Force Key Comparison CCM.F-K2.a.2

(5 kN to 200 kN)

Final Report

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Contents

1 Foreword

This report describes CIPM Key Comparison CCM.F-K2.a.2, for force values of 5 kN, 10 kN, 20 kN, 50 kN, 100 kN, and 200 kN.

2 Background to the comparison

The CCM Force Working Group met in October 1998 in Sydney and made decisions about CIPM Key Comparisons for the unit of force. These were to cover four force ranges, with four different pilot laboratories:

i)	5 kN – 10 kN	Pilot: MIKES-Raute, Finland
ii)	50 kN – 100 kN	Pilot: NPL, United Kingdom
iii)	500 kN – 1 MN	Pilot: PTB, Germany
iv)	2 MN – 4 MN	Pilot: NIST, USA

Key Comparison ii), piloted by NPL, was officially designated CCM.F-K2.a (Scheme A, two force values of 50 kN and 100 kN) and CCM.F-K2.b (Scheme B, one force value of 50 kN) by BIPM. CCM.F-K2.a.2 is a subsequent bilateral key comparison conducted to tie PTB's new 200 kN deadweight machine into the results of CCM.F-K2.a and, as such, it was also piloted by NPL using similar protocols.

NPL's CMCs are 10 ppm in the range from 0.025 kN to 1 200 kN. PTB's CMCs are 20 ppm in the range from 0.000 5 kN to 2 000 kN. PTB claims a CMC of 10 ppm for the 200 kN deadweight force standard machine in the range from 5 kN to 200 kN.

All CMCs are given as relative expanded uncertainties with a 95 % level of confidence.

3 Participants in the comparison

The two participants in the comparison were NPL (United Kingdom), who acted as the pilot, and PTB (Germany). The work at NPL was performed in January 2019 and the work at PTB in December 2018 and February 2019.

4 Principles of the comparison

The purpose of Key Comparisons is to compare the units of measurement as realised throughout the world. In the area of force, the way this is done is by the use of high quality force transducers subjected to similar loading profiles in national force standard machines, following a strict measurement protocol and using similar instrumentation.

The two-force (Scheme A) loading scheme shown in Figure 1 was proposed by the CCM Force Working Group and used in CCM.F-K2.a, with a slightly-modified version (rotating by 90° rather than 60° between measurements, to reduce the overall duration) used in CCM.F-K2.a.2.

