Final Report on Supplementary Force Comparison COOMET.M.F-S1

Measurand Force: 50 kN, 100 kN, 200 kN, 500 kN, 1 MN, 1,5 MN, 1,95 MN.

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6. **Summary**

1. General information about the COOMET.M.F-S1

A working group from the NMIs of Russia, Belarus and Ukraine decided to conduct supplementary comparison of force standards. The following ranges were agreed upon in force – 50 kN, 100 kN, 200 kN, 500 kN, 1 MN, 1,5 MN and 1,95 MN. A laboratory from VNIIM was designated as a pilot laboratory for conducting comparison. This report for comparison is designated as COOMET.M.F-S1. Three laboratories, including the pilot one, took part in the supplementary comparison (see Table 1).

The intercomparison was carried out in 4 ranges with 7 measurement points. Comparison in the range of 1,95 MN was carried out only in the laboratories of BELGIM and VNIIM. For this comparison, the pilot laboratory (VNIIM) provided a set of transducers.

Table 1: Participants in the COOMET.M.F-S1 supplementary comparison

Participant	Period of measurements	Measurement points
VNIIM (Russia)	02.03.2010 – 05.03.2010	50 kN, 100 kN, 200 kN, 500 kN, 1 MN
Ukrmetrteststandard (Ukraine)	13.04.2010 – 15.04.2010	50 kN, 100 kN, 200 kN, 500 kN, 1 MN
VNIIM (Russia)	21.04.2010 – 25.05.2010	50 kN, 100 kN, 200 kN, 500 kN, 1 MN
BelGIM (Belarus)	16.07.2010 – 22.07.2010	50 kN, 100 kN, 200 kN, 500 kN, 1 MN, 1,5 MN, 1,95 MN
VNIIM (Russia)	10.08.2010 – 08.09.2010	50 kN, 100 kN, 200 kN, 500 kN, 1 MN

2. Principles of the comparison

The purpose of this comparison is to compare the measuring and calibration capabilities of the NMIs of Russia, Belarus and Ukraine. In the field of force, this is done by using force transducers of high quality, high-precision carrier-frequency amplifiers and very stable bridge standards. The force transducers were subject to similar loading schemes in the force standard machines of the participants following a strict measurement protocol and using similar amplifiers.

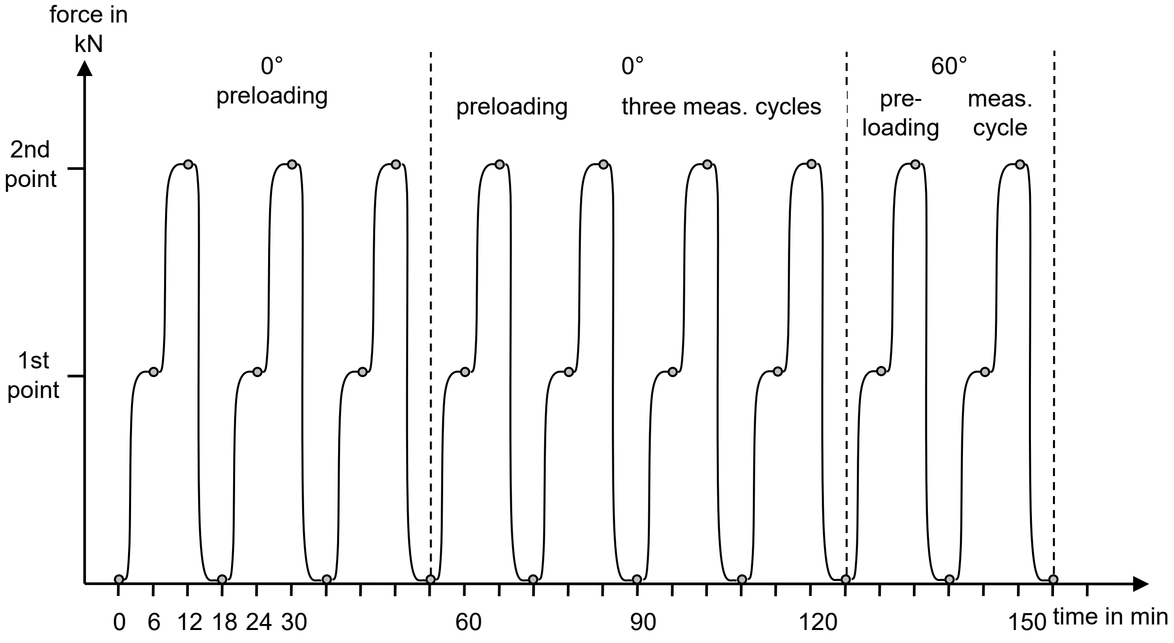

Figure 1: Diagram of the measurement sequence of the COOMET.M.F-S1

During comparison in the 2 range, preloading and measurements were carried out only at the 200 kN point.

The force transducer was rotated from 0° to 720° with 60° steps. Except the first mounting position with seven load cycles – four for stabilization and three for the repeatability measurement - in all other positions one preload and one measurement cycle (as shown for the 60° position in figure 1) were carried out, i.e. at transducer positions of 120°, 180°, 240°, 300°, 360°, 420°, 480°, 540°, 600°, 660° and 720°. All transfer standards are shown in Table 2.

