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APMP.M.F-K3.a and b

High force measurements

KEY COMPARISON

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Force Key Comparison APMP.M.F-K3.a and APMP.M.F-K3.b
(500 kN and 1000 kN)

Final Report

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Contents

1 Introduction

The APMP.M.F-K3 Key Comparison (KC) is based on the decision of the APMP TCM Meeting held in October 2004 in Beijing. The purpose of this comparison is to determine the degree of equivalence among the national standards of force and provide the evidence for the calibration and measurement capability (CMC) acclaimed by the participating NMIs in Asia-Pacific region. The APMP TCM approved that NIM of China serve as pilot laboratory of APMP.M.F-K3 key comparison. The APMP.M.F-K3 key comparison has two schemes which are APMP.M.F-K3.a (Scheme A) using two force steps of 500 kN, 1 MN and APMP.M.F-K3.b (Scheme B) using one force step of 500 kN. PTB and NMIJ would be link laboratories of APMP.M.F-K3.a and APMP.M.F-K3.b respectively.

This report describes the APMP.M.F-K3 KC and reports the results of the comparison.

2 Participants in the comparison

There are 10 laboratories including the pilot. The participants are listed in Table 1.

PTB, Germany and NMIJ, Japan is as link laboratory of APMP.M.F-K3.a and APMP.M.F-K3.b respectively in order to link the KCRV to this APMP KC.

Laboratory	Economy	Code	Scheme	Expanded relative uncertainty of force machine	Type of machine	Month	Remark
NIM	China	1	A	2.00E-05	DWM	Pilot	Pilot, Link k=3
			B	2.00E-05	DWM		
PTB	Germany	2	A	2.00E-05	DWM	2013.05	Link
NMIA	Australia	3	A	2.00E-04	BM	2013.10	
A*STAR	Singapore	4	A	2.00E-04	LM	2014.05	
			B	2.00E-04	LM	2020.07	
NPLI, India	India	5	A	9.00E-05	LM	2014.10	
SCL	Hong Kong, China	6	A	5.00E-04	HM	2015.02	
			B	2.00E-04	HM	2019.09-10	
CMS/ITRI	Chinese Taipei	7	A	5.00E-04	HM	2015.06	
RCM-LIPI	Indonesia	8	A	2.00E-04	LM	2016.06	
VMI	Vietnam	9	A	1.00E-04	LM	2017.02	
NMIJ	Japan	10	B	2.00E-05	DWM	2020.11	Link

Table 1: Participating laboratories including the code number used in the report. DWM, Dead Weight Machine; BM, Build-up Machine; LM, Lever Machine; HM, Hydraulic Machine

3 Principles of the comparison

The APMP KC follows the protocol of its relevant CCM KC CCM.F-K3. The loading schemes are shown in Figure 1.

The force transducer was rotated through a total of 720° in both schemes. 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 at 60° in figure 1) were carried out at 60°, 120°, 180°, 240°, 300°, 360°/0°, 60°, 120°, 180°, 240°, 300°, and 360°. The total loading and reading period of six minutes was selected to minimize the influence of creep.

The comparison measurements were carried out using four transducers, two with nominal capacity 1 MN for Scheme A and two with nominal capacity 500 kN for Scheme B. The construction principles of the two transducers for each scheme are different in order to consider the different effects of the interaction between different types of force transducers and force standard machines. The transducers were selected for their stable characteristics.

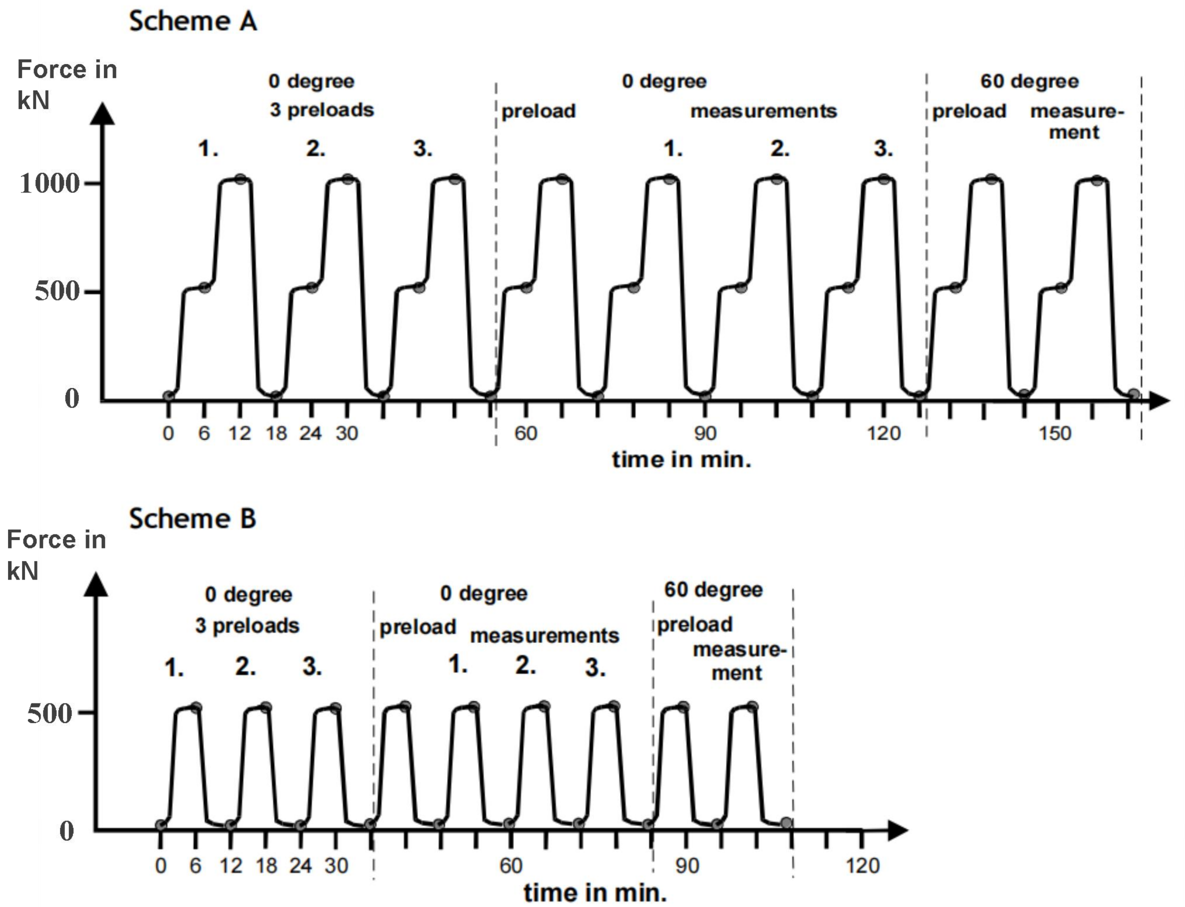


Figure 1: Loading Schemes

The transducers used are detailed in Table 2.