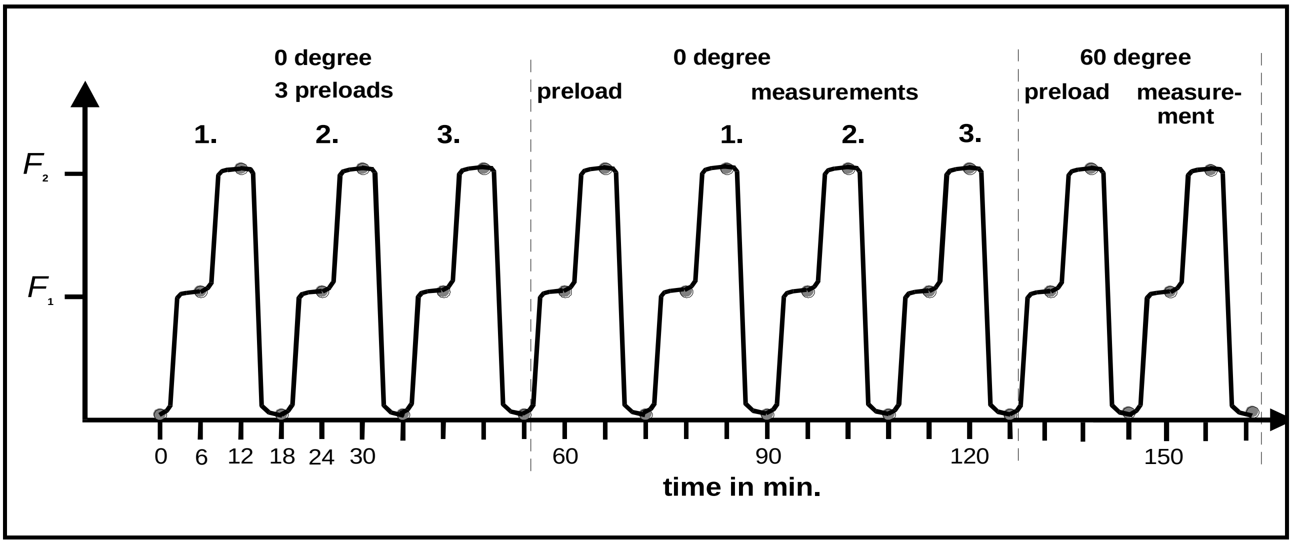

Figure 1: 100 kN loading scheme with F_1 = 50 kN and F_2 = 100 kN

After initial preloads and measurements at 0°, the force transducer is rotated through a total of 720°. One preload and one measurement (as at 60° in Figure 1) is carried out at 90°, 180°, 270°, 360°/0°, 90°, 180°, 270°, and 360°, resulting in eight evenly-distributed deflection values. The relatively-long reading period of six minutes was selected to minimise the influence of creep.

The comparison was carried out using five transducers of various capacities as detailed in Table 1. The temperature sensitivities of each were determined by PTB. Temperature corrections were only made for TrB and TrD as corrections for the other three, due to the combination of the temperature coefficient and the similarities in temperature in the two laboratories, would all have been less than 1 ppm.

Table 1: Transducers used in the comparison

ID Code	Manufacturer / Type	Serial Number	Capacity / kN	Temperature Sensitivity	
				Coefficient / (ppm·K^{-1})	Expanded Uncertainty / (ppm·K^{-1})
TrA	HBM / TOPZ30a	051630022	10	-2.3	0.9
TrB	GTM / KTN-D	40278	20	-14.7	2.5
TrC	GTM / KTN-D	30835	50	-5.2	0.4
TrD	GTM / KTN-D	66296	100	22.0	7.1
TrE	GTM / KTN-D	63123	200	0.2	4.4

Each transducer was used at 50 % and 100 % of its capacity in the two laboratories, except for the 50 kN one which was used at 20 kN and 50 kN. All five transducers were calibrated in PTB's 200 kN deadweight machine. At NPL, the 200 kN transducer was calibrated in the 1.2 MN deadweight machine – the other four were calibrated in the 120 kN deadweight machine (the machine used in CCM.F-K2.a). The selection of transducers and force values meant that forces of 10 kN, 20 kN, 50 kN, and 100 kN were each compared using two different transducers, whereas forces of 5 kN and 200 kN were compared each using a single transducer.

5 Format of the comparison

The comparison was made in an ABA format; the transducers were first calibrated at PTB, then at NPL, then finally back at PTB.

6 Instrumentation used in the comparison

All measurements were made with the force transducer connected to the same high-precision DMP41 AC ratio bridge, serial number 819192502, supplied by HBM. A bridge energisation voltage of 5 V, a measuring range of 2.5 mV·V^{-1}, a resolution of 0.000 001 mV·V^{-1}, and a Bessel filter of 0.1 Hz were selected.

An HBM BN100A bridge calibration unit was used to check for any drift in the DMP41 output before and after each set of measurements at a number of voltage ratio settings representative of those seen during the calibration. No significant drift or difference in DMP41 output was seen throughout the whole period of the work at PTB and NPL – this stability of DMP41 performance meant that no corrections needed to be made to its calculated deflections. Although no corrections were made, an instrumentation stability (estimated to be equal to ±3 ppm) uncertainty contribution was incorporated within the uncertainty budget for each calculated deflection.

7 Results obtained at PTB

Because the quality of the comparison is dependent upon the three measurements made (two at PTB and one at NPL), the stability of each transducer's sensitivity is critical. Table 2 to Table 6 detail the results and transducer drift obtained at PTB.

For each mean deflection, the standard uncertainty is calculated as the square root of summed squared standard uncertainty components relating to reproducibility (the standard deviation of the mean deflection), applied force (5 ppm), indicator resolution, and indicator stability.

For all but TrE, the PTB overall mean is simply the weighted mean of the two PTB mean deflections, with an uncertainty calculated from those of the two mean deflections, treating the correlated (applied force uncertainty) and uncorrelated components separately. For TrE, due to its significantly larger drift, the mean value is calculated as the value associated with a linear drift at the time that the measurements were made at NPL (on 22 Jan 2019). A uniform (rectangular) distribution for the range determined by the two results obtained at PTB was assumed and a corresponding contribution calculated and incorporated within the PTB TrE uncertainty budget, the only transducer for which a drift uncertainty component was considered necessary.

