IMEKO 22nd TC3, 12th TC5 and 3rd TC22 International Conferences
3 to 5 February, 2014, Cape Town, Republic of South Africa

METHODS TO CONFIRM THE MEASUREMENT CAPABILITY OF THE FORCE STANDARD MACHINES AFTER REINSTALLATION

A. A. Pusa/Presenter[1], *B. J. Korhonen*[1], *and C. R. Kumme*[2]

[1] Centre for Metrology and Accreditation, MIKES, Kajaani, Finland
[2]Physikalisch-Technische Bundesanstalt, PTB, Braunschweig, Germany

Abstract: This paper describes the method to evaluate the force standard machines measurement capability after their complete relocation.

Keywords: Measurement, capability, traceability, comparison, force measurement.

1. INTRODUCTION

In Finland, Lahti Precision Oy acted as designed institute for force and torque until June 2010. The force measurement capability of the laboratory has proved with several comparisons and as well with the Key comparison CCM.F-K1.a and K1.b, where the laboratory worked as Pilot [2]. This activity was moved to MIKES-Kajaani between June 2010 – September 2011. The all standard machines were dismantled in Lahti and reassembled in Kajaani. The laboratory has dead weight force standard machines (DWFSM) with nominal capacities of 1 kN, 20 kN and 100 kN. For a capacity of 1 MN the laboratory has a hydraulic amplified force standard machine (HFSM). To confirm the functionality of the standard machines were applied several methods, using the characteristics of transfer force transducers which are known well as well as a final confirmation by a comparison with the Physikalisch-Technische Bundesanstalt (PTB).

2. INVESTIGATIONS IN KAJAANI

Due to the relatively long time between the last measurements in Lahti and the first measurements in Kajaani, the sensitivity of the transfer transducers was not good enough as a parameter to confirm the correct reassembly in Kajaani. Therefore, the linearity, the rotation effect and the hysteresis of the transfer transducers were used as indicators because these characteristics are constant. The method used has shown that these parameters render very good information on the correct functioning of standard machines.

2.1 Use of the constant characteristic of force or torque transducers

Relocating of force standard machines or torque standard machines means destroying the measurement capability of the machine by dismantling it. In practice, the standard machine does not undergo any changes because it is a mechanical device but due to its reinstallation, its behaviour may be different. The goal of reinstalling the machines is to achieve a mechanical construction which is similar to or even better than before. It must however be confirmed that the machines were installed correctly and subsequently work correctly. The normal way of doing this is to undertake comparisons with another laboratory but this takes quit a long time to realise. To speed up the confirmation of the quality of the reinstallation, the constant characteristics of transducers can be exploited. These characteristics are the linearity and the hysteresis which do not change in the course of time as long as the transducer is not overloaded.
The third characteristic is the rotation effect, which is given by the manufacturing of the transducer. Unfortunately, this behaviour cannot be measured exactly due to the fact that we do not have an ideal force standard machine which works without the rotation effect of the machine itself.
Sensitivity is a characteristic which changes during time and it also depends on the activity performed in using the transducer, i.e. the comparison measurement, which gives the final confirmation, has to be carried out in a short a time as possible.

2.2 Results of linearity and hysteresis

2.2.1 100 kN DWFSM

The following figures illustrate the results of the measurements taken in Lahti before the relocation and after reinstallation in Kajaani. The first figures, 1 and 2, give information on a 100 kN dead weight force standard machine. The linearity in figure 1 has a deviation between the two measurements of less than $8 \cdot 10^{-6}$ and the hysteresis is even less. This is uniform confirmation that the reassembly in Kajaani was undertaken successfully.