Identification Code	Manufacturer	Serial Number	Capacity	Scheme
Tr1	HBM	82807	1 MN	A
Tr2	GTM	65639	1 MN	A
Tr3	HBM	100930025	500 kN	B
Tr4	GTM	52842	500 kN	B

Table 2: Transducers used in the comparison

The reference ambient temperature of this KC was 20 °C, temperature fluctuation exceeding ±0.2 °C, which is the limit in the CCM KCs, could be accepted provided that the influence of temperature fluctuation on measurement results was properly taken into account.

4 Format of the comparison

The comparison was made in a star format; the transducers came back to the pilot after each participating laboratory's measurements. One complete measurement cycle (pilot – participating laboratory – pilot) is called a loop. The pilot's first measurement is denoted the A-measurement and its second, after the participating laboratory, is called the B-measurement. The change at the pilot (B-measurement − A-measurement) is called the drift for that particular loop. The reference value for each loop is taken as the mean of the two pilot measurements – this is called the loop value.

5 Stability of transducer sensitivity

Because the quality of the comparison is dependent upon the three measurements made during each loop, the stability of each transducer's sensitivity is critical. Figures 2 to 7 show the stability of the force transducers over the period of this KC, which is determined as the relative deviations of measurement results at the pilot with respect to an arithmetical mean value of them.