Table 2: Results obtained from TrA at PTB

		***F* = 5 kN**	***F* = 10 kN**
6 Dec 2018	Mean deflection / (mV·V^{-1})	1.000 193	2.000 467
	Standard uncertainty / (mV·V^{-1})	0.000 005	0.000 011
	Temperature / °C	20.43	
4 Feb 2019	Mean deflection / (mV·V^{-1})	1.000 180	2.000 456
	Standard uncertainty / (mV·V^{-1})	0.000 005	0.000 011
	Temperature / °C	20.44	
Overall mean / (mV·V^{-1})		1.000 187	2.000 462
Standard uncertainty of overall mean / (mV·V^{-1})		0.000 005	0.000 010
Drift / (mV·V^{-1})		-0.000 012	-0.000 012
Drift / ppm		-12.2	-5.7

Table 3: Results obtained from TrB at PTB

		***F* = 10 kN**	***F* = 20 kN**
10 Dec 2018	Mean deflection / (mV·V^{-1})	1.002 302	2.005 004
	Standard uncertainty / (mV·V^{-1})	0.000 005	0.000 011
	Temperature / °C	20.51	
15 Feb 2019	Mean deflection / (mV·V^{-1})	1.002 316	2.005 028
	Standard uncertainty / (mV·V^{-1})	0.000 006	0.000 011
	Temperature / °C	20.49	
Overall mean / (mV·V^{-1})		1.002 309	2.005 016
Standard uncertainty of overall mean / (mV·V^{-1})		0.000 005	0.000 010
Drift / (mV·V^{-1})		0.000 015	0.000 024
Drift / ppm		14.5	11.8

Table 4: Results obtained from TrC at PTB

		F = 20 kN	F = 50 kN
12 Dec 2018	Mean deflection / (mV·V^{-1})	0.800 995	2.003 038
	Standard uncertainty / (mV·V^{-1})	0.000 004	0.000 011
	Temperature / °C	20.53	
6 Feb 2019	Mean deflection / (mV·V^{-1})	0.800 997	2.003 046
	Standard uncertainty / (mV·V^{-1})	0.000 004	0.000 011
	Temperature / °C	20.49	
Overall mean / (mV·V^{-1})		0.800 996	2.003 042
Standard uncertainty of overall mean / (mV·V^{-1})		0.000 004	0.000 010
Drift / (mV·V^{-1})		0.000 002	0.000 008
Drift / ppm		2.5	3.9

Table 5: Results obtained from TrD at PTB

		F = 50 kN	F = 100 kN
11 Dec 2018	Mean deflection / (mV·V^{-1})	1.000 734	2.001 283
	Standard uncertainty / (mV·V^{-1})	0.000 007	0.000 013
	Temperature / °C	20.50	
28 Feb 2019	Mean deflection / (mV·V^{-1})	1.000 738	2.001 288
	Standard uncertainty / (mV·V^{-1})	0.000 006	0.000 013
	Temperature / °C	20.51	
Overall mean / (mV·V^{-1})		1.000 736	2.001 286
Standard uncertainty of overall mean / (mV·V^{-1})		0.000 006	0.000 012
Drift / (mV·V^{-1})		0.000 004	0.000 005
Drift / ppm		4.0	2.4

Table 6: Results obtained from TrE at PTB

		F = 100 kN	F = 200 kN
5 Dec 2018	Mean deflection / (mV·V^{-1})	1.001 165	2.002 248
	Standard uncertainty / (mV·V^{-1})	0.000 006	0.000 011
	Temperature / °C	20.41	
11 Feb 2019	Mean deflection / (mV·V^{-1})	1.001 206	2.002 326
	Standard uncertainty / (mV·V^{-1})	0.000 006	0.000 012
	Temperature / °C	20.48	
Overall mean / (mV·V^{-1})		1.001 194	2.002 303
Standard uncertainty of overall mean / (mV·V^{-1})		0.000 006	0.000 011
Drift / (mV·V^{-1})		0.000 042	0.000 078
Drift / ppm		41.8	38.8

8 Results obtained at NPL

Table 7 to Table 11 detail the results obtained at NPL and give the difference from PTB's overall mean value in both absolute and relative terms. The standard uncertainty associated with each mean deflection is again calculated as the square root of summed squared standard uncertainty components relating to reproducibility (the standard deviation of the mean deflection), applied force (5 ppm), indicator resolution, and indicator stability. Where a temperature correction has been made (for TrB and TrD), an additional contribution relating to the magnitude of the correction is incorporated within the uncertainty calculation.

