FINAL REPORT

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Comparison of interferometric measuring systems for measuring steel tapes with length of 20 m

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1. Introduction

The metrological equivalence of national measurement standards and calibration certificates issued by national metrology institutes is established by a set of key comparisons chosen and organised by the Consultative Committees of the CIPM or by the regional metrology organisations in collaboration with the Consultative Committees.

At the meeting of TC 1.5 “Length and angle” in 2009 it was decided to do a comparison of interference units for measuring steel tapes with a length of 20 m. VNIIM was chosen as a pilot-laboratory. The result of this international comparison contributes to the Mutual Recognition Arrangement (MRA) between the national metrology institutes of the Metre Convention.

2. Participants

Table 1. Participants in the comparison

NMI	Address	Contact person	Contacts
VNIIM	190005 Moskovsky pr. 19, St. Petersburg, Russia	Natalia Kononova	Tel.: + 7 812 323 96 69 Fax: + 7 812 323 96 64 E-mail: n.a.kononova@vniim.ru
BelGIM	93, Starovilensky trakt, 220053 Minsk, Belarus	Vladimir Makarevich	Tel.: +375 17 239 23 38 Fax: +375 17 288 09 38 E-mail: makarevich@belgim.by
KazInMetr	Mangilik El Str. 11, 010000 Astana, Left bank, Esil district, «Reference center» building, Kazakhstan	Aydar Dauletbaev	Tel.: +7172 79 33 63 E-mail: aydar1982@mail.ru

3. Organisation

3.1.Schedule

The comparison has been carried out in a circulation form.
The circulation schedule is in table 2.

Table 2. The circulation schedule

NMI	Country	Date
VNIIM	Russia	2011
KazInMetr	Kazakhstan	2012
BelGYM	Belarus	2013
VNIIM	Russia	2014
Report	Russia	2015-2017

3.2. Artefact

The artifact to be measured is a measuring steel tape with nominal length of 24 m, № 50. Views of the tape are on figures 1, 2.

Figure 1 – The main view of the tape

Figure 2 – The view of the tape on coil

Technical and metrological characteristics of the tape are given in the table 3.

Table 3. Technical and metrological characteristics of the tape

Parameter	Value
Nominal length, m	24
Permitted deviations, mm: millimetric scale; centimetric scale; decametric and metre scales; whole length: - 10 m; - 20 m.	 ± 0,1 ± 0,2 ± 0,3 ± 1,0 ± 2,0

Width of the tape, mm	19
Thickness of the tape, mm	0,19
Width of a line mark, mm	0,05
Overall dimensions of the tape on the spool, mm	450x50
Mass of the tape on the spool, g	5800
Tape's material	Stainless steel
Thermal linear expansion coefficient, $^oC^{-1}$	$(10\pm1)\cdot10^{-6}$
Nominal tensile force, N	100±10
Manufactured date	2010

4. Measurement instructions and reporting of results

Conditions of comparison:
- air temperature, °C 20±0,5;
- air humidity, % 60±20.

The tape has to be located on unit horizontally. The initial end of a tape has to be fixed in the special element. The other end has to be connected with weight or force gauge. Tension has to be (100±10) N. It is should to keep the tape on load during an hour. Zero mark is the start point of measuring. The tape has to be measured from 1 m to 20 m via 1 m. The results have to be corrected to 20°C. Uncertainty of measurement has to be expressed according to ISO Guide 98-1:2009. Uncertainty of measurement.

5. The results

5.1. The results by VNIIM, Russia

The tape was measured by the 30 metre Linear Laser Interferometer from the State Primary Standard of the unit of length – GET 2-2010, which consists of the XL-80 laser interferometer by «Renishaw plc», the optical-mechanical system, the measuring system of temperature, pressure and humidity.

The view of the 30 metre Linear Laser Interferometer from the GET 2-2010 is given on figure 3.

Figure 3 – The view of the 30 metre Linear Laser Interferometer from the GET 2-2010

The air refraction coefficient was determined on Edlen formula.

The temperature was measured by a temperature measuring system POLIKON. The uncertainty of measurement is 0,28 °C.

The humidity was measured by a humidity and temperature measuring system IVTM-7M. The uncertainty of measurement is 0,37 mm Hg.

Measurements conditions:

- air temperature – (20±0,5) ^{0}C;
- air humidity – (60±20) %;
- air pressure – (760±20) mm Hg.

Measurements of the tape in VNIIM were twice, because of VNIIM is the pilot laboratory. The results of the tape's measuring in 2011 are given in the table 4. The results of the tape's measuring in 2014 are given in the table 5.

Table 4. The results of the tape's measuring in 2011

Nominal length, mm	Measured length, mm	Standard deviation, µm
1000	1000,043	6
2000	2000,052	1
3000	3000,233	4
4000	4000,137	2
5000	5000,313	5
6000	6000,337	5
7000	7000,408	2
8000	8000,356	3
9000	9000,464	10
10000	10000,500	8
11000	11000,531	6
12000	12000,575	12
13000	13000,522	2
14000	14000,697	7
15000	15000,791	5
16000	16000,566	5
17000	17000,769	8
18000	18000,998	5
19000	19000,814	7
20000	20000,983	6

Table 5. The results of the tape's measuring in 2014

Nominal length, mm	Measured length, mm	Standard deviation, µm
1000	1000,039	2
2000	2000,051	3
3000	3000,229	6
4000	4000,149	5
5000	5000,309	3
6000	6000,342	3
7000	7000,412	4
8000	8000,361	4

9000	9000,471	4
10000	10000,507	8
11000	11000,526	3
12000	12000,574	9
13000	13000,525	4
14000	14000,700	7
15000	15000,788	3
16000	16000,575	5
17000	17000,772	2
18000	18000,992	5
19000	19000,812	6
20000	20000,977	5

The results are given at 20 ºC.
Sources of uncertainty are given in the table 6.

Table 6. Sources of uncertainty

Source of uncertainty	Type of uncertainty	Standard uncertainty, $u(x_i)$	Sensibility factor, $c_i = dL/dx_i$	Standard uncertainty, $u_i(L)$
Measurement of laser's wavelength in vacuum	B	$1{,}0\cdot10^{-8}\cdot\lambda$	L/λ	$1{,}0\cdot10^{-8}\cdot L$
Edlen formula	B	$2{,}9\cdot10^{-8}$	L	$2{,}9\cdot10^{-8}\cdot L$
Measurement of air temperature	B	0,1 °C	$0{,}93\cdot10^{6}\cdot L$/°C	$9{,}3\cdot10^{-8}\cdot L$
Measurement of air pressure	B	20,0 Pa	$2{,}7\cdot10^{-9}\cdot L$/Pa	$5{,}4\cdot10^{-8}\cdot L$
Measurement of air humidity	B	3,0 %	$1{,}0\cdot10^{-8}\cdot L$/%	$3{,}0\cdot10^{-8}\cdot L$
Measurement of tape's temperature	B	0,3 °C	$10{,}5\cdot10^{-6}\cdot L$/°C	$3{,}1\cdot10^{-6}\cdot L$
Thermal linear expansion coefficient	B	$1{,}0\cdot10^{-6}$ m/°C	2 °C	$2{,}0\cdot10^{-6}\cdot L$
Cosine error	B	$2{,}0\cdot10^{-8}$	L	$2{,}0\cdot10^{-8}\cdot L$
Abbe error	B	6,0 µm	1	6,0 µm
Friction force	B	1,0 N	$1{,}0\cdot10^{-6}\cdot L$/N	$1{,}0\cdot10^{-6}\cdot L$
Measurement of line mark's center	A	5,0 µm	1	5,0 µm
Uncertainty of registration system of measured value	A	5,0 µm	1	5,0 µm

Combined standard uncertainty is $u_c(L) = \sqrt{(9{,}3\cdot10^{-6})^2 + (3{,}8\cdot10^{-6}\cdot L)^2}$ m. So combined standard uncertainty at the length of 20 m is 76,6 µm.

Expanded uncertainty Up at the confidence coefficient of 0,95 for a coverage factor of k=2 at the length of 20 m is 153,2 µm.

5.2. The results by BelGIM, Belarus

The tape was measured by the XL-80 laser system with XC-80 compensator by «Renishaw plc», which is traceable to the National standard of the unit of length – metre in the field of attestation of radiation sources and measuring instruments for measure wave lights 0,63 μm.

The view of the XL-80 laser system with XC-80 compensator is given on figure 4.

Figure 4 – The view of the BelGIM's XL-80 laser system with XC-80 compensator

Measurements conditions:
- air temperature – (20±0,5) °C;
- air humidity – (53,5±15,0) %.

The results are given in the table 7.

Table 7. The results

Nominal length, mm	Measured length, mm	Standard deviation, μm
1000	1000,0586	6,5
2000	2000,0386	1,4
3000	3000,1890	1,3
4000	4000,1032	0,5
5000	5000,2445	0,6
6000	6000,3435	6,9
7000	7000,3606	1,0
8000	8000,3156	1,6
9000	9000,3731	2,8
10000	10000,4364	5,3
11000	11000,5068	6,2
12000	12000,5473	6,8
13000	13000,5082	3,4
14000	14000,6709	3,3

15000	15000,7862	9,9
16000	16000,4783	4,5
17000	17000,6903	10,4
18000	18000,9687	20,9
19000	19000,7213	13,5
20000	20000,9499	27,8

Sources of uncertainty are given in the table 8.

Table 8. Sources of uncertainty

Input value	Value x_i, mm	Range ±r	Type of uncertainty	Standard uncertainty $u(x_i)$, µm	Sensibility factor c_i	Source of uncertainty $u_i(L)$, µm
L_u	L	-	A	8,425	1	8,425
δ_{INT}	0	$0{,}5 \cdot L$	B	$0{,}25 \cdot L$	1	$0{,}25 \cdot L$
$\delta_{INT.p}$	0	0,0005	B	0,0003	1	0,0003
δ_T	0	$1{,}1 \cdot L$	B	$0{,}635 \cdot L$	1	$0{,}635 \cdot L$
δ_{MT}	0	0,375	B	0,217	1	0,217
δ_{COS}	0	$0{,}0012 \cdot L$	B	$0{,}0007 \cdot L$	1	$0{,}0007 \cdot L$
δ_F	0	$0{,}852 \cdot L$	B	$0{,}492 \cdot L$	1	$0{,}057 \cdot L$
δ_{Abbe}	0	16,484	B	9,517	1	9,517
δ_{LM}	0	-	B	2,610	1	2,610

L – the measured length, mm;

L_u – the arithmetic average of registrations of XL-80 laser system, mm;

δ_{INT} – the correction due to registrations of XL-80 laser system, mm;

$\delta_{INT.p}$ – the correction due to resolution of XL-80 laser system, mm;

δ_T – the correction due to tape's temperature deviation from normal;

δ_{MT} – the correction due to lost motion, mm;

δ_{COS} – the correction due to cosine error, mm;

δ_F – the correction due to tape's tension, friction and deflection of the tape, mm;

δ_{Abbe} – the correction due to Abbe error, mm;

δ_{LM} – the correction due to determination of line mark's center and drift of base line mark, mm.