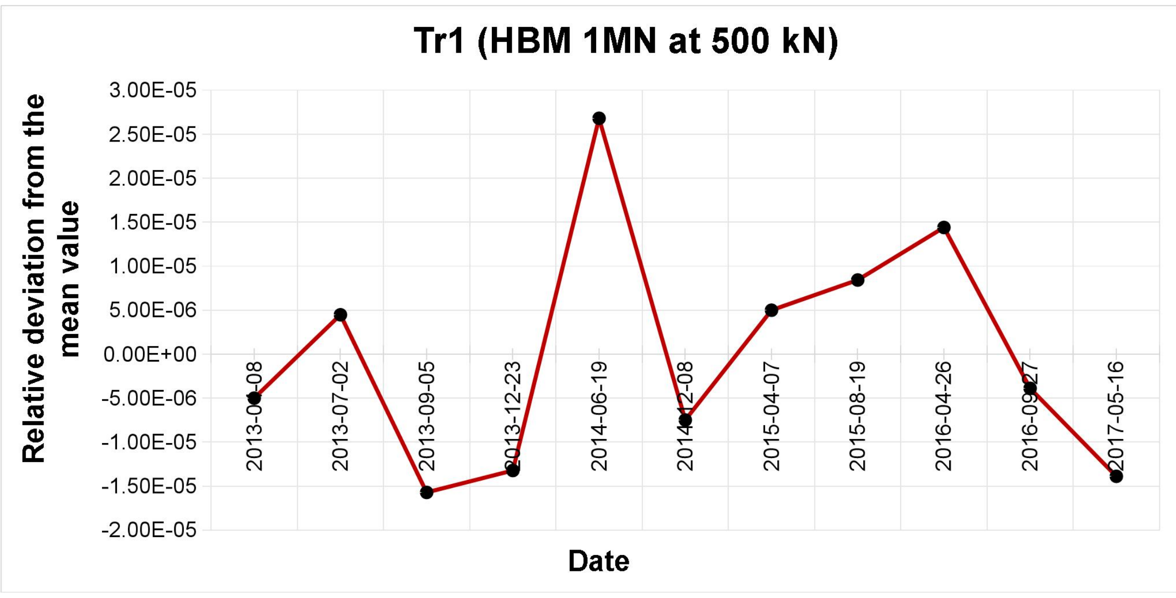


Figure 2: Stability of Tr1 at 500 kN throughout the comparison

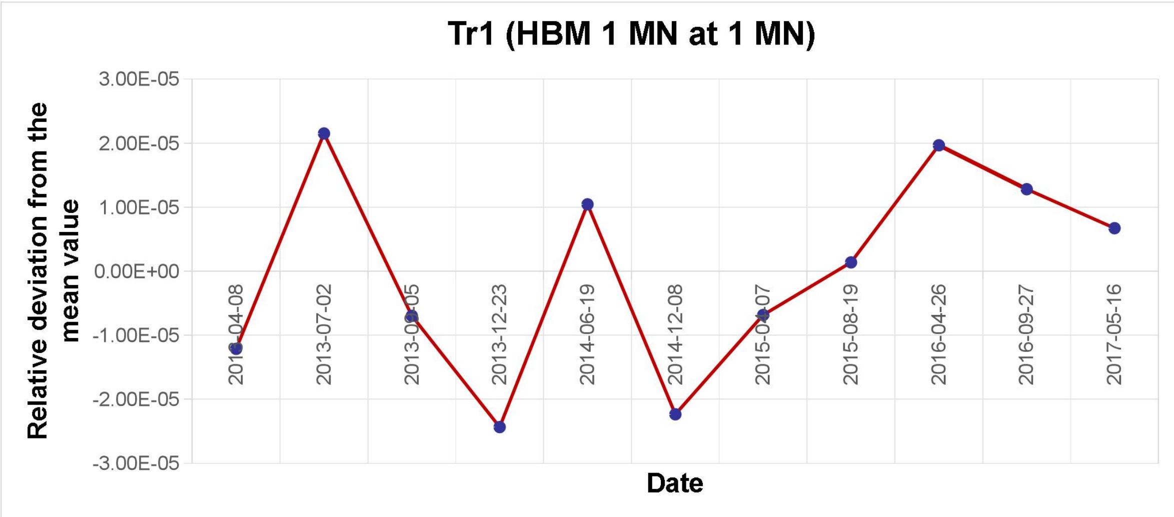


Figure 3: Stability of Tr1 at 1 MN throughout the comparison

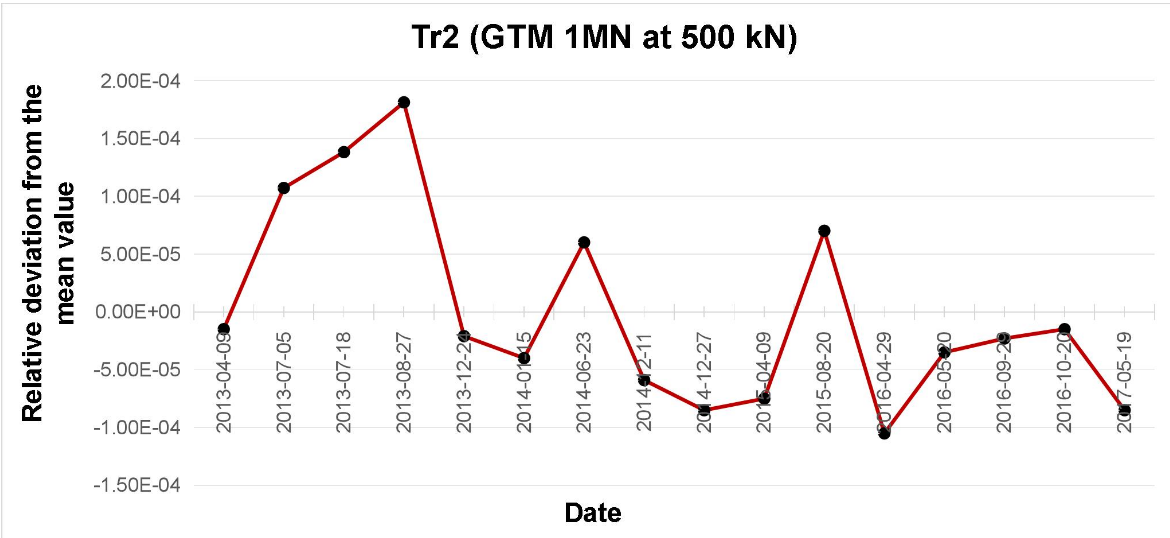


Figure 4: Stability of Tr2 at 500 kN throughout the comparison

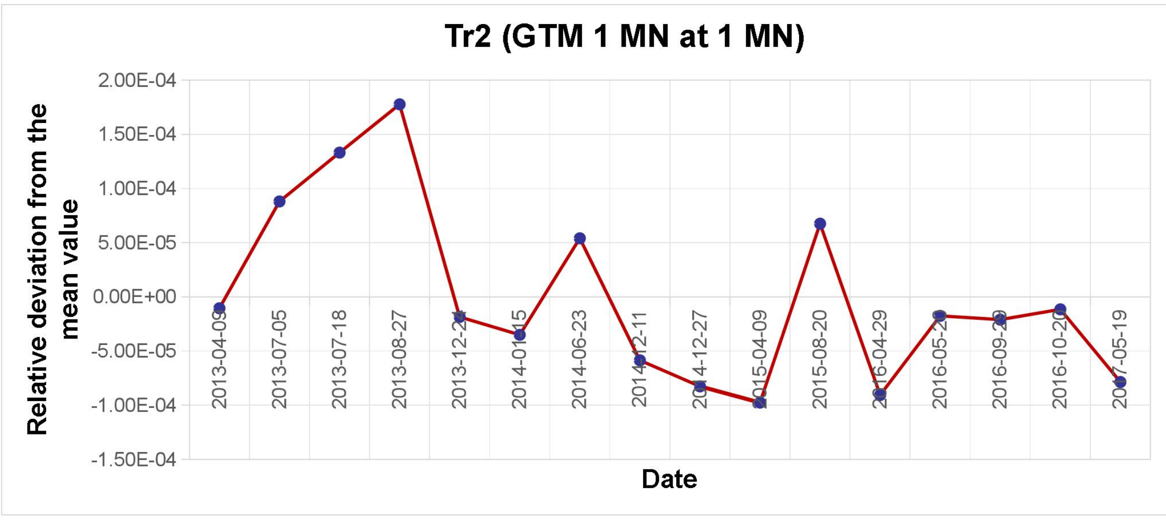


Figure 5: Stability of Tr2 at 1 MN throughout the comparison

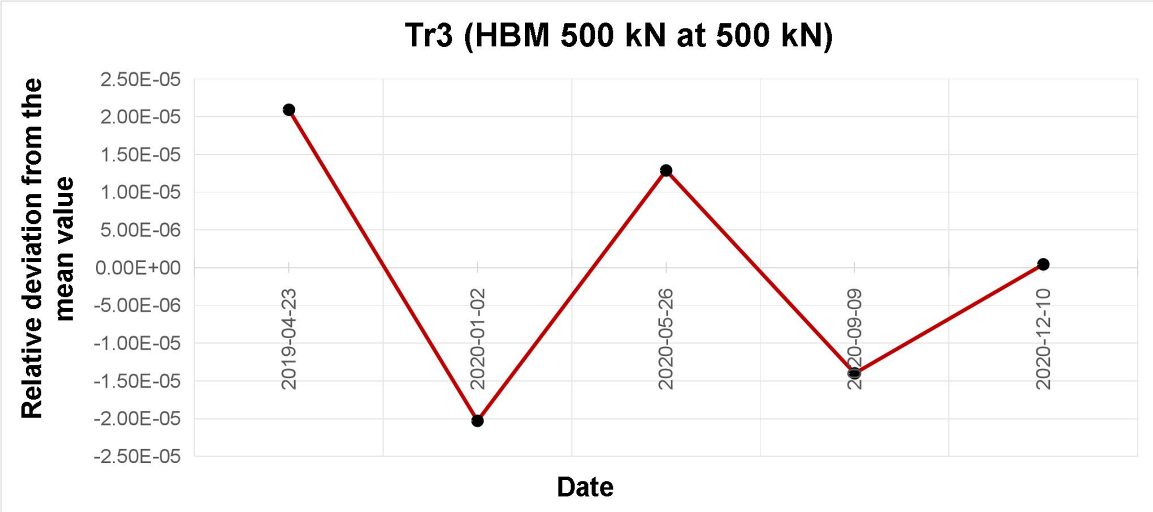


Figure 6: Stability of Tr3 at 500 kN throughout the comparison

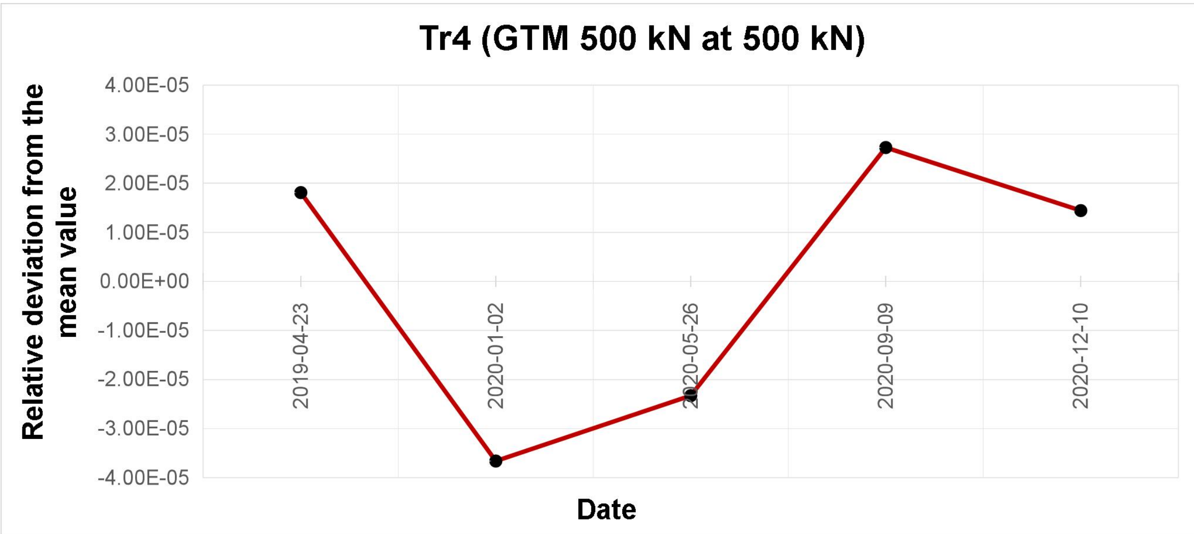


Figure 7: Stability of Tr4 at 500 kN throughout the comparison

6 Reported results and uncertainties

Tables 3 to 8 show the measurement results in chronological order which are reported deflection, corrected deflection, relative expanded uncertainty of corrected deflection, loop value, relative deviation from loop value in two force steps using 4 transducers, and relative expanded uncertainty of relative deviation. The reported deflection from the participating laboratories is corrected in three ways, that means correction for the use of different DMP40, correction for the different ambient temperature, and the correction for the unit of force generation.

In the estimation of the uncertainty of corrected deflection, uncertainty components due to force standard machine, repeatability, reproducibility, resolution of indicator, BN100 correction, temperature correction as well as the correction for the unit of force generation were taken into account. In the estimation of the uncertainty of relative deviation, the uncertainty components due to corrected deflection from participating laboratory, corrected deflection from pilot laboratory as well as sensitivity drift of force transducers were taken into account.

Code	Date	Deflection	Corrected deflection	Relative uncertainty of corrected deflection (k=2)	Loop value	Relative deviation	Relative uncertainty of relative deviation （k=2）
		mV/V	mV/V		mV/V		
Pilot	2013-04-08	1.001730	1.001726	2.16E-05			
2	2013-05-08	1.001721	1.001721	2.28E-05	1.001731	-9.30E-06	3.30E-05
Pilot	2013-07-02	1.001728	1.001735	2.55E-05			
Pilot	2013-09-05	1.001710	1.001715	2.20E-05			