Table 7: Results obtained from TrA at NPL (on 15 Jan 2019)

	***F* = 5 kN**	***F* = 10 kN**
Mean deflection /(mV·V^{-1})	1.000 196	2.000 480
Standard uncertainty / (mV·V^{-1})	0.000 005	0.000 011
Temperature / °C	20.81	
Difference from PTB deflection / (mV·V^{-1})	0.000 009	0.000 018
Difference from PTB deflection / ppm	9.2	9.2

Table 8: Results obtained from TrB at NPL (on 16 Jan 2019)

	***F* = 10 kN**	***F* = 20 kN**
Mean deflection / (mV·V^{-1})	1.002 317	2.005 005
Temperature / °C	21.03	
Temperature-corrected deflection / (mV·V^{-1})	1.002 325	2.005 021
Standard uncertainty / (mV·V^{-1})	0.000 007	0.000 014
Difference from PTB deflection / (mV·V^{-1})	0.000 016	0.000 005
Difference from PTB deflection / ppm	15.6	2.6

Table 9: Results obtained from TrC at NPL (on 17 Jan 2019)

	***F* = 20 kN**	***F* = 50 kN**
Mean deflection / (mV·V^{-1})	0.800 997	2.003 037
Standard uncertainty / (mV·V^{-1})	0.000 005	0.000 013
Temperature / °C	20.48	
Difference from PTB deflection / (mV·V^{-1})	0.000 001	-0.000 005
Difference from PTB deflection / ppm	1.1	-2.3

Table 10: Results obtained from TrD at NPL (on 18 Jan 2019)

	***F* = 50 kN**	***F* = 100 kN**
Mean deflection / (mV·V^{-1})	1.000 742	2.001 297
Temperature / °C	20.66	
Temperature-corrected deflection / (mV·V^{-1})	1.000 739	2.001 290
Standard uncertainty / (mV·V^{-1})	0.000 007	0.000 016
Difference from PTB deflection / (mV·V^{-1})	0.000 003	0.000 004
Difference from PTB deflection / ppm	2.6	2.2

Table 11: Results obtained from TrE at NPL (on 22 Jan 2019)

	***F* = 100 kN**	***F* = 200 kN**
Mean deflection / (mV·V^{-1})	1.001 203	2.002 326
Standard uncertainty / (mV·V^{-1})	0.000 006	0.000 012
Temperature / °C	19.86	
Difference from PTB deflection / (mV·V^{-1})	0.000 009	0.000 024
Difference from PTB deflection / ppm	9.2	11.8

9 Analysis of results

In order to combine measurements at the same force made by different transducers, the following approach was used:

- For the first transducer, calculate the force required to generate the mean deflection recorded at PTB, assuming that the mean deflection obtained at NPL would result from the application of the specified force and that the relationship between force and deflection is purely linear
- Estimate an uncertainty associated with this force value from the uncertainty of the mean PTB deflection and the sensitivity of the transducer
- Repeat the previous two steps for the second transducer
- Calculate the weighted mean PTB force value equivalent to a correct NPL force value, together with an associated weighted uncertainty, again calculated treating its correlated and uncorrelated components separately
- Estimate a weighted uncertainty for the NPL force value from the uncertainties of the two weighted mean deflections and the transducer sensitivities, again treating the correlated and uncorrelated components separately
- Calculate the arithmetic mean force value and plot deviations from this value, with associated uncertainty bars, for the results obtained at the two laboratories (note that a weighted mean force value could also be used but, as the aim of the exercise is simply to determine the differences between the two laboratories, the absolute position of the intersection of the x-axis with the y-axis is insignificant)

This process was followed for forces of 10 kN, 20 kN, 50 kN, and 100 kN. At forces of 5 kN and 200 kN, for each of which only one transducer was used, the same approach was followed but no weighted values needed to be calculated. Results are shown in Figure 2 to Figure 7.