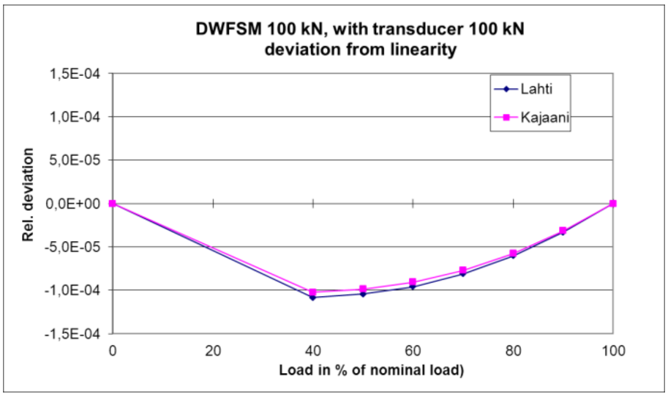

Figure 1. Linearity curves from measurements before and after the relocation of the 100 kN DWFSM.

The measurements of the hysteresis in dead weight force standard machines are more unique. There is no friction and the differences of the hysteresis are practical inside of the measurement uncertainty in the case that DWFSM works well.

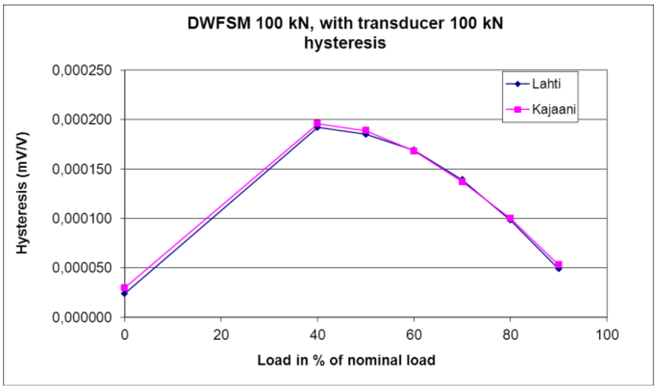

Figure 2. Hysteresis of the curves from linearity measurements before and after the relocation of the 100 kN DWFSM.

To evaluate the quality of the reinstallation with rotation effect the maximal deviation for each load in all 4 rotation positions is compared by calculating the difference between measurements taken before and after relocation as the relative difference.

Differences in rotation measurement between measurements in Lahti and Kajaani using the 100 kN transducer and the 100 kN DWFSM	
Load [%]	Rel. difference
40	6.3E-06
50	-3.0E-06
60	-2.5E-06
70	1.4E-06
80	6.3E-06
90	5.6E-06
100	1.1E-05

Table 1. The relative difference of the rotation effect with the 100 kN transducer of the 100 kN DWFSM between measurements in Lahti and in Kajaani.

2.2.2 HFSM 1 MN

Figures 3 and 4 show the measurement in the 1 MN hydraulic amplified force standard machine (HFSM) with the 1 MN transducer and the deviation in linearity being in magnitude approximately $3 \cdot 10^{-5}$. Based on the hydraulic amplified force standard machine, this value fulfils the requirements successfully.

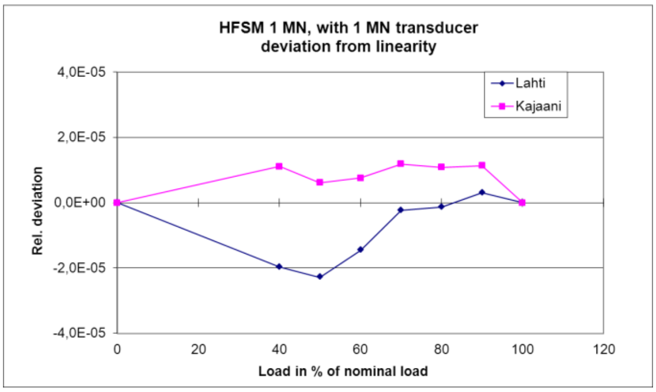

Figure 3. Linearity curves for the 1 MN transducer from measurements before and after the relocation of the 1 MN HFSM.

