Report on the key comparison, CCM.F-K23 in force at 200 N and 500 N

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Report on the key comparison,

CCM.F-K23

in force at 200 N and 500 N

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Final report

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Abstract

The comparison CCM.F-K23 is a key comparison in force involving nine laboratories in three regional metrological organizations (RMO). The comparison adopted a scheme where each participant provides its own set of transfer standards. The measurements have been realized in 2020 and the equivalence between the participants is demonstrated.

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1 Introduction

The working group force of the CCM decided to make a comparison at 200 N and 500 N at the meeting held in Kajaani in November 2014. At the meeting held in Braunschweig in June 2017 it was decided that METAS would be the pilot of this comparison.

The working group agreed that the transfer standard would be independently organized by each participating laboratory according to the principle "bring your own device". This solution would reduce the work needed by the pilot and would allow for a faster conclusion of the comparison.

The participants have been chosen according to their actual CMC and to the expected uncertainty of their reference system.

2 Principle of the comparison

The comparison explores the equivalence of the participants at 200 N and 500 N using a set of strain gauge sensors working in compression as transfer standard. Each participant has to provide at least two sensors and at the maximum four sensors in order to establish the link between the pilot and the participant. Each participant has also to provide a reference bridge BN100, which is used for its stability [1], to establish a link on the electrical units measured by the participant and the pilot laboratory.

2.1 Load schemes

Two different measurement schemes will be applied depending on the range of the transducer.

The 500 N transducers are measured at 200 N and 500 N and the 200 N are measured only at 200 N. The measurement of a 500 N sensor only at 200 N is acceptable if the laboratory is unable to make the measurement at 500 N. It is also accepted to measure a 500 N sensor successively on two different force reference systems, in the case that the laboratory is unable to achieve the 200 N and the 500 N on the same primary standard.

Each force step is held for 4 minutes before taking the measurement. At an angle of 0° there are four preloads then three measurements. Then the sensor is rotated 60° and there is one preload and one measurement. Then this last step is repeated as many times as needed to achieve a total of rotation of 720°. The load scheme depicted in figure 1 shows the dual force measurement with a 500 N transducer and the figure 2 shows the load scheme for a single step (200 N or 500 N). The total time needed, from before the preload to the end of all measurements is 6 hours 31 minutes in the case of dual force step measurement and 4 hours 24 minutes in the case of single force step measurement.

The cycles 1 to 4 are preload cycles to bring the sensor in measurement condition. The cycles 5 to 7 give the possibility to assess the reproducibility of the sensor without applying any rotation. From cycles 8 to 31 the even number is a preload that is not taken into account. The cycles with an odd number are processed in order to determine the average value and the standard deviation. It is the measurand that is finally used for the comparison of the force definition.

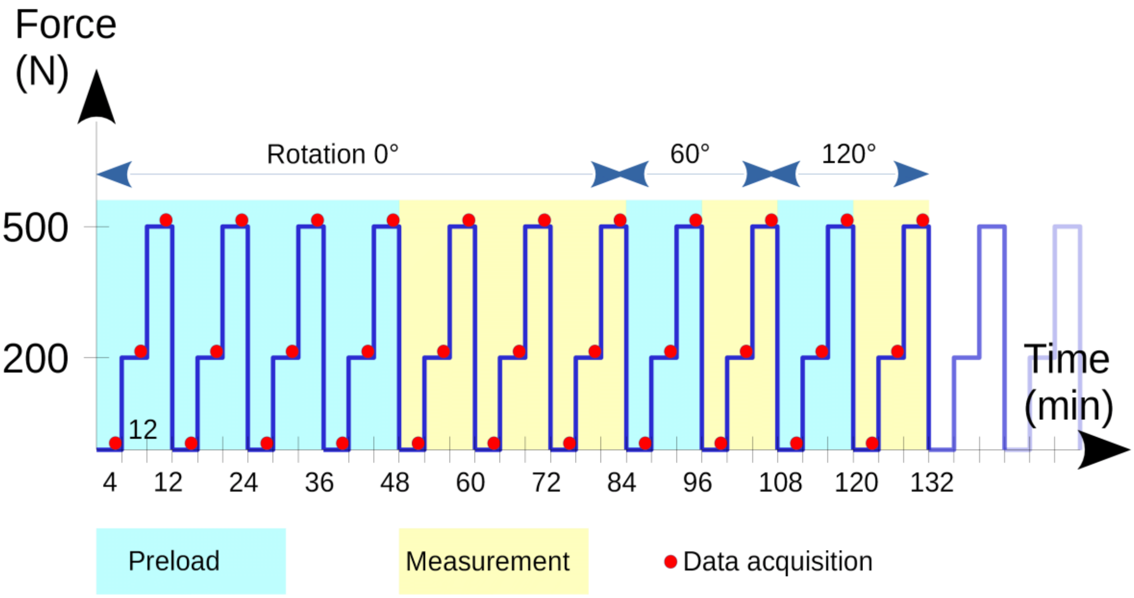

Figure 1: Load scheme used for dual force measurement (200 N and 500 N) with a 500 N transducer.

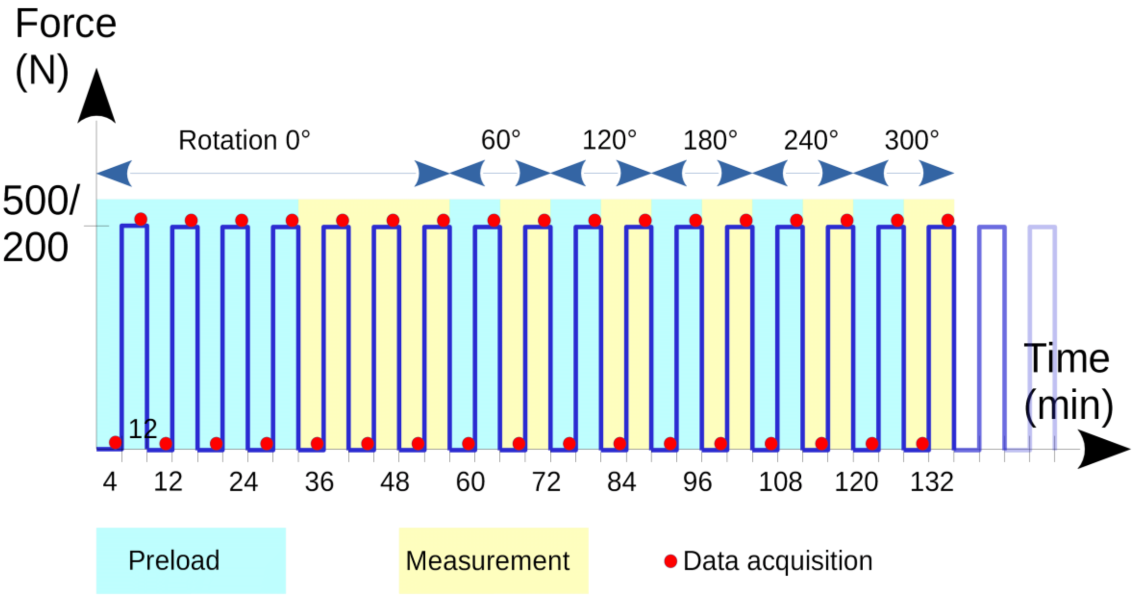

Figure 2: Load scheme used for a single force measurement (200 N or 500 N).