Table 2: Force transducers used in supplementary comparison

№	Transfer standard (type, model, serial No.)	Mass, kg	Dimensions, mm
1	Force transducer TOP-Z4A/100 kN, ident. No. 122730006 with the nominal capacities of 100 kN.	6	Ø 150; 140
2	Force transducer ODC -20, ident. No. 185866 with the nominal capacities of 200 kN.	6	Ø 100; 190
3	Force transducer ODC -100, ident. No. 166256 with the nominal capacities of 1000 kN.	12	Ø 100; 190
4	Build-Up System ODC -300 No.1 with the capacity up to 3 MN incorporating: - force transducer ODC -100, ident. No. 166288 with the nominal capacities of 1000 kN; - force transducer ODC -100, ident. No. 166292 with the nominal capacities of 1000 kN; - force transducer ODC -100, ident. No. 166271 with the nominal capacities of 1000 kN; - set of connecting wires.	58	Ø 280; 400
5	Measuring amplifier MGCplus with: - display panel AB22A, ident. No. 801118789; - measuring module ML38B (channel 1) ident. No. 118810001102; - measuring module ML38B (channel 3) ident. No. 118810004102; - measuring module ML38B (channel 5) ident. No. 118810002102.	11	460; 370; 170
6	Calibrator BN 100A, ident. No. 13132 with equipment cable and connecting wires.	7	170; 370; 255

Table 3: Force machine used in supplementary comparison

Participant	Force machine	Range	Relative standard uncertainty of force realized, w_{fr}	Method applied
VNIIM (Russia)	EU-10	up to 100 kN	$1 \cdot 10^{-5}$	Deadweight
	EU-100	up to 1 MN	$1 \cdot 10^{-5}$	Deadweight
Ukrmetrteststandard (Ukraine)	LTM20T	up to 200 kN	$1 \cdot 10^{-4}$	Hydraulic amplification
	OSM 2-100-5	up to 1 MN	$1 \cdot 10^{-4}$	Lever-type amplification
BelGIM (Belarus)	UNN-10	up to 100 kN	$5 \cdot 10^{-5}$	Deadweight
	OSM 2-200-10	up to 2 MN	$1 \cdot 10^{-4}$	Lever-type amplification

3. Realization of the comparison

For this supplementary comparison a star type formation had been chosen. That means that the transducers were returned to the pilot laboratory after the measurement at each participant. The pilot repeated all measurements before sending the instruments to the next participant. One complete measurement cycle (pilot – participating laboratory – pilot) is called a loop.

Delivery of the transfer standards to each participant of the comparison and back is arranged by the pilot-laboratory. Transportation costs are held by the participating laboratories. The time of transportation between laboratories shall not exceed 4 weeks. The transfer standards are delivered in the transportation box together with the manual which gives information on packing, unpacking and mounting of the standards to the force standard machines subject to the comparison.

After transportation and unpacking the devices have to reach the measurement temperature which is + 20,0 ˚C ± 0,2 ˚C.

For establishing thermal equilibrium on the day before the measurement the force transducers are connected to the MGCplus channels, the calibrator BN 100A is connected to the measuring channel 7. The whole system shall be switched on overnight. Then, during measurements, the force transducers: TOP-Z4A/100 kN No. 122730006, ODC -20 No. 185866, ODC -100 No. 166256 are connected to the 1st measuring channel of the MGCplus; the force transducers: ODC -100 No. 166288, ODC -100 No. 166292, ODC -100 No. 166271 are connected to the 1st, 3rd and 5th MGCplus measuring channels respectively. Each MGCplus measuring channel used during the measurements shall be calibrated with the calibrator BN 100A before and after each measurement. If there is any deviation, it can be reduced by repeating the internal auto calibration of MGCplus several times. The internal auto calibration has to be switched on during the measurements. All results of the MGCplus calibration are placed on the protocol of the measurements

The following MGCplus settings are specified in the protocol of the measurements:

- 0,1 Hz Bessel-Filter;

- measuring range of 2,5 mV/V;

- resolution of 0,000 002 mV/V.

The measurements are carried out at +20,0 °C ± 0,2 °C air temperature.

Environmental conditions: the air temperature in °C, the relative humidity of the air in %, the air pressure in hPa are recorded into the protocol of the measurements.

4. Results of the measurements in the range up to 1 MN: reported deviation and uncertainties, calculated corrections and evaluation of the data

4.1. Symbols used:

d – relative deviation of measurement;

X_{PA} – measurements A in mV/V carried out in the pilot-laboratory before measurements in the participating laboratory;

X_{PB} – measurements B in mV/V carried out in the pilot-laboratory after the measurements in the participating laboratory;

X_{P} – average values of measurements X_{PA} and X_{PB} in mV/V obtained within one measuring cycle in mV/V;

X'_{L} – measurements in mV/V carried out in the participating laboratory;

$\bar{X}$ – average value from 12 measured values for each range of measurements;

$\bar{X}_{\mathrm{r}}$ – average value from 3 measured values for each range of measurements;

$C_{\mathrm{MGC,L}}$ – MGCplus readings' correction value in mV/V;

X_{L} – measurements in mV/V carried out in the participating laboratory considering the corrections (corrections of MGCplus readings, temperature, extrapolation);

X_i – a result of measurements in mV/V on measuring cycles 4 – 15;

w_1 – relative standard uncertainty of force realized by the pilot-laboratory's machines;

w_{fr} – relative standard uncertainty of force realized by the participant-laboratory's machines;

w_2 – is defined as relative standard deviation of average value of readings of the transducer at different positions of the transducer relative to the axis of application of force;

w_3 – is defined as relative standard deviation of average value of the transducer readings at the same position of the transducer relative to the axis of application of force (at 0°) on measuring cycles 1, 2, 3;

w_4 – relative standard uncertainty of the MGCplus resolution;

w_5 – relative standard uncertainty associated with temperature changes in the operating temperature range during measurements;

w_6 – relative standard uncertainty associated with the correction of temperature changes during measurements;

w_{stab}– relative standard uncertainty associated with the stability of transfer standards;

W_{PA} – relative expanded uncertainty of X_{PA};

W_{PB} – relative expanded uncertainty of X_{PB};

W_{P} – relative expanded uncertainty of X_{P};

W_{L} – relative expanded uncertainty of X_{L}.

4.2. Calculation of d - relative deviation of values X_L obtained in the participating laboratory and X_P obtained in the pilot-laboratory.

Relative deviations d are calculated by the following formula:

$$d = \frac{X_\mathrm{L} - X_\mathrm{P}}{X_\mathrm{P}} \tag{4.1}$$

with X_L - measurement in mV/V carried out in the participating laboratory considering the corrections (corrections of MGCplus readings, temperature, extrapolation);

X_P - measurement in mV/V carried out in the pilot laboratory considering the corrections (corrections of MGCplus readings, temperature, extrapolation).