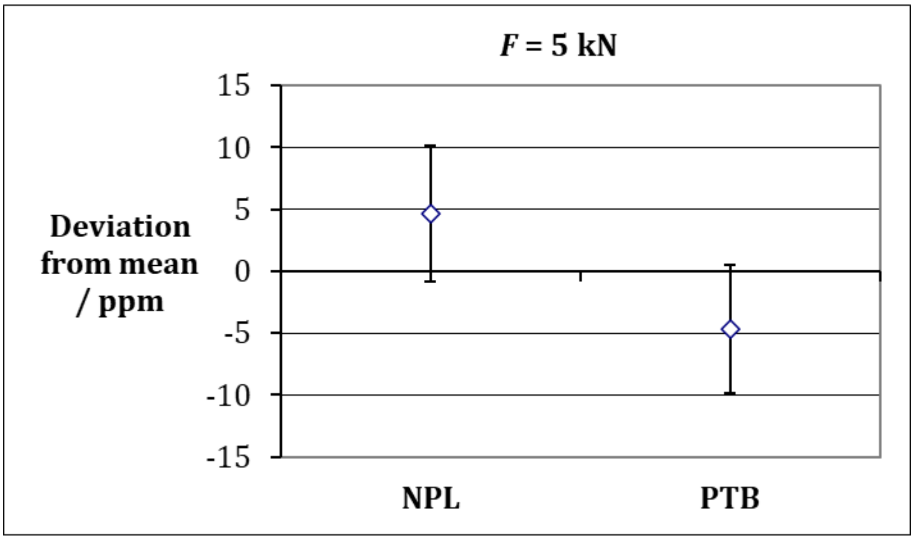

Figure 2: Agreement between NPL and PTB at 5 kN, using TrA (standard uncertainty error bars)

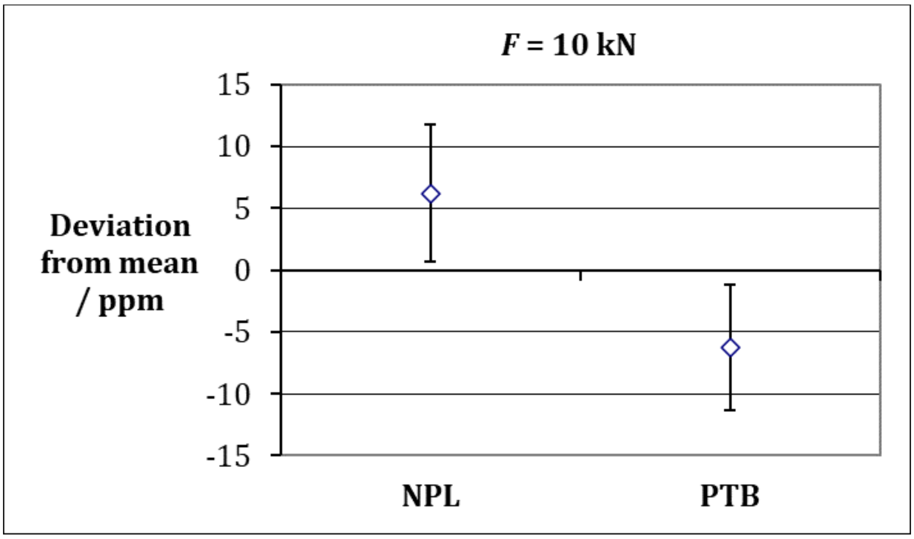

Figure 3: Agreement between NPL and PTB at 10 kN, using TrA and TrB (standard uncertainty error bars)

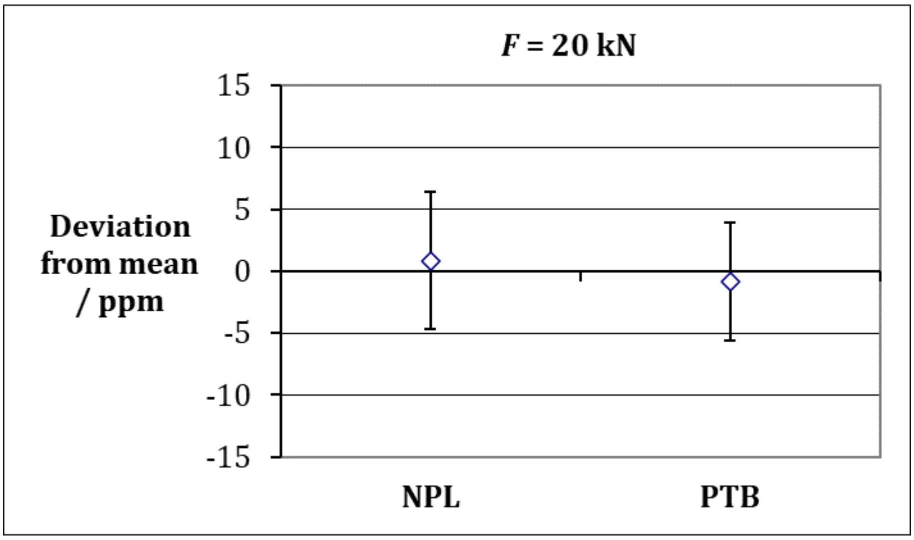

Figure 4: Agreement between NPL and PTB at 20 kN, using TrB and TrC (standard uncertainty error bars)

