 м соответственно.

PACS: 06.60.Sx

INTRODUCTION

The practice of metrology and survey support of the large scale physics research set-ups assembly and construction by the commonly used measurement methods meets difficulties. Among those are the absolute online measurements of the space location of ATLAS subdetectors during data-taking run, the attempts to reach a precision "connection" of coordinate systems of LHC and of ATLAS, CMS, LHCb, ALICE.

It seems possible and perspective to apply for the above tasks the new measurement methodic — the Laser Fiducial Line [2–5]. The authors earlier performed first comparative independent measurements by the LFL and by the Total Station complex [6]. The tacheometric method precision was 0.12 mm and both method's data agree within that figure.

To further study of the LFL measurements accuracy in function of the distance between laser source and point to be measured, the authors in this work used more precise control measurement set-up — the Laser Tracker AT-401 [1] with measurement precision of 20 μm. The comparative measurements were performed in open air media both by 50 m long LFL and by the AT-401.

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THE LASER FIDUCIAL LINE AS A MEASUREMENT METHOD

The Laser Fiducial Line is an *instrumental complex* including the laser ray limited by the beginning point O (the center of Local Coordinate System XYZ) and by the final point E located at the known distance from the point O (Fig. 1).

The Y-axis is directed along the laser beam; the Z-axis is perpendicular to Y and located in the plane created by the gravity vector and laser beam axis. The X-axis is perpendicular to Z and Y.

Using two adjustable tubes A and B positioned at the beginning and final points O and E together with the special cylindrical adapter equipped by quadrant photoreceiver (QPr), one achieves the desirable adjustment and fixation of the LFL (Fig. 2).

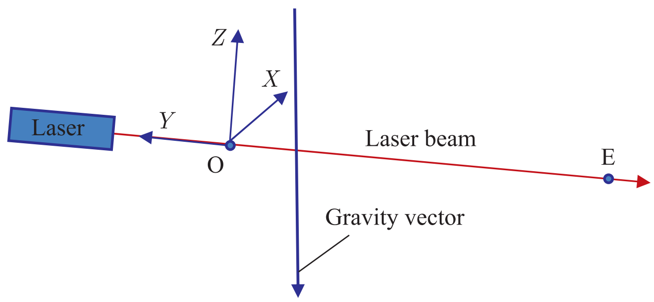

Fig. 1. The Laser Fiducial Line with Local Coordinate System XYZ

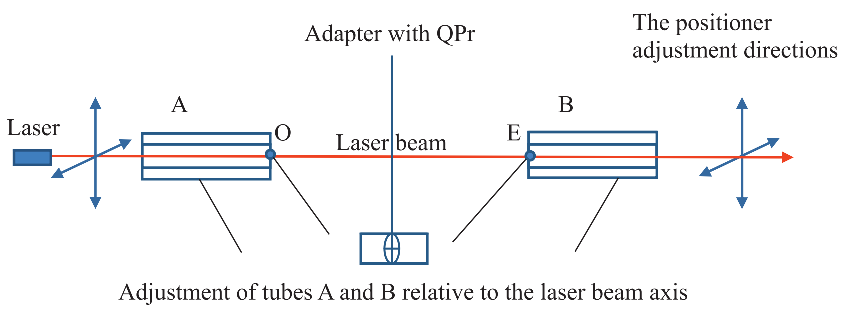

Fig. 2. Organization of the beginning and final points of the LFL

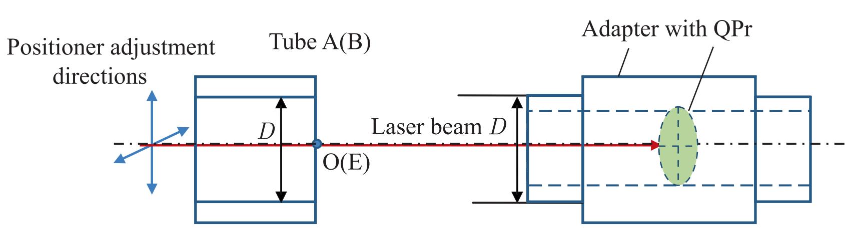

Fig. 3. The adjustment of the tube along the laser-ray axis by means of the cylindrical adapter with the QPr photosensor

The "adjustment of the LFL" is essentially the positioning of the laser-ray axis along the A(B) tube both for the beginning and final points O(E). It is made by the two-coordinate positioners (Fig. 3). For the precise coinciding of the axes of ray and of tube, one uses the cylindrical adapter with the QPr photosensor [7]. The adapter is a hollow cylinder with an external diameter equal to internal diameter of tube with QPr positioned inside adapter so that the QPr's plane surface is parallel to that of an adapter edges.