3	2013-10-29	1.001961	1.001968	2.02E-04	1.001717	2.51E-04	2.03E-04
Pilot	2013-12-23	1.001715	1.001718	2.12E-05			
4	2014-05-08	1.001725	1.001717	2.06E-04	1.001738	-2.07E-05	2.08E-04
Pilot	2014-06-19	1.001751	1.001758	2.43E-05			
5	2014-10-08	1.001745	1.001751	9.75E-05	1.001741	1.06E-05	1.02E-04
Pilot	2014-12-08	1.001722	1.001724	2.15E-05			
6	2015-02-12- 2015-02-13	0.999834	0.999826	5.03E-04	1.001730	-1.90E-03	5.03E-04
Pilot	2015-04-07	1.001736	1.001736	2.20E-05			
7	2015-06-11	1.002189	1.002135	5.01E-04	1.001738	3.96E-04	5.01E-04
Pilot	2015-08-19	1.001728	1.001739	2.13E-05			
Pilot	2016-04-26	1.001743	1.001745	2.16E-05			
8	2016-06-21	1.001691	1.001698	2.01E-04	1.001736	-3.78E-05	2.02E-04
Pilot	2016-09-27	1.001713	1.001727	2.38E-05			
9	2017-02-03	1.001854	1.001854	1.04E-04	1.001722	1.32E-04	1.07E-04
Pilot	2017-05-16	1.001713	1.001717	2.44E-05			

Table 3: Chronological order of measurement for Tr1 (HBM 1MN) at 500 kN

Code	Date	Deflection	Corrected deflection	Relative uncertainty of corrected deflection (k=2)	Loop value	Relative deviation	Relative uncertainty of relative deviation （k=2）
		mV/V	mV/V		mV/V		
Pilot	2013-04-08	2.003350	2.003343	2.03E-05			
2	2013-05-08	2.003400	2.003399	2.26E-05	2.003377	1.13E-05	3.63E-05
Pilot	2013-07-02	2.003403	2.003410	2.12E-05			
Pilot	2013-09-05	2.003345	2.003353	2.05E-05			
3	2013-10-29	2.003940	2.003949	2.01E-04	2.003336	3.06E-04	2.03E-04
Pilot	2013-12-23	2.003319	2.003319	2.03E-05			
4	2014-05-08	2.003172	2.003170	2.02E-04	2.003353	-9.13E-05	2.04E-04
Pilot	2014-06-19	2.003380	2.003388	2.06E-05			
5	2014-10-08	2.003392	2.003403	9.73E-05	2.003355	2.37E-05	1.02E-04
Pilot	2014-12-08	2.003324	2.003323	2.03E-05			
6	2015-02-12- 2015-02-13	2.000777	2.000763	5.03E-04	2.003338	-1.29E-03	5.03E-04
Pilot	2015-04-07	2.003355	2.003354	2.08E-05			
7	2015-06-11	2.004090	2.004065	5.01E-04	2.003362	3.51E-04	5.01E-04
Pilot	2015-08-19	2.003350	2.003370	2.06E-05			
Pilot	2016-04-26	2.003405	2.003407	2.01E-05			
8	2016-06-21	2.003295	2.003315	2.01E-04	2.003400	-4.24E-05	2.02E-04
Pilot	2016-09-27	2.003370	2.003393	2.24E-05			
9	2017-02-03	2.003504	2.003516	1.06E-04	2.003387	6.43E-05	1.09E-04
Pilot	2017-05-16	2.003376	2.003381	2.17E-05			