Combined standard uncertainty is $u_c(L) = \sqrt{(12{,}98 \cdot 10^{-6})^2 + (0{,}84 \cdot 10^{-6} \cdot L)^2}$ m. So combined standard uncertainty at the length of 20 m is 21,2 µm.

Expanded uncertainty Up at the confidence coefficient of 0,95 for a coverage factor of k=2 at the length of 20 m is 42,4 µm.

5.3. The results by KazInMetr, Kazakhstan

The tape was measured by The Secondary State Standard of the unit of length at the range of (0,001-20) m. The Secondary State Standard consists of linear interferometer with stabilized He-Ne laser (LGN-302), optical mechanicals system, system of ambient conditions measuring.

The view of The State Secondary standard of the Unit of Length at the range of (0,001-20) m is given on figure 5.

Figure 5 – The view of The State Secondary standard of the Unit of Length at the range of (0,001-20) m

Air refraction factor was calculated with Edlen formula according to humidity, pressure and temperature.

Tape temperature was measured by thermohygrometer Fluke 1620A. Uncertainty of tape temperature measurement is 0,28 °C.

Air humidity was measured by thermohygrometer Fluke 1620A. Uncertainty of humidity measurement is 0,37 mm Hg.

Air pressure was measured by barometer BRS-1M-2. Uncertainty of air pressure measurement is 0,09 mm Hg.

Measurements conditions:

- air temperature – (20±0,7) ^{0}C;
- air humidity – (15±5) %;
- air pressure – (735±10) mm Hg.

The results are given in the table 9.

Table 9. The results

Nominal length, mm	Measured length, mm	Standard deviation, μm
1000	999,820	1
2000	1999,745	2
3000	2999,854	5
4000	3999,683	5
5000	4999,808	6
6000	5999,817	6
7000	6999,605	21

8000	7999,629	22
9000	8999,500	32
10000	9999,653	32
11000	10999,753	63
12000	11999,710	65
13000	12999,685	72
14000	13999,831	55
15000	14999,789	64
16000	15999,455	85
17000	16999,683	94
18000	17999,957	21
19000	18999,668	27
20000	19999,840	26

The results are led to 20 ºC.
Sources of uncertainty are in the table 10.

Table 10. Sources of uncertainty

Input value	Type of uncertainty	Standard uncertainty	Sensibility factor	Standard uncertainty, μm
Independent of length				
Optics correction	A	9	1	9
Determination of line mark's center correction	B	3	1	3
Determination of line mark's edge correction	B	5	1	5
Nonlinearity of interferometer correction	B	11	1	11
Dependent of length				
Uncertainty of measuring long length	A			12·L
Laser wavelength correction	B	$2 \cdot 10^{-8}$	$L \cdot 10^{6}$	0,02·L
Air temperature correction u (t)	B	0,28 °C	0,947·L	0,26·L
Air pressure correction u (p)	B	0,09 (мм рт. ст.)	0,364·L	0,03·L
Humidity correction u (e)	B	0,37 (мм рт. ст.)	0,056·L	0,02·L
Air refraction factor u (n)	B	$\sqrt{u^2(t)+u^2(p)+u^2(e)}$	0,26·L	
Edlen formula correction	B	$5 \cdot 10^{-8}$	$L \cdot 10^{6}$	0,05·L
Tape's temperature correction	B	0,28	10·L	2,8·L
Tape's temperature gradient correction	B	0,28	10·L	2,8·L
Uncertainty TCLE at (20-T=0,1) ºC	B	$1 \cdot 10^{-7}$	$0,1 \cdot 10^{6} \cdot L$	0,01·L

A combined standard uncertainty is $u_c(L) = \sqrt{236 + 159{,}8 \cdot L^2}$ μm, where L is a measured length. So the combined standard uncertainty at the length of 20 m is 253 μm.

The expanded uncertainty Up with confidence coefficient of 0,95 and with coverage factor of 2 at the length of 20 m is 506 μm.

6. Calculations

6.1. Stability of the artefact

The tape as the artefact was measured twice at the beginning and at the end of comparison. The results of analysis of stability are in the table 11.

Table 11. The results of analysis of stability

Nominal length, mm	Measured length at the beginning of comparison x_1, mm	Measured length at the end of comparison x_2, mm	Mean value of measured length x_i, mm	Standard deviation at the beginning of comparison S_{x_1}, μm	Standard deviation at the end of comparison S_{x_2}, μm	$u_c(L)$, mm	$x_2 - x_1$, mm	$U(x_2 - x_1)$, mm
1000	1000,043	1000,039	1000,041	6	2	0,010	-0,004	0,013
2000	2000,052	2000,051	2000,052	1	3	0,012	-0,001	0,006
3000	3000,232	3000,224	3000,228	4	6	0,015	-0,008	0,014
4000	4000,137	4000,148	4000,143	2	5	0,018	0,011	0,011
5000	5000,294	5000,291	5000,293	5	3	0,021	-0,003	0,011
6000	6000,337	6000,342	6000,340	5	3	0,025	0,005	0,011
7000	7000,408	7000,412	7000,410	2	4	0,028	0,004	0,009
8000	8000,356	8000,361	8000,359	3	4	0,032	0,005	0,009
9000	9000,443	9000,451	9000,447	10	4	0,035	0,008	0,022
10000	10000,500	10000,507	10000,504	8	8	0,039	0,007	0,022
11000	11000,531	11000,526	11000,529	6	3	0,043	-0,005	0,013
12000	12000,575	12000,574	12000,575	12	9	0,047	-0,001	0,030
13000	13000,522	13000,525	13000,524	2	4	0,050	0,003	0,008
14000	14000,697	14000,700	14000,699	7	7	0,054	0,003	0,020
15000	15000,791	15000,788	15000,790	5	3	0,058	-0,003	0,011
16000	16000,566	16000,575	16000,571	5	5	0,061	0,009	0,014
17000	17000,769	17000,772	17000,771	8	2	0,065	0,003	0,017
18000	18000,998	18000,992	18000,995	5	5	0,069	-0,006	0,014
19000	19000,814	19000,812	19000,813	7	6	0,073	-0,002	0,019
20000	20000,983	20000,977	20000,980	6	5	0,077	-0,006	0,015

6.2. Calculation of comparison's data

6.2.1. Determination of the Key Comparison Reference value

The reference value is calculated according to (1) and (2)

$$x_{ref} = \frac{\sum_1^n \frac{1}{u_i^2} \cdot x_i}{\sum_1^n \frac{1}{u_i^2}}; \qquad (1)$$

$$u_{ref}^2 = \frac{1}{\sum_1^n \frac{1}{u_i^2}}. \qquad (2)$$

6.2.2. Analysis of the results

The E_n value is calculated according to (3)

$$E_n = \frac{x_i - x_{ref}}{2\sqrt{u_i^2 - u_{ref}^2}}. \quad (3)$$

If $|E_n| < 1$ and confidence coefficient is 0,95, the value of uncertainty are confirmed.

The results of measurements with standard uncertainty of all countries are in the table 12. Due to the good agreement between measurements the average values of both results of VNIIM are in the table 12.

Table 12. The results of measurements with standard uncertainty.

x_{nom}, mm	VNIIM		BelGIM		KazInMetr	
	x_i, mm	u_i, mm	x_i, mm	u_i, mm	x_i, mm	u_i, mm
1000	1000,041	0,010	1000,059	0,013	999,820	0,020
2000	2000,052	0,012	2000,039	0,013	1999,745	0,029
3000	3000,228	0,015	3000,189	0,013	2999,854	0,041
4000	4000,143	0,018	4000,103	0,013	3999,683	0,053
5000	5000,293	0,021	5000,245	0,014	4999,808	0,065
6000	6000,340	0,025	6000,344	0,014	5999,817	0,077
7000	7000,410	0,028	7000,361	0,014	6999,605	0,089
8000	8000,359	0,032	8000,316	0,015	7999,629	0,102
9000	9000,447	0,035	9000,373	0,015	8999,500	0,114
10000	10000,504	0,039	10000,436	0,015	9999,653	0,127
11000	11000,529	0,043	11000,507	0,016	10999,753	0,139
12000	12000,575	0,047	12000,547	0,016	11999,710	0,152
13000	13000,524	0,050	13000,508	0,017	12999,685	0,164
14000	14000,699	0,054	14000,671	0,018	13999,831	0,177
15000	15000,790	0,058	15000,786	0,018	14999,789	0,190
16000	16000,571	0,061	16000,478	0,019	15999,455	0,202
17000	17000,771	0,065	17000,690	0,019	16999,683	0,215
18000	18000,995	0,069	18000,969	0,020	17999,957	0,227
19000	19000,813	0,073	19000,721	0,021	18999,668	0,240
20000	20000,980	0,077	20000,950	0,021	19999,840	0,252

The results of all participants are given on diagram on figure 6.