After the QPr was consequently positioned inside the tubes A and B, these tubes are being adjusted using the QPr data and two-coordinate positioner. Having tubes adjusted along the ray axis, these tubes ends centers (O and E) are used as the beginning and final LFL points.

Let us consider (on concrete example of determining of the coordinates of the centers of exit holes of the tubes under measurements) the measurement method used in this work with the LFL.

THE MEASUREMENTS WITH AN ADAPTER QUADRANT PHOTOSENSOR AND USE OF "CALIBRATION CURVE"

The QPr is positioned by its crosshair at the centre of an exit hole of the tube to be measured (Fig. 4).

As the tube to be measured is positioned not exact along the ray axis, the laser beam spot, in this case, is located near the crosshair of the QPr. To determine the coordinates of the QPr's center, one uses the "calibration curve". The "calibration curve" preparation procedure

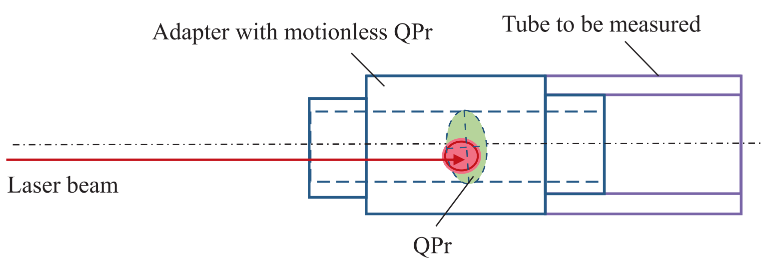

Fig. 4. The measurement of coordinates of exit holes of the tube by the "calibration curve" method

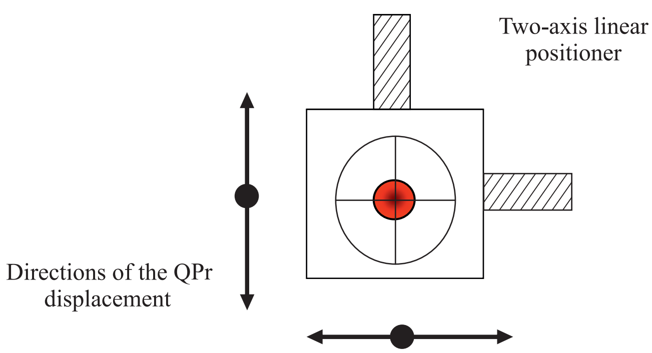

Fig. 5. The measurement scheme for "calibration curve"

is illustrated by Fig. 5. The QPr is able to move in four directions relative to ray spot; it is made by two-coordinate positioner.

With special metrology procedure one determines the value of signals from QPr in function of the distance between the QPr's center and laser spot centre. This dependence is being presented graphically as the "calibration curve". More details concerning the "calibration curve" preparation can be found in [6].

VERIFICATION OF THE LFL BY THE NEW EXTERNAL MEASUREMENT SYSTEM — LASER TRACKER AT-401

It is essential to note that the LFL under study can be verified by higher precision external measurement system and be included into the Global Coordinate System. These both operations are executed by the AT-401 equipped with the tacheometric adapter. The adapter is a cylinder with diameter D equal to the internal diameter of A and B tubes and it has a hole to position the tacheometric prism (Fig. 6).

After the tacheometric adapter was consequently inserted into edges of A and B tubes at the beginning and the end of the LFL, then, by means of AT-401 with the tacheometric prism, one measures the coordinates of the beginning (O) and of the final (E) points of the LFL in the Global Coordinate System. Similar to the adapter with QPr (Fig. 4), the tube under measurements has internal diameter D equal to external diameter of the tacheometric adapter. It allows one to determine the coordinates of centers of holes of the T-tube ends. After that, with the tacheometric adapter (positioned inside the T tube), one determines the coordinates of centers of the T-tube ends. Knowing the LFL coordinates of (O and E) points in the Global Coordinate System, one can determine the coordinates of centers of exit holes of the measured T tube with respect to the LFL axis in the Local Coordinate System (see Fig. 1). The tacheometric coordinates obtained in such a procedure are being compared with the similar LFL data; this is an expected estimate of the LFL method measurement precision.