The hysteresis measurement in the hydraulic amplified machine has its own friction from the hydraulic system, the measurement piston and the working piston. The hysteresis of the transducer cannot be distinguished from the hysteresis of the hydraulic system. Also the results are not so stable, because the generation of force is not as stable as in the dead weight force standard machine. Figure 4 shows the hysteresis with the 1 MN transducer of the 1 MN HFSM. The difference is approximately $2 \cdot 10^{-5}$ and it is also an acceptable result.

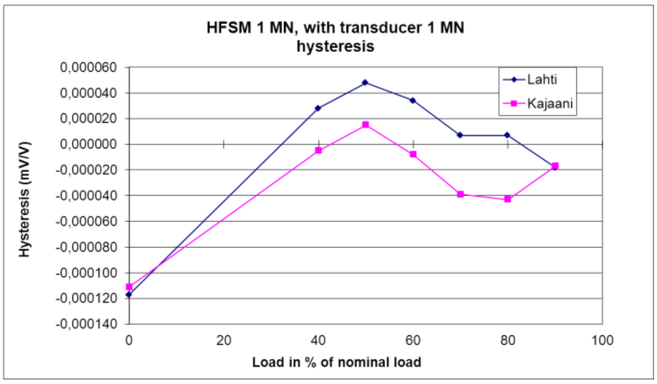

Figure 4. Hysteresis of the curves with the 1 MN transducer from linearity measurements before and after the relocation in 1 MN HFSM.

With the 1 MN transducers, the HFSM worked well. The measurement with the 200 kN force transducer has however shown some problems. The linearity curve, Figure 5, shows more deviation with lower forces and the hysteresis, Figure 6, also shows more deviation than expected. Finally the rotation measurement, Table 2, shows unique differences in measurements between Lahti and Kajaani.

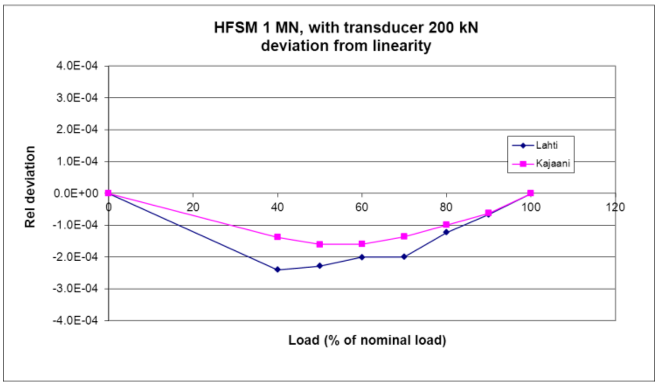

Figure 5. Linearity curves for the 200 kN transducer from measurements before and after the relocation of the 1 MN HFSM.

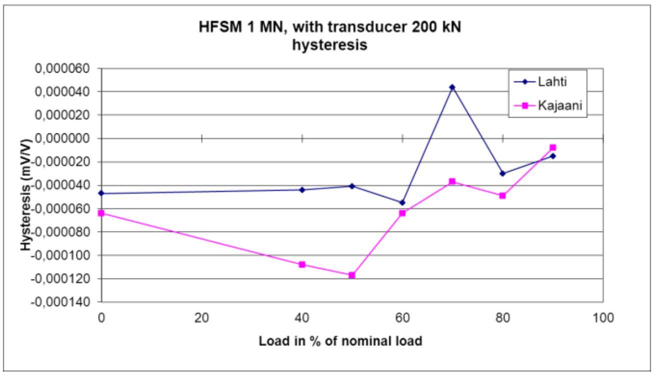

Figure 6. Hysteresis of the curves with the 200 kN transducer from linearity measurements before and after the relocation of the 1 MN HFSM.

Differences in rotation measurement between measurements in Lahti and Kajaani with 1 MN and 200 kN transducers in 1 MN HFSM		
Load [%]	Rel. difference with 1 MN transducer	Rel. difference with 200 kN transducer
40	4,0E-06	1.6E-04
50	-1,4E-05	1.6E-04
60	-2,6E-05	2.3E-04
70	-4,1E-05	2.2E-04
80	-6,6E-05	2.7E-04
90	-6,2E-05	3.1E-04
100	-5,9E-05	3.3E-04

Table 2. The relative difference of rotation effects with the 1 MN and the 200 kN transducers in the 1 MN HFSM between measurements in Lahti and in Kajaani.

