The Harmonized high-pressure Natural Gas cubic meter in Europe and its benefit for the user and metrology.

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EXPANDED SUMMARY:
The paper describes the method of the harmonization process for the natural gas cubic meter and the backgrounds of the harmonized reference values for the cubic meter of Natural Gas which are in use in Germany and The Netherlands since November 1st 1999, see [1]. The prerequisites of the harmonization process, underlying procedures, results obtained so far and the mutual benefits will be pointed out as well as the economic consequences for the European market. This harmonization process can be considered as the first step towards the realization of a European unit of volume for Natural Gas at operating conditions.

1. PTB and NMi-VSL operate independently realized Traceability-Chains. At NMi-VSL a system based on mass-comparison of gas-flow is in use, whereas the German National facility for high-pressure gas-flow standards, PIGSAR has its traceability-chain in operation based on a Piston-Prover (Volume comparison) and is the national lab for natural gases under supervision of PTB.
2. The uncertainty-budget of each of the systems is fully known, understood and accepted.
3. A permissible difference between the two systems smaller than the Root Square Sum of the corresponding uncertainties is established (i.e. observed differences are not significant).
4. The stability of each chain (sets of reference values) is demonstrated. Stability refers to the reproducibility of the Reference Values over the years.
5. The Degree of Equivalency is established (based on historic performance and on accepted uncertainties) In addition it is required that the partners have overlapping flow-rates and similar pressures. PTB and NMi-VSL have applied three sets of different turbine meters (two in series) to allow a maximum of overlap.

The paper describes the application of a quadratic weighing technique to obtain Harmonized Reference Values which represent the best known reference values of the two facilities. Under the umbrella of the Mutual recognition Arrangement (MRA), see [2], this technique has also been recommended by an expert team of the BIPM to define Reference Values, mainly for so-called Key Comparisons as will be explained in detail, see e.g. [3].

The accepted degree of equivalency, based on the total uncertainty of each traceability-system, is applied again to establish the harmonized uncertainty.

Again this process follows a BIPM recommendation, summarized in [3]. The harmonized uncertainty consists of the uncertainties of either primary realization together with the uncertainty of the comparison. This will be explained in all details.
Both partners have agreed to search continuously for improvements of the two independently realized traceability chains to meet future demands for more stable Reference Values with smaller uncertainties. The main benefit for customers is the same and equivalent calibration of meters at any calibration test rig in Germany and The Netherlands. The harmonization as accomplished by PTB and NMi-VSL is principally open to third parties if all five prerequisites can be met and if it is practically feasible.

The harmonization procedure has already been described in a previous paper presented at FLOMEKO 2003 in Groningen [4] to point out the philosophy of the procedure. Here we want to present more details on the actually obtained measurements. As Germany is a large gas consumer and a transit country for natural gas, The Netherlands are exporting and importing large gas quantities, custody transfer manipulations are highly important, see [5].

HIGH-PRESSURE GAS FACILITIES IN EUROPE

The following figure 1 presents a visualization of the available European high-pressure gas facilities which are currently in use for calibration of gas meters.

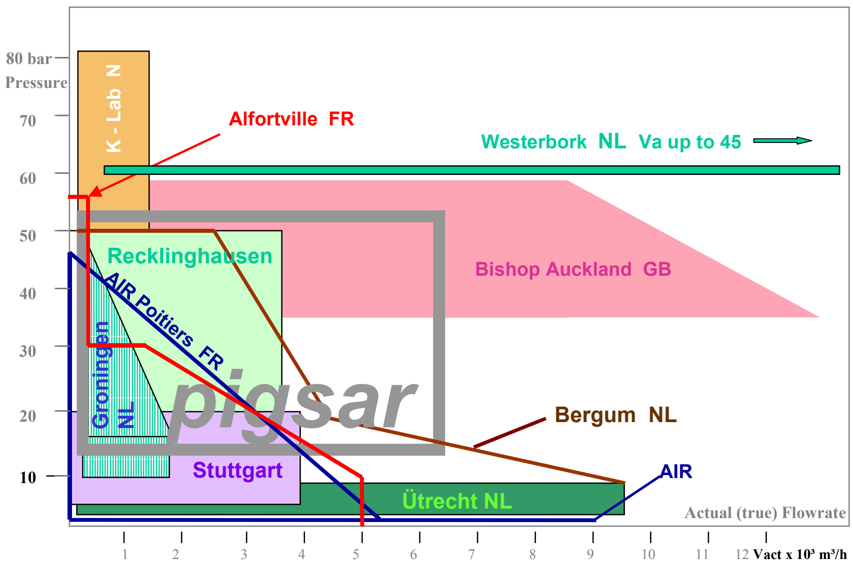

*Figure 1: Visualization of the European calibration and Measuring Capabilities of all test rigs for natural gases which are currently in use. The harmonization process has been realized between **pigsar**, Bergum, Groningen and Westerborg. All other facilities like Stuttgart, Recklinghausen, Ütrecht and Bishop Auckland are traceable to the harmonized reference values.*

As it can bee seen from Fig. 1, the overlapping range between ***pigsar*** and Bergum is quite large and very appropriate for the process of defining common reference values.
We consider in the future to harmonize with BNM in France using the facilities in Alfortville and Poitier, the French National Standards of BNM.

NMi-VL realize a traceability chain based on their basic verification system, using mass comparison with gas flow, see [6]. More details are available in [4]. PTB and ***pigsar*** realize a cubic meter based on a piston prover operated at pressures up to 50 bar with a very attractive short traceability chain, see [7] and [8]

It has to be pointed out, that both facilities are completely independent of each other as they realize the natural gas cubic meter in very different techniques. Therefore, prerequisite #1 is fulfilled.

The uncertainty budgets of both facilities have been published, see e.g. [6] for NMI-VSL and [9] , [10] and [11] for ***pigsar***, and have been accepted .

The long-term stability of both facilities has been demonstrated and published, see e.g. [4] for NMi-VSL. Here we will demonstrate ***pigsar's*** stability over years in detail.
Therefore, prerequisites #2 and #4 are fulfilled.