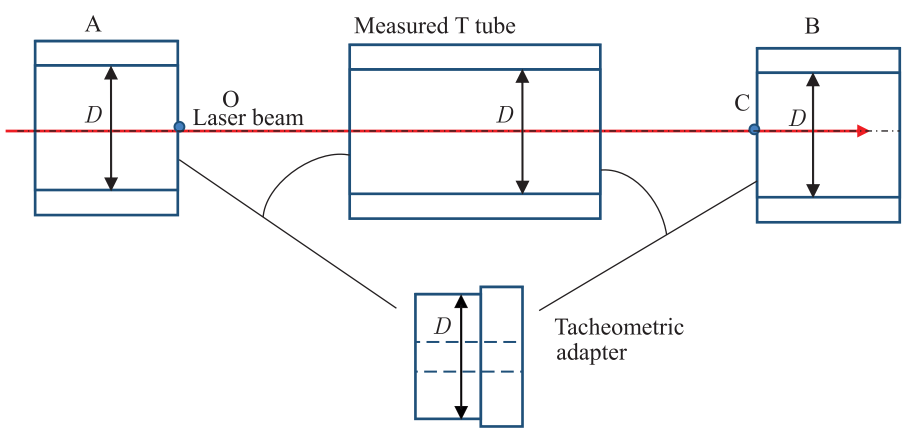

Fig. 6. The use of the tacheometric adapter and including of the LFL into the Global Coordinate System

THE MEASUREMENT PRECISION OF THE LASER FIDUCIAL LINE

The Measurement Precision in Function of Distance. The measurements have been performed in open air media. It seems that the most significant limitations of the LFL measurement precision are brought by fluctuations of the refraction index of air media. It limits by the 50 m distance the precision use of laser ray: the experimental σ(rms) obtained in [5] at the 50 m distance was 90 μm.

Figure 7 illustrates schematically the diapason of laser-ray axis transversal fluctuations in function of ray passed way.

If we use the 50 m long LFL, the "rms" deviations σ_0, σ_{50} of the beginning and final points B and E "geometrically" limit the rms value $\sigma_L^{\rm M}$ for the measured intermediate point M:

$$\sigma_L^{\rm M} = \sigma_0 + L\tan\varphi = \sigma_0 + \frac{L}{50\ \rm m}(\sigma_{50} - \sigma_0). \quad (1)$$

As σ_0 at the LFL beginning point B is much smaller than σ_{50} at the end $\sigma_0 \ll \sigma_{50}$, we have

$$\sigma_L^{\rm M} = \frac{L}{50}\sigma_{50}. \quad (2)$$

To summarize, we estimated — with Fig. 8 — the L dependence of the 50 m long LFL measurement precision σ_L. This precision is limited by the laser-ray axis fluctuation displacement in air media.

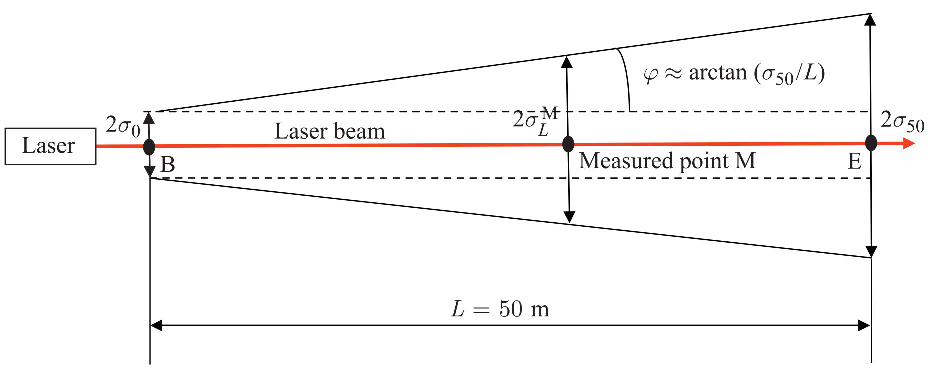

Fig. 7. Determination of precision $\sigma_L^{\rm M}$ of measurement of the point M transversal coordinate in function of σ_0 and σ_{50} precisions at beginning B and final E points of the LFL