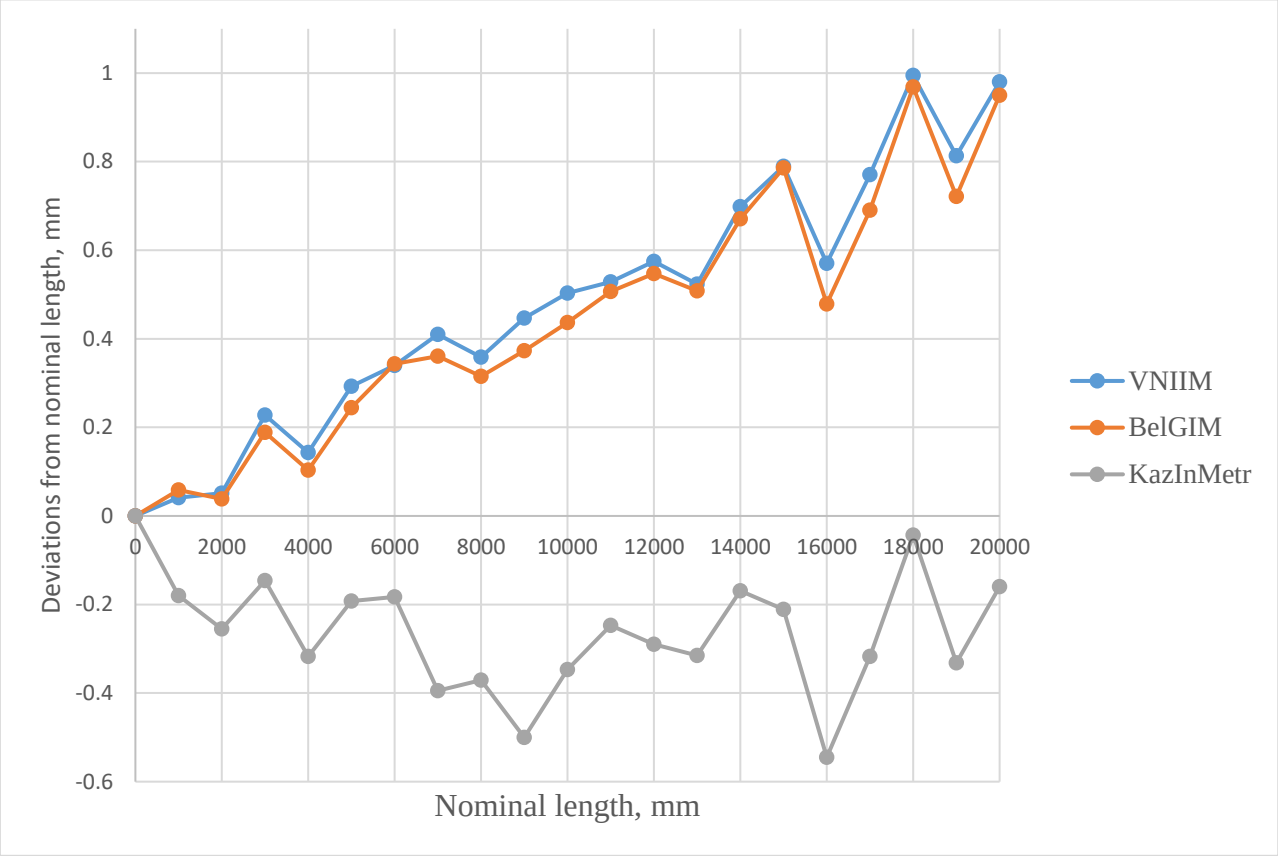

Figure 6 – The results of all participants

As shown on the diagram on figure 6, the results of KazInMetr are far from the results of VNIIM and BelGIM, that's why it has been decided not to consider the results of KazInMetr during determination of reference value .

The results of data consistency of VNIIM and BelGIM are shown in the table 13.

Table13. E_n - values

x_{ref} , mm	u_{ref} , mm	E_n
1000,048	0,008	0,47
2000,046	0,009	0,37
3000,206	0,010	0,92
4000,117	0,011	0,86
5000,259	0,011	0,95
6000,343	0,012	0,06
7000,371	0,013	0,79
8000,323	0,013	0,61
9000,385	0,014	0,97
10000,446	0,014	0,80
11000,509	0,015	0,24
12000,550	0,016	0,28
13000,510	0,016	0,15
14000,674	0,017	0,25
15000,786	0,017	0,03

16000,486	0,018	0,73
17000,697	0,018	0,59
18000,971	0,019	0,18
19000,728	0,020	0,61
20000,952	0,020	0,19

The results of BelGIM and of VNIIM are shown on figures 7-26. Deviations from Xref are shown with expanded uncertainties.