X_P are calculated by the following formula:

$$X_\mathrm{P} = \frac{X_\mathrm{PA} + X_\mathrm{PB}}{2} \tag{4.2}$$

with X_PA – measurements A in mV/V carried out in the pilot-laboratory before measurements in the participating laboratory;

X_PB – measurements B in mV/V carried out in the pilot-laboratory after the measurements in the participating laboratory in mV/V.

If time intervals between measurements of one cycle (measurements A → participating laboratory measurements → measurements B) are different**,** the time correction of the pilot's values X_P are calculated by the following formula:

$$X_\mathrm{P} = X_\mathrm{PA} + \Delta_\mathrm{corr} \tag{4.3}$$

$$\Delta_\mathrm{corr} = \frac{(X_\mathrm{PB} - X_\mathrm{PA})}{t_\mathrm{total}} \times t_1 \tag{4.4}$$

with t_1 – time between measurements carried out by the pilot (measurements A) and measurements carried out by the participating laboratory;

t_2 – time between measurements carried out by the participant and measurements carried out by the pilot (measurements B).

$$t_\mathrm{total} = t_1 + t_2 \tag{4.5}$$

It is important to consider the correction $C_\mathrm{MGC,L}$ related to the correction of MGCplus readings, which is calculated as follows:

$$C_\mathrm{MGC,L} = X_\mathrm{MGC,P} - X_\mathrm{MGC,L} \tag{4.6}$$

with $X_\mathrm{MGC,L}$ – readings of MGCplus signal in mV/V set from the calibrator BN100, which are obtained in the participating laboratory before the beginning of the force measurements and after them;

$X_\mathrm{MGC,P}$ – readings of MGCplus signal in mV/V set from the calibrator BN100, which are obtained in the pilot-laboratory before the beginning of the force measurements and after them.

For each measurement range (50 kN - 100 kN, 200 kN, and 500 kN – 1 000 kN), all participants performed MGCplus calibration using BN100 within the range of 0,0 to 2,5 mV/V in increments of 0,2 mV/V. Between the points 2,4 mV/V and 2,5 mV/V, the step size was 0,1 mV/V. Calibration was conducted both before and after each measurement.

Further the correction is implemented as follows:

$$X_{\mathrm{L}} = X'_{\mathrm{L}} + C_{\mathrm{MGC,L}} \tag{4.7}$$

with X'_{L}– measurements in mV/V carried out in the participating laboratory.

Table 4: The effect of creep on the sensitivity of the transfer standards

Transfer standard	The creep in 6 minutes after the application of the nominal force, nV/V	Relative creep change between the 4th and the 6th minutes after application of nominal force (rel. creep/min)
Z4A/100 kN	55	$5,0 \cdot 10^{-7}$
ODC - 20	- 95	$2,1 \cdot 10^{-6}$
ODC - 100	- 80	$1,5 \cdot 10^{-6}$
ODC - 300	- 115	$2,4 \cdot 10^{-6}$

Due to the fact that each of the standards involved in the comparison has a different time to of application of force (from 1 to 3 minutes) and in order to minimize the effect of the creep effect of comparison standards on the measurement results, studies of comparison standards were conducted on VNIIM deadweight machines. According to the research results, the optimal time interval for recording readings was chosen: between 4 and 6 minutes after the application of force. The values of the force transducer creep in this time interval turned out to be negligible and were not taken into account in further calculations.

$$w_{\mathrm{stab}} = \frac{|X_{\mathrm{PA}} - X_{\mathrm{PB}}|}{2\sqrt{3} \times X_{\mathrm{P}}} \tag{4.8}$$

Table 5: Stability of transfer standards (before and after Ukrmetrteststandard)

Transfer standard	Force, kN	X_{PA} before Ukrmetrteststandard, mV/V	X_{PB} after Ukrmetrteststandard, mV/V	Relative standard uncertainty associated with the stability of transfer standards, w_{stab}
TOP-Z4A	50	1,000 186	1,000 199	$3,82 \cdot 10^{-6}$
TOP-Z4A	100	2,000 536	2,000 559	$3,22 \cdot 10^{-6}$
ODC-20	200	2,034 891	2,034 866	$3,58 \cdot 10^{-6}$
ODC-100	500	1,097 929	1,097 902	$7,14 \cdot 10^{-6}$
ODC-100	1000	2,195 267	2,195 234	$4,26 \cdot 10^{-6}$

Table 6: Stability of transfer standards (before and after BelGIM)

Transfer standard	Force, kN	X_{PA} before BelGIM, mV/V	X_{PB} after BelGIM, mV/V	Relative standard uncertainty associated with the stability of transfer standards, w_{stab}
TOP-Z4A	50	1,000 199	1,000 214	$4,21 \cdot 10^{-6}$
TOP-Z4A	100	2,000 559	2,000 579	$2,95 \cdot 10^{-6}$
ODC-20	200	2,034 866	2,034 844	$3,10 \cdot 10^{-6}$
ODC-100	500	1,097 902	1,097 886	$4,16 \cdot 10^{-6}$
ODC-100	1000	2,195 234	2,195 208	$3,39 \cdot 10^{-6}$

4.3. The list and the calculations of the main components of the uncertainty of the deviation determination

The average value $\bar{X}$ derived from 12 measured values for each range of measurements is calculated as follows:

$$\overline{X} = \frac{1}{12} \times \sum_{i=4}^{15} X_i \tag{4.9}$$

with X_i – a result of measurements in mV/V on measuring cycles from 4 to 15;

The relative standard uncertainty of force realized by the pilot-laboratory's machines w_1**:**

$$w_1 = 1 \cdot 10^{-5} \tag{4.10}$$

$$w_2 = \frac{1}{\left|\overline{X}\right|} \times \frac{1}{\sqrt{12}} \times \sqrt{\frac{1}{(12-1)} \times \sum_{i=4}^{15} \left(X_i - \overline{X}\right)^2} \tag{4.11}$$

with w_2 – is defined as relative standard deviation of average value of readings of the transducer at different positions of the transducer relative to the axis of application of force;

$$w_3 = \frac{1}{\left|\overline{X_\mathrm{r}}\right|} \times \frac{1}{\sqrt{3}} \times \sqrt{\frac{1}{(3-1)} \times \sum_{i=1}^{3} \left(X_i - \overline{X_\mathrm{r}}\right)^2} \tag{4.12}$$

with w_3 – is defined as relative standard deviation of average value of the transducer readings at the same position of the transducer relative to the axis of application of force (at 0˚) on measuring cycles 1, 2, 3;

$\bar{X}_\mathrm{r}$ calculated by the formula:

$$\overline{X_\mathrm{r}} = \frac{1}{3} \times \sum_{i=1}^{3} X_i \tag{4.13}$$

with X_i – a result of measurements in mV/V measuring cycles 1, 2, 3.