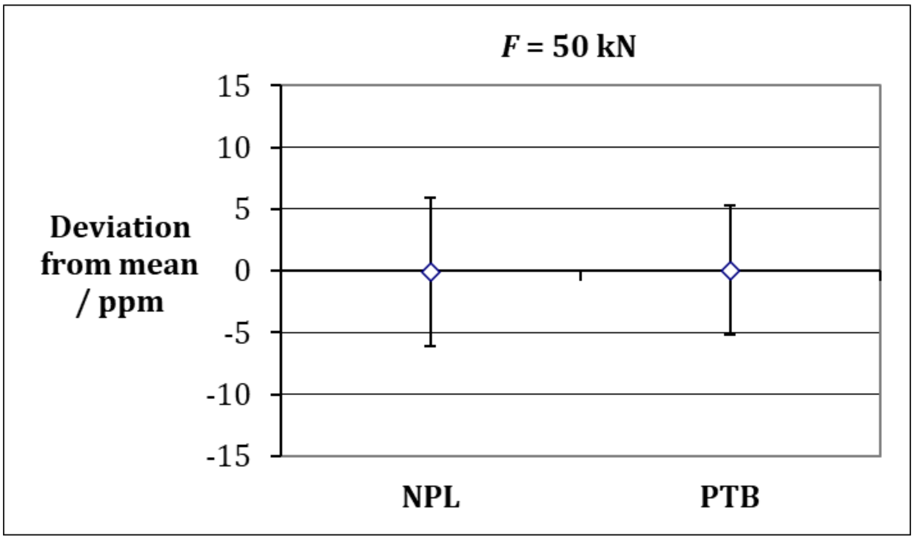

Figure 5: Agreement between NPL and PTB at 50 kN, using TrC and TrD (standard uncertainty error bars)

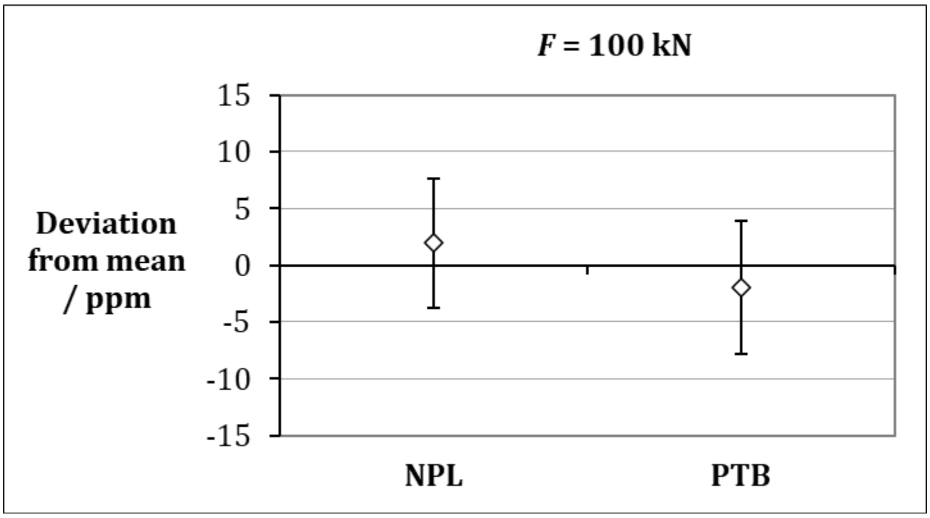

Figure 6: Agreement between NPL and PTB at 100 kN, using TrD and TrE (standard uncertainty error bars)