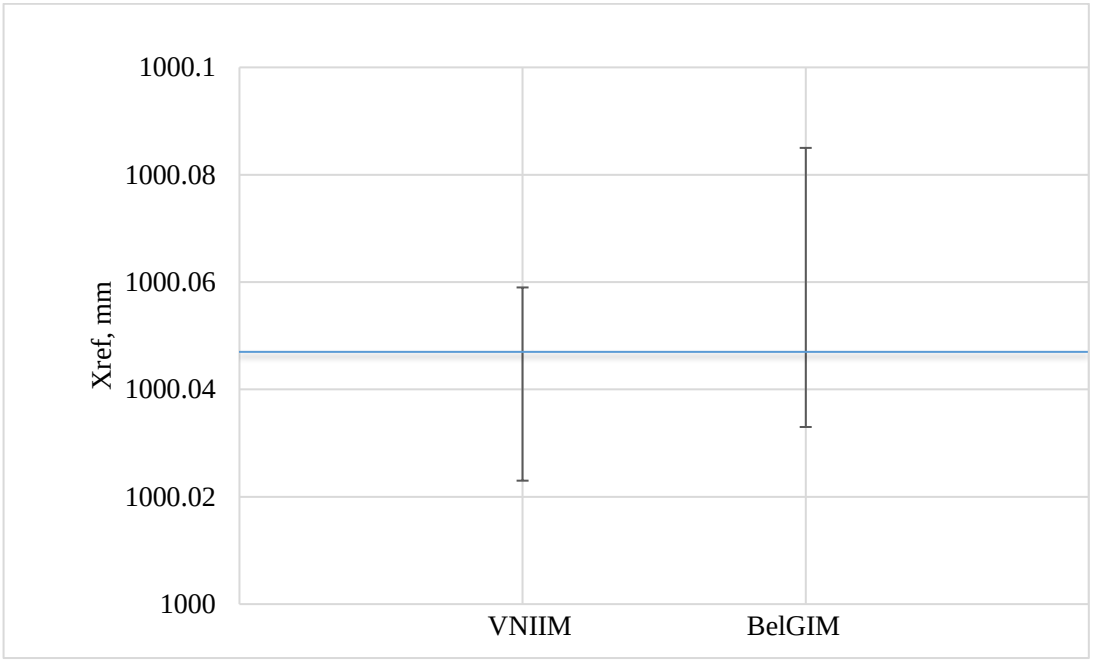

Figure 7 – Deviations from Xref on length 1000 mm

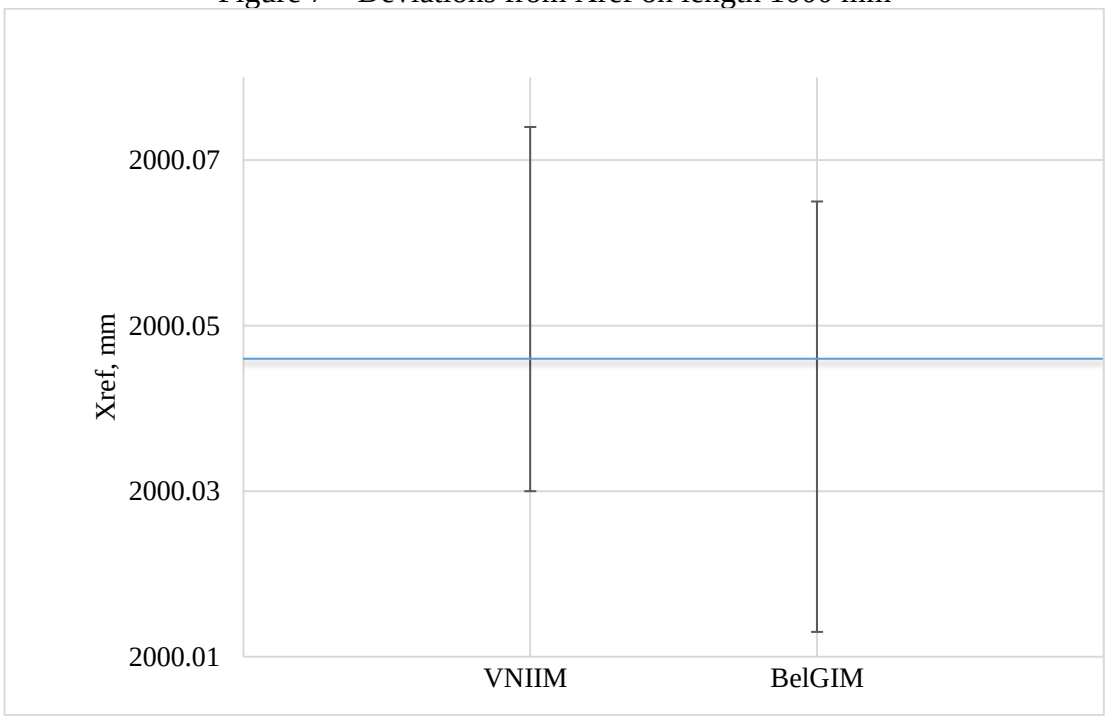

Figure 8 – Deviations from Xref on length 2000 mm

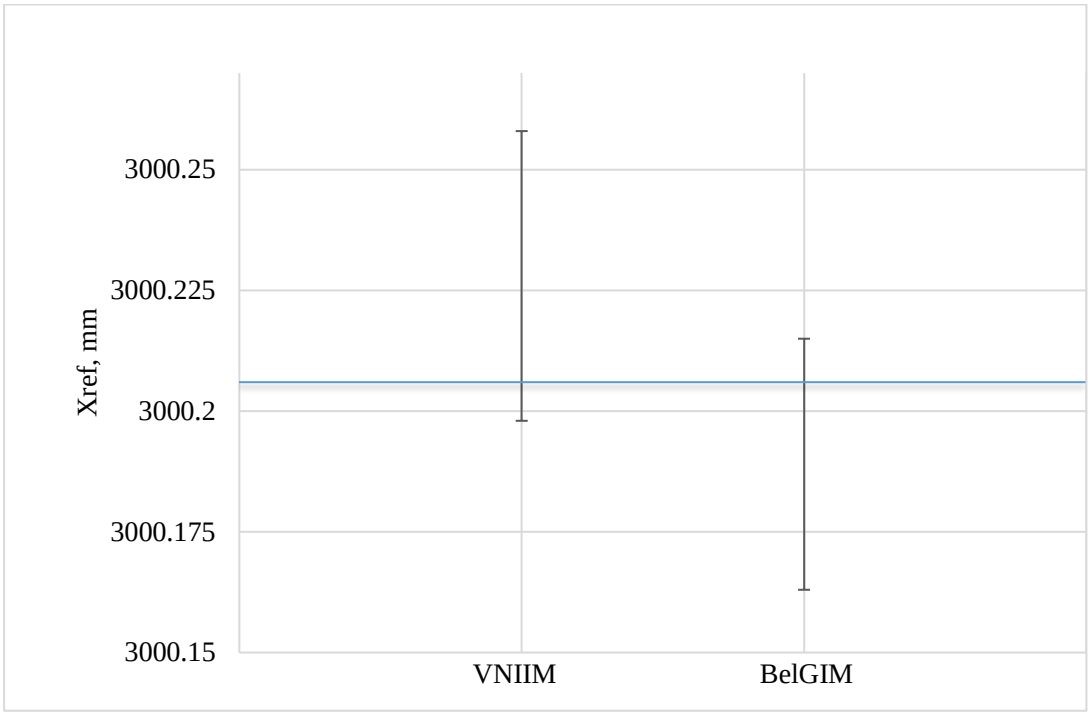

Figure 9 – Deviations from Xref on length 3000 mm

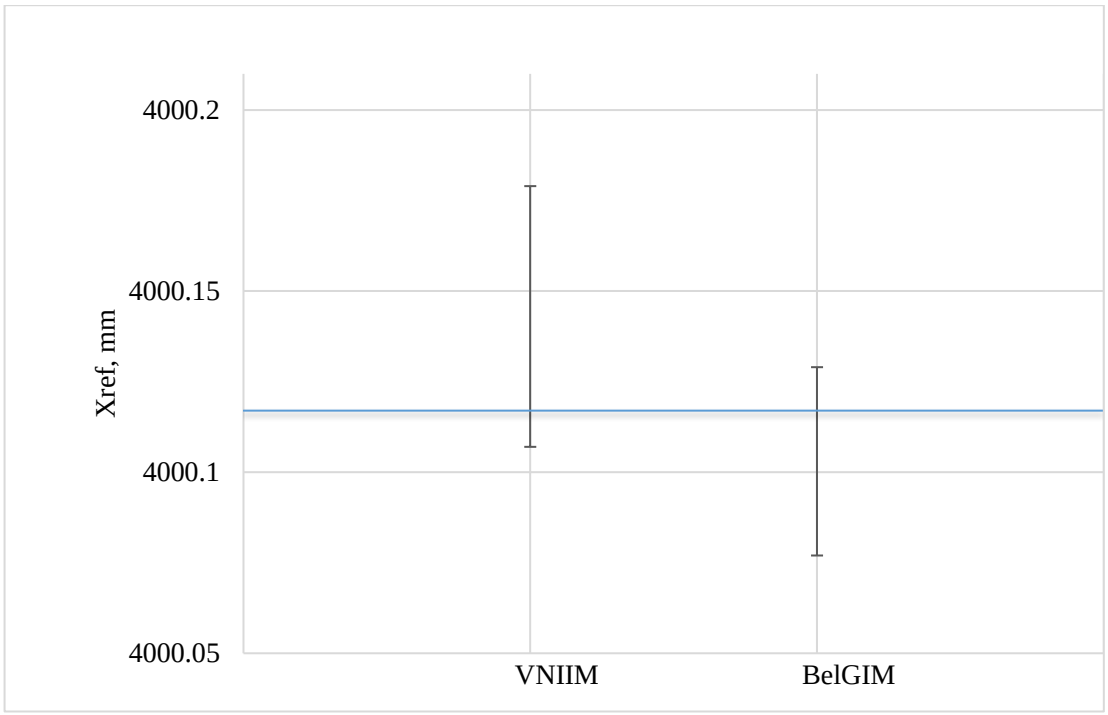

Figure 10 – Deviations from Xref on length 4000 mm

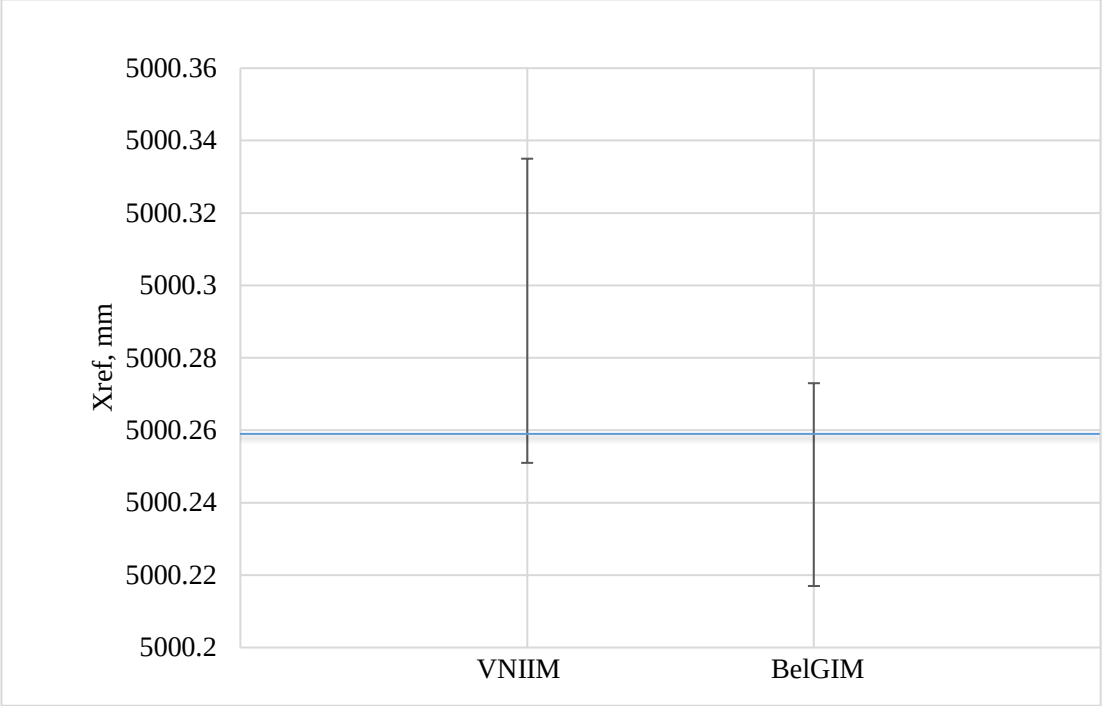

Figure 11 – Deviations from Xref on length 5000 mm

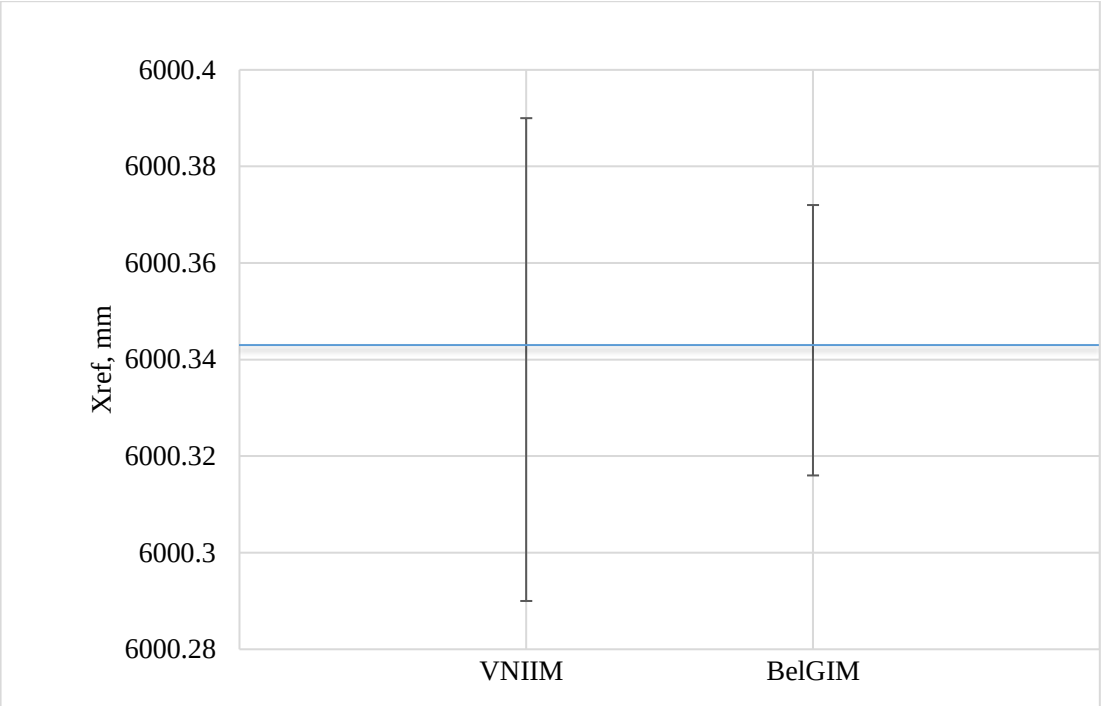