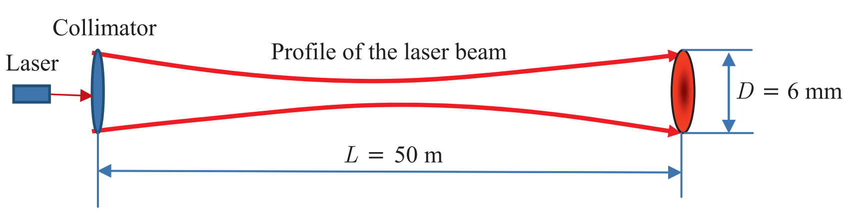

Fig. 8. Optimal collimation LFL

The Systematic Error in the LFL. The LFL system has different sources of the systematic errors. The following factors contribute to the systematic errors:

Power density nonsymmetric distribution across the laser ray. Experiment shows that power density distribution asymmetry across a ray may reach $\pm 30\ \mu$m [5].

Nonprecise positioning of the quadrant photoreceiver inside an adapter. When using the special metrology microscope, the quadrant photoreceiver positioning precision inside an adapter was estimated to be $\pm 30\ \mu$m.

Nonprecise manufacture of adapters used in experiment. Machining precision (by diameter) of the aluminum adapter we used is typically $\pm 30\ \mu$m.

Uniformity in local sensitivity of single photoreceivers in quadrant. In this work, it is estimated on $\pm 30\ \mu$m level. The QPr manufactures quote the instrumental measurement uncertainty of coordinate of centre of one-mode laser as $\pm 10\ \mu$m for 1 mm beam diameter [6].

Influence of temperature gradients along the laser-ray propagation. An estimate [4] shows that for 10 m long zones with temperature gradient $\cong 1\,^{\circ}$C along the way of ray propagation the resulting beam displacement is 10 μm and tilt angle is $\cong 7 \cdot 10^{-7}$ rad. It results in final beam displacement of $\cong 30\ \mu$m on the 40 m length. So, the temperature gradient control along ray propagation is needed with about $1\,^{\circ}$C precision.

Laser source heating affects the ray radiation direction. The long-time (a few hours) angular drift can reach 10^{-5} rad [8] and biases the laser ray on 0.5 mm at the 50 m distance. The temperature change in the air media around the laser source also changes the ray propagation direction. The use of the laser source with optical fiber exit for radiation expectedly solves the problems.

MEASUREMENTS PERFORMING

For the measurement period the LFL was positioned in the 49.5 m long corridor of the laboratory building. The ray collimation is shown in Fig. 8; the ray diameter at the beginning and final points did not exceed the diameter of quadrant photoreceiver. In the case described, the one-mode laser-ray diameter for the 50 m distance was 6 mm [4].

Two points at 16 and 34 m distances from the laser source were chosen for the measurements and comparison of the LFL and AT-401 data in function of distance from the source and also to check the formula (2) validity.

As the “measurement object” the 12 cm long piece of tube has been used; it was fixed at the corridor wall on special base and had the possibility for displacements by two-coordinate positioner perpendicular to the laser beam.

As was mentioned above, the measurements with the use of the “calibration curves” have some limitation, because the part of the laser radiation escapes out of the limits of quadrant photoreceiver when it has been biased. This factor contributes some uncontrolled measurement error as was demonstrated in the first series of our comparative measurements [6]. To be specific: at larger than 1 mm bias of laser spot on photoreceiver surface (with 3 mm of beam diameter) the definite worsening of the LFL and tacheometric data coincidence has been observed.

In our new measurements (this work) with the Laser Tracker AT-401, the measured tube 0.3 mm displacements have been used end-controlled by the positioner with $\pm 3\ \mu$m precision.

The measurement process stages:

• First, the adjustment of the LFL was performed. With the help of two-coordinate positioners the beginning and final tubes (Fig. 2) have been adjusted located coaxial with respect to laser ray. At this stage, the control was performed by the universal adapter with quadrant photoreceiver.