SITUATION PREVIOUS TO HARMONIZATION

Figure 2 gives a typical results of a meter calibration done at PTB (***pigsar***) and NMi-VSL (Bergum) at pressure stages 20 and 50 bar before harmonization. The meter readings of ***pigsar*** and NMi-VSL are a little bit different , however, he uncertainties due overlap in the entire Reynolds range, far better than the specified uncertainties. This demonstrate the high reproducibility of meters commercial available. Due to this high reproducibility which is much better than the uncertainty, a difference $\Delta_{PTB\text{-}NMi}$ between the calibration in Netherlands and Germany can be observed. It has to be emphasised that such difference is not significant (because it is less than the uncertainty range) but the "Homus Oeconomicus" could made use of this small difference, as we have explained recently, see [4].

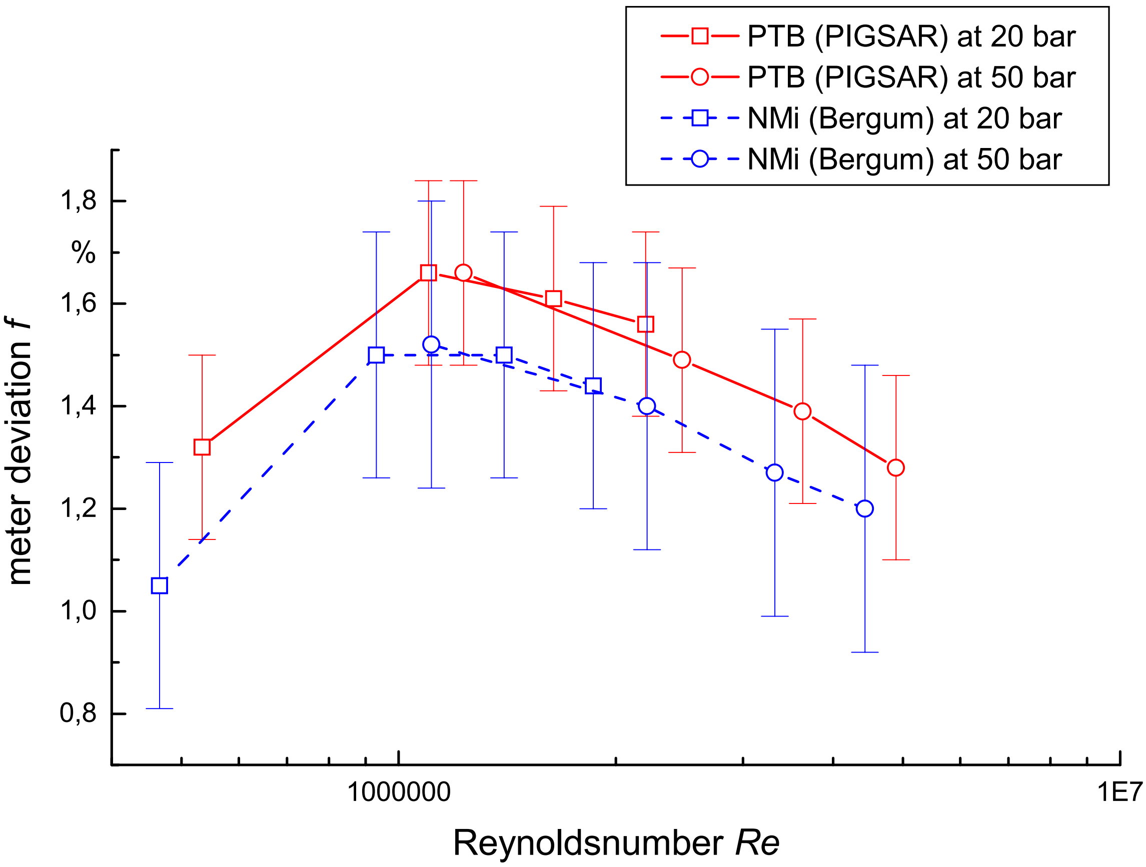

*Figure 2: Typical results of meter calibration done at **pigsar** and NMi-VSL (Bergum) before harmonisation. All results of meter deviation f are inside the overlapping range of the uncertainty levels. Only due to high reproducibility of both calibration facilities as well as gas meters (which is much better than the uncertainties) a difference $\Delta_{PTB\text{-}NMi} = f_{PTB}\text{-}f_{NMi}$ can be observed. The uncertainty levels (k = 2) shown in the graph are the particular uncertainties of **pigsar** and NMi-VSL.*

EQUIVALENCY OF FACILITIES

As PTB's and VMI-VSL's facilities are equivalent to each other, the harmonization process can be finalized according to the aforementioned recommendation of and expert team of the BIPM, see [3]. In this recommendation, summarized by Cox, the technique for comparing facilities with the aim to define reference Values has been described. It must be pointed out here, that the harmonization process of PTB and NMi-VSL follow strictly this recommendation as described in chapter 2 (Conditions of use) and chapter 5 (Procedure A) of [3].

Equivalence was defined as:

Stability of each of the chains has been demonstrated. Stability refers to the reproducibility of the reference value over the years.
The uncertainty budget of each of the systems is fully known and mutually accepted.
A permissible difference between the two systems smaller than Root Square Sum of the corresponding uncertainties (2σ) is established. Figure 2 demonstrates visually, that the prerequisites #3 and #5 are fulfilled. A more analytical approach has been presented in [3].

Both calibration chains are completely independent of each other.
To reach the aim of harmonisation in a maximum range a huge number of comparison measurements had to be done. For that purpose three transfer packages were built. The technical data are given in table 1 and an outline in Figure 3 .

Table 1: Technical Data of Transfer Packages, see also Fig. 3

Type of meters	Reynolds balanced turbine meters
Number of meters per package	2 (two different constructions in each package)
Diameters	DN100 (4"); DN250 (10"); DN400 (16") all packages in ANSI600
Pressure stages used in harmonisation	20 and 50 bar
Flow rates (working conditions)	40 ... 400 m^3/h (DN100); 400 ... 4000 m^3/h (DN250); 650 ... 6500 m^3/h (DN400)
Length of inlet pipe (each meter)	5 diameter
Length of outlet pipe (each meter)	3 diameter
Flow conditioner at inlet	Zanker-type
Over all length per package	22 diameter

With every transfer package a comparison measurement at pressure stages 20 and 50 bar[1] where done by both partners. So, in summary 12 pairs of comparable meter calibrations were collected.