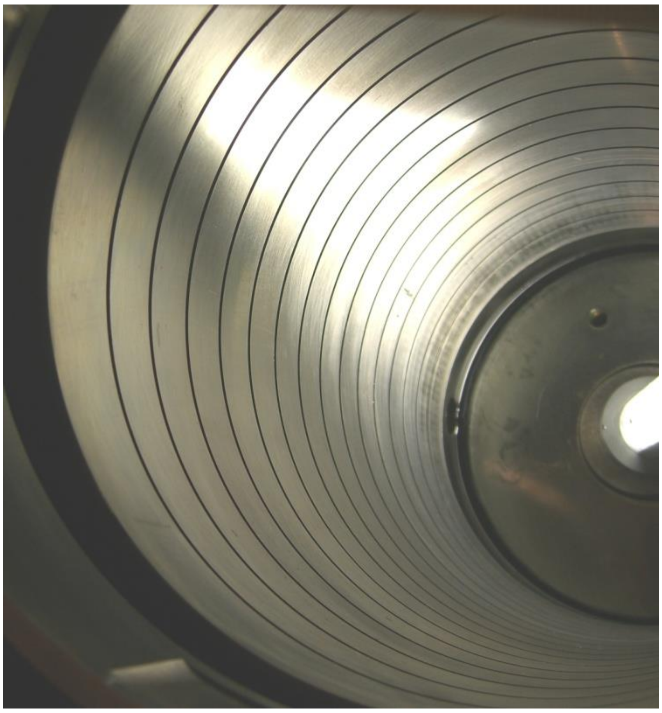

Figure 7. Inside of the working cylinder of 1 MN HFSM with grooves.

The measurements have shown, that with lower force ranges, below 200 kN, the big piston has not worked correctly. It has not rotated perfectly. The investigation has shown that between the cylinder and piston was to high friction. The cause for that has been the collection of fine fibres in to grooves of cylinder, which are located inside of the cylinder and with the lower pressure the fibres have touched the piston. At higher pressure the deformation of the cylinder was high enough to allow the correct working of the piston. A cap has been formed between the piston and the fibres in the groove has form cap that the friction has been reduced.

The investigation has shown, that after refilling of the hydraulic oil by reinstallation, the fibres from filter material has been loosen from walls and built up in to grooves of working cylinder in 1 MN HFSM. Figure 7 shows the inside of cylinder

The reason for the amount of fibres in the hydraulic system was too long a period before changing the filter in Lahti. During the reinstallation it was not possible to clean the oil tank in-depth. The construction of the oil tank makes the cleaning difficult without destroying the tank.

After the correction the results for the rotation effect has returned on the normal level and the rotation of the working cylinder is perfect, rotation effect with magnitude $< 5 \cdot 10^{-5}$.

2.1 Summary of the measurements after reinstallation

Using the constant characteristics of the transfer transducer which is known well it is possible to measure the correct functionality of the force standard machine. A prerequisite is that the transducers are measured at least once in the dead weight force standard machine. For the sensitivity of the rotation effect, it is recommendable to measure them in a dead weight force standard machine which is familiar to the user, where the characteristics of the force machine itself are well known. The final confirmation of the measurement capability is always implementing by a comparison.

3. COMPARISON WITH PTB

The final confirmation was undertaken as a bilateral comparison between PTB and MIKES. For this comparison transfer standards from MIKES were used as well as one transfer force transducer from PTB. The comparison covered the range from 20 kN up to 1 MN. For lower values MIKES carried out comparisons between its own dead weight force standard machines. The results show the importance of time between the calibrations and the need for stable transfer standards.