• After that, the adjustment of the coaxiality of the laser ray and of the tube measured was made with the help of two-coordinate positioner and universal adapter with quadrant photoreceiver. Having this adjustment performed (with the help of tacheometric adapter), the laser-tracker measurements of the coordinate of the center of the measured tube were made.

• From the coaxial — with laser ray — position the tube under measurement was displaced by two-coordinate positioner in the plane perpendicular to the laser-ray direction. In this position in the Local Coordinate System (see Fig. 1), the coordinates of the ends of the measured tube have been determined by the LFL. The similar measurements in the Global Coordinate System were also performed by the Laser Tracker AT-401.

• The obtained AT-401 data have been transferred to the Local Coordinate System and there *compared* with the LFL data. To guarantee the maximal precision, the LFL has been adjusted before every measurement set on the tube measured.

In total, common (LFL and AT-401) independent measurements of two transversal (with respect to the laser-ray axis direction) coordinates of the centre of the tube measured have been made at the 16 m distance and four series at the 34 m distance of the above sort measurements.

THE MEASUREMENT RESULTS

The determination of the coordinates of the centers of ends of the tube measured in the Local Coordinate System is made by the LFL and using the "calibration curves" [6]. To obtain the "calibration curves", the graphs of dependence of the signal function $S_{\rm mean}$[1] on the displacement δ of laser spot (on the quadrant photoreceiver surface) have been made for two measurement points: at 16 m (Fig. 9) and at 34 m (Fig. 10).

After determining in the Local Coordinate System of coordinates of points measured in the LFL, the similar calculations were also performed with the AT-401 received data. The comparison procedure consisted simply in the subtraction of coordinates obtained by two methods.

Tables 1 and 2 contain the data of independent AT-401 and LFL measurements at two points:

Table 1 is for the 16 m distance from the laser source.

Table 2 is for the 34 m distance from the laser.

All the Tables' data are the processed and analyzed results of the AT-401 and LFL measurements in the Local Coordinate System.

[1] $S_{\rm mean} = \overline{S_1 + S_2 + S_3 + S_4}$, $S_1 = \dfrac{I_1 + I_2 - I_3 + I_4}{I}$, $S_2 = \dfrac{I_3 + I_4 - I_1 + I_2}{I}$, $S_3 = \dfrac{I_1 + I_3 - I_2 + I_4}{I}$, $S_4 = \dfrac{I_2 + I_4 - I_1 + I_3}{I}$, $I = I_1 + I_2 + I_3 + I_4$, I_1, I_2, I_3, I_4 — the currents from the photoreceiver of quadrant.

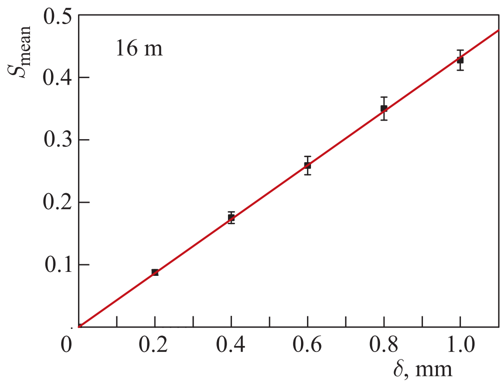

Fig. 9. The "calibration curve" for measurements at the 16 m distance from the laser source

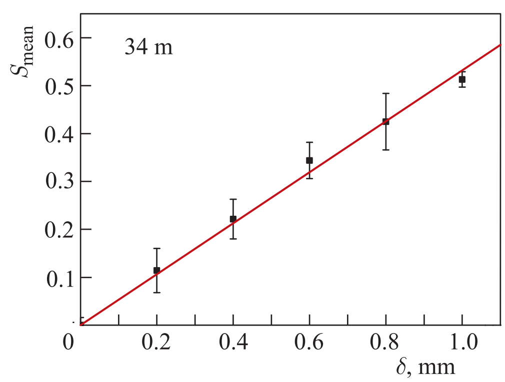

Fig. 10. The "calibration curve" for measurements at the 34 m distance from the laser source

Table 1. **The comparison of two independent (by AT-401 and LFL) measurements of X coordinates and Z coordinates of the point located at the 16 m distance from the laser source**