Figure 12 – Deviations from Xref on length 6000 mm

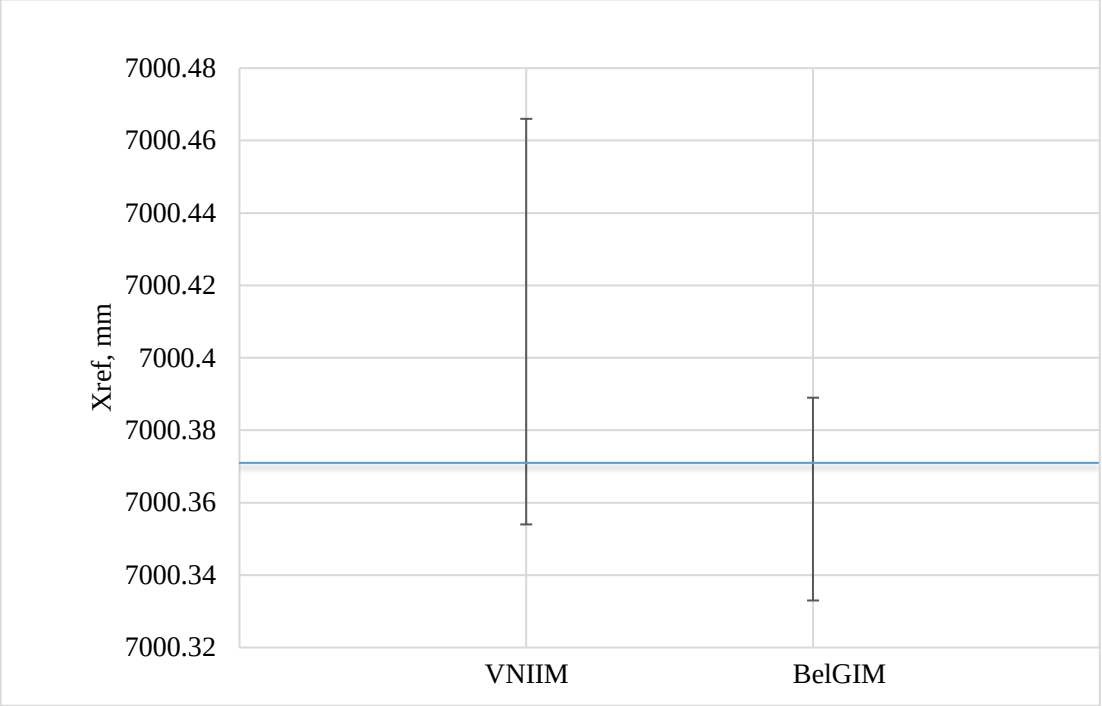

Figure 13 – Deviations from Xref on length 7000 mm

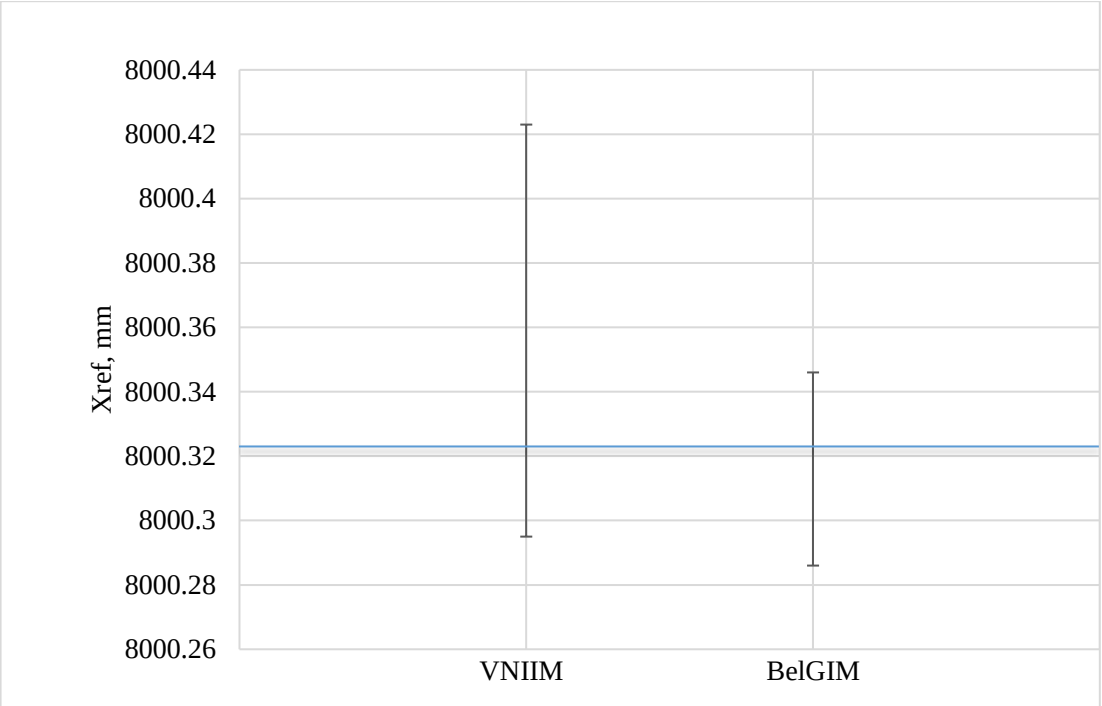

Figure 14 – Deviations from Xref on length 8000 mm

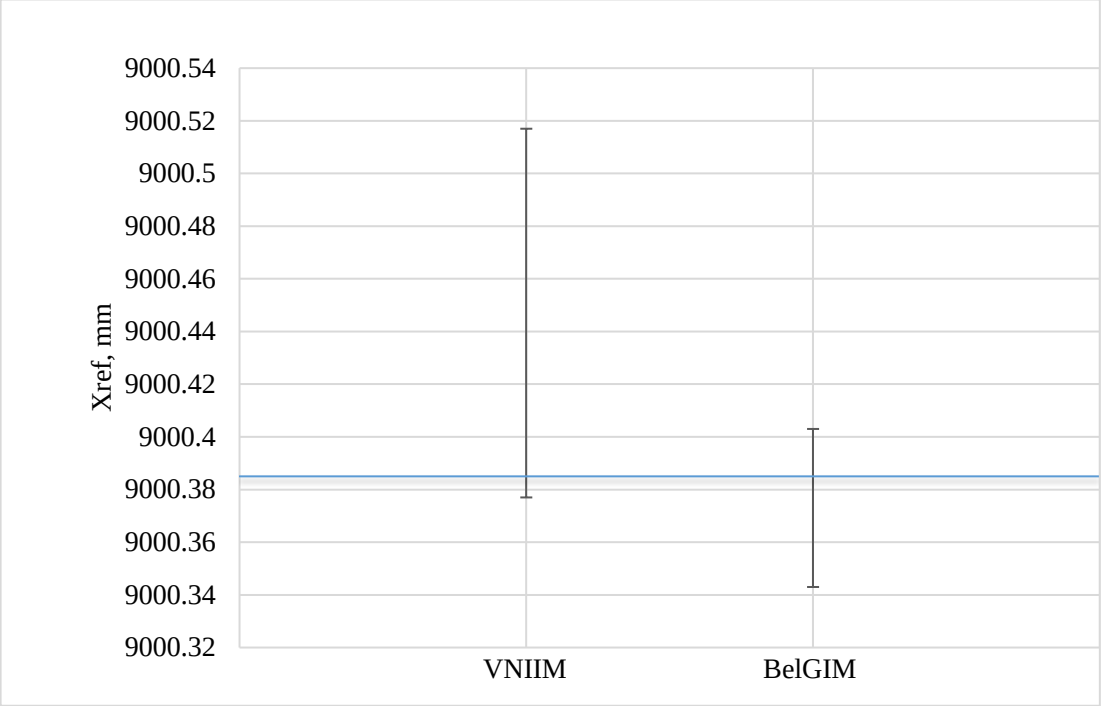

Figure 15 – Deviations from Xref on length 9000 mm

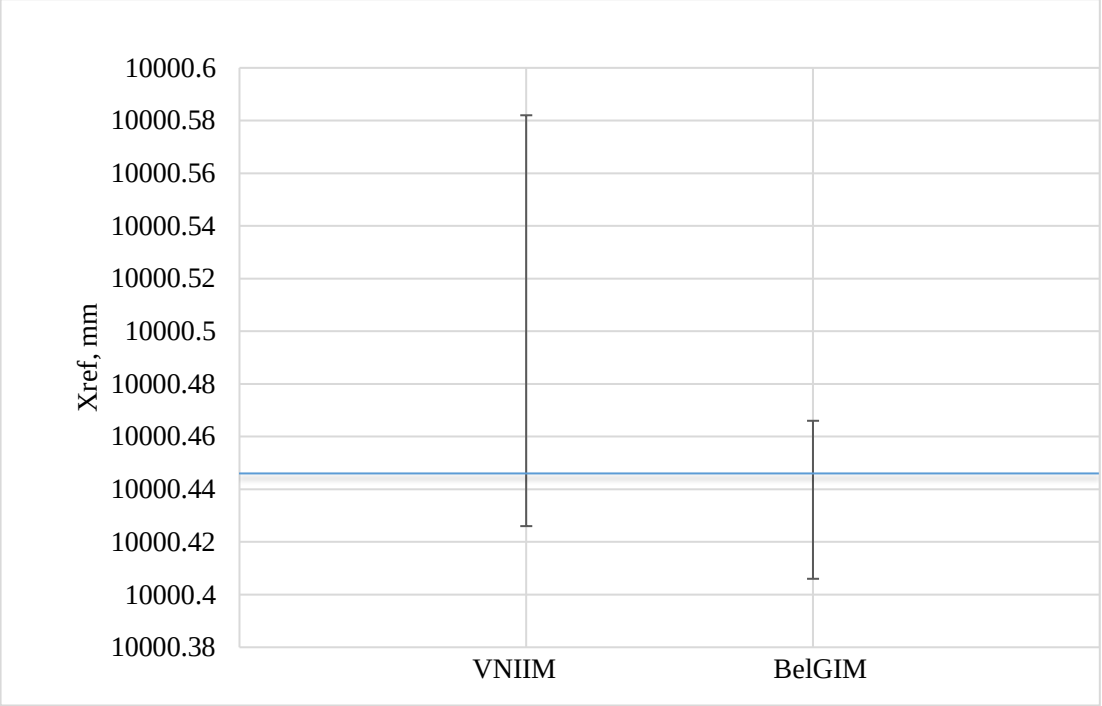

Figure 16 – Deviations from Xref on length 10000 mm

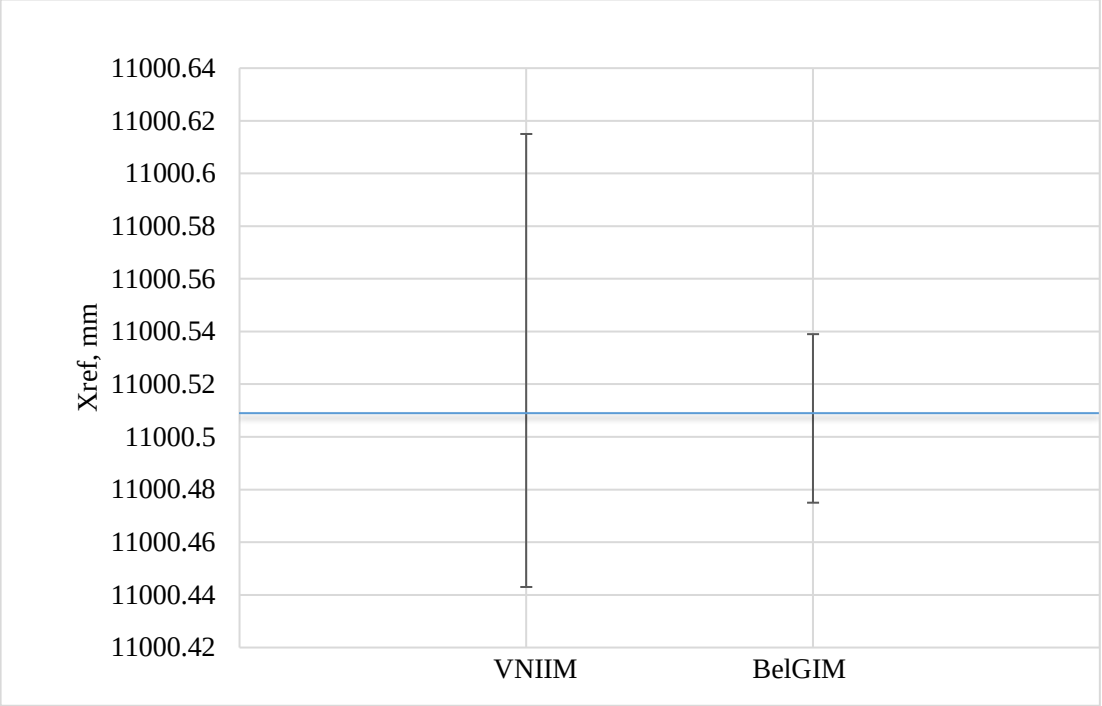

Figure 17 – Deviations from Xref on length 11000 mm