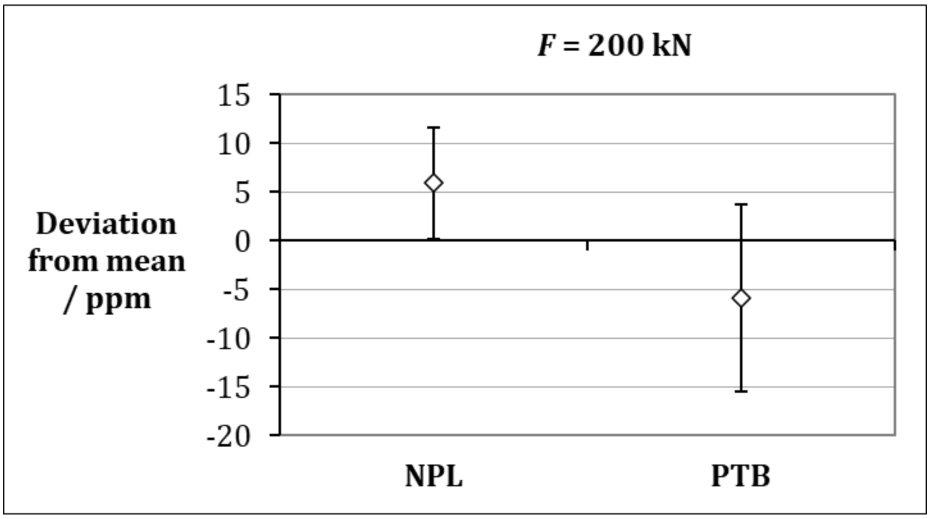

Figure 7: Agreement between NPL and PTB at 200 kN, using TrE (standard uncertainty error bars)

Appendix A – Key Comparison Reference Values

CIPM Key Comparison CCM.F-K2.a (50 kN and 100 kN force levels) was piloted by NPL using the 120 kN deadweight force standard machine used in this exercise to calibrate transducers TrA, TrB, TrC, and TrD. The 200 kN transducer TrE was calibrated in NPL's 1.2 MN deadweight machine and so its results cannot contribute to a link between PTB and the Key Comparison Reference Values (KCRVs) from CCM.F-K2.a, as there will be an unknown systematic deviation between the 100 kN force levels generated by the 120 kN and 1.2 MN machines.

Two transducers (TrC and TrD) were subjected to nominal forces of 50 kN in the 120 kN machine and one (TrD) to a nominal force of 100 kN – the link to CCM.F-K2.a needs to be based on these three sets of results. At 50 kN, the results shown in Figure 5 can be used. For a force of 100 kN, only the results from TrD can be used – these have been analysed as for the 200 kN force applied to TrE, with the results given in Figure 8.

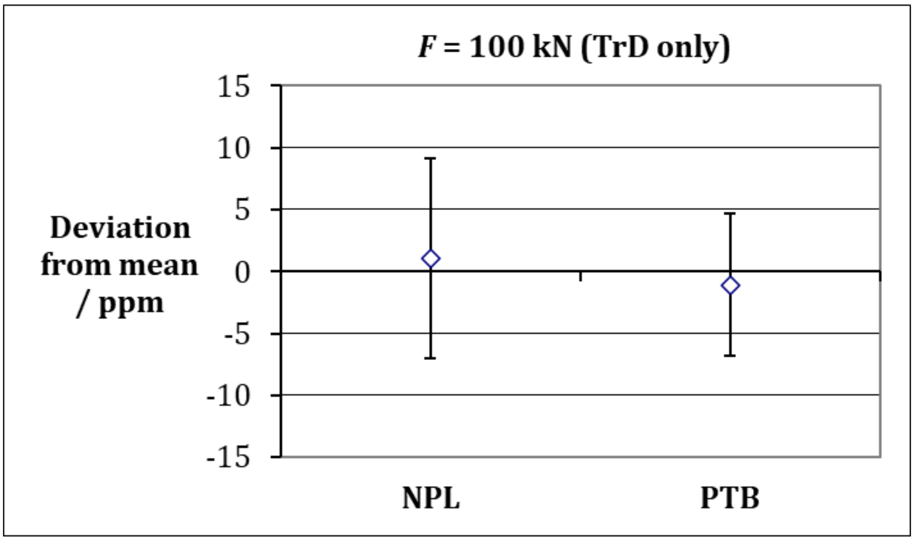

Figure 8: Agreement between NPL and PTB at 100 kN, using TrD only (standard uncertainty error bars)

In order to link the results of this comparison to the KCRVs determined in CIPM Key Comparison CCM.F-K2.a, the assumption is made that the forces generated by the machine at NPL have not changed significantly. The results of CCM.F-K2.a indicate that the 50 kN and 100 kN forces generated by NPL are both 5 ppm smaller than the KCRV, with expanded uncertainty values of 16 ppm and 17 ppm respectively.