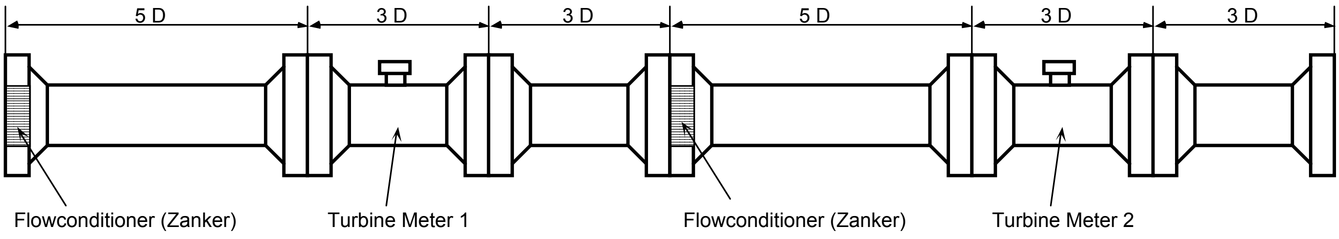

Figure 3: Block diagram of transfer packages used for harmonisation.

HARMONIZATION PROCESS FOR REFERENCE VALUES

Based on the facts equivalence and independence of calibration chains, the "true value" f_{Ref} of meter deviation shall be assumed as the weighted average of any pair of results. In figure 4 an example of one pair of meter calibration is given. The meters used in the packages are Reynolds balanced, therefore the determination of difference $\Delta_{\mathrm{PTB\text{-}Ref}}$ ($\Delta_{\mathrm{NMi\text{-}Ref}}$ resp.) to the common reference level is done with respect to Reynolds number. In practise each pair of measuring point is close together but is not exactly at the same Reynolds number. Thus polynomial approximation of calibration curve f is used as to be seen in figure 4. The weighted average f_{Ref} is calculated now using the polynomials. The differences $\Delta_{\mathrm{PTB\text{-}Ref}}$ and $\Delta_{\mathrm{NMi\text{-}Ref}}$ are determined for each measured point relative to average polynomial.

$$f_{\mathrm{Ref}} = w_{\mathrm{NMi}} f_{\mathrm{NMi}} + w_{\mathrm{PTB}} f_{\mathrm{PTB}} \quad \text{with} \quad w_{\mathrm{NMi}} = \frac{1}{\frac{U_{\mathrm{NMi}}^2}{U_{\mathrm{PTB}}^2} + 1} \quad \text{and} \quad w_{\mathrm{PTB}} = \frac{1}{\frac{U_{\mathrm{PTB}}^2}{U_{\mathrm{NMi}}^2} + 1}$$

$$\Delta_{PTB-\mathrm{Ref}} = f_{\mathrm{PTB}} - f_{\mathrm{Ref}} \quad \text{and} \quad \Delta_{NMi-\mathrm{Ref}} = f_{\mathrm{NMi}} - f_{\mathrm{Ref}}$$

f - meter deviation w - weighing factor

Δ - difference U - uncertainty (k = 2)

[1] In the case of DN400-package, NMi-VSL performed also measurements at 60 bar (Westerborg).

f_{Ref} is the meter deviation of the meter under test based on the harmonised high pressure cubic meter of NMi-VSL and PTB

This weighted average has been defined in exactly the same way as recommended by Cox, see [3], chapter 5.

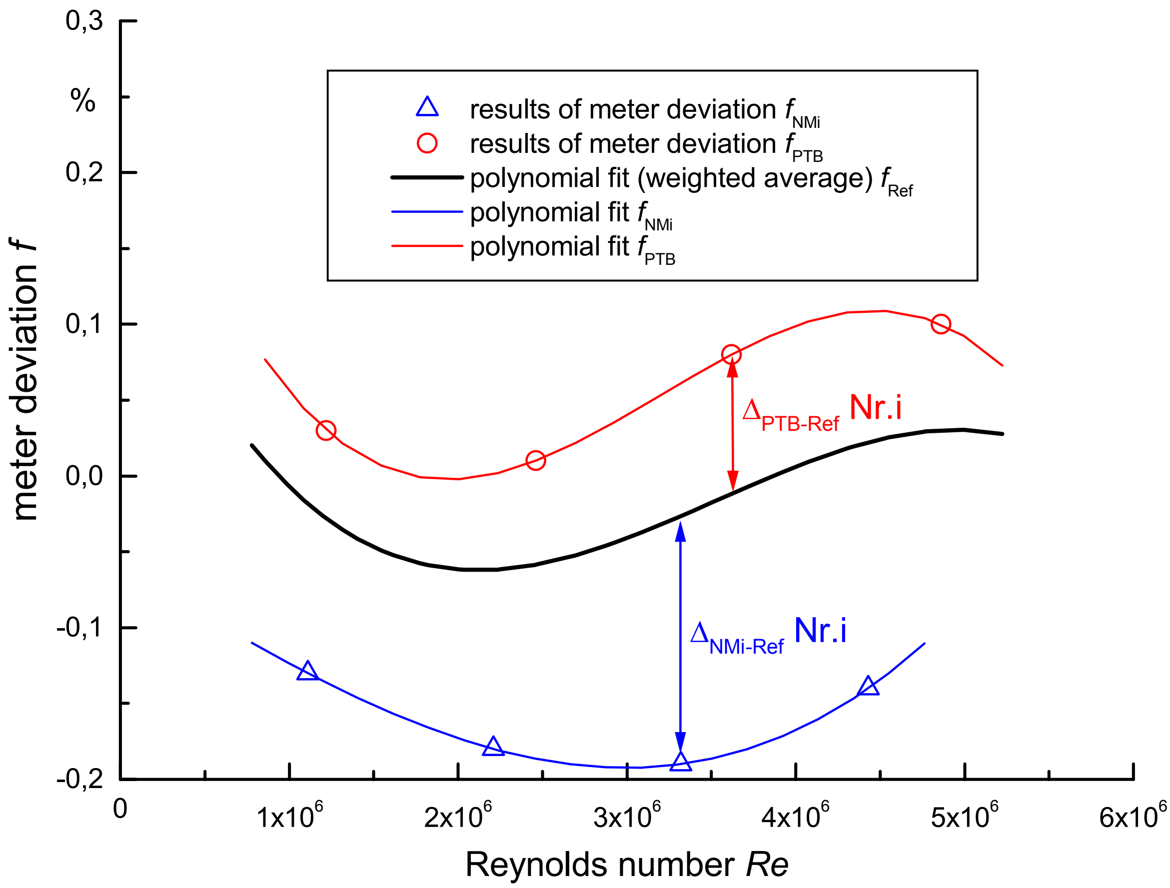

Figure 4. Results of comparison for one meter in one pressure stage and determination of differences $\Delta_{PTB-Ref}$ and $\Delta_{NMi-Ref}$