The result of each measurement is the difference between the measurement result obtained under load and the result of measurement at zero load. Thus, the uncertainty of the MGCplus resolution is described by two rectangular distributions of probabilities, each of which is $\frac{r}{2\sqrt{3}}$, where r = 0,000 002 mV/V, and is calculated by the formula:

$$w_4 = \frac{\sqrt{2}}{2\sqrt{3}} \times \frac{r}{\left|\overline{X}\right|} = \frac{1}{\sqrt{6}} \times \frac{r}{\left|\overline{X}\right|} \tag{4.14}$$

$$w_5 = K \times \frac{\Delta T}{2} \times \frac{1}{\sqrt{3}} \tag{4.15}$$

with w_5 – the uncertainty related to the temperature change in the measurement stream is described by a rectangular distribution of probabilities;

K - a coefficient of the temperature dependence of the force transducer (determined experimentally or specified by the manufacturer in technical documentation);

ΔT – a range of temperature change during the measurements (ΔT = 0,4 °C).

Table 7: Temperature coefficients of the transfer standards and relative uncertainty related to the temperature changes within ΔT during the measurements

Transfer standard	Temperature coefficient K, 1/°C	Relative uncertainty related to the temperature changes within ΔT during the measurements, w_5
Z4A/100 kN	$2{,}79 \cdot 10^{-5}$	$3{,}22 \cdot 10^{-6}$
ODC - 20	$1{,}83 \cdot 10^{-5}$	$2{,}11 \cdot 10^{-6}$
ODC - 100	$1{,}83 \cdot 10^{-5}$	$2{,}11 \cdot 10^{-6}$
ODC - 300	$1{,}83 \cdot 10^{-5}$	$2{,}11 \cdot 10^{-6}$

During all measurements, the temperature changes did not exceed the operational temperature range. Therefore, it was not necessary to calculate the uncertainty associated with correcting for temperature changes w_6 during the measurements.

Relative expanded uncertainty of the deviation determination W is calculated as follows:

$$w_{\mathrm{L}} = \sqrt{w_{\mathrm{fr}}^2 + \sum_{i=1}^{6} w_i^2} \qquad (4.16)$$

$$W_{\mathrm{L}} = k \times w_{\mathrm{L}} \qquad (4.17)$$

with k = 2.

$$w_{\mathrm{PA,PB}} = \sqrt{\sum_{i=1}^{6} w_i^2} \qquad (4.18)$$

$$W_{\mathrm{PA,PB}} = k \times w_{\mathrm{PA,PB}} \qquad (4.19)$$

with k = 2.

$$W_{\mathrm{P}} = k \times \sqrt{\frac{w_{\mathrm{PA}}^2 + w_{\mathrm{PB}}^2}{2} + w_{\mathrm{stab}}^2} \qquad (4.20)$$

with k = 2.

4.5. Degree of equivalence of the standards under comparison

The degree of equivalence between the compared standards is determined with the relative deviations of the force values which are obtained in the participating laboratory from the force values which are obtained in the pilot-laboratory and the expanded relative uncertainty of these deviations.

Table 8: The measured values with applied corrections at various force levels and the values of the expanded relative uncertainty of measurements obtained in the pilot-laboratory and the participating laboratories

NMI	Transfer standard	Force	X'_{L}	$C_{\mathrm{MGC,L}}$	X_{L}	W_{L}	X_{PA}	W_{PA}	X_{PB}	W_{PB}	X_{P}	W_{P}
	type, No.	kN	mV/V	$\times 10^{-6}$ mV/V	mV/V	$\times 10^{-4}$	mV/V	$\times 10^{-5}$	mV/V	$\times 10^{-5}$	mV/V	$\times 10^{-5}$
Ukrmetrteststandard	Z4A/100 kN	50	1,000 230	-0,5	1,000 230	2,02	1,000 186	2,33	1,000 199	1,99	1,000 192	2,17
	Z4A/100 kN	100	2,000 602	-4,0	2,000 598	2,02	2,000 536	2,04	2,000 559	1,92	2,000 546	1,98
	ODC-20	200	2,034 752	1,0	2,034 753	2,02	2,034 891	2,06	2,034 866	2,17	2,034 880	2,12
	ODC-100	500	1,097 967	-1,0	1,097 966	2,02	1,097 929	2,28	1,097 902	2,40	1,097 918	2,34
	ODC-100	1000	2,195 322	0,0	2,195 322	2,03	2,195 267	2,43	2,195 234	3,14	2,195 253	2,80
BelGIM	Z4A/100 kN	50	1,000 169	2,5	1,000 172	1,03	1,000 199	1,99	1,000 214	1,93	1,000 207	1,96
	Z4A/100 kN	100	2,000 564	-0,5	2,000 564	1,02	2,000 559	1,92	2,000 579	1,98	2,000 569	1,95
	ODC-20	200	2,034 805	2,5	2,034 808	2,02	2,034 866	2,17	2,034 844	2,11	2,034 855	2,14
	ODC-100	500	1,097 844	0,0	1,097 844	2,09	1,097 902	2,40	1,097 886	2,56	1,097 894	2,48
	ODC-100	1000	2,195 774	-1,5	2,195 773	2,08	2,195 234	3,14	2,195 208	3,17	2,195 221	3,16

Table 9: The relative deviation between the pilot-laboratory and the participating laboratory, and the relative expanded uncertainty of the deviation determination during the comparison of the force of 50 kN