Data AT-401, mm		Data LFL, mm		Differences data AT-401 and LFL, mm		Differences after systematic correction applied, mm	
X (AT-401)	Z (AT-401)	X (LFL)	Z (LFL)	X (AT-401)– X (LFL)	Z (AT-401)– Z (LFL)	X (AT-401)– X (LFL)– 0.47	Z (AT-401)– Z (LFL)– 0.08
0.54	0.06	0.00	0.00	0.54	0.06	0.07	–0.03
0.23	0.03	–0.31	0.03	0.54	0.00	0.07	–0.09
0.51	0.06	0.00	0.00	0.51	0.06	0.04	–0.03
0.18	0.39	–0.26	0.33	0.44	0.06	–0.03	–0.03
0.46	0.06	0.00	0.00	0.46	0.06	–0.01	–0.03
0.46	0.36	0.03	0.31	0.42	0.05	–0.05	–0.04
0.49	0.09	0.00	0.00	0.49	0.09	0.02	0.00
0.76	0.40	0.34	0.26	0.42	0.14	–0.05	0.05
0.48	0.09	0.00	0.00	0.48	0.09	0.01	0.00
0.69	0.11	0.29	–0.03	0.40	0.14	–0.07	0.05
0.49	0.09	0.00	0.00	0.49	0.09	0.02	0.00
				Aver. 0.47 mm	Aver. 0.08 mm	SD = 0.043 mm	

The Tables also show the corresponding difference of these independent measurements and the very final figures for differences after all corrections due to systematical errors have been taken into account.

The detected systematical errors are mainly connected to the noncentrality of quadrant photoreceiver location inside the universal adapter. There was no precision check of the QPr location coordinate inside adapter by measurement microscope.

The systematical errors we determine are based on the 16 m data and equal to 0.47 mm (X-axis) and 0.08 mm (Z-axis). For the 34 m data we used also these corrections as they were determined on better stabilities.

Table 2. **The comparison of two independent (by AT-401 and LFL) measurements of X coordinates and Z coordinates of the point located at the 34 m distance from the laser source**

Data AT-401, mm		Data LFL, mm		Differences data AT-401 and LFL, mm		Differences after systematic correction applied, mm	
X (AT-401)	Z (AT-401)	X (LFL)	Z (LFL)	X (AT-401)– X (LFL)	Z (AT-401)– Z (LFL)	X (AT-401)– X (LFL)– 0.47	Z (AT-401)– Z (LFL)– 0.08
0.48	0.03	0	0	0.48	0.03	0.01	–0.05
0.59	0.01	0	0	0.59	0.01	0.12	–0.07
0.39	–0.04	0	0	0.39	–0.04	–0.08	–0.12
0.2	–0.02	–0.28	0	0.49	–0.02	0.02	–0.1
						SD = 0.079 mm	

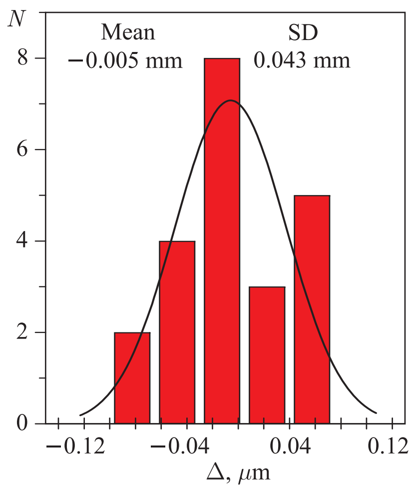

Fig. 11. Differences Δ of the LFL and laser-tracker AT-401 measurements at the 16 m distance from the laser source (both the X and Z data together)

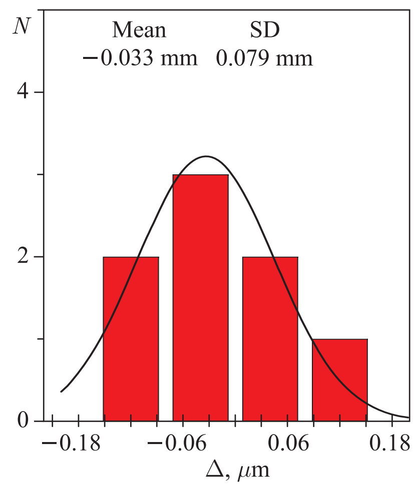

Fig. 12. Differences Δ of the LFL and laser-tracker AT-401 measurements at the 34 m distance from the laser source (both the X and Z data together)

Figures 11 and 12 show the distributions of the differences Δ of the LFL and AT-401 data: 22 separate measurements at the 16 m length and 8 measurements at the 34 m length (both the X and Z data together).