Finally, all determined differences $\Delta_{PTB-Ref}$ and $\Delta_{NMi-Ref}$ for all meters in all pressure stages were put in to one graph depending on Reynolds number (figure 5). The reproducibility (double standard deviation) of calibrations are less than the half of the uncertainty budget of each participant. Nearly every result of one participant lies in the uncertainty interval of the other. Although three different meter sizes and two different pressure stages for each size were used, there is no significant discontinuity to be seen. This is an evident demonstration of high quality and reliability of calibration work of both partners, NMi-VSL and ***pigsar***.

The determined difference $\Delta_{\text{PTB-NMi}}$ between NMi-VSL and ***pigsar*** increases slightly with Reynolds number. The slope of the results of NMi-VSL is only a mathematical effect of the weighing process because the uncertainty U_{NMi} of NMi´s chain increases with pressure stage. The trends for $\Delta_{\text{PTB-Ref}}$ and $\Delta_{\text{NMi-Ref}}$ in Figure 5 finally approximated by a linear function depending on logarithm of Reynolds number. These linear functions are used as correction functions in order to disseminate a harmonised value of cubic meter high pressure natural gas in both countries.

Due to the comparison measurements we have two independent sources of information of the "true value" given by both calibration chains, hence we obtain a lower uncertainty level U_{Ref} of meter deviation f_{Ref} based on harmonisation:

$$U_{\text{Ref}} = \sqrt{w_{\text{NMi}}^2 U_{\text{NMi}}^2 + w_{\text{NMi}}^2 U_{\text{PTB}}^2} \quad \text{with} \quad w_{\text{NMi}} = \frac{1}{\dfrac{U_{\text{NMi}}^2}{U_{\text{PTB}}^2} + 1} \quad \text{and} \quad w_{\text{PTB}} = \frac{1}{\dfrac{U_{\text{PTB}}^2}{U_{\text{NMi}}^2} + 1}$$

U - uncertainty (k = 2) w - weighing factor

U_{Ref} is uncertainty of the deviation of meter under test based on the harmonised high pressure cubic meter of NMi-VSL and PTB

E.g. if both parties would have equal uncertainties of U_{NMi} = U_{PTB} = 0,1 % the resulting uncertainty would be U_{Ref} = 1/sqrt(2·0,1) % = 0,07 %. In the harmonisation process an over-all uncertainty level U_{Ref} = 0,15 % was determined.

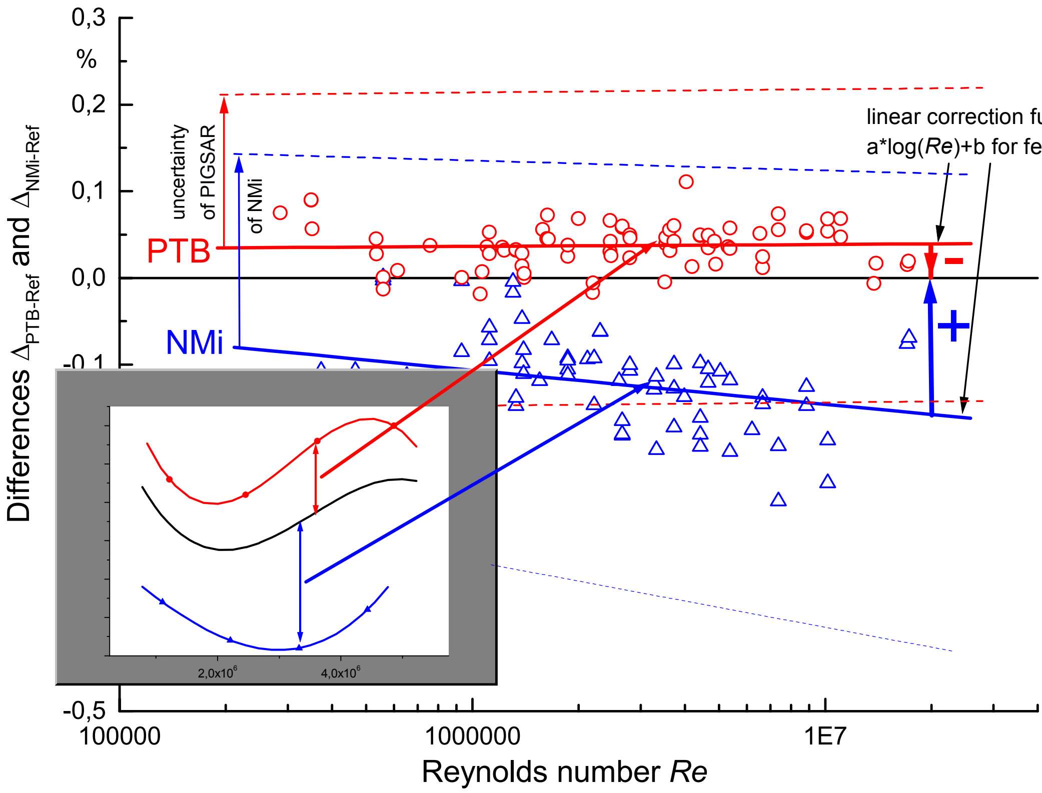

Figure 5: Summary of all determined differences $\Delta_{PTB-Ref}$ and $\Delta_{NMi-Ref}$ for all meters in all pressure stages plotted as function of the Re-number. The difference between both traceability chains is clearly to be seen but much smaller than the uncertainties . Within the reproducibility of the results there is no significant discontinuity although three different meter sizes and two different pressure stages for each size were used. To implement the feed back of comparison results linear approximations of differences $\Delta_{PTB-Ref}$ and $\Delta_{NMi-Ref}$ were determined.
*The uncertainty levels (k = 2) shown in the graph are the particular uncertainties of **pigsar** and NMi-VSL.*

What does that mean for the actual calibration of a meter?
The cubic meter obtained at ***pigsar*** is a little bit too large and the cubic meter obtained at Bergum is a little bit too small and therefore both sides have to correct their results with a correction factor (which is actually a function of Re number, pressure and flow rate).