NMI	Relative deviation between the pilot laboratory and the participating laboratory, d	Relative expanded uncertainty of the deviation determination, W
VNIIM	0,00	$2{,}09 \cdot 10^{-5}$
Ukrmetrteststandard	$3{,}80 \cdot 10^{-5}$	$2{,}03 \cdot 10^{-4}$
BelGIM	$-3{,}50 \cdot 10^{-5}$	$1{,}05 \cdot 10^{-4}$

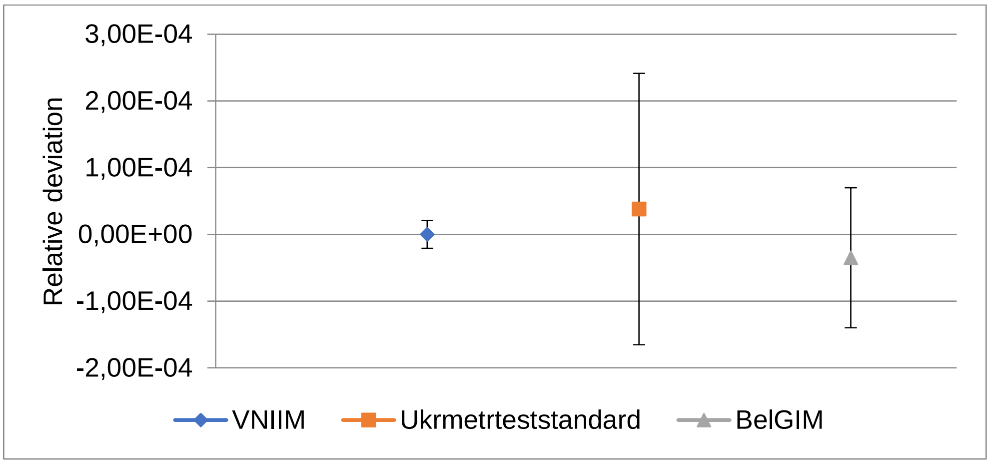

Figure 2: The degree of equivalence during the comparison of the force of 50 kN

Table 10: The relative deviation between the pilot-laboratory and the participating laboratory, and the relative expanded uncertainty of the deviation determination during the comparison of the force of 100 kN

NMI	Relative deviation between the pilot laboratory and the participating laboratory, d	Relative expanded uncertainty of the deviation determination, W
VNIIM	0,00	$1{,}98 \cdot 10^{-5}$
Ukrmetrteststandard	$2{,}60 \cdot 10^{-5}$	$2{,}03 \cdot 10^{-4}$
BelGIM	$-0{,}25 \cdot 10^{-5}$	$1{,}04 \cdot 10^{-4}$

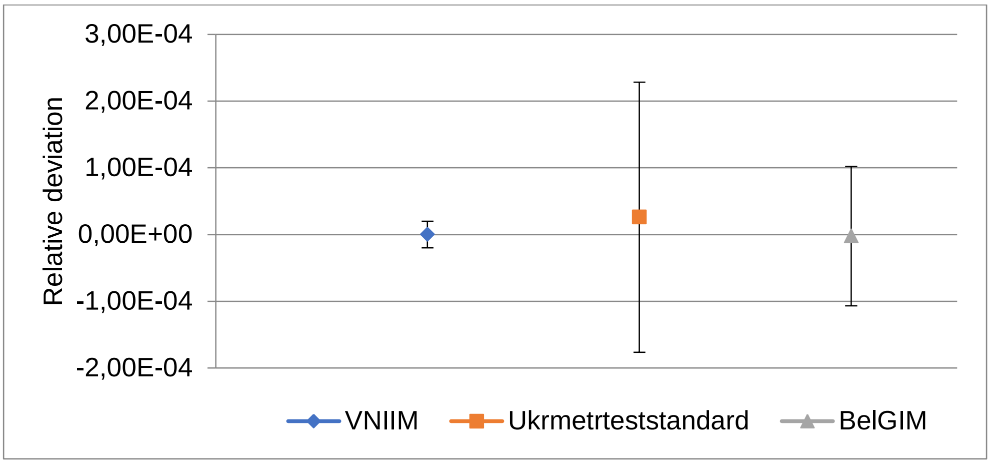

Figure 3: The degree of equivalence during the comparison of the force of 100 kN

Table 11: The relative deviation between the pilot-laboratory and the participating laboratories, and the relative expanded uncertainty of the deviation determination during the comparison of the force of 200 kN

NMI	Relative deviation between the pilot laboratory and the participating laboratory, d	Relative expanded uncertainty of the deviation determination, W
VNIIM	0,00	$2{,}11 \cdot 10^{-5}$
Ukrmetrteststandard	$-6{,}24 \cdot 10^{-5}$	$2{,}03 \cdot 10^{-4}$
BelGIM	$-2{,}31 \cdot 10^{-5}$	$2{,}03 \cdot 10^{-4}$

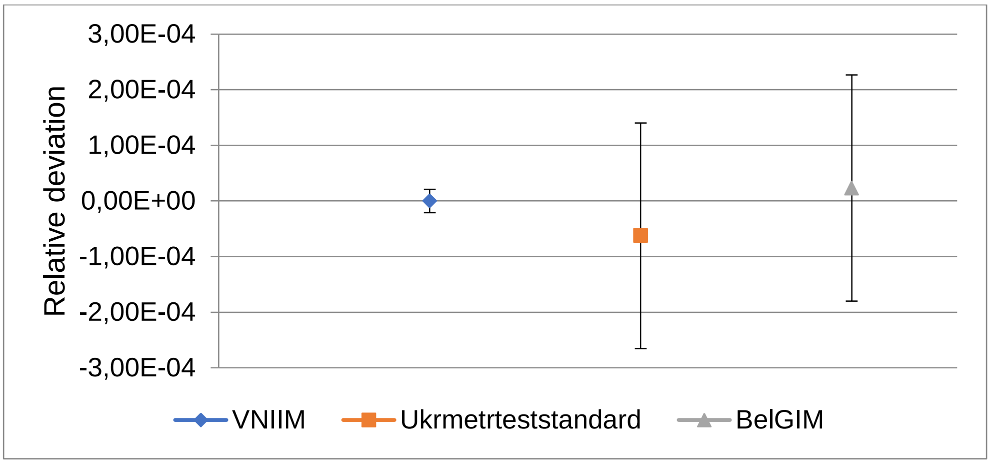

Figure 4: The degree of equivalence during the comparison of the force of 200 kN

Table 12: The relative deviation between the pilot-laboratory and the participating laboratories, and the relative expanded uncertainty of deviation determination during the comparison of the force of 500 kN