Table 4: Chronological order of measurement for Tr1 (HBM 1MN) at 1 MN

Code	Date	Deflection	Corrected deflection	Relative uncertainty of corrected deflection (k=2)	Loop value	Relative deviation	Relative uncertainty of relative deviation （k=2）
		mV/V	mV/V		mV/V		
Pilot	2013-04-09	0.999270	0.999270	1.75E-05			
2	2013-05-13	0.999319	0.999319	2.26E-05	0.999331	-1.21E-05	7.66E-05
Pilot	2013-07-05	0.999385	0.999392	1.95E-05			
Pilot	2013-07-18	0.999413	0.999423	2.06E-05			
Pilot	2013-08-27	0.999459	0.999466	2.08E-05			
3	2013-10-31	0.999449	0.999457	2.01E-04	0.999365	8.43E-05	2.33E-04
Pilot	2013-12-24	0.999262	0.999264	1.77E-05			
Pilot	2014-01-15	0.999244	0.999245	1.79E-05			
4	2014-05-20	0.999228	0.999228	2.02E-04	0.999295	-6.69E-05	2.11E-04
Pilot	2014-06-23	0.999339	0.999345	1.96E-05			
5	2014-10-22	0.999302	0.999307	9.18E-05	0.999286	1.66E-05	1.16E-04
Pilot	2014-12-11	0.999227	0.999226	1.79E-05			
Pilot	2014-12-17	0.999198	0.999200	3.18E-05			
6	2015-02-17 2015-02-18	0.997310	0.997306	5.01E-04	0.999205	-1.90E-03	5.02E-04
Pilot	2015-04-09	0.999208	0.999210	2.97E-05			
7	2015-06-12	0.999755	0.999709	5.01E-04	0.999282	4.73E-04	5.08E-04
Pilot	2015-08-20	0.999346	0.999355	1.80E-05			
Pilot	2016-04-29	0.999190	0.999180	1.83E-05			
Pilot	2016-05-20	0.999259	0.999250	1.92E-05			
8	2016-06-28	0.999293	0.999299	2.02E-04	0.999256	3.71E-05	2.03E-04
Pilot	2016-09-29	0.999263	0.999262	3.33E-05			
Pilot	2016-10-20	0.999271	0.999270	1.94E-05			
9	2017-02-23	0.999326	0.999331	1.09E-04	0.999235	9.12E-05	1.18E-04
Pilot	2017-05-19	0.999202	0.999200	1.98E-05			

Table 5: Chronological order of measurement for Tr2 (GTM 1MN) at 500 kN

Code	Date	Deflection	Corrected deflection	Relative uncertainty of corrected deflection (*k*=2)	Loop value	Relative deviation	Relative uncertainty of relative deviation （*k*=2）
		mV/V	mV/V		mV/V		
Pilot	2013-04-09	1.998511	1.998508	1.71E-05			
2	2013-05-13	1.998578	1.998579	2.25E-05	1.998606	-1.44E-05	6.36E-05
Pilot	2013-07-05	1.998695	1.998705	1.84E-05			
Pilot	2013-07-18	1.998781	1.998795	1.81E-05			
Pilot	2013-08-27	1.998873	1.998884	2.05E-05			
3	2013-10-31	1.999005	1.999014	2.01E-04	1.998688	1.58E-04	2.31E-04
Pilot	2013-12-24	1.998494	1.998492	1.73E-05			
Pilot	2014-01-15	1.998463	1.998459	1.72E-05			
4	2014-05-20	1.998380	1.998376	2.02E-04	1.998548	-8.43E-05	2.09E-04
Pilot	2014-06-23	1.998631	1.998637	1.96E-05			
5	2014-10-22	1.998604	1.998615	9.09E-05	1.998524	3.97E-05	1.14E-04
Pilot	2014-12-11	1.998411	1.998412	1.77E-05			
Pilot	2014-12-17	1.998365	1.998364	2.83E-05			
6	2015-02-17 2015-02-18	1.996375	1.996371	5.03E-04	1.998349	-9.88E-04	5.03E-04
Pilot	2015-04-09	1.998371	1.998334	2.25E-05			
7	2015-06-12	1.999137	1.999095	5.01E-04	1.998499	3.19E-04	5.11E-04
Pilot	2015-08-20	1.998647	1.998664	1.78E-05			
Pilot	2016-04-29	1.998361	1.998348	1.81E-05			
Pilot	2016-05-20	1.998505	1.998494	1.78E-05			
8	2016-06-28	1.998476	1.998492	2.01E-04	1.998491	-7.74E-06	2.03E-04
Pilot	2016-09-29	1.998484	1.998487	3.51E-05			
Pilot	2016-10-20	1.998504	1.998506	1.91E-05			
9	2017-02-23	1.998470	1.998481	1.19E-04	1.998439	1.55E-05	1.26E-04
Pilot	2017-05-19	1.998371	1.998372	1.75E-05			

Table 6: Chronological order of measurement for Tr2 (GTM 1MN) at 1 MN

Code	Date	Deflection	Corrected deflection	Relative uncertainty of corrected deflection (*k*=2)	Loop value	Relative deviation	Relative uncertainty of relative deviation （*k*=2）
		mV/V	mV/V		mV/V		
Pilot	2019-04-23	1.998591	1.998588	1.94E-05			
6	2019-09-30	1.998966	1.998980	2.14E-04	1.998547	2.17E-04	2.16E-04
Pilot	2020-01-02	1.998505	1.998505	1.90E-05			
Pilot	2020-05-26	1.998568	1.998572	1.92E-05			
4	2020-07-02	1.998327	1.998335	2.01E-04	1.998545	-1.05E-04	2.03E-04
Pilot	2020-09-09	1.998499	1.998518	1.94E-05			
10	2020-11-10	1.998477	1.998484	2.28E-05	1.998532	-2.45E-05	3.10E-05
Pilot	2020-12-10	1.998547	1.998547	1.91E-05			

Table 7: Chronological order of measurement for Tr3 (HBM 500 kN) at 500 kN

Code	Date	Deflection	Corrected deflection	Relative uncertainty of corrected deflection (*k*=2)	Loop value	Relative deviation	Relative uncertainty of relative deviation （*k*=2）
		mV/V	mV/V		mV/V		
Pilot	2019-04-23	2.001626	2.001622	4.75E-05			
6	2019-10-04	2.001982	2.001984	2.25E-04	2.001567	2.08E-04	2.32E-04
Pilot	2020-01-03	2.001514	2.001512	5.11E-05			
Pilot	2020-05-27	2.001533	2.001539	5.14E-05			
4	2020-07-07	2.001370	2.001378	2.03E-04	2.001589	-1.06E-04	2.11E-04
Pilot	2020-09-10	2.001628	2.001640	4.84E-05			
10	2020-11-09	2.001451	2.001457	2.89E-05	2.001627	-8.47E-05	5.70E-05
Pilot	2020-12-11	2.001618	2.001614	4.88E-05			