The positive outcome for the customer is, that he gets always the same calibration in Germany and the Netherlands at any test facility and he can enjoy the benefit of a very stable and small uncertainty of the harmonized reference value.

The benefit for metrology is the reduced uncertainty of the harmonized reference value.
Finally, it should be pointed out explicitly, that both NMIs, namely PTB (Germany) and NMi-VSL are disseminating since November 1999 the same ("harmonised")

high pressure natural gas cubic meter for all calibrations, which are performed at their test facilities.

WATCH-DOG CHECKS FOR QUALITY ASSURANCE

After establishing and disseminating the harmonised cubic meter since November 1999 regular checks have been necessary. These checks (so-called watchdog checks) have been done every half year with at least one of the transfer packages. With an example of these results this paper should close. In figure 6 the result of two watchdog checks for one meter of the DN250-package (10") are given. Comparing these results with the example in figure 2 the improvement is to be seen. First there is no difference between German and Dutch calibration which can be utilised. Secondly the uncertainty is reduced to the common level of 0,15 % and thirdly the reliability of long term stability of calibration chains is improved due to the regular checks.

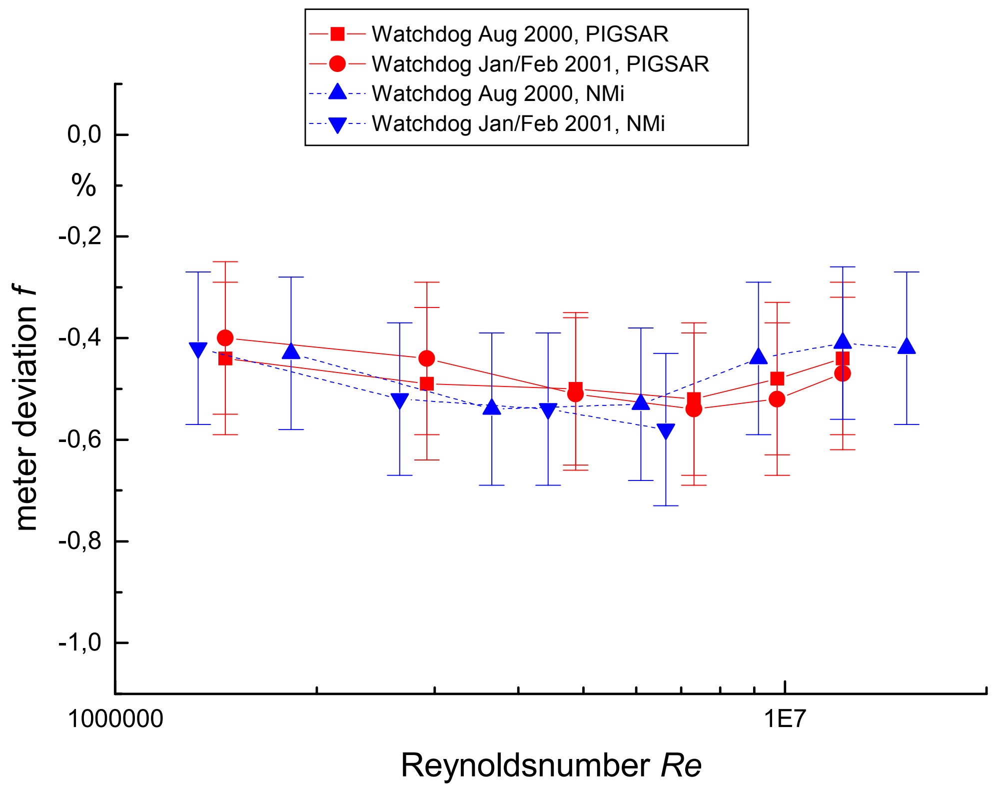

Figure 6: Calibration of a turbine meter DN250 (10") as watchdog checks . The uncertainty level (k = 2) shown in the graph is the uncertainty U_{Ref} = 0,15 % of the harmonised reference value of PTB ***(pigsar)*** *and NMi-VSL.*
See also figure 2 to observe the effect of harmonisation. The scale for meter deviation f in figure 6 has the same partition of 0,2 % as in figure 2.

The harmonization process using weighted averages of both facilities leads to a very stable reference value and reduced uncertainty for the reference value.
In the following chapters we will demonstrate the long-term stability of ***pigsar***, as the time line of NMi-VSL facilities has recently been figured out, see [4].

LONG TERM STABILITY AND REPRODUCABILITY OF ***pigsar***

In the following we want to figure out an estimation for the long term stability and reproducibility of the working standards used at ***pigsar*** and of the harmonised reference value as well as the reproducibility of the transfer meter used in the harmonisation. For that purpose we evaluate a large data base containing the calibration values of workings standards at ***pigsar*** and the intercomparisons between NMi-VSL and PTB ***(pigsar).***

The progression of the calibration values of working standards at ***pigsar***

At ***pigsar*** there are nine working standards in use. Fore details see e.g. [7], [8] and [12]. Nine (9) working standards are commercial available turbine meters. They have three sizes: 1xG100 (Q_{max}=160 m^3/h), 4xG250 (Q_{max}=400 m^3/h), 4x G1000 (Q_{max}=1600 m^3/h), compare Fig. 7.

Figure 7: Outline of the national lab ***pigsar*** *of PTB. In the right corner one recognizes the working standards which will be used to calibrate meters.*

In the calibration process at ***pigsar*** each working standard no.# *i* gets a calibration value $C_i(Re)$ as a function of Reynolds number. The recalibration at ***pigsar*** have been performed every third year, so we get calibration values for every standard for the years 1995, 1998 and 2001 ($C_{i,95}$, $C_{i,98}$, $C_{i,01}$). For evaluation of the stability and reproducibility it is helpful to look at the differences from recalibration to recalibration:

$$\Delta_{cal,i,X->Y} = C_{i,year\ X} - C_{i,year\ Y}$$

All values $\Delta_{C,i}$ are presented in Fig.8.