2.2 Thermal and time loading compensation

In order to be able to compensate for the influence of different temperature or different loading time between the reference system of the pilot or the participant, it has been asked that all sensor shall be characterized for the change of signal due to temperature or loading time. Finally, there was only a small difference in temperature between the pilot and the participants and the loading time was also similar enough to make these compensations not relevant.

3 Participating laboratories.

Nine laboratories, including the pilot, took part in the comparison. The participants cover three regional metrological organizations (RMOs). The participants were selected according to their actual CMC and the ability of their force system to achieve 10 ppm uncertainty. The participants also had to take the commitment to organize the transfer standards needed for their respective link with the pilot laboratory.

All the participants had an uncertainty (k=2) on their reference system of 10 ppm of the generated force. All the participants had CMC of 20 ppm that take into account the drift of the measurement system and the reproducibility of the transfer standard. It has also to be mentioned that all the participants are independent in the definition of the force.

Table 1: List of participants with their country, RMO, and uncertainty.

Laboratory	Country	RMO	standard uncertainty 200 N	standard uncertainty 500 N
CENAM	México	SIM	0.0010 N	0.0025 N
INRIM	Italy	Euramet	0.0010 N	0.0025 N
KRISS	Korea	APMP	0.0010 N	0.0025 N
LNE	France	Euramet	0.0010 N	0.0025 N
METAS	Switzerland	Euramet	0.0010 N	0.0025 N
NIM	Peoples Republic of China	APMP	0.0010 N	0.0025 N
NIST	United States	SIM	0.0010 N	0.0025 N
NMIJ	Japan	APMP	0.0010 N	0.0025 N
PTB	Germany	Euramet	0.0010 N	0.0025 N

3.1 Reference and transfer standards of CENAM

The CENAM reference standard is a force deadweight machine where, by means of suspended masses, applies weights directly without the intervention of any amplification mechanism, such as a lever or a hydraulic multiplier.

The measurement range of this national force standard is from 50 N to 2.5 kN. The force is generated in newtons by using masses and considering the local gravity acceleration at the laboratory. The masses can be used independently, achieving various combinations of forces according to the applied masses. The independent forces that can be applied are the following:

- 1 structural frame with a load of 50 N;
- 1 weight of 50 N;
- 1 weight of 200 N;
- 9 weights of 250 N.

This National Force Standard is located in the Force Laboratory, building H, at CENAM premises, Queretaro, Mexico.

The reference standard of CENAM has been adjusted for a different location and a different combination of gravitation field and air buoyancy than the actual conditions. The result is that the reference standard does not give exactly the nominal force and CENAM had to calculate the effective force generated by this equipment.

Table 2: Characteristics of the reference standard and transfer standard used by CENAM for this comparison.

Meas Number	1	2
Steps	200 N + 500 N	200 N + 500 N
Force Standard	Morehouse	
S/N	M-6998	
Sensor	HBM	HBM
Typ	TOP-Z30A-500N	TOP-Z30A-1000N
S/N	182913022	819471201
Range	500 N	1000 N
Initial meas.	24.07.2020	27.07.2020
Metas meas.	20.08.2020	19.08.2020
Final Meas	12.10.2020	07.10.2020

3.2 Reference and transfer standards of INRIM

Table 3: Characteristics of the reference standard and transfer standard used by INRIM for this comparison.

Meas Number	1	2
Steps	200 N	200 N + 500 N
Force Standard	MCF2 INRIM2	
S/N	INRIM2000	
Sensor	HBM	HBM
Typ	TOP-Z30A-200N	TOP-Z30A-1000N
S/N	94330068	819471201
Range	200 N	1000 N
Initial meas.	11.02.2020	10.02.2020
Metas meas.	06.03.2020	09.03.2020
Final Meas	06.08.2020	05.08.2020

3.3 Reference and transfer standards of KRISS

The 200 N and 500 N ranges have been measured separately using difference machines of 200 N-capacity and 2 kN capacity deadweight machines at KRISS, respectively. The 200 N and 2 kN force machines were developed by KRISS and commissioned in 2006 and 2019, respectively. Fully-automated operation is possible except for the rotation of the force transducers, for both machines.

They have sequential weight stacks with loading frames which generate the first and minimal load of 2.5% of their nominal capacities, and can produce loads of 110% capacities for the overloading test of loadcells

Three transfer artifacts have been used with an overlap use of the 500 N transducer.

Table 4: Characteristics of the reference standard and transfer standard used by KRISS for this comparison.

Meas Number	1	2	3	4
Steps	200 N	200 N	500 N	500 N
Force Standard	KRISS 200 N		KRISS-2 kN	
S/N	DFSM-200N-01		DFSM-2 kN-01	
Sensor	HBM	HBM		HBM
Typ	TOP-Z30A-500N	TOP-Z30A-500N		TOP-Z30A-1000N
S/N	182913022	171113012		171113039
Range	500 N	500 N		1000 N
Initial meas.	06.11.2020	23.03.2020	18.03.2020	17.03.2020
Metas meas.	14.12.2020	28.04.2020	23.04.2020	23.04.2020
Final Meas	21.01.2021	03.07.2020	10.08.2020	14.07.2020

3.4 Reference and transfer standards of LNE

The reference standard of LNE used for this comparison is a deadweight force standard machine with a capacity of 5 kN. The loads are generated with sequential weight stacks of 100 N, 200 N and 500 N. A structural frame with a load of 100 N allows the forces to be applied in tension or compression. This national force standard can be operated automatically both for incremental and decremental forces as well as for the rotations of the force transducers.

Table 5: Characteristics of the reference standard and transfer standard used by LNE for this comparison.