3.1 Comparison principle

The comparison was implemented with methods for standard machines (FSM). That meant the measurement of transducers in four (steps of 90°) rotational positions, with two increasing loading series for each position and an additional fifth position (360°) with one increasing and decreasing loading. The transducers used for comparison are listed in table 3. All devices are old transfer transducers, which are familiar to the operators and have been used for comparisons over several decades.

Transducer	Type	Serial Nr
1 kN	BA3-100kg-C4	22796
10 kN	BA3-1t-C4	34104
2 kN	BA-200	36242
20 kN	GTM	00221
100 kN	C4, HBM	B52769
200 kN	C12, HBM	#1
500 kN	C12, HBM	#1
1 MN	C4, HBM	82814

Table 3. The force transducers used in the comparison.

3.2 Evaluation of the results

Measurements were performed for all transducers first by MIKES, then by PTB and lastly by MIKES again. Only the transducer C12, used for the 200 kN and 500 kN ranges, was measured first and last by PTB.

For the lower range, 10 kN and 1 kN, the comparison was made between the dead weight force standard machines by MIKES and the results were connected using the 100 kN DWFSM to PTB’s values.

The traceability for dead weights force standard machines is based on the local gravity constant and on the uncertainty determination of masses, which both are below the value $5 \cdot 10^{-6}$. Additional components are the vectorially effect of the force and the gravity constant and the mechanical inhomogeneity of the mechanical construction in the force standard machine. All these components are generally giving the uncertainty for the traceability of a dead weight standard machines lower than $2 \cdot 10^{-5}$.

The evaluation for the hydraulic amplified force standard machine is based on the paper of Dr. A. Sawla, “Uncertainty scope of the force calibration machines”, published in the proceedings of the IMEKO World Congress held in Vienna 2000 [1].

The calculation is based on the following general equations for force generation by means of hydraulic amplified force standard machine:

$$F_{\mathrm{FCM}} = m \cdot g_{\mathrm{loc}}(1 - \frac{\rho_{\mathrm{L}}}{\rho_m}) \cdot Q \cdot (1 - \Delta_{\mathrm{Traceability}}) \quad (1)$$

with

m	the value of mass used to generate the force
g_{loc}	the local gravity constant
ρ_{L}	the air density
ρ_{L}	the density of masses
Q	the multiplication ratio

The uncertainty is calculated as follow:

$$w(F_{\text{FCM}}) = \sqrt{w^2(m) + w^2(g_{loc}) + \left(-\frac{\rho_L}{\rho_m}\right)^2 w^2(\rho_L) + \left(\frac{\rho_L}{\rho_m}\right) w^2(\rho_m) + w^2(Q) + w^2(\Delta_{\text{Traceability}})} \quad (2)$$

where

$$w^2\left(\Delta_{\text{Traceability}}\right) = w^2(\bar{F}_{\text{FCM}}) + w^2\left(\Delta_{\text{HysFCM}}\right) + w^2\left(\Delta_{\text{Drift\_TraStd}}\right) + w^2(\bar{F}_{\text{FSM}}) + w^2(\Delta_{\text{RelDev}}) + w^2(\Delta_{\text{Realization}}) \quad (3)$$

with

$\bar{F}_{\text{FCM}}$	the mean value of forces indicated by the transfer standard in the force calibration machine (FCM)
$\bar{F}_{\text{FSM}}$	the mean value of forces indicated by the transfer standard in the force standard machine (FSM)
$\Delta_{\text{Drift\_TraStd}}$	the relative long-term drift of the transfer force transducer (interval between measurements at the comparing laboratory and in the institute)
$\Delta_{\text{Realization}}$	the relative standard uncertainty of force realisation at the comparing laboratory (PTB)
Δ_{HysFCM}	the relative hysteresis of the FCM determined taking the hysteresis of the transfer standard in the FSM into account
Δ_{RelDev}	the relative deviation of the mean force values indicated between the FCM and the FSM

The uncertainty components for the density of the mass used and air are simplified to their measurement uncertainty. These changes are negligible for the final result.
The complete calculation is made in Excel and it is not possible to show all calculations in this document.