In order to determine degrees of equivalence for PTB, their deviations from NPL need adjusting by the deviation between NPL and the KCRV, and the uncertainties increasing to incorporate the uncertainty in this deviation. When this is done, the figures in Table 12 are calculated and plotted in Figure 9.

The conclusion to be drawn from these results, at both force values, is that the PTB results are consistent with their uncertainty claims.

Table 12: Degrees of equivalence of PTB, all relative figures in ppm

50 kN		100 kN	
Deviation from KCRV	Standard Uncertainty of Deviation	Deviation from KCRV	Standard Uncertainty of Deviation
-5	11	-7	13

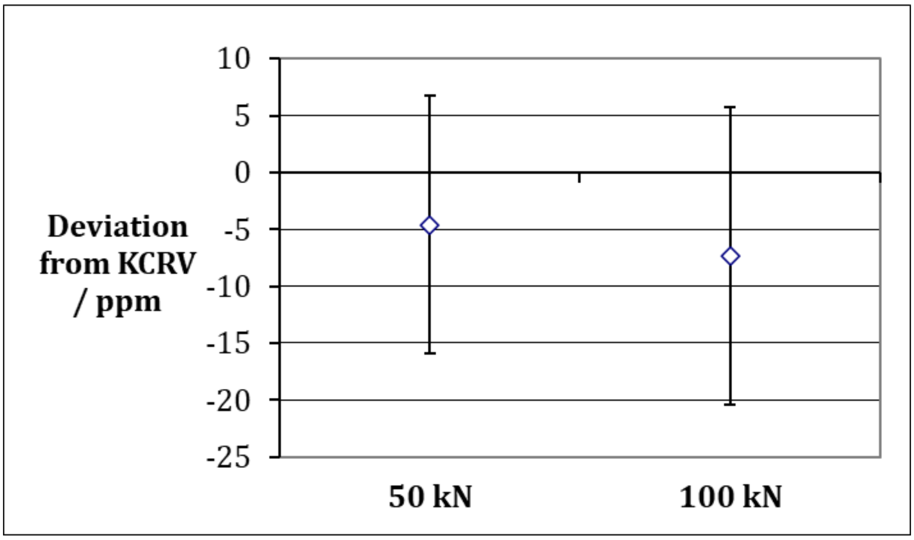

Figure 9: Agreement between PTB's 200 kN machine and KCRV (standard uncertainty error bars)

Appendix B – Normalised errors

Key Comparison Reference Values for the CCM.F-K2.a comparison are only available at the 50 kN and 100 kN force levels. However, in this comparison additional force levels were investigated, namely 5 kN, 10 kN, 20 kN and 200 kN. For all force levels, including 50 kN and 100 kN, the normalised errors E_n were calculated according to the equation:

$$E_\mathrm{n} = \frac{F_\mathrm{PTB} - F_\mathrm{NPL}}{\sqrt{U_\mathrm{PTB}^2 + U_\mathrm{NPL}^2}}$$

with F_PTB and F_NPL being the comparison result for force level F obtained at PTB and NPL, respectively, and U_PTB and U_NPL being the associated expanded ($k = 2$) uncertainties of measurement as follows:

- in case A: calculated from the full measurement results and
- in case B: taken only as the PTB-claimed and NPL-approved CMC value of 10 ppm.

The calculated figures are given in Table 13.

Table 13: Normalised errors

	Normalised error	
Force	**Case A**	**Case B**
5 kN	-0.61	-0.66
10 kN	-0.83	-0.88
20 kN	-0.12	-0.13
50 kN	0.01	0.01
100 kN	-0.24	-0.27
200 kN	-0.53	-0.84

It is interesting to note that all of these values (except the one for 50 kN, which is essentially zero) are negative. That means that the PTB results are slightly smaller than the ones obtained by NPL. Furthermore, there is no significant change when the target uncertainty of the (claimed) CMC is used compared to the values calculated from the measurement results, with the exception of 200 kN for which Case A incorporates the drift uncertainty contribution. Most important is that none of the values has an absolute amount exceeding unity, indicating that there is sufficient consistency between the results obtained in PTB and NPL to support the claimed uncertainties.