Meas Number	1	2
Steps	200 N + 500 N	200 N + 500 N
Force Standard	LNE Deadweight	
S/N	961128A	
Sensor	GTM	HBM
Typ	KTN-Z/D-500N	TOP-Z30A-500N
S/N	67846	202313057
Range	500 N	500 N
Initial meas.	11.01.2021	12.01.2021
Metas meas.	21.01.2021	25.01.2021
Final Meas	04.05.2021	03.05.2021

3.5 Reference standard and equipment of METAS

The reference standard used by METAS in this work is a reference deadweight system built by GTM in Germany with a full capacity of 5.5 kN and the first step is 50 N. The system is based on the principle of the chain of mass and is completely controlled by a computer in order to make automatic measurements. Before the comparison the system had been completely dismantled and recalibrated as some discrepancies, within our acknowledged measurement capability, had been discovered. The system is adjusted in order to provide the nominal value of the force step for average air pressure in the laboratory. For this work we calculated for each measurement the effective force generated based on the actual air density in the laboratory.

The 5.5 kN system of METAS provides the possibility to measure the two force steps of the comparison. In the case that the participant had to use two different reference standards for the two force steps, then METAS would also perform the measurement in two sets of cycles.

The measurement of the response of the sensors was made using a bridge DMP 40 provided by METAS, unless the participant required to use their own bridge.

3.6 Reference and transfer standard of NIM

The National Institute of Metrology (NIM) took part with two different primary standard systems.

The 200 N force standard machine is the new founded force standard machine with six individual mass stacks that generate the force in the range of 0.1 N to 200 N in sequence.

The 1 kN force primary standard machine was founded over 30 years ago, with two coaxial mass stacks that generate the force in the range of 20 N to 1000 N in sequence.

Table 6: Characteristics of the reference standard and transfer standard used by NIM for this comparison.

Meas Number	1	2
Steps	200 N	200 N + 500 N
Force Standard	TSD 200 N	NIM 1 kN
S/N	20160001	1963
Sensor	HBM	HBM
Typ	TOP-Z30A-200N	TOP-Z30A-500N
S/N	185013035	194213025
Range	200 N	500 N
Initial meas.	04.08.2020	27.07.2020
Metas meas.	15.02.2021	11.02.2021
Final Meas	29.04.2021	27.04.2021

3.7 Reference and transfer standards of NIST

The NIST reference dead weight machine used for this comparison has a total nominal capacity of 2246.35 N (505 lbf) and consists of 12 stainless steel masses [3, 4]. The yoke/shaft assembly constitutes the first step and is 44.48 N (10 lbf). From the initial step, we then have capability to proceed to the machine capacity in 4.448 N (1 lbf) increments if necessary. The machine is fully automated and with weight manipulation controlled by air actuators. Since the machine was designed to be nominally in lbf, the force points for this comparison were bracketed above and below the target values of 200 N and 500 N and interpolated to get the output at the specific forces needed.

Table 7: Characteristics of the reference standard and transfer standard used by NIST for this comparison.

Meas Number	1	2
Steps	200 N	200 N + 500 N
Force Standard	NIST 505 lbf	
S/N		
Sensor	HBM	HBM
Typ	TOP-Z30A-200N	TOP-Z30A-500N
S/N	213313050	213313010
Range	200 N	500 N
Initial meas.	21.09.2020	30.09.2020
Metas meas.	21.12.2020	22.12.2020
Final Meas	19.04.2021	22.04.2021

3.8 Reference and transfer standards of NMIJ

The reference standard of NMIJ is a deadweight force standard machine with a capacity of 3 kN and the first step of 100 N [5], manufactured by Chiyoda Seiko Co., Ltd., in Japan. The machine has two linkage-weight stacks of 100 N×10 and 200 N×10 and imparts both 200 N and 500 N forces using the same weight stacks [6]. A force transducer under calibration can be rotated by an electromagnetic motor and can be calibrated automatically.

Table 8: Characteristics of the reference standard and transfer standard used by NMIJ for this comparison.

Meas Number	1	2
Steps	200 N + 500 N	200 N + 500 N
Force Standard	Chiyoda Seiko Co.,Ltd. 3 kN DWM	
S/N	FT FSM12	
Sensor	Showa Measuring Instruments Co.	HBM
Typ	RCU-500N-S2	TOP-Z30A-500N
S/N	A170065001	094330043
Range	500 N	500 N
Initial meas.	15.05.2020	14.05.2020
Metas meas.	05.06.2020	04.06.2020
Final Meas	13.07.2020	16.07.2020

3.1 Reference and transfer standards of PTB

The 2 kN force standard machine is a machine of the deadweight type where the weight of weight pieces, each with well-known mass, is used for the generation of the force acting on the force transducer. The local gravitational acceleration as well as the density of the ambient air have been included in the calculation of the resulting force. The expanded (k = 2) relative measurement uncertainty is better than 0.002 %. The machine is located in the main hall of the Gauss building at PTB in Braunschweig, Germany. With this machine, forces between 50 N and 2 kN (in 50 N steps up to 400 N, further in 100 N steps up to 1 kN, and finally in 200 N steps up to 2 kN) can be realized. The weight pieces are coupled in series from the smallest (top) to the largest (bottom). A loading frame is used to transmit the force to the force transducer in the upper part of the machine. Series with incremental as well as with decremental forces can be measured both in compression and in tension force directions. A programmable logic controller allows an automatic and a manual operation of the machine. Measurement data is recorded automatically. The environmental data (temperature, relative air humidity and ambient air pressure) are logged for the machine as part of the monitoring system of the whole building.

Table 9: Characteristics of the reference standard and transfer standard used by PTB for this comparison.

Meas Number	1	2
Steps	200 N	200 N + 500 N
Force Standard	GTM 2 kN-K-NME	
S/N	A1.21-0007	
Sensor	HBM	GTM
Typ	TOP-Z30A-200N	KTN-D
S/N	160330082	00058
Range	200 N	500 N
Initial meas.	03.06.2020	04.06.2020
Metas meas.	02.07.2020	06.07.2020
Final Meas	18.08.2020	19.08.2020

4 Numerical treatment of the results

In the mathematical treatment we distinguish the relative uncertainties by using the letter w (like in **w**ithout unit) from the absolute uncertainties where we use the letter u (like in **u**nit).