The following table shows the output of the calculation as example for one force step, 400 kN, in the hydraulic amplified force standard machine.

Quantity	Estimate	Relative half-width value a	Probability distribution	Relative standard uncertainty	Sensitivity cofficient	Relative uncertainty contribution
m	4072,663442	1,0E-06	rectangular	5,8E-07	1	5,8E-07
g_{loc}	9,821729	5,0E-07	rectangular	2,9E-07	1	2,9E-07
ρ_L	1,15	3,0E-02	rectangular	1,7E-02	1,5E-04	2,6E-06
ρ_m	7850	1,0E-02	rectangular	5,8E-03	1,5E-04	8,7E-07
Q	10	4,0E-05	rectangular	2,3E-05	1	2,3E-05
$\Delta_{\text{Realization}}$	0kN		normal	1,00E-05	1	1,0E-05
F_{FSM}	400		normal	1,2E-05	1	1,2E-05
F_{FCM}	400		normal	6,6E-06	1	6,6E-06
Δ_{HysFCM}	0	6,2E-07	rectangular	3,6E-07	1	3,6E-07
$\Delta_{\text{Drift\_TraSta}}$	0	3,2E-06	rectangular	1,8E-06	1	1,8E-06
Δ_{RelDev}		-2,7E-05	triangular	-1,1E-05	1	-1,1E-05
F_{FCM}	400					3,09E-05
Expanded rel. uncertainty $W = k\,w(F_{FCM})$ for $k = 2$						6,18E-05
Normalised error E_n related to W				$E_n = \Delta_{\text{Re}\,lAbw} / W$		-0,88
Specification of best measurement capability W_{cmc}						1,00E-04
Normalised error E_n related to best measurement capability				$E_n = \Delta_{\text{RelAbw}} / W_{cmc}$		-0,55

Table 4. Example of the calculation of the measurement uncertainty for 400 kN in 1 MN HFSM.

3.3. Summary of the results of the comparison

The target was to obtain the best Calibration and Measurement capability (CMC): for the range from 80 kN to 1 MN, lower than $1\cdot10^{-4}$; and for the other ranges, $< 5\cdot10^{-5}$. This was also the earlier CMC with the exception for range from 2 kN to 10 kN, where the CMC was $< 2\cdot10^{-5}$. The Figure 8 shows the results for the range from 80 kN to 1 MN with the corresponding measurement uncertainties. For the lower value, it must be taken into account that measurement is made with a 500 kN transducer using the range from 0 kN to 200 kN.

The upper range from 400 kN to 1 MN had relative long period between the first and the second measurements, which may have influenced the result.

The range from 8 kN to 100 kN, Figure 9, has, for 20 kN a small deviation to the comparing value. This effect may result from the small error in the 20 kN DWFSM zero point. The mechanical and electrical zero points had small difference and this was detected after the comparison.

The results of the lowest range, from 0,4 kN to 10 kN, are shown on Figure 10, comparison between two DWFSM of the laboratory.