NMI	Relative deviation between the pilot laboratory and the participating laboratory, d	Relative expanded uncertainty of the deviation determination, W
VNIIM	0,00	$2{,}41 \cdot 10^{-5}$
Ukrmetrteststandard	$4{,}37 \cdot 10^{-5}$	$2{,}04 \cdot 10^{-4}$
BelGIM	$-4{,}55 \cdot 10^{-5}$	$2{,}10 \cdot 10^{-4}$

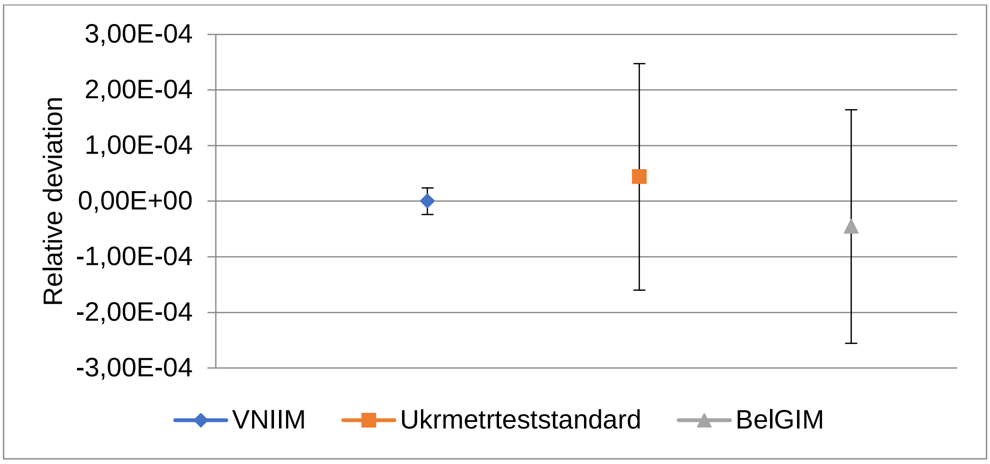

Figure 5: The degree of equivalence during the comparison of the force of 500 kN

Table 13: The relative deviation between the pilot-laboratory and the participating laboratories, and the relative expanded uncertainty of the deviation determination during the comparison of the force of 1 MN

NMI	Relative deviation between the pilot laboratory and the participating laboratory, d	Relative expanded uncertainty of the deviation determination, W
VNIIM	0,00	$2{,}91 \cdot 10^{-5}$
Ukrmetrteststandard	$3{,}14 \cdot 10^{-5}$	$2{,}06 \cdot 10^{-4}$
BelGIM	$2{,}52 \cdot 10^{-4}$	$2{,}10 \cdot 10^{-4}$

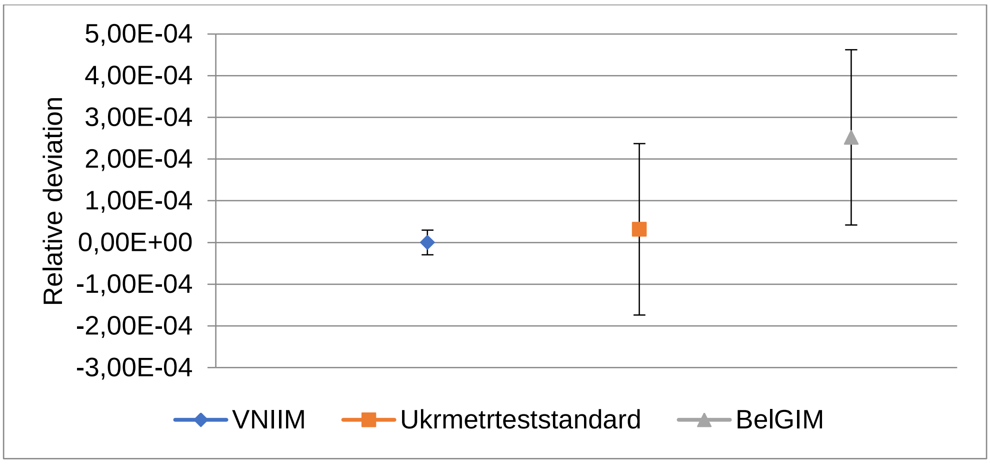

Figure 6: The degree of equivalence during the comparison of the force of 1 MN

5. Results of the measurements in the range up to 1,95 MN: reported deviation, deflection and uncertainties, calculated corrections and evaluation of the data

5.1. Symbols used:

d – relative deviation;

F_{L}– combined force values in kN measured by the participating laboratory;

F_{N} – nominal value of force in kN;

F_{P} – force values in kN measured by the pilot laboratory;

w_1 – relative standard uncertainty of force realized by the pilot-laboratory's machines;

w_2 – relative standard uncertainty of the average readings of the transducer;

w_3 – relative standard uncertainty of the MGCplus resolution;

w_{BUS} – relative expanded standard uncertainty of build-up system;

w_{st1} – relative standard uncertainty of the results of measurements 1st transducer of the group in pilot-laboratory;

w_{st2} – relative standard uncertainty of the results of measurements 2nd transducer of the group in pilot-laboratory;

w_{st3} – relative standard uncertainty of the results of measurements 3rd transducer of the group in pilot-laboratory;w_{int} – relative standard uncertainty of interpolation;

w_{2L} – relative standard uncertainty of the average readings of the transducer in the participating laboratory;

w_{L} – relative standard uncertainty of F_{L};

W_{L} – relative expanded uncertainty of F_{L}.