4.1 Abbreviations

abbr.	unit	description
$C_{i,j,k}$	none	Ratio between the measurement by a participant respective to the measurement by the pilot.
$\hat{C}_{i,j}$	none	Weighted mean between all the sensors involved in the measurement of a force step for a given laboratory.
$F\mathrm{nom}_j$	N	Nominal value of the force step j.
$F_{i,j}$	N	Value of the force defined by the participant i for the nominal value of the step j of the comparison, based on the definition of the pilot laboratory.
$\tilde{F}_{i,j}$	N	Value of the force defined by the participant i for the nominal value of the step j of the comparison, based on the reference value of the comparison.
$F\mathrm{rv}_j$	N	Reference value of the comparison for the step of force j.
i	-	Index of the participant to the comparison or of the measurement loop related to this participant. The index i is 0 for the pilot and ranges from 1 to m for the participants.
j	-	Index of the force step. The value of j is 0 for the 0 N step, 1 for 200 N step and 2 for the 500 N step.
k	-	Index of the sensor used by a participant to establish the link with the pilot at a given force step. In this work the minimal value for k is 1 and the maximal value is 2.
l	-	l is the number used to identify the stage in the loop of circulation of the artefact. We define l=1 for the measurement by the participant before the circulation of the artefact, l=2 for the measurement by the pilot and l=3 for the measurement by the participant after the circulation of the transfer standard.
$R_{i,j,k,l}$	mV/V	Reference signal measured by the readout electronics (DMP 40 or DMP 41) when connected to the reference bridge BN100.
$S_{i,j,k,l}$	mV/V	Deflection calculated from the signals measured by the readout electronics (DMP 40 or DMP 41).
$\tilde{S}_{i,j,k,l}$	none	Deflection calculated from the signals measured by the readout electronics (DMP 40 or DMP 41) normalized by the signal measured by the reference bridge for a similar signal strength.

abbr.	unit	description
$wC_{i,j,k}$	none	Uncertainty of the coefficient observed between the force definition by a participant and the pilot.
$\widehat{wC}_{i,j}$	none	Uncertainty of the force defined for a participant obtained by the weighted mean between all the sensors involved in the measurement.
$wd_{i,j,k}$	none	Uncertainty due to the drift of the transfer standard k used by the laboratory i for the force step j.
$uF_{i,j}$	N	Uncertainty on the contribution to the laboratory i to the definition of the reference value of the comparison for the force step j.
$\widetilde{uF}_{i,j}$	N	Uncertainty of the force defined by a participant based on the reference value of the comparison.
$wr_{i,j,k}$	none	Uncertainty due to the repeatability of the transfer standard k used by the laboratory i for the force step j.
$ws_{i,j}$	none	Uncertainty of the reference standard of the laboratory i for the force step j.

4.2 Measurements included in the comparison

All the measurements of all the participants have been included in the calculation of the reference value and the degree of equivalence. The only exception is for laboratories who took part to the 200 N step with sensors of 200 N as well as sensors of higher range (500 N) we retained only the measurements made with the sensor of 200 N. The reason for this decision is that a sensor of 500 N used to measure 200 N is only working at 40 % of its full capacity and in practice should not be able to deliver a better uncertainty than the sensor with a full range of 200 N. It has also been difficult to apply a correct estimator for the assessment of the uncertainty of some sensors of 500 N full range, used for the measurement at 200 N. This led in some case for the same sensor to smaller relative uncertainties for the point at 200 N than for the point at 500 N, which raised questions about the validity of the estimator. We observe that by applying this technique, we achieved a better chi2 test and this improvement of the test was due to improvement of the results of several participants.

4.3 Correction of the electrical response of the bridge

A reference bridge BN100 is circulated with the transfer standard in order to link the strain gauge amplifier (DPM40 or DMP41) used by the pilot and the participant.

4.4 Uncertainties

When we establish the link between a participant and the pilot we consider the following sources of uncertainty:

4.4.1 Uncertainty of the force standard system of the participant:

This uncertainty is given by the errors on the value of the mass used for the generation of the force but also by the error on the angle at which the force is introduced on the sensor or the error due to the estimation of the air buoyancy. We assume that this type B uncertainty is highly repeatable and the error is the same on all the measurement made at a given force step for a given participant. The standard uncertainty of the reference system of each participant is $5.0 \cdot 10^{-6}$ the force generated; we will write it as:

$$ws_{i,j} = 5.0 \cdot 10^{-6} \tag{1}$$

4.4.2 Uncertainty due to the reproducibility of the sensor

We consider the standard deviation observed by the pilot and the participant at the different rotation angles of the sensor as an uncertainty due to the repeatability. This standard deviation is a type A uncertainty and is taken as a contribution to the uncertainty of the link between the two laboratories. We take into account the larger standard deviation observed by the participant. Usually, the standard deviation observed on the results of the pilot is higher than the standard deviation observed on the results of the participant and the second term of the equation is negligible. We expect a slight problem of angle between the force and the table of the machine of the pilot to be responsible for this effect.

$$wr_{i,j,k} = \sqrt{\left(\frac{\mathrm{StDEv}(S_{i,j,k,2})}{R_{i,j,k,2} - R_{i,0,k,2}}\right)^2 + \left(\max_{l=1,3} \frac{\mathrm{StDEv}(S_{i,j,k,l})}{R_{i,j,k,l} - R_{i,0,k,l}}\right)^2} \tag{2}$$

4.4.3 Uncertainty due to the drift of the sensor

We consider that the drift observed by the participant on the response of the sensor, before and after the transport, is an estimator of the uncertainty contribution due to the long-term stability. We divide the drift by two to obtain a standard uncertainty. We assume that the two measurements are values from a normal distribution, each set to lie one standard deviation from its mean value.

$$wd_{i,j,k} = 0.5 \cdot \left| \frac{S_{i,j,k,1}}{R_{i,j,k,1} - R_{i,0,k,1}} - \frac{S_{i,j,k,3}}{R_{i,j,k,3} - R_{i,0,k,3}} \right| \tag{3}$$

4.5 Determination of the ratio between a participant and the pilot

In a first step we normalize the results obtained by the laboratories by the signal measured on the BN100.

$$\tilde{S}_{i,j,k,l} = \frac{S_{i,j,k,l}}{R_{i,j,k,l} - R_{i,0,k,l}} \tag{4}$$

We can then determine the coefficient between the signal measured at the pilot and the signal measured at the participant place:

$$C_{i,j,k} = \frac{\tilde{S}_{i,j,k,1} + \tilde{S}_{i,j,k,3}}{2 \cdot \tilde{S}_{i,j,k,2}} \tag{5}$$

The uncertainty on this coefficient is given as a combination of the uncertainty related to the drift and the uncertainty related to the standard deviation as measured by the pilot:

$$wc_{i,j,k} = \frac{\sqrt{\left(ur_{i,j,k}\right)^2 + \left(ud_{i,j,k}\right)^2}}{\tilde{S}_{i,j,k,2}} \tag{6}$$

Note that the correction factor $\tilde{S}_{i,j,k,2}$ could easily be neglected as it is very close to 1 if the signal from the reference bridge BN100 is very close from the signal measured on the sensor.