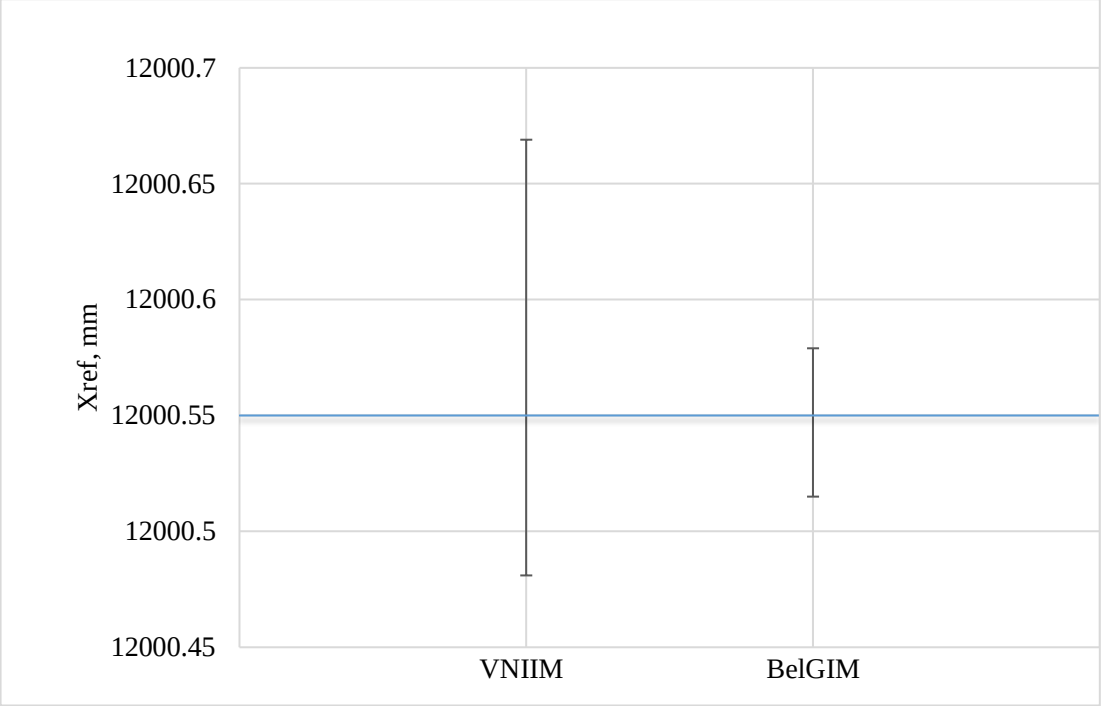

Figure 18 – Deviations from Xref on length 12000 mm

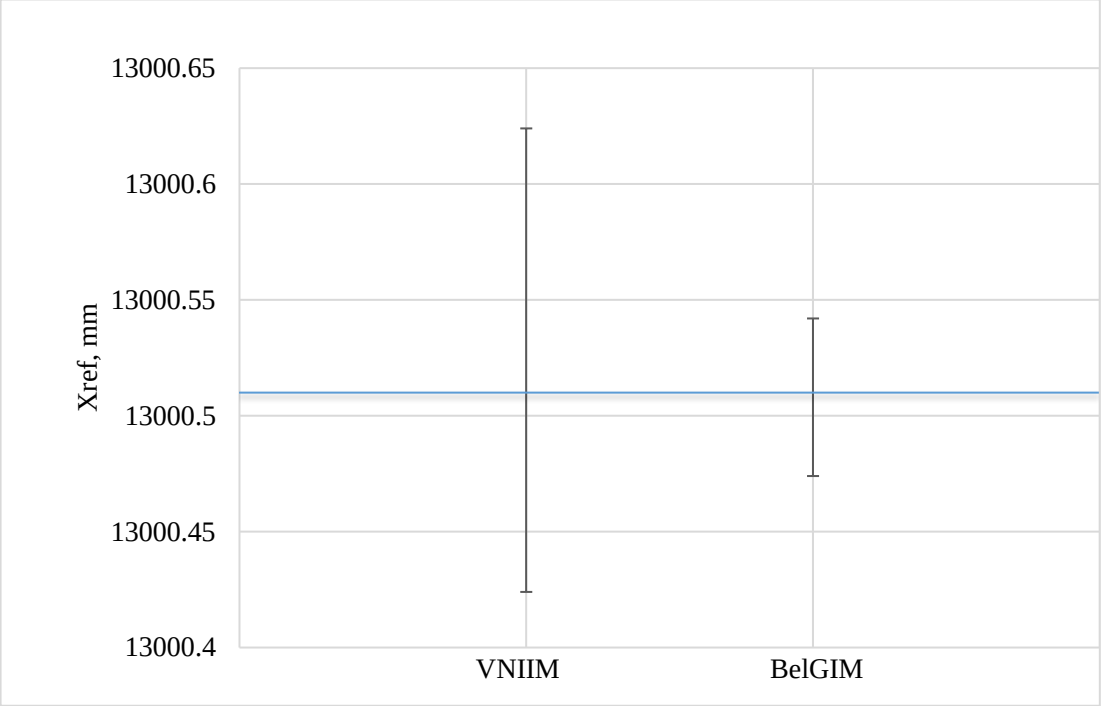

Figure 19 – Deviations from Xref on length 13000 mm

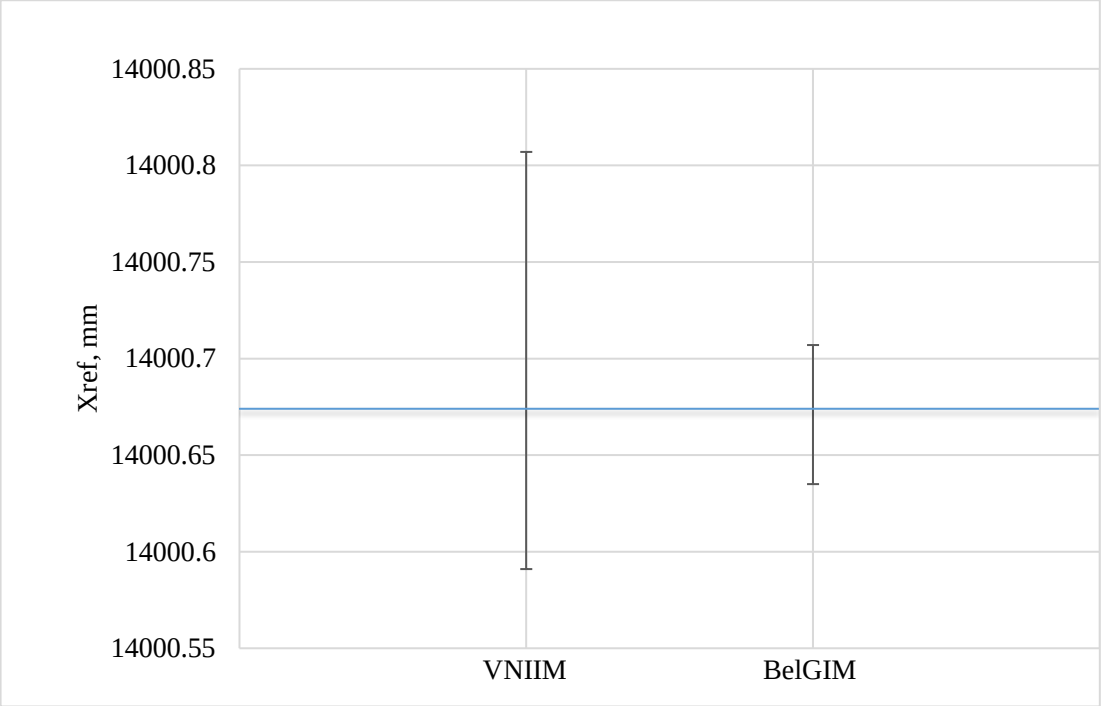

Figure 20 – Deviations from Xref on length 14000 mm

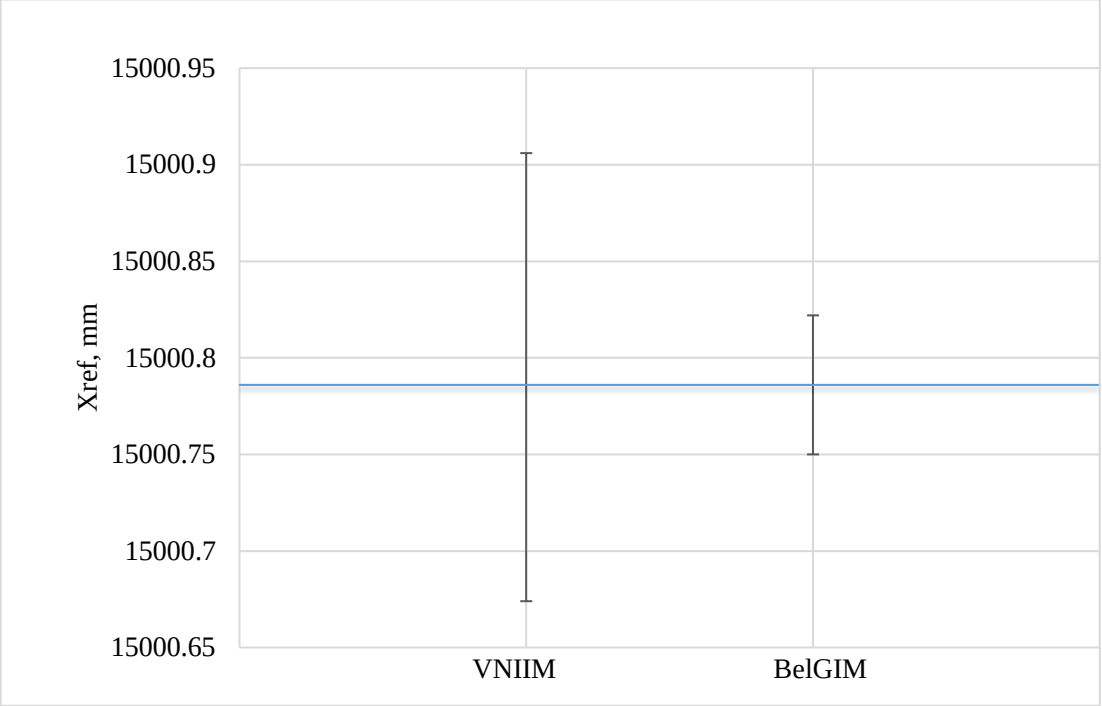

Figure 21 – Deviations from Xref on length 15000 mm

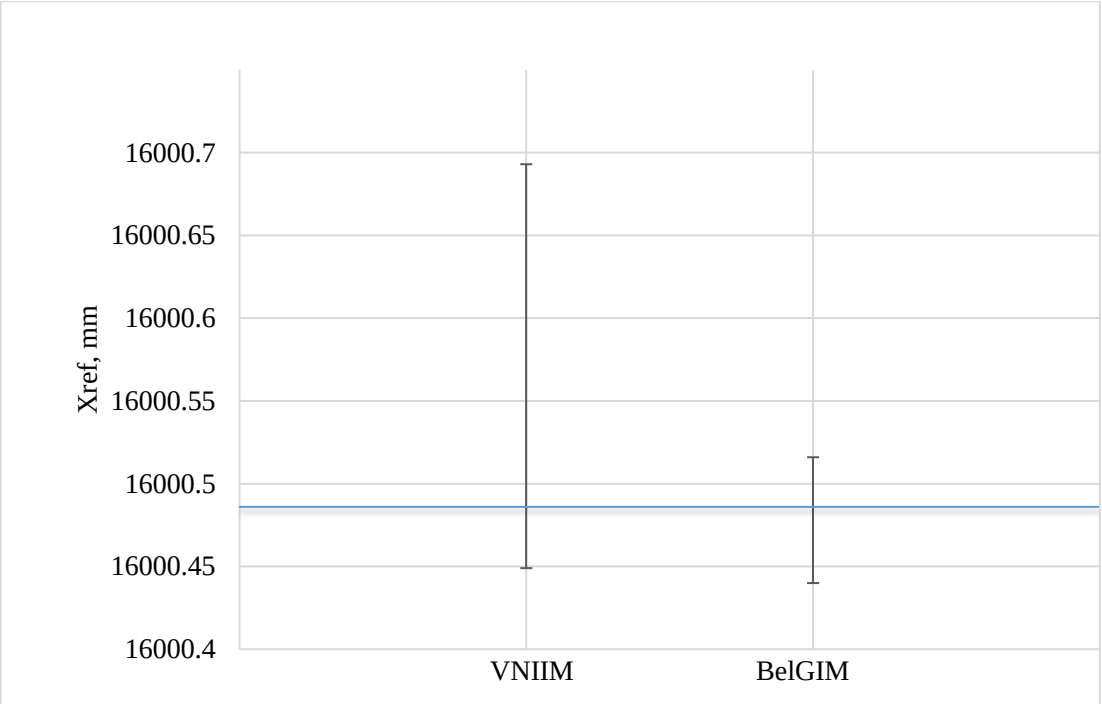

Figure 22 – Deviations from Xref on length 16000 mm

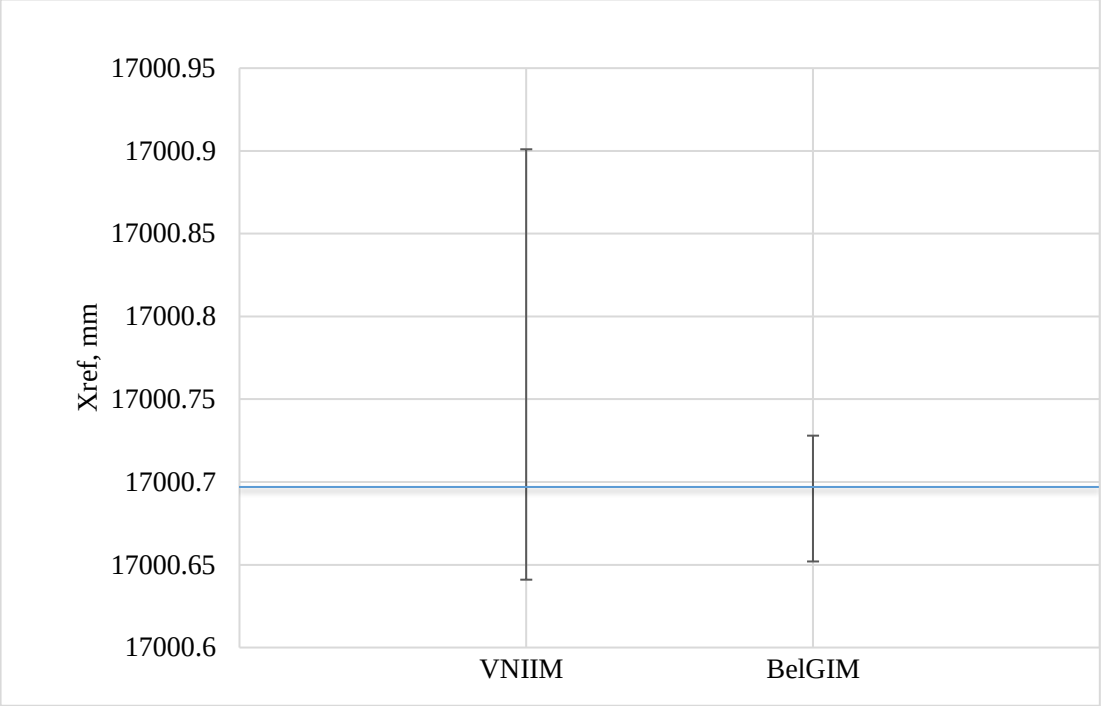