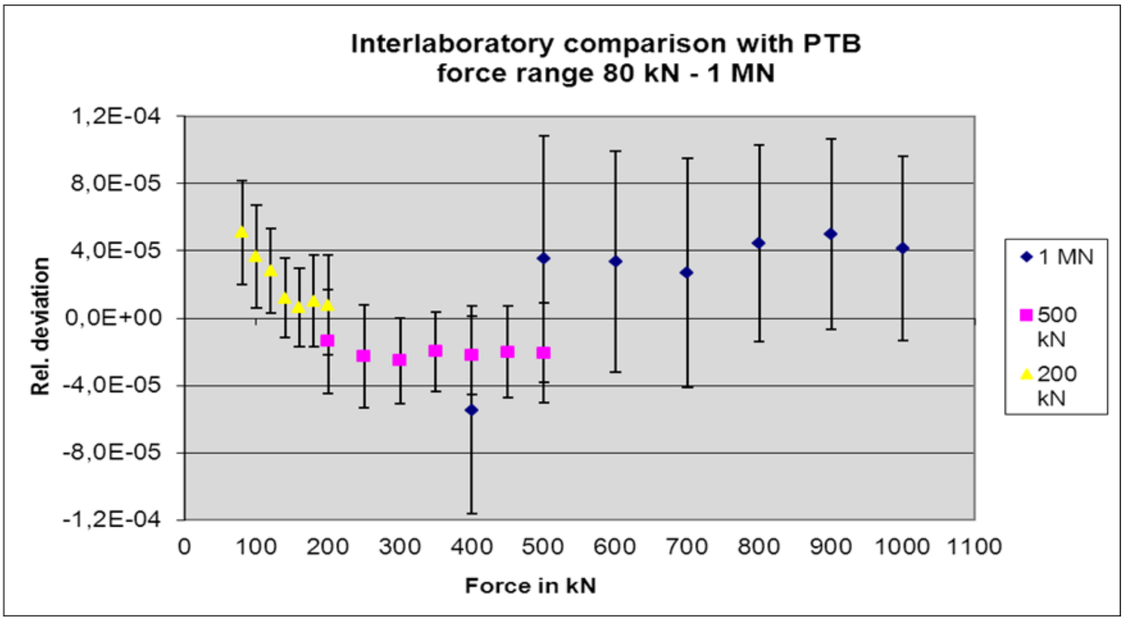

Figure 8. Summary of the results of the comparison between PTB and MIKES for the range from 80 kN to 1 MN.

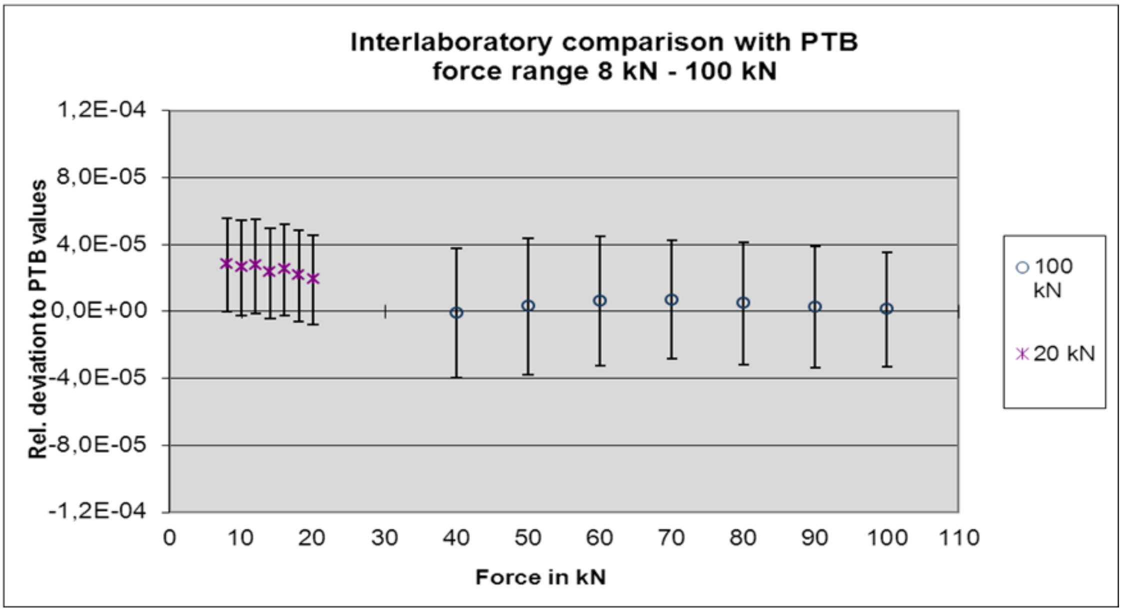

Figure 9. Summary of the results of the comparison between PTB and MIKES for the range from 8 kN to 100 kN.