4.6 Determination of the force defined by a participant

The force defined by a participant is the product of the nominal value of the force multiplied by the weighted mean of the coefficient for that value of the force:

$$\hat{C}_{i,j} = \frac{\sum_k \frac{C_{i,j,k}}{\left(wc_{i,j,k}\right)^2}}{\sum_k \frac{1}{\left(wc_{i,j,k}\right)^2}} \tag{7}$$

$$F_{i,j} = F\text{nom}_j \cdot \hat{C}_{i,j} \tag{8}$$

Uncertainty on the force defined by a participant:

$$\widehat{wC}_{i,j} = \sqrt{\frac{1}{\sum_k \frac{1}{\left(wc_{i,j,k}\right)^2}}} \tag{9}$$

$$uF_{i,j} = F\text{nom}_j \cdot \sqrt{\left(ws_{i,j}\right)^2 + \left(\widehat{wC}_{i,j}\right)^2} \tag{10}$$

The force defined by a participant is given as the nominal force multiplied by the weighted mean of the coefficients between the participant and the pilot.

4.7 Determination of the force defined by the pilot

In the calculation we apply, the definition the force determined by the pilot is always the nominal value of the force.

$$F_{0,j} = F\mathrm{nom}_j \tag{11}$$

The uncertainty on this value is given as a combination of the uncertainty of the force system of the pilot combined with the weighted mean of all the coefficients established with the pilot and the participants:

$$\widehat{wC}_{0,j} = \sqrt{\frac{1}{\sum_i \frac{1}{\left(\widehat{wC}_{i,j}\right)^2}}} \tag{12}$$

$$uF_{0,j} = F\mathrm{nom}_j \cdot \sqrt{\left(ws_{0,j}\right)^2 + \left(\widehat{wC}_{0,j}\right)^2} \tag{13}$$

4.8 Determination of the reference value

We apply the technique described by Cox and obtain the reference value of the force by a weighted mean of the definition of the force by each participant:

$$F\mathrm{rv}_j = \frac{\sum_i \frac{F_{i,j}}{\left(uF_{i,j}\right)^2}}{\sum_i \frac{1}{\left(uF_{i,j}\right)^2}} \tag{14}$$

And the uncertainty on the force is:

$$uF\mathrm{rv}_j = \sqrt{\frac{1}{\sum_i \frac{1}{\left(uF_{i,j}\right)^2}}} \tag{15}$$

4.9 Definition of the force of the participants respective to the reference value

In order to calculate the force defined by the participants respective to the reference value we apply a correction given by the ratio between the nominal value of the force which was given by the pilot by the value of the reference value.

$$\tilde{F}_{i,j} = F_{i,j}\frac{F_j}{F\mathrm{rv}_j} \tag{16}$$

The uncertainty on the value of the force is not affected by this normalization:

$$\widetilde{uF}_{i,j} = uF_{i,j} \tag{17}$$

The offset of the participants respective to the reference value is given the following way:

$$d_{i,j} = \tilde{F}_{i,j} - F\mathrm{rv}_j \tag{18}$$

And the uncertainty on the offset is given by a combination of the respective uncertainties taking into account their correlation:

$$u(d_{i.j}) = \sqrt{\left(\widetilde{uF}_{i,j}\right)^2 - \left(uF\mathrm{rv}_j\right)^2} \tag{19}$$

5 Results of the participants

The results of the participants are summarized in the following tables. Each table provides the measurements made by the participant, before and after the transport, as well as the measurement made by the pilot laboratory. The measurements of the signal of the sensors are in fact averaged values on the load cycles with odd numbers spanning between cycle 8 and cycle 31 as described in Fig.1 and Fig.2. The measurements are denoted by the letter M followed by a number which corresponds to the setup described in the description of the participating laboratories in the tables 2 to 9 . The measurement of the reference bridge is denoted by the abbreviation BN100. The coefficient $\hat{C}_{i,j}$ gives the ratio between the force definition made by the participant and the pilot laboratory as defined in equation 7.

All the measurements of the pilot laboratory have been corrected for the effective air buoyancy at the time of measurement. This correction is always smaller than 1.5 ppm and should not affect the results.

5.1 Results of Cenam

Table 10: Values measured with the transfer standard provided by CENAM during the loop performed to link the CENAM to METAS

		0 N	Force	200 N	Force	500 N
		Value	Value	StDev	Value	StDev
		mV/V	mV/V	mV/V	mV/V	mV/V
CENAM before transport	M1	0.0000000	0.7999243	0.0000078	1.9998819	0.0000261
	BN100	0.0000000	0.7999973	0.0000024	2.0000017	0.0000019
	M2	0.0000000	0.4000977	0.0000025	1.0003324	0.0000034
	BN100	0.0000000	0.3999990	0.0000016	0.9999957	0.0000021
CENAM after transport	M1	0.0000000	0.7999186	0.0000141	1.9998873	0.0000237
	BN100	-0.0000010	0.7999970	0.0000016	2.0000013	0.0000012
	M2	0.0000000	0.4001046	0.0000091	1.0003457	0.0000128
	BN100	-0.0000010	0.3999970	0.0000000	0.9999960	0.0000008
METAS as link of the comp.	M1	0.0000000	0.8000930	0.0000034	2.0001734	0.0000038
	BN100	0.0000060	0.8000153	0.0000005	2.0000220	0.0000008
	M2	0.0000000	0.4001906	0.0000021	1.0004949	0.0000019
	BN100	0.0000060	0.4000097	0.0000012	1.0000080	0.0000008
Coefficient		$\hat{C}_{i,j}$	Ratio	Uncert.	Ratio	Uncert
			1.0000307	0.0000149	1.0000191	0.0000098

5.2 Results of INRIM

Table 11: Values measured with the transfer standard provided by INRIM during the loop performed to link the INRIM to METAS

		0 N	Force	200 N	Force	500 N
		Value	Value	StDev	Value	StDev
		mV/V	mV/V	mV/V	mV/V	mV/V
INRIM before transport	M1	0.0000000	1.9985718	0.0000177		
	BN100	0.0000060	1.9999970	0.0000014		
	M2	0.0000000			2.0006372	0.0000189
	BN100	0.0000050			1.9999997	0.0000009
INRIM after transport	M1	0.0000000	1.9986345	0.0000175		
	BN100	0.0000050	2.0000027	0.0000012		
	M2	0.0000000			2.0006243	0.0000359
	BN100	0.0000040			2.0000003	0.0000012
METAS as link of the comp.	M1	0.0000000	1.9985991	0.0000482		
	BN100	0.0000020	1.9999963	0.0000005		
	M2	0.0000000			2.0005778	0.0000393
	BN100	0.0000080			1.9999987	0.0000005
Coefficient		$\hat{C}_{i,j}$	Ratio	Uncert.	Ratio	Uncert
			1.0000017	0.0000292	1.0000249	0.0000269

5.3 Results of KRISS

Table 12: Values measured with the transfer standard provided by KRISS during the loop performed to link the KRISS to METAS