Table 8: Chronological order of measurement for Tr4 (GTM 500 kN) at 500 kN

7 Relative deviation of participating laboratories from the pilot

For each of the force transducers, a measured result $X_{\mathrm{L}i}$ of the participant is an arithmetical mean of 12 values measured at orientations from 60 degree to 720 degree. Relative deviation $d_{\mathrm{L}i}$ of the measured result $X_{\mathrm{L}i}$ of the participant from that of the pilot $X_{\mathrm{Pm}i}$ is calculated by referring to the proceeding measurement result and the succeeding measurement result at the pilot for each loop. Uncertainty $u(d_{\mathrm{L}i})$ is evaluated with considering corrected deflection from participating laboratory, corrected deflection from pilot laboratory, as well as sensitivity drift of the force transducer.

$$d_{\mathrm{L}i} = \frac{X_{\mathrm{L}i} - X_{\mathrm{Pm}i}}{X_{\mathrm{Pm}i}} \tag{1}$$

$$u(d_{\mathrm{L}i}) = \sqrt{\left(\frac{u(X_{\mathrm{L}i})}{X_{\mathrm{Pm}i}}\right)^2 + \left(\frac{u(X_{\mathrm{Pm}i})}{X_{\mathrm{Pm}i}}\right)^2 + \left(\frac{u(X_{\mathrm{P}i})}{X_{\mathrm{Pm}i}}\right)^2} \tag{2}$$

where

$$X_{\mathrm{Pm}\,i} = \frac{X_{\mathrm{P\_a}} + X_{\mathrm{P\_b}}}{2} \tag{3}$$

$$u(X_{\mathrm{Pm}i}) = \sqrt{\frac{1}{4}\left\{u(X_{\mathrm{P\_a}})^2 + u(X_{\mathrm{P\_b}})^2 + 2r(X_{\mathrm{P\_a}}, X_{\mathrm{P\_b}})u(X_{\mathrm{P\_a}})u(X_{\mathrm{P\_b}})\right\}} \tag{4}$$

$$u(X_{\mathrm{P}i}) = \frac{\left|X_{\mathrm{P\_a}} - X_{\mathrm{P\_b}}\right|}{2\sqrt{3}} \tag{5}$$

The relative overall deviation of a laboratory from the pilot is estimated by taking a weighted mean of each relative deviations using the two force transducers. For participating laboratories in Scheme A, the weighted means of each relative deviations using Tr1 and Tr2 were estimated at 500 kN and 1 MN. For participating laboratories in Scheme B, the weighted means of each relative deviations using Tr3 and Tr4 were estimated at 500 kN. For the participating laboratories in Scheme A/B, the weighted means at 500 kN from Tr1-Tr2 set and Tr3-Tr4 set were merged again to deduce one value for a laboratory.

Relative overall deviation $d_{\mathrm{L}i}$ of a laboratory i from the pilot is calculated by taking a weighted mean of relative deviations using the two force transducers as follows. Its uncertainty $u(d_{\mathrm{L}i})$ is evaluated with considering correlation of the relative deviations of the two force transducers, because the two measurements were made on the same force standard machine in the participating lab and pilot lab.

$$d_{\mathrm{L}i} = \frac{d_{\mathrm{L}i,\mathrm{Tr1}} / u(d_{\mathrm{L}i,\mathrm{Tr1}})^2 + d_{\mathrm{L}i,\mathrm{Tr2}} / u(d_{\mathrm{L}i,\mathrm{Tr2}})^2}{1/u(d_{\mathrm{L}i,\mathrm{Tr1}})^2 + 1/u(d_{\mathrm{L}i,\mathrm{Tr2}})^2} \qquad (6)$$

$$u(d_{\mathrm{L}i}) = \frac{u(d_{\mathrm{L}i,\mathrm{Tr1}})u(d_{\mathrm{L}i,\mathrm{Tr2}})}{u(d_{\mathrm{L}i,\mathrm{Tr1}})^2 + u(d_{\mathrm{L}i,\mathrm{Tr2}})^2} \times \sqrt{u(d_{\mathrm{L}i,\mathrm{Tr1}})^2 + u(d_{\mathrm{L}i,\mathrm{Tr2}})^2 + 2r(d_{\mathrm{L}i,\mathrm{Tr1}}, d_{\mathrm{L}i,\mathrm{Tr2}})u(d_{\mathrm{L}i,\mathrm{Tr1}})u(d_{\mathrm{L}i,\mathrm{Tr2}})} \qquad (7)$$

where, $r(d_{\mathrm{L}i,\mathrm{Tr1}}, d_{\mathrm{L}i,\mathrm{Tr2}})$ is the correlation coefficient between the measurements of Tr1 and Tr2. The relative overall deviation from Tr3 and Tr4 is estimated as the same way.

Code	500 kN		1 MN	
	Relative deviation ($d_{\mathrm{L}i}$)	Relative expanded uncertainty $U(d_{\mathrm{L}i})$	Relative deviation ($d_{\mathrm{L}i}$)	Relative expanded uncertainty $U(d_{\mathrm{L}i})$
1	0	2.18E-05	0	2.02E-05
2	-9.74E-06	3.98E-05	4.95E-06	4.30E-05
3	1.79E-04	2.16E-04	2.42E-04	2.15E-04
4	-4.36E-05	2.09E-04	-8.79E-05	2.07E-04
5	1.32E-05	1.09E-04	3.08E-05	1.07E-04
6	-1.90E-03	5.03E-04	-1.14E-03	5.03E-04
7	4.34E-04	5.05E-04	3.35E-04	5.06E-04
8	-4.51E-07	2.03E-04	-2.51E-05	2.02E-04
9	1.13E-04	1.12E-04	4.36E-05	1.16E-04

Table 9: Weighted means of each relative deviation with Tr1 and Tr2 at 500 kN and at 1 MN in Scheme A

Code	500 kN	
	Relative deviation (d_{Li})	Relative expanded uncertainty $u(d_{Li})$
1	0	2.33E-05
4	-1.05E-04	2.07E-04
6	2.13E-04	2.24E-04
10	-3.82E-05	3.69E-05

Table 10: Weighted means of each relative deviations with Tr3 and Tr4 at 500 kN in Scheme B

Code	500 kN		1 MN	
	Relative deviation (d_{Li})	Relative expanded uncertainty $U(d_{Li})$	Relative deviation (d_{Li})	Relative expanded uncertainty $U(d_{Li})$
1	0	2.25E-05	0	2.02E-05
2	-9.74E-06	3.98E-05	5.25E-06	4.30E-05
3	1.79E-04	2.16E-04	2.42E-04	2.15E-04
4	-7.49E-05	2.08E-04	-8.79E-05	2.07E-04
5	1.32E-05	1.09E-04	3.08E-05	1.07E-04
6	-1.36E-04	2.70E-04	-1.14E-03	5.03E-04
7	4.34E-04	5.05E-04	3.35E-04	5.06E-04
8	-4.51E-07	2.03E-04	-2.51E-05	2.02E-04
9	1.13E-04	1.12E-04	4.36E-05	1.16E-04
10	-3.82E-05	3.69E-05		