5.2. Determination of the calibrating characteristics of the Build-Up System ODC -300

For comparison in the range of more than 1 MN to 2 MN, a build-up system ODC-300, consisting of 3 force transducers ODC-100 with a measurement range from 100 kN to 1 MN each was used.

According to the results of measurements obtained in the pilot-laboratory on the reference installation of the EU-100 for each transducer ODC-100, a calibration characteristic, determining the dependence of the applied force F in kN on the MGCplus readings X in mV/V, is built.

The obtained calibration characteristics have the form of the cubic polynomial:

$$F_{\mathrm{int}}\,(X_n) = a_k X_n + b_k {X_n}^2 + c_k {X_n}^3 \tag{5.1}$$

with a_k , b_k, c_k - coefficients of a cubic polynomial for ODC-100 force transducers, obtained from measurements in the pilot-laboratory before and after measurements in the participating laboratory;

X_n – indications of the transducer ODC-100;

k – transducer number (1, 2, 3);

n – number of measurement points.

Table 14. The values of the cubic polynomial coefficients for the force transducers ODC-100.

k	a_k	b_k	c_k
1	456,330	0,028 1	0,024 5
2	455,650	0,023 4	0,029 0
3	456,176	0,003 2	0,034 1

The coefficients of the cubic polynomial are calculated based on the measurements results of increasing and decreasing forces shown in Table 15.

Table 15. The average values of the readings and deflections from 3 ODC-100 transducers, based on 12 measurements, during calibration by the pilot.

Nominal Force, kN	1st ODC-100, mV/V	Deflection of 1st ODC-100, mV/V	2nd ODC-100, mV/V	Deflection of 2nd ODC-100, mV/V	3rd ODC-100, mV/V	Deflection of 3rd ODC-100, mV/V
0	0,030 311	0,000 000	0,035 604	0,000 000	0,042 623	0,000 000
500	1,125 846	1,095 535	1,132 782	1,097 178	1,138 582	1,095 959
600	1,344 888	1,314 577	1,352 175	1,316 572	1,357 733	1,315 109
700	1,563 953	1,533 642	1,571 541	1,535 937	1,576 853	1,534 230
800	1,782 952	1,752 642	1,790 869	1,755 266	1,795 941	1,753 317
900	2,001 943	1,971 633	2,010 142	1,974 538	2,014 966	1,972 343
1000	2,220 843	2,190 532	2,229 346	2,193 742	2,233 942	2,191 319
900	2,001 907	1,971 596	2,010 104	1,974 500	2,014 924	1,972 301
800	1,782 932	1,752 621	1,790 771	1,755 167	1,795 882	1,753 259
700	1,563 964	1,533 653	1,571 509	1,535 905	1,576 810	1,534 187
600	1,344 939	1,314 628	1,352 168	1,316 564	1,357 716	1,315 092
500	1,125 892	1,095 582	1,132 796	1,097 192	1,138 588	1,095 964

Table 16. The force values obtained from interpolation equations (cubic polynomial) at each nominal force and relative deviations between these two values.

Nominal Force, kN	1st ODC-100, kN	Relative deviation 1st ODC-100	2nd ODC-100, kN	Relative deviation 2nd ODC-100	3rd ODC-100, kN	Relative deviation 3rd ODC-100
500	499,991	$- 1{,}734 \cdot 10^{-5}$	499,996	$- 8{,}280 \cdot 10^{-6}$	499,998	$- 3{,}090 \cdot 10^{-6}$
600	599,985	$- 2{,}507 \cdot 10^{-5}$	600,003	$4{,}713 \cdot 10^{-6}$	600,004	$6{,}420 \cdot 10^{-6}$
700	700,001	$1{,}699 \cdot 10^{-6}$	700,010	$1{,}468 \cdot 10^{-5}$	700,009	$1{,}265 \cdot 10^{-5}$
800	800,001	$1{,}301 \cdot 10^{-6}$	800,016	$2{,}010 \cdot 10^{-5}$	800,014	$1{,}780 \cdot 10^{-5}$
900	900,012	$1{,}343 \cdot 10^{-5}$	900,013	$1{,}447 \cdot 10^{-5}$	900,009	$9{,}645 \cdot 10^{-6}$
1000	999,998	$- 2{,}204 \cdot 10^{-6}$	999,998	$- 2{,}091 \cdot 10^{-6}$	1000,000	$1{,}671 \cdot 10^{-7}$
900	899,995	$- 5{,}011 \cdot 10^{-6}$	899,996	$- 4{,}787 \cdot 10^{-6}$	899,990	$- 1{,}162 \cdot 10^{-5}$
800	799,992	$- 1{,}026 \cdot 10^{-5}$	799,971	$- 3{,}595 \cdot 10^{-5}$	799,987	$- 1{,}572 \cdot 10^{-5}$
700	700,006	$9{,}091 \cdot 10^{-6}$	699,996	$- 6{,}111 \cdot 10^{-6}$	699,989	$- 1{,}550 \cdot 10^{-5}$
600	600,008	$1{,}399 \cdot 10^{-5}$	599,999	$- 9{,}854 \cdot 10^{-7}$	599,996	$- 6{,}320 \cdot 10^{-6}$
500	500,012	$2{,}496 \cdot 10^{-5}$	500,002	$4{,}634 \cdot 10^{-6}$	500,001	$2{,}005 \cdot 10^{-6}$

5.3 The list and the calculations of the main components of the measurement uncertainty

Relative standard uncertainty of force realized by the pilot-laboratory's machines w_1:

$$w_1 = 1 \cdot 10^{-5} \tag{5.2}$$

Relative standard uncertainty of the average readings of the transducer w_2 is calculated by the formula:

$$w_2 = \frac{1}{|\overline{X}|} \times \frac{1}{\sqrt{12}} \times \sqrt{\frac{1}{(12-1)} \times \sum_{i=4}^{15} \left(X_i - \overline{X}\right)^2} \tag{5.3}$$

Relative standard uncertainty of the MGCplus resolution w_4 is calculated by the formula:

$$w_3 = \frac{\sqrt{2}}{2\sqrt{3}} \times \frac{r}{|\overline{X}|} = \frac{1}{\sqrt{6}} \times \frac{r}{|\overline{X}|} \tag{5.4}$$

Relative standard uncertainty of interpolation w_{int} is calculated by the formula:

$$w_{\mathrm{int}} = \frac{F_{\mathrm{MAX}}}{F_{\mathrm{N}} \times X_{\mathrm{MAX}}} \sqrt{\frac{\delta}{n-b-1}} \tag{5.5}$$

with F_{MAX} – maximum calibration force in kN;

X_{MAX} – deflection corresponding to the maximum calibration force;

δ – is the sum of the squared deviations between the mean deflection and the value calculated from the interpolation equation;

n – number of measured points ($n = 11$);

b – degree of polynomial ($b = 3$);

F_{N} – nominal value of force in kN.