		0 N	Force	200 N	Force	500 N
		Value	Value	StDev	Value	StDev
		mV/V	mV/V	mV/V	mV/V	mV/V
KRISS before transport	M1	0.0000000	2.0005410	0.0000115		
	BN100	0.0000020	2.0000063	0.0000026		
	M3	0.0000000			1.9996555	0.0000030
	BN100	0.0000180			2.0000070	0.0000014
	M4	0.0000000			0.9942828	0.0000016
	BN100	0.0000200			1.0000230	0.0000008
KRISS after transport	M1	0.0000000	2.0005048	0.0000120		
	BN100	0.0000000	2.0000063	0.0000012		
	M3	0.0000000			1.9996665	0.0000012
	BN100	0.0000160			2.0000003	0.0000005
	M4	0.0000000			0.9942623	0.0000010
	BN100	0.0000200			1.0000133	0.0000012
METAS as link of the comp.	M1	0.0000000	2.0005086	0.0000197		
	BN100	0.0000030	1.9999910	0.0000008		
	M3	0.0000000			1.9996828	0.0000083
	BN100	0.0000060			2.0000117	0.0000005
	M4	0.0000000			0.9942788	0.0000081
	BN100	0.0000080			1.0000057	0.0000005
Coefficient		$\hat{C}_{i,j}$	Ratio	Uncert.	Ratio	Uncert
			0.9999983	0.0000149	0.9999973	0.0000051

5.4 Results of LNE

Table 13: Values measured with the transfer standard provided by LNE during the loop performed to link the LNE to METAS

		0 N	Force	200 N	Force	500 N
		Value	Value	StDev	Value	StDev
		mV/V	mV/V	mV/V	mV/V	mV/V
LNE before transport	M1	0.0000000	0.8006070	0.0000051	2.0012923	0.0000107
	BN100	0.0000070	0.8000083	0.0000005	2.0000087	0.0000005
	M2	0.0000000	0.8000132	0.0000011	2.0000694	0.0000018
	BN100	0.0000040	0.8000040	0.0000008	2.0000030	0.0000014
LNE after transport	M1	0.0000000	0.8006581	0.0000072	2.0014283	0.0000166
	BN100	0.0000140	0.8000143	0.0000005	2.0000153	0.0000005
	m2	0.0000000	0.8000028	0.0000007	2.0000451	0.0000011
	BN100	0.0000140	0.8000160	0.0000016	2.0000167	0.0000025
METAS as link of the comp.	M1	0.0000000	0.8006938	0.0000081	2.0014801	0.0000167
	BN100	-0.0000050	0.7999993	0.0000012	2.0000027	0.0000009
	M2	0.0000000	0.8000203	0.0000041	2.0000885	0.0000064
	BN100	-0.0000037	0.8000017	0.0000009	2.0000070	0.0000008
			Ratio	Uncert.	Ratio	Uncert
Coefficient		$\hat{C}_{i,j}$	0.9999858	0.0000089	0.9999871	0.0000075

5.5 Results of NIM

Table 14: Values measured with the transfer standard provided by NIM during the loop performed to link the NIM to METAS

		0 N	Force	200 N	Force	500 N
		Value	Value	StDev	Value	StDev
		mV/V	mV/V	mV/V	mV/V	mV/V
NIM before transport	M1	0.0000000	1.9997169	0.0000050		
	BN100	-0.0000310	1.9999667	0.0000005		
	M2	0.0000000			1.9999438	0.0000126
	BN100	-0.0000290			1.9999713	0.0000021
NIM after transport	M1	0.0000000	1.9996494	0.0000056		
	BN100	-0.0000190	1.9999793	0.0000005		
	M2	0.0000000			1.9998661	0.0000049
	BN100	-0.0000280			1.9999697	0.0000012
METAS as link of the comp.	M1	0.0000000	1.9996837	0.0000034		
	BN100	0.0000050	2.0000143	0.0000005		
	M2	0.0000000			1.9998540	0.0000038
	BN100	0.0000040			2.0000130	0.0000014
			Ratio	Uncert.	Ratio	Uncert
Coefficient		$\hat{C}_{i,j}$	1.0000055	0.0000174	1.0000313	0.0000198

5.6 Results of NIST

Table 15: Values measured with the transfer standard provided by NIST during the loop performed to link the NIST to METAS

		0 N	Force	200 N	Force	500 N
		Value	Value	StDev	Value	StDev
		mV/V	mV/V	mV/V	mV/V	mV/V
NIST before transport	M1	0.0000000	1.9996438	0.0000163		
	BN100	-0.0000100	1.9999931	0.0000005		
	M2	0.0000000			1.9999206	0.0000141
	BN100	-0.0000090			1.9999916	0.0000002
NIST after transport	M1	0.0000000	1.9996254	0.0000180		
	BN100	-0.0000110	1.9999984	0.0000001		
	M2	0.0000000			1.9998903	0.0000104
	BN100	-0.0000120			1.9999988	0.0000002
METAS as link of the comp.	M1	0.0000000	1.9996008	0.0000132		
	BN100	0.0000030	2.0000063	0.0000005		
	M2	0.0000000			1.9998634	0.0000033
	BN100	0.0000050			2.0000090	0.0000008
Coefficient		$\hat{C}_{i,j}$	Ratio	Uncert.	Ratio	Uncert
			1.0000157	0.0000128	1.0000201	0.0000123

5.7 Results of NMIJ

Table 16: Values measured with the transfer standard provided by NMIJ during the loop performed to link the NMIJ to METAS

		0 N	Force	200 N	Force	500 N
		Value	Value	StDev	Value	StDev
		mV/V	mV/V	mV/V	mV/V	mV/V
NMIJ before transport	M1	0.0000000	0.8023914	0.0000038	2.0054490	0.0000111
	BN100	0.0000140	0.8000117	0.0000009	2.0000190	0.0000008
	M2	0.0000000	0.8003189	0.0000017	2.0008857	0.0000053
	BN100	0.0000050	0.8000037	0.0000005	2.0000027	0.0000012
NMIJ after transport	M1	0.0000000	0.8023754	0.0000044	2.0054221	0.0000111
	BN100	0.0000150	0.8000097	0.0000012	2.0000100	0.0000008
	M2	0.0000000	0.8003293	0.0000017	2.0009068	0.0000030
	BN100	0.0000140	0.8000113	0.0000017	2.0000147	0.0000009
METAS as link of the comp.	M1	0.0000000	0.8024644	0.0000302	2.0056491	0.0000522
	BN100	0.0000150	0.8000137	0.0000012	2.0000197	0.0000009
	M2	0.0000000	0.8003226	0.0000067	2.0008944	0.0000125
	BN100	0.0000130	0.8000127	0.0000012	2.0000173	0.0000005
Coefficient		$\hat{C}_{i,j}$	Ratio	Uncert.	Ratio	Uncert
			0.9999957	0.0000110	0.9999943	0.0000078

The transfer standard #1 (RCU-500N-S2) showed sensitivity dependence on ambient pressure change in the plural calibrations with various weather. The difference of approximately 70 hPa in the ambient pressure between the pilot laboratory and the participant caused non-negligible deviation in the sensitivity.