Table 11: Relative overall deviation of participating laboratories from the pilot

8. Degree of equivalence to the KCRV

Mean value at 500 kN, $d_{\mathrm{Link,500kN}}$ of the relative deviations of the link laboratories 1, 2, and 10 from the pilot and its uncertainty $u(d_{\mathrm{Link,500kN}})$ are calculated as follows by taking a weighted mean.

$$d_{\mathrm{Link,500kN}} = \frac{d_{\mathrm{Link1,500kN}} / u(d_{\mathrm{Link1,500kN}})^2 + d_{\mathrm{Link2,500kN}} / u(d_{\mathrm{Link2,500kN}})^2 + d_{\mathrm{Link10,500kN}} / u(d_{\mathrm{Link10,500kN}})^2}{1/u(d_{\mathrm{Link1,500kN}})^2 + 1/u(d_{\mathrm{Link2,500kN}})^2 + 1/u(d_{\mathrm{Link10,500kN}})^2} \tag{8}$$

$$u(d_{\mathrm{Link,500kN}}) = \sqrt{\frac{1}{1/u(d_{\mathrm{Link1,500kN}})^2 + 1/u(d_{\mathrm{Link2,500kN}})^2 + 1/u(d_{\mathrm{Link10,500kN}})^2}} \tag{9}$$

Mean value at 1 MN, $d_{\mathrm{Link,1MN}}$ of the relative deviations of the link laboratories 1, and 2 from the pilot and its uncertainty $u(d_{\mathrm{Link,1MN}})$ are calculated as follows by taking a weighted mean.

$$d_{\mathrm{Link,1MN}} = \frac{d_{\mathrm{Link1,1MN}} / u(d_{\mathrm{Link1,1MN}})^2 + d_{\mathrm{Link2,1MN}} / u(d_{\mathrm{Link2,1MN}})^2}{1/u(d_{\mathrm{Link1,1MN}})^2 + 1/u(d_{\mathrm{Link2,1MN}})^2} \tag{10}$$

$$u(d_{\mathrm{Link,1MN}}) = \sqrt{\frac{1}{1/u(d_{\mathrm{Link1,1MN}})^2 + 1/u(d_{\mathrm{Link2,1MN}})^2}} \tag{11}$$

Weighted means of the deviations of link laboratories and their relative expanded uncertainties are shown in Table 12.

500 kN		1 MN	
Relative deviations $d_{\mathrm{Link,500kN}}$	Relative expanded uncertainty $U(d_{\mathrm{Link,500kN}})$	Relative deviations $d_{\mathrm{Link,1MN}}$	Relative expanded uncertainty $U(d_{\mathrm{Link,1MN}})$
-1.02E-05	1.73E-05	8.91E-07	1.83E-05

Table 12: Overall relative deviations of link laboratories and associate relative expanded uncertainties

The relative deviations $d_{\mathrm{Link}i\text{-KCRV}}$ of the three link laboratories from the key comparison reference value (KCRV) and their expanded uncertainties $U(d_{\mathrm{Link}i\text{-KCRV}})$ are shown in Table 13[1]. The weighted mean of the deviations $d_{\mathrm{Link\text{-}KCRV}}$ and their relevant uncertainties $U(d_{\mathrm{Link\text{-}KCRV}})$ are listed in Table 14.

Link Laboratory	500 kN		1 MN	
	Relative Deviation $d_{\mathrm{Link}i\text{-KCRV}}$	Relative expanded uncertainty $U(d_{\mathrm{Link}i\text{-KCRV}})$	Relative Deviation $d_{\mathrm{Link}i\text{-KCRV}}$	Relative expanded uncertainty $U(d_{\mathrm{Link}i\text{-KCRV}})$
1	7.80E-06	1.40E-05	1.03E-05	1.61E-05
2	1.50E-06	2.02E-05	4.20E-06	2.22E-05
10	-4.40E-06	1.25E-05		

Table 13: Overall relative deviations of link laboratories and associate relative expanded uncertainties

500 kN		1 MN	
Relative deviations $d_{\text{Link-KCRV}}$	Relative expanded uncertainty $U(d_{\text{Link-KCRV}})$	Relative deviations $d_{\text{Link-KCRV}}$	Relative expanded uncertainty $U(d_{\text{Link-KCRV}})$
1.10E-06	8.47E-06	8.20E-06	1.31E-05

Table 14: The weighted mean of the deviations $d_{\text{Link-KCRV}}$ and their relevant uncertainties $U(d_{\text{Link-KCRV}})$

For each participating institutes, the relative deviation to the KCRV, $d_{\text{L}i\text{-KCRV}}$ and its expanded uncertainty $U(d_{\text{L}i\text{-KCRV}})$ (k=2) are calculated as follows.

$$d_{\text{L}i\text{-KCRV}} = d_{\text{L}i} - (d_{\text{Link}} - d_{\text{Link-KCRV}}) \tag{12}$$

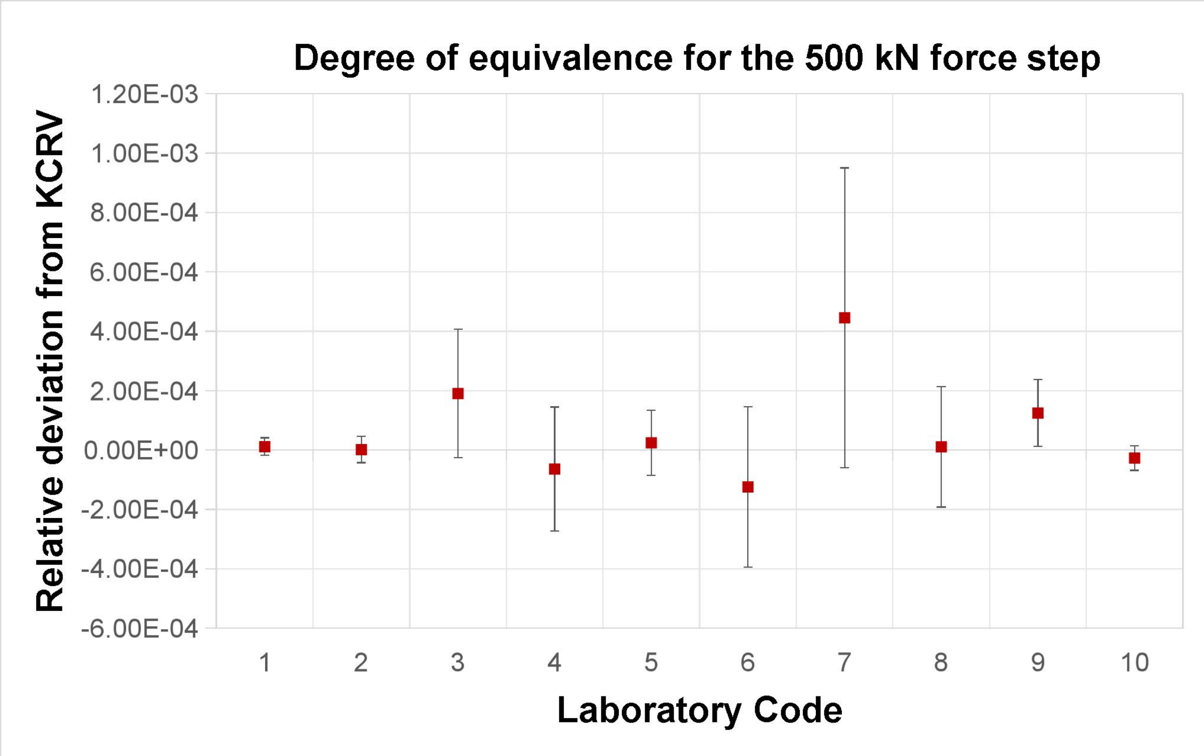
$$u(d_{\text{L}i\text{-KCRV}}) = \text{k} \cdot \sqrt{u(d_{\text{L}i})^2 + u(d_{\text{Link}})^2 + u(d_{\text{Link-KCRV}})^2} \tag{13}$$