The combining of the X data and Z data in the distributions of Figs. 11 and 12 is motivated not only by limited statistics but, essentially, by the independence of uncorrelated X, Z measurements.

Our task is to experimentally determine the LFL measurement precision at 16 and 34 m distances from the laser source.

With an average $\bar{\Delta} \cong 0$ in both (16 and 34 m) distributions the differences spread is small having the rms sigmas of $\sigma_{\Delta}^{16} = (43 \pm 7)$ μm and $\sigma_{\Delta}^{34} = (79 \pm 20)$ μm (small statistics of Figs. 11 and 12 is reminded).

For the AT-401 precision $\sigma_T = 20$ μm, when performing of common with the LFL measurements, and because of two methods independence, the σ_Δ(rms) of the experimentally obtained Δ distribution are

$$\sigma_\Delta^{16} = \sqrt{\sigma_T^2 + (\sigma_L^{16})^2} = 43\ \mu\text{m}; \quad \sigma_\Delta^{34} = \sqrt{\sigma_T^2 + (\sigma_L^{34})^2} = 79\ \mu\text{m},$$

with T for AT-401 and L for LFL. σ_L^{16} and σ_L^{34} are to be determined.

The calculation gives the necessary LFL precision

$$\sigma_L^{16} = (36 \pm 7)\ \mu\text{m} \quad \text{and} \quad \sigma_L^{34} = (76 \pm 20)\ \mu\text{m}.$$

In [4], there was determined the laser-ray coordinate uncertainty σ_{QPr}^{50} directly on the QPr surface at the 50 m distance from the laser source. Having in mind this figure, one obtains the set (Table 3) of the LFL measurement precisions in Fig. 13 as a function of distances from the laser source.

The dash-dotted line in Fig. 13 is a linear dependence (2); the solid line is the linear fit of Table's 3 points.

Table 3. **Accuracy of LFL from length**

σ, μm	Distance from the laser source, m
1	Close to 0
35	16
76	34
90	50

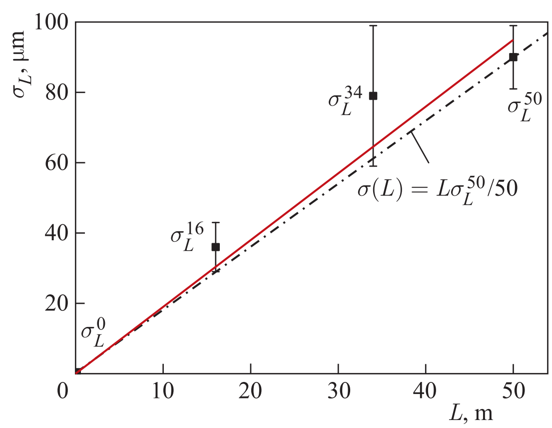

Fig. 13. The LFL measurement precision σ_L as a function of distance

Having in mind that the dash-dotted line is an estimate of an expected maximal LFL resolution, Fig. 13 shows that in the LFL applied one has reached the limit in achievable resolution.

CONCLUSION

On the base of 30 pairs of independent measurements (by Laser Fiducial Line and by Laser Tracker AT-401), the LFL measurement precision in an open air as a function of length was obtained. With 20 μm of the AT-401 measurement precision, the LFL measurement precision at the 16 m distance was (36 ± 7) μm and (76 ± 20) μm at 34 m. This precision depends mainly on laser-ray fluctuation displacements because of air turbulent motion and coincides with the preliminary estimates of the limit value of achievable precision.

The Laser Fiducial Line measurement precision in open air media might be increased if using feedback system between the beginning and final LFL points.

Acknowledgements. The authors thank V. Bednyakov, V. Glagolev and G. Shirkov for significant help which made possible this work. JINR group thanks the BMBF (Germany) for the financial support of R&D's stage performed. At the JINR S. Studenov contributed strongly to many phases of experimental equipment creation in Dubna.

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Received on October 27, 2014.