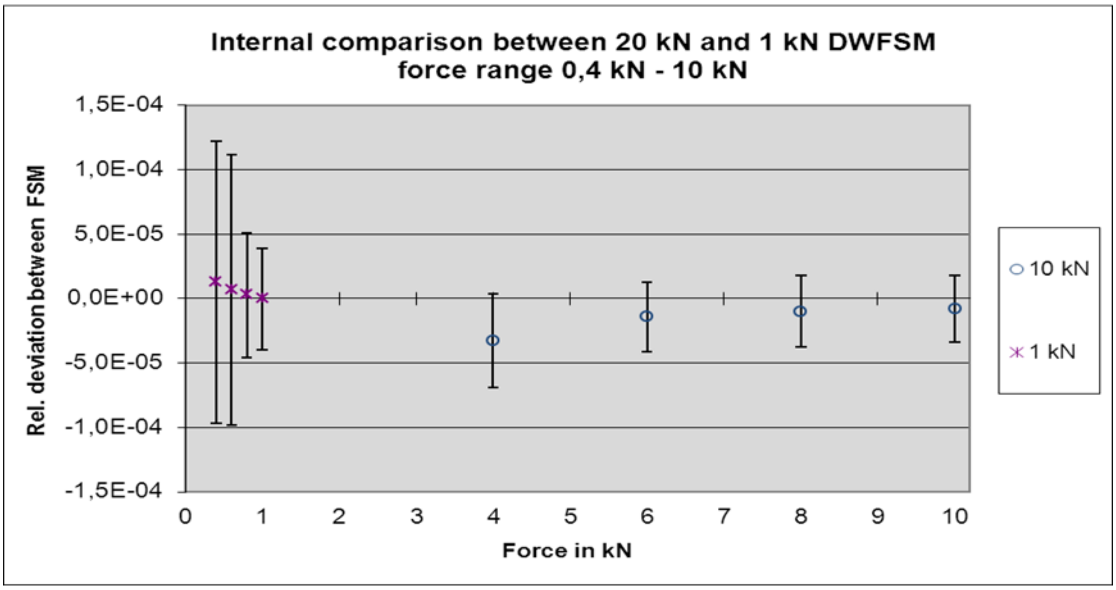

Figure 10. Summary of the results of the comparison between the DWFSM (1 kN and 20 kN) by MIKES for the range from 0,8 kN to 10 kN.

4. CONCLUSION

The complete time schedule planned to relocate the laboratory from Lahti to Kajaani, which is about 450 km north of Lahti, was 9 months and it was kept to. The biggest problem was unexpected friction in the working cylinder in the 1 MN HFSM. The related investigation and repairs took approximately 1 month. The other problem effecting the final accuracy was the small zero error in 20 kN DWFSM as well the small unexpected swinging of the masses. These types of errors can be detected only in the final comparison and when researches have become familiar with the devices. To undertake a time analysis the relocation started in February 2011 and the installation work was completed at the end of October 2011. In the beginning of 2012 the intercomparison started and it was finished at the end of June 2013. Some additional measurements were still performed in September 2013.

As a result the relative uncertainties can be confirmed as follows:

80 kN to 1 MN	CMC < $1•10^{-4}$
8 kN to 100 kN	CMC < $5•10^{-5}$
1 N to.. 10 kN	CMC < $5•10^{-5}$.

5. REFERENCES

References:

[1] Sawla, A.: Uncertainty scope of the force calibration machines. Proc. IMEKO World Congress, Vienna, Austria, 2000.

[2] Euramet: EURAMET cg-4, version 2.0(03/2011), Uncertainty of Force Measurement.

[3] Pusa. A.: Force Key Comparison CCM.F-K1.a and CCM.F-K.1.b 5 kN and 10 kN, BIPM.