The relative deviations of participating laboratories to the KCRV and their expanded uncertainties are listed in Table 15.

Code	500 kN		1 MN	
	Relative deviation $d_{\text{L}i\text{-KCRV}}$	Relative expanded uncertainty $U(d_{\text{L}i\text{-KCRV}})$	Relative deviation $d_{\text{L}i\text{-KCRV}}$	Relative expanded uncertainty $U(d_{\text{L}i\text{-KCRV}})$
1	1.13E-05	2.96E-05	7.31E-06	3.02E-05
2	1.56E-06	4.42E-05	1.23E-05	4.85E-05
3	1.90E-04	2.17E-04	2.49E-04	2.16E-04
4	-6.36E-05	2.09E-04	-8.06E-05	2.08E-04
5	2.45E-05	1.10E-04	3.81E-05	1.09E-04
6	-1.24E-04	2.70E-04	-1.13E-03	5.04E-04
7	4.45E-04	5.05E-04	3.43E-04	5.06E-04
8	1.09E-05	2.04E-04	-1.78E-05	2.03E-04
9	1.25E-04	1.13E-04	5.09E-05	1.18E-04
10	-2.69E-05	4.16E-05		

Table 15: Degrees of equivalence of individual laboratories

For each participating laboratories, the degree of equivalence to the KCRV at 500 kN and 1MN is respectively shown in Figures 8 and 9, in the graph, the error bar indicates associate relative expanded uncertainty.



Figures 8: Degrees of equivalence and expanded uncertainties (*k*=2) at 500 kN

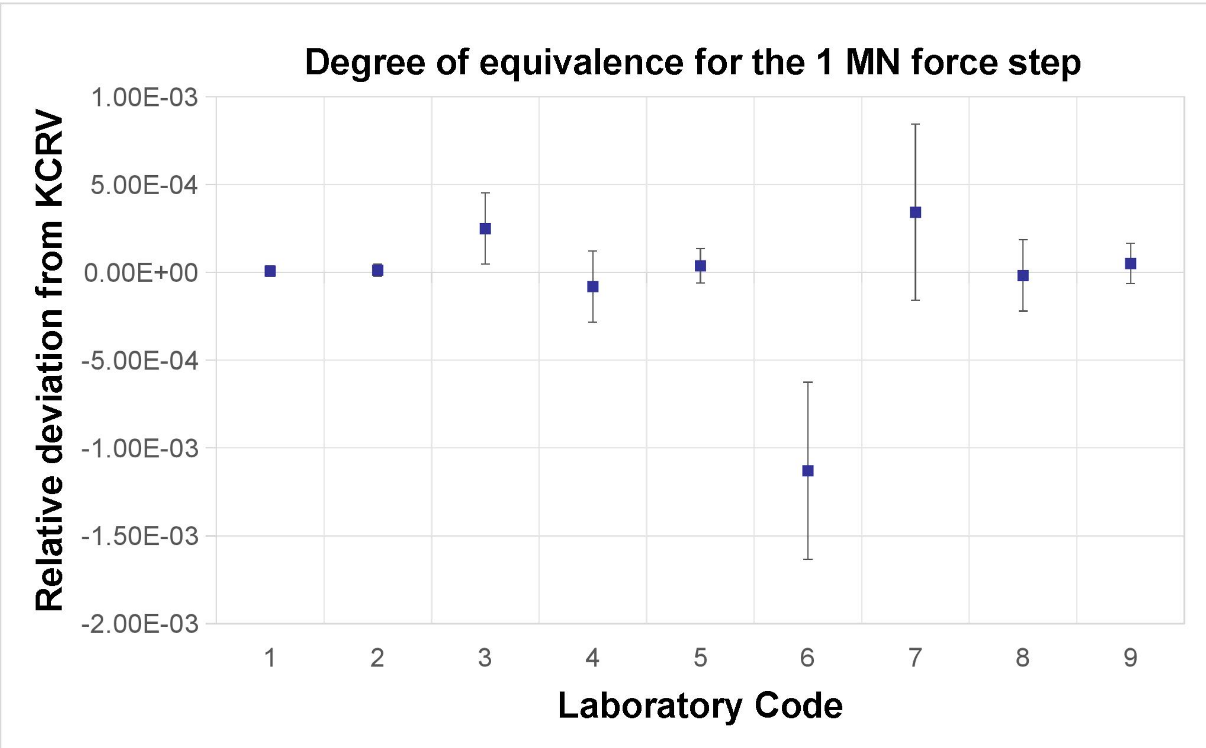


Figure 9: Degrees of equivalence and expanded uncertainties (*k*=2) at 1 MN

9. Summary

The APMP.M.F-K3 key comparison in the 500 kN and 1 MN force range revealed that all results of the 10 participants are equivalent to the KCRV within their uncertainties except laboratory 9 at 500 kN, and laboratory 3, 6 at 1 MN.

References

[1] R. Kumme et al., “Final report on the force key comparison CCM.F-K3”, Metrologia, Tech. Suppl., Vol. 56, pp. 07001, 2019.

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[3] K.Ueda et al., Final report on APMP.M.F-K4.b key Comparison for 2 MN force,” Metrologia Tech. Suppl., Vol. 49, pp. 07008, 2012.

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