5.8 Results of PTB

Table 17: Values measured with the transfer standard provided by PTB during the loop performed to link the PTB to METAS

		0 N	Force 200 N		Force 500 N	
		Value	Value	StDev	Value	StDev
		mV/V	mV/V	mV/V	mV/V	mV/V
PTB before transport	M1	0.0000000	1.9989352	0.0000281		
	BN100	0.0000180	2.0000187	0.0000012		
	M2	0.0000000			2.0088123	0.0000039
	BN100	0.0000200			2.0000217	0.0000005
PTB after transport	M1	0.0000000	1.9989349	0.0000386		
	BN100	0.0000240	2.0000223	0.0000005		
	M2	0.0000000			2.0087928	0.0000033
	BN100	0.0000230			2.0000243	0.0000005
METAS as link of the comp.	M1	0.0000000	1.9989651	0.0000484		
	BN100	0.0000220	2.0000240	0.0000008		
	M2	0.0000000			2.0087742	0.0000156
	BN100	0.0000240			2.0000253	0.0000005
Coefficient		$\hat{C}_{i,j}$	Ratio	Uncert.	Ratio	Uncert
			0.9999861	0.0000309	1.0000142	0.0000093

6 Validity of the measurements and reference value

6.1 Results respective to the pilot laboratory (METAS)

All the participants are in pretty good agreement with the measurements of the pilot laboratory and no serious discrepancy is visible at this stage.

Table 18: Value of force determined for each participant based on the definition of the pilot (METAS). The uncertainty of the link is given by the characteristics of repeatability and reproducibility of the transfer standard. The uncertainty of the laboratory is given by combining the uncertainty of the link with the uncertainty of the reference standard.

Participant	Force	u(link)	u(labo)	Force	u(link)	u(labo)
	$F_j \hat{C}_{i,j}$	$F_j u\hat{C}_{i,j}$	$uF_{i,j}$	$F_j \hat{C}_{i,j}$	$F_j u\hat{C}_{i,j}$	$uF_{i,j}$
CENAM	200.0063	0.0030	0.0031	500.0095	0.0049	0.0055
INRIM	200.0003	0.0058	0.0059	500.0121	0.0134	0.0137
KRISS	199.9997	0.0030	0.0031	499.9986	0.0025	0.0036
LNE	199.9972	0.0018	0.0020	499.9936	0.0038	0.0045
METAS	200.0000	0.0010	0.0014	500.0000	0.0027	0.0036
NIM	200.0011	0.0035	0.0036	500.0153	0.0099	0.0102
NIST	200.0031	0.0026	0.0028	500.0100	0.0062	0.0066
NMIJ	199.9991	0.0022	0.0024	499.9972	0.0039	0.0046
PTB	199.9972	0.0062	0.0063	500.0069	0.0046	0.0053

6.2 Determination of the reference value

We determine the reference by applying the formula of Cox [2] described in the calculation part. We also apply the test of the Chi2 test, for 9 independant contributors, in order to know if the quality of the results are in agreement with this technique. The results are summarised in the following table and validate this calculation technique.

Table 19: Reference values obtained by weighted mean and values of the chi 2 test according to Cox.

Nominal force	Reference force	Uncertainty of force ref	χ^2 observed	χ^2 maximal
F_j	$F\mathrm{rv}_j$	$uF\mathrm{rv}_j$		
N	N	N		
200	200.00015	0.00086	7.58	15.51
500	500.00125	0.00168	12.08	15.51

6.3 Values of the participants respective to the reference value

The normalisation by the reference value obtained through a the weighted mean of all the participants results gives the force defined by each participant. We can see on the following tables that all the participants have an offset smaller than twice the standard uncertainty except for one force step for on single participant. Taking into account that we have 18 results for equivalence in this comparisation it is statistically expected to have a measurement slightly out of tolerance.

Table 20: Value of the force defined by each participant at 200 N nominal value. The offset respective to the reference value and the uncertainty associated and the degree of equivalence are also reported.

Participant	Force	Offset	u(offset)	Offset / unc
	$\tilde{F}_{i,j}$	$d_{i,j}$	$u(d_{i,j})$	$d_{i,j} / u(d_{i,j})$
CENAM	200.0061	0.0061	0.0030	2.015
INRIM	200.0002	0.0002	0.0059	0.031
KRISS	199.9995	-0.0005	0.0030	-0.161
LNE	199.9970	-0.0030	0.0019	-1.613
METAS	199.9998	-0.0002	0.0012	-0.133
NIM	200.0009	0.0009	0.0035	0.268
NIST	200.0030	0.0030	0.0026	1.145
NMIJ	199.9990	-0.0010	0.0023	-0.448
PTB	199.9971	-0.0029	0.0062	-0.471

The uncertainty of the result of the PTB, at 200 N, is sensibly larger than for other participants. This is due to a poor stability of the 200 N sensor used by the PTB. Better results had been obtained with the 500 N sensor for PTB but it was previously decided not to retain the results of the 500 N sensor if a sensor of 200 N was present. This also shows a limitation of a comparison where the sensors are provided by the participants and not carefully selected by the pilot.

Table 21: Value of the force defined by each participant at 500 N nominal value. The offset respective to the reference value and the uncertainty associated and the degree of equivalence are also reported.

Participant	Force	Offset	u(offset)	Offset / unc
	$\tilde{F}_{i,j}$	$d_{i,j}$	$u(d_{i,j})$	$d_{i,j}/u(d_{i,j})$
CENAM	500.0083	0.0083	0.0052	1.587
INRIM	500.0109	0.0109	0.0136	0.804
KRISS	499.9973	-0.0027	0.0032	-0.851
LNE	499.9923	-0.0077	0.0042	-1.838
METAS	499.9988	-0.0012	0.0032	-0.385
NIM	500.0140	0.0140	0.0101	1.392
NIST	500.0088	0.0088	0.0064	1.368
NMIJ	499.9959	-0.0041	0.0043	-0.943
PTB	500.0057	0.0057	0.0050	1.134