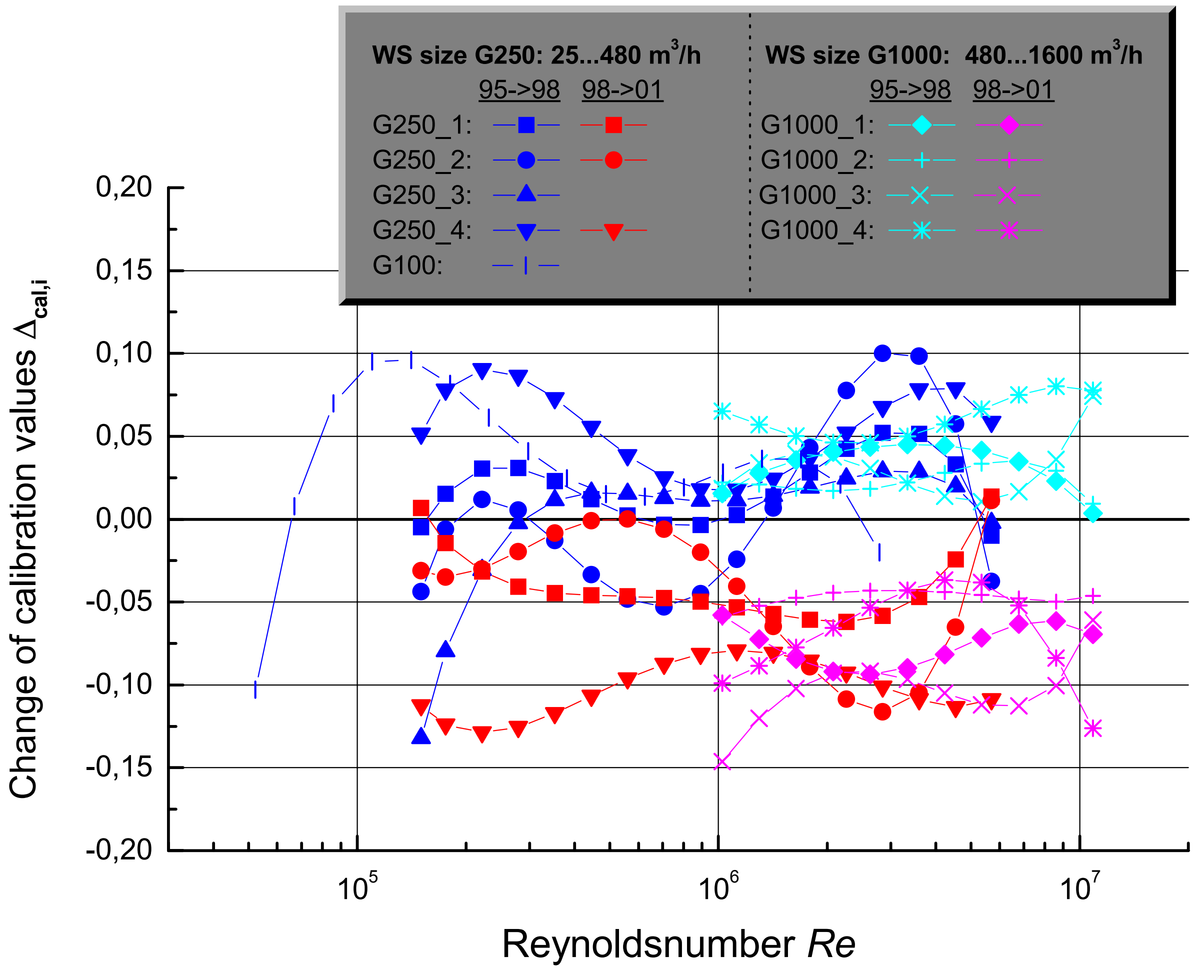

*Figure 8: Progression of $\Delta_{cal,i}$ for all working standards at **pigsar**. Missing values for period 98 to 01 are working standards which were replaced due to damages (history got lost).*

In Figure 8 we find an arrangement in groups for the different calibration periods 1995 to 1998 (blue and cyan) and 1998 to 2001 (red and magenta). Therefore it is useful to split the values $\Delta_{C,i}$ into two parts: Δ_{ref} – the common shift of all working standards and $\Delta_{WS,i}$ – the individual shift of every working standard WS_i.

$$\Delta_{cal,i} = \Delta_{ref} + \Delta_{WS,i}$$

The common shift Δ_{ref} we can interpret as a change of reference at ***pigsar***. For this change Δ_{ref} we get a good estimation using the arithmetic average:

$$\Delta_{ref} = \frac{1}{n}\sum_{i=1}^{n}\Delta_{cal,i}$$

In Fig. 9 the results for Δ_{ref} are shown. We split the working standards into two groups (below 480 m^3/h and above 480 m^3/h). The reason is the scaling-up-procedure used for the calibration of the larger workings standards, so we have two different numbers of calibration steps starting from the high pressure piston prover (two steps more for the standards G1000).