Figure 23 – Deviations from Xref on length 17000 mm

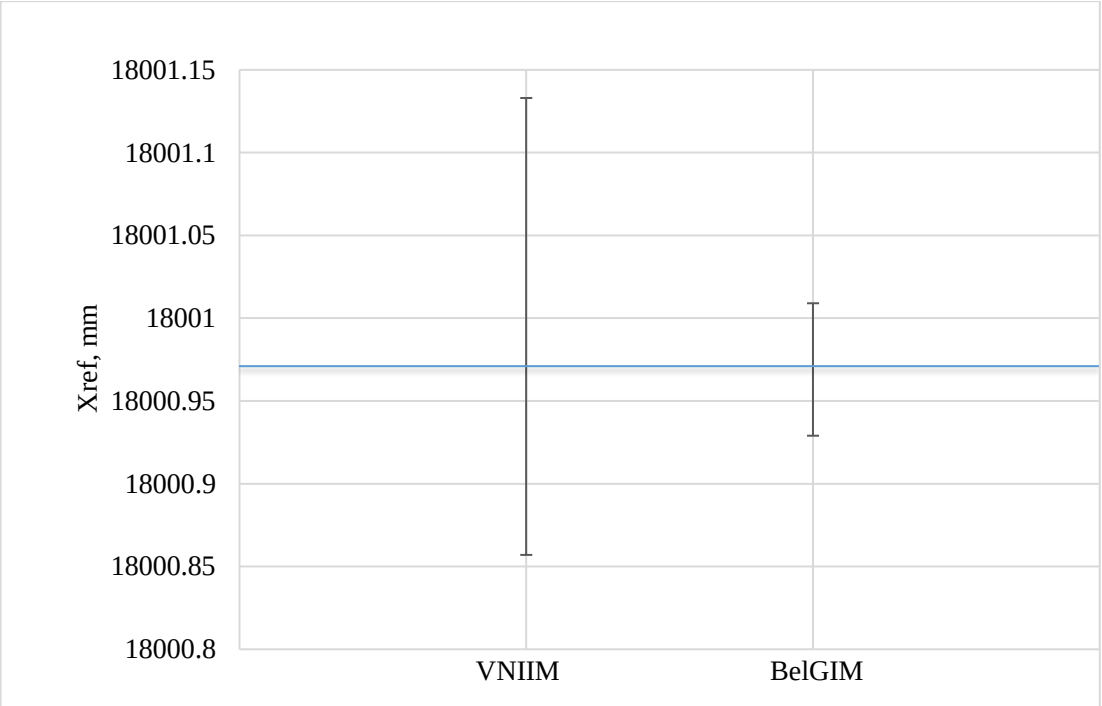

Figure 24 – Deviations from Xref on length 18000 mm

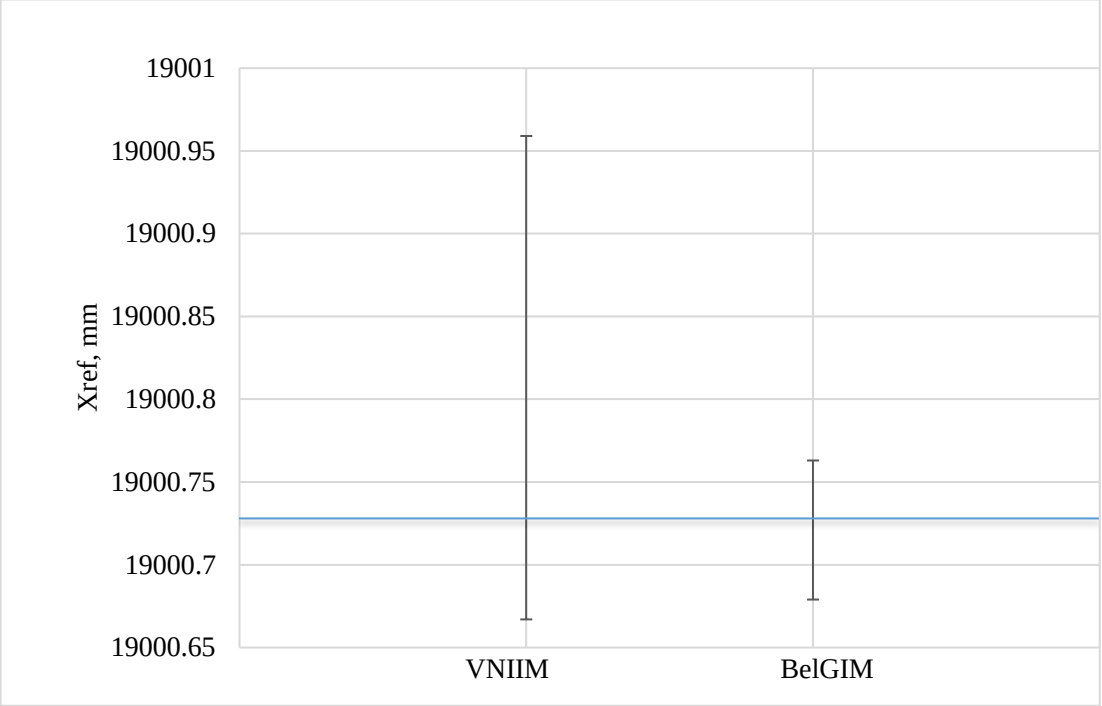

Figure 25 – Deviations from Xref on length 19000 mm

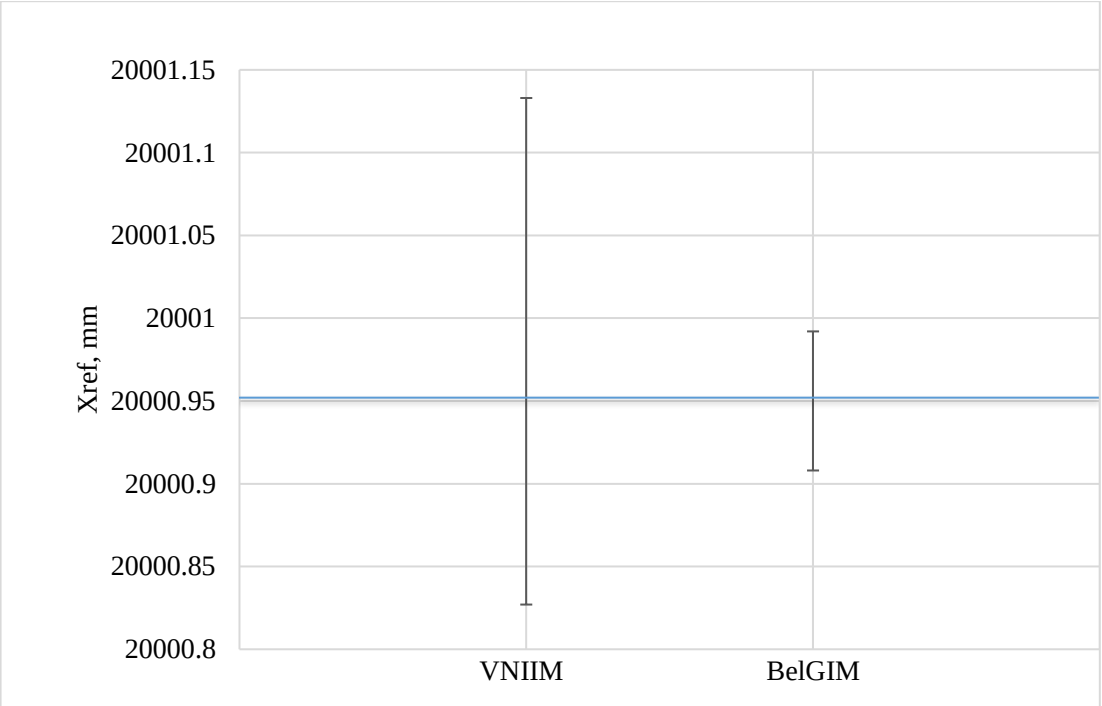

Figure 26 – Deviations from Xref on length 20000 mm

The summary diagram is on the figure 27. The length deviations from nominal length with the expanded uncertainty are on diagram.

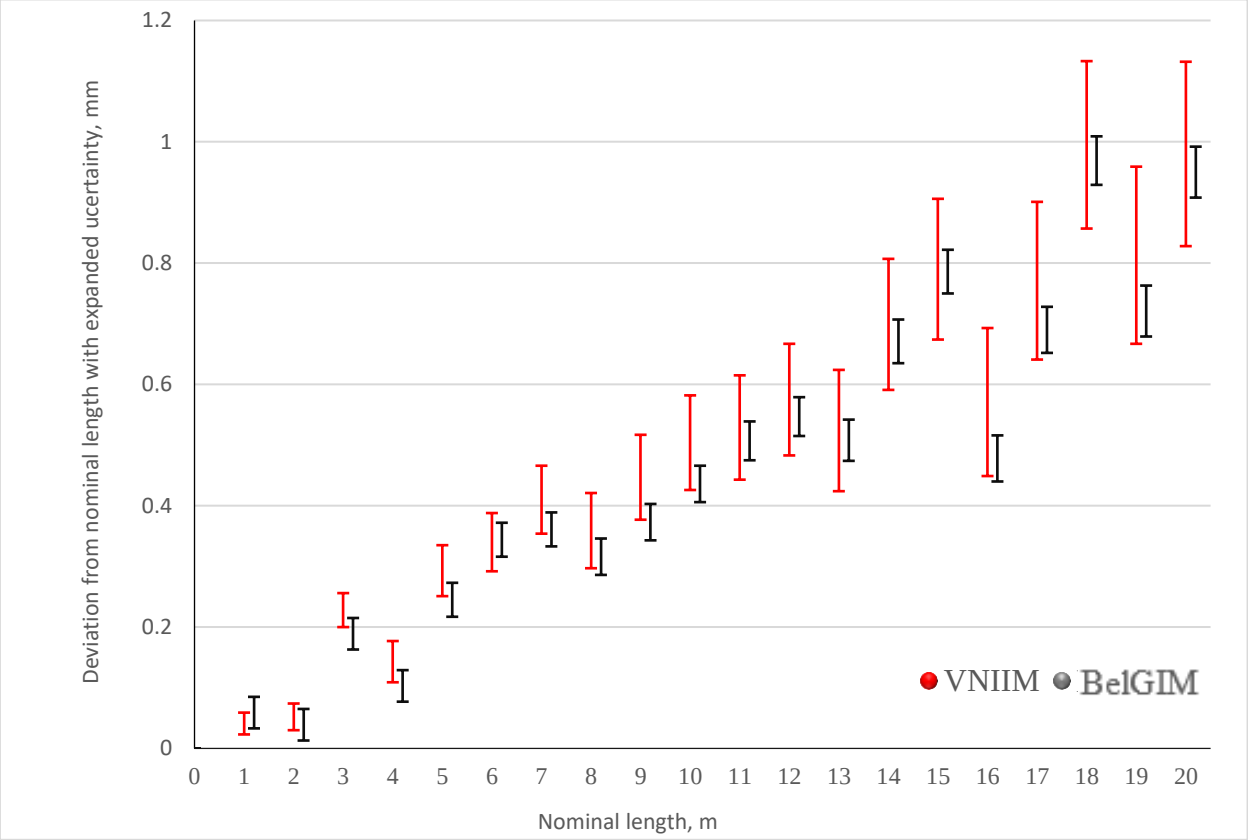