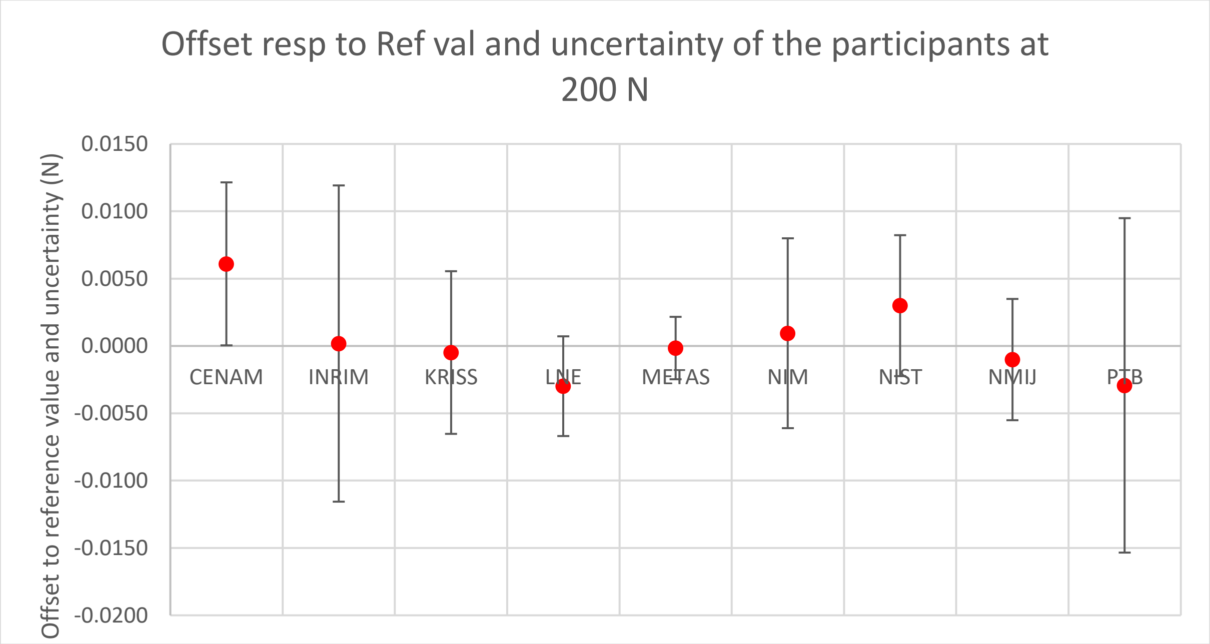

Figure 3: Plot of the degree of equivalence of the participants at 200 N

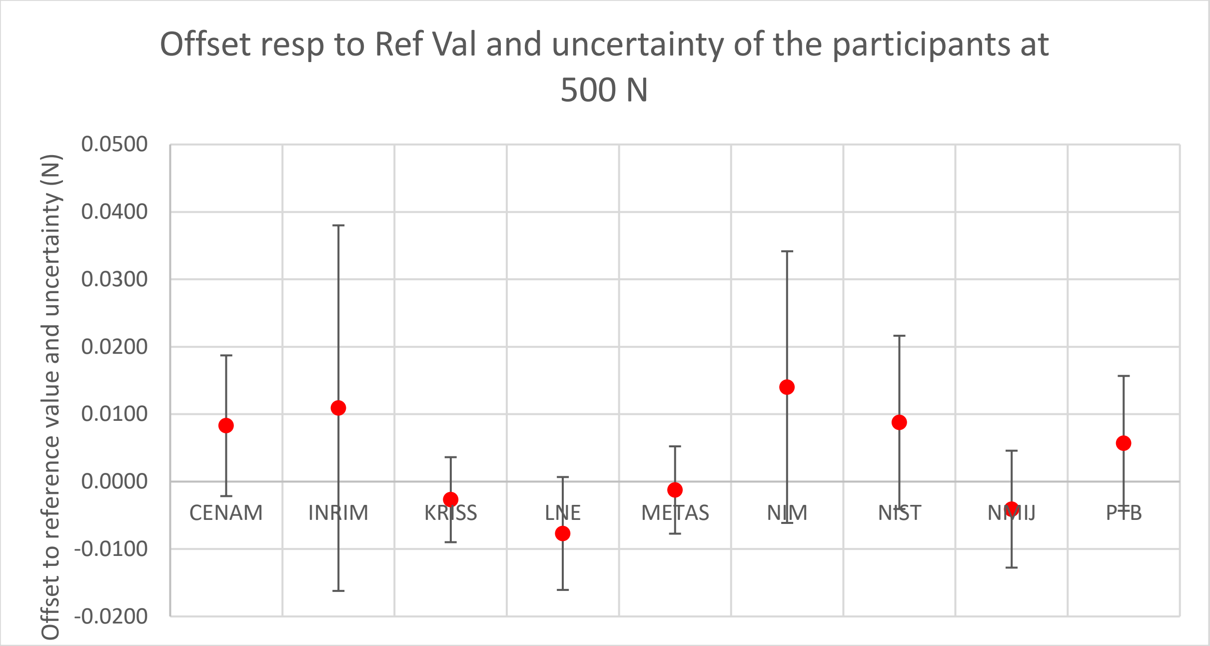

Figure 4: Plot of the degree of equivalence of the participants at 500 N

6.4 Comments about the calculation technique

6.4.1 Influence of METAS on the reference value

We could argue that the small uncertainty of the pilot laboratory has an influence on the definition of the reference value of the comparison. In order to be sure that METAS did not pull the reference value in the process we determined the weighted mean without the results of METAS. Table 22 shows that the exclusion of the measurements of METAS has mostly an influence on the uncertainty of the weighted mean but not much on the value itself.

Table 22: Weighted mean of the values provided by the participants obtained with and without the contribution of METAS. No significant influence is seen respective to the uncertainty.

	METAS included		METAS excluded	
Nominal force	Weighted mean	Uncertainty of the mean	Weighted mean	Uncertainty of the mean
N	N	N	N	N
200	200.00015	0.00086	200.00024	0.00107
500	500.00125	0.00168	500.00158	0.00224

6.4.2 Influence of the correction of effective air buoyancy at METAS

In this work, we applied a correction of the effective air buoyancy at METAS and did not simply took the nominal value of the force for a standard air density. This correction is small and has almost no influence on the reference value. It is however noticeable on the chi 2 value of the comparison as shown in table 23.

Table 23: Weighted mean of the values provided by the participants obtained with and without the correction of the variation of air buoyancy at METAS. No change is seen on the reference value but the correction of the air buoyancy improves the chi 2 test.

	Nominal air buoyancy		Effective air buoyancy	
Nominal force	Weighted mean	χ^2	Weighted mean	χ^2
N	N		N	
200	200.00007	8.36	200.00015	7.58
500	500.00106	13.46	500.00125	12.08

7 Conclusion

This comparison has successfully demonstrated the equivalence of the nine participants at the force step 200 N and 500 N. The circulation scheme of the transfer standard made difficult for some participants to have a high-quality transfer standard but gave the opportunity to have a fast circulation scheme within one year. This work was realized in 2020 during the strong disruptions of the transport industry and closure of institutes due to the pandemic of covid-19. It was however possible to continuously perform measurement at the pilot laboratory, due to the full independence of the participants.

8 References

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