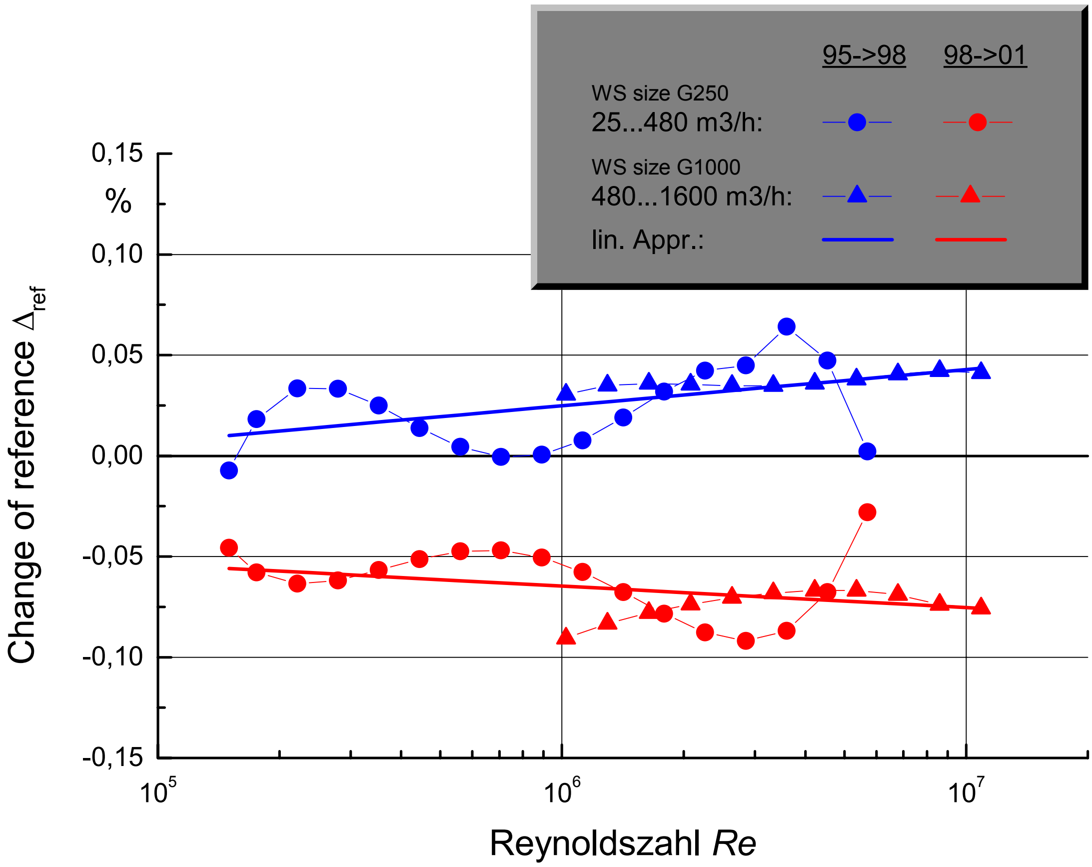

Figure *9: Change of reference Δ_{ref} at **pigsar** from 1995 to 1998 and 1998 to 2001.*

It can bee recognized in Fig 9 that there is no additional shift in the reference due to the scaling-up-procedure. This is one more proof for the reliability of the calibration procedure at ***pigsar***. Over all we get values for Δ_{ref} in the order up to (±)0,08%.

Up to here it can not be decided whether the change Δ_{ref} is generated by the recalibration process or due to a drift within the facility over the time. This can be proofed only by comparison with an independent facility and is shown later on with the evaluation of the history of harmonisation between NMi-VSL and PTB.

Analogue we look now to the individual shifts of the working standards $\Delta_{WS,i}$ which is:

$\Delta_{WS,i} = \Delta_{cal,i} - \Delta_{ref}$ The results are given in Fig. 10.

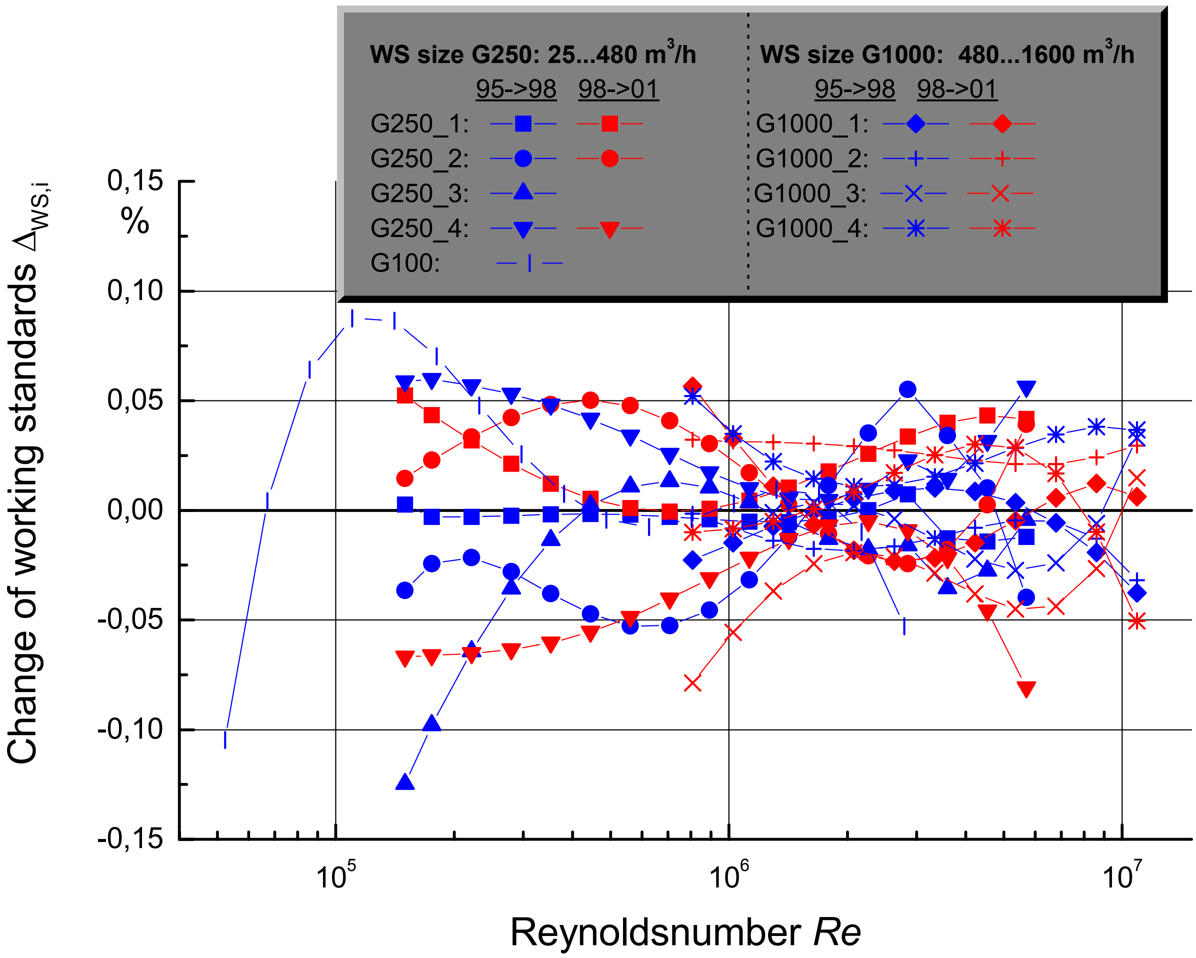

*Figure 10: Individual shifts of working standards $\Delta_{WS,i}$ at **pigsar** from 1995 to 1998 and 1998 to 2001.*

The individual shifts can be interpreted as an indication of long term stability of each working standard which mainly affect the reproducibility of the test facility. As an overall estimation we find in Fig. 10 a uncertainty $U_{repro,WS}$ = 0.05 % which is exceeded in Fig. 10 only rarely or at the extreme operating edges. The total reproducibility of ***pigsar*** shall be a little bit higher because there is also all other instrumentation included ($U_{repro,WS} \geq U_{repro,WS}$). These values have to be found also in the analysis of the history of harmonisation between NMi-VSL and PTB.