Figure 27 – Deviations from nominal length at the full range

Consistency of results of VNIIM and BelGIM are on the figure 28.

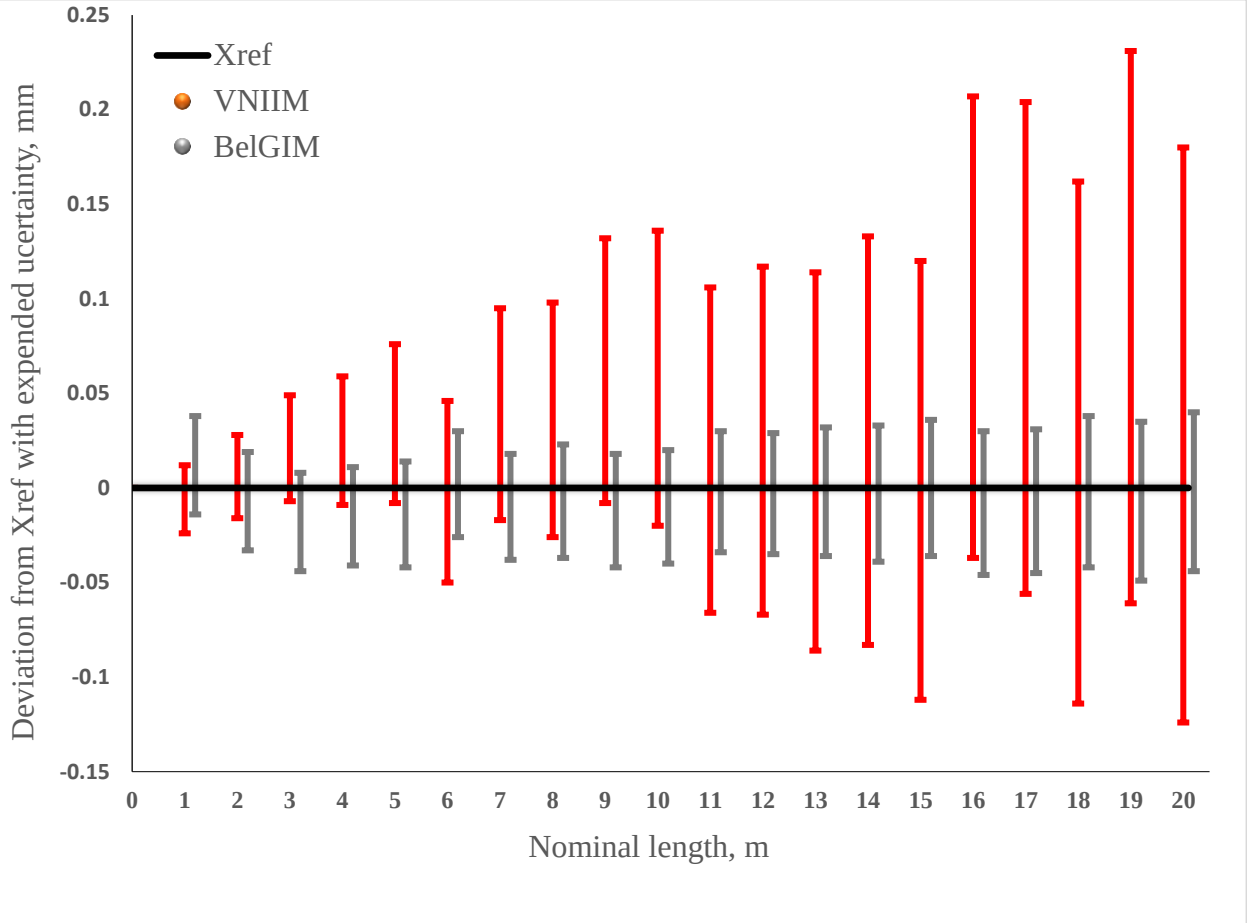

Figure 28 – Deviations from Xref with the expanded uncertainty at the full range

6.3. Conclusion

The comparison showed agreement between BelGIM and VNIIM. This is the confirmation of countries uncertainties.

KazInMetr is recommended to carry out the analysis of reasons for rejection of the results and repeat participation in comparison.