Relative standard uncertainty of transducer w_{st} is calculated by the formula:

$$w_{\mathrm{st}} = \sqrt{w_1^2 + w_2^2 + w_3^2 + w_{\mathrm{int}}^2} \tag{5.6}$$

Table 17: The uncertainty of the force transducers.

	w_1×10^{-5}	w_2×10^{-5}	w_3×10^{-7}	w_{int}×10^{-5}	w_{st}×10^{-5}
1st transducer	1,00	2,52	7,45	2,15	3,47
2nd transducer	1,00	3,44	7,44	2,86	4,59
3rd transducer	1,00	0,84	7,45	2,10	2,27

Table 17 shows the maximum uncertainty values among the points at which force transducers were calibrated by the pilot. Uncertainty of build-up system is estimated with a margin using the following formula:

$$w_{\mathrm{BUS}} = \sqrt{{w_{\mathrm{st1}}}^2 + {w_{\mathrm{st2}}}^2 + {w_{\mathrm{st3}}}^2} \tag{5.7}$$

5.4 The list and the calculations of the main components of the measurement uncertainty in participating laboratory

The result of force measurements of 1,5 MN and 1,95 MN carried out in the participating laboratory will be the average value of 12 measurements of the sum of forces from 3 ODC-100 transducers expressed in kN. Combined force F_{L} in participating laboratory applied to the composite transducer ODC-300 is calculated by the formula:

$$F_{\mathrm{L}} = F_1(X_1) + F_2(X_2) + F_3(X_3) \tag{5.8}$$

with $F_1(X_1)$ – indications of the 1st transducer ODC-100;

$F_2(X_2)$ – indications of the 2nd transducer ODC-100;

$F_3(X_3)$ – indications of the 3rd transducer ODC-100.

The result of the comparison will be deviations of the measured values F_L of the force in the participating laboratory from the nominal values F_N of the force, and the estimation of the expanded relative uncertainty of this deviation.

Relative deviation d is calculated by the formula:

$$d = \frac{F_\mathrm{L} - F_\mathrm{N}}{F_\mathrm{N}} \tag{5.9}$$

with F_N – nominal value of force in kN (1 500 kN, 1 950 kN);

F_L – combined force values in kN measured by the participating laboratory.

Relative standard uncertainty of the average readings of the transducer w_2L in participating laboratory is calculated by the formula:

$$w_\mathrm{2L} = \frac{1}{|\overline{F}|} \times \frac{1}{\sqrt{12}} \times \sqrt{\frac{1}{(12-1)} \times \sum_{i=4}^{15} \left(F_{\mathrm{L}i} - \overline{F}\right)^2} \tag{5.10}$$

The average value obtained from 12 measured values $F_{\mathrm{L}i}$ (from 4 to 15 measuring cycles) in kN under forces of 1,5 MN is determined by the formula:

$$\overline{F} = \frac{1}{12} \times \sum_{i=4}^{15} F_{\mathrm{L}i} \tag{5.11}$$

with F_i – result of measurements in kN on measuring cycles.

Relative expanded uncertainty of the deviation determination is calculated as follows:

$$w_\mathrm{L} = \sqrt{w_\mathrm{BUS}^2 + w_\mathrm{fr}^2 + w_\mathrm{2L}^2} \tag{5.12}$$

$$W_\mathrm{L} = k \times w_\mathrm{L} \tag{5.13}$$

with k = 2.

Table 18: Uncertainty budget.

	w_{int} × 10^{-5}	w_{st} × 10^{-5}		
1st transducer	2,15	3,47		
2nd transducer	2,86	4,59		
3rd transducer	2,10	2,27		
Nominal Force, kN	w_{BUS} × 10^{-5}	w_{fr} × 10^{-4}	w_{L} × 10^{-4}	W_{L} × 10^{-4}
1 500	6,18	1,00	1,28	2,55
2 000		1,00	1,30	2,60

Table 19: The relative deviation between the pilot-laboratory and the participating laboratory, and the relative expanded uncertainty of the deviation determination during the comparison of the force of 1,5 MN

NMI	Relative deviation, d	Relative expanded uncertainty of the deviation determination, W_{L}
BelGIM	$2{,}47 \cdot 10^{-4}$	$2{,}55 \cdot 10^{-4}$

Table 20: The relative deviation between the pilot-laboratory and the participating laboratory, and the relative expanded uncertainty of the deviation determination during the comparison of the force of 1,95 MN

NMI	Relative deviation, d	Relative expanded uncertainty of the deviation determination, W_{L}
BelGIM	$5{,}66 \cdot 10^{-4}$	$2{,}60 \cdot 10^{-4}$

6 Summary

The results of the measurements (deviations and uncertainties) reported by the participants of the supplementary force comparison COOMET.M.F-S1 to the pilot laboratory were evaluated. The results of the comparison up to 1 000 kN are presented in Tables 9 – 13 and in Figures 2 – 6. It has been revealed that the lines of uncertainty do not intersect the reference value of comparison of the BelGIM force machine at 1 000 kN point.

For comparison at points 1 500 kN and 1 950 kN has been used build-up system. Based on pilot calibration results, coefficients for the cubic polynomial and the uncertainty of build-up system where determined. These coefficients and uncertainty were used for determination of participating laboratory deviation and uncertainty. The results of the comparison at 1 500 kN and 1 950 kN points are presented in Tables 19 – 20.