LONG TERM STABILITY AND REPRODUCABILITY OF THE HARMONIZED REFRENCE VALUE BETWEEN ***pigsar*** NMi-VSL

Within the harmonisation between NMi-VSL and PTB we have got a large data base of intercomparisons which allows us to find out something about long term stability and reproducibility of the test facilities and transfer meters. As mentioned above we perform our intercomparisons always with meter packages containing two meters, so we are able to split the variations in the results into the parts of facilities and transfer meters using a method like "Youden" analysis.

To make this a little bit more transparent we look in the following to the total differences $\Delta_{NMI\text{-}PTB,\ meter\ i}$ of calibration values of transfer meter *i* determined at NMi $C_{NMi,meter\ i}$ (test facility Bergum) and PTB $C_{PTB,meter\ i}$ (test facility ***pigsar***):

$$\Delta_{NMi-PTB,Meter\ i} = C_{NMi,Meter\ i} - C_{PTB,Meter\ i}$$

For the harmonisation campaigns 1999 and 2001 we got a lot of single data $\Delta_{NMI\text{-}PTB,\ meter\ i}$ (from each transfer meter of each transfer package at different pressures and flow rates) which are plotted in Fig. 11 against the Reynolds number.

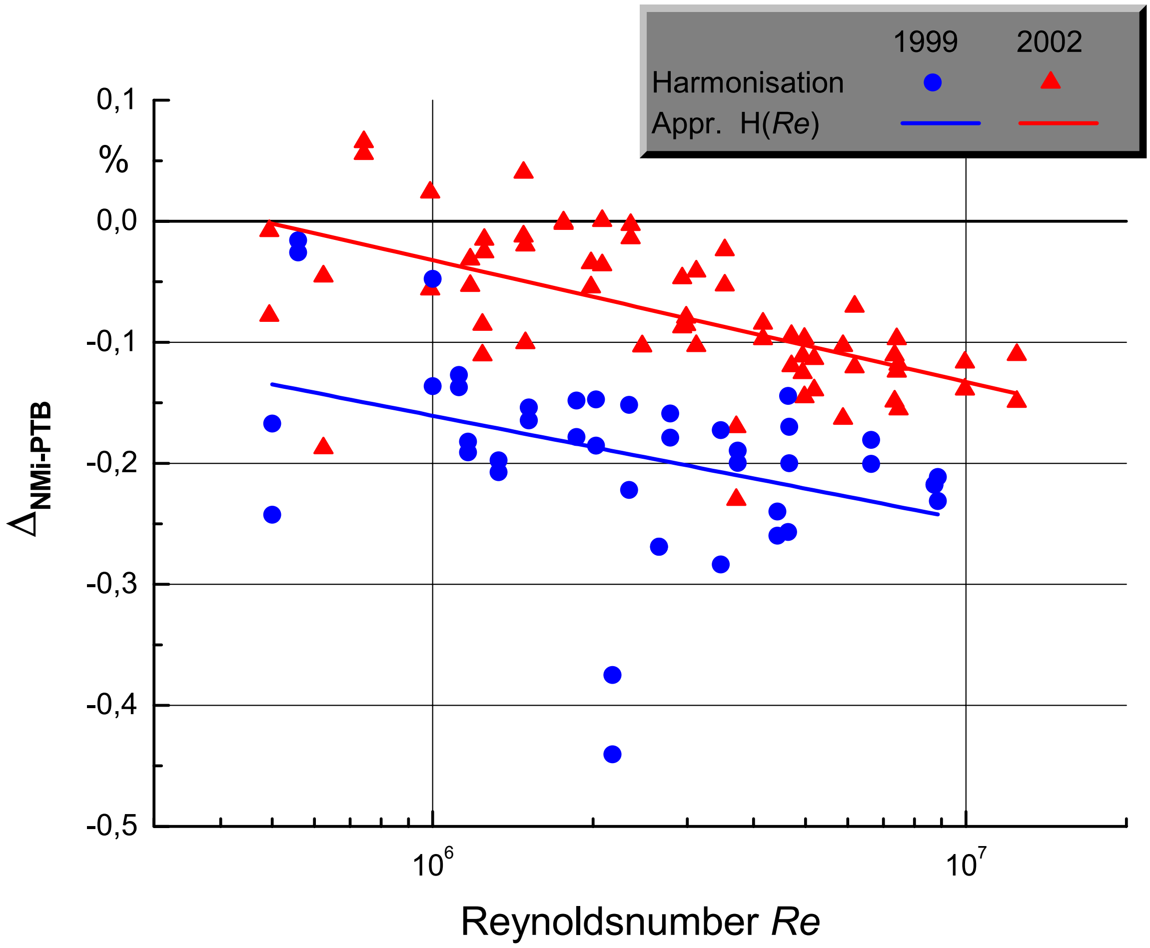

*Figure 11: Individual shifts of working standards $\Delta_{WS,i}$ at **pigsar** from 1995 to 1998 and 1998 to 2001.*

In Fig. 11 it is not possible to detect a significant differences between the values determined at different pressures, flow rates or diameters of transfer package. Overall we can approximate the difference between NMi-VSL and PTB by a linear function against the logarithm of Reynolds number:

$$\overline{\Delta}_{NMi-PTB} = H(\mathrm{Re}) = a_0 + a_1 \log(\mathrm{Re})$$

This function $H(Re)$ is naturally the difference between the correction functions of PTB and NMi-VSL for the feed back as shown above in Fig. 11.

After the application of the harmonisation in each facility we want to look now to the remaining differences $\Delta_{\mathrm{harm,meter}\ i}$ of meter indications:

$$\Delta_{Harm,Meter\ i} = \Delta_{NMi-PTB,Meter\ i} - H(\mathrm{Re})$$

There are three groups of measurements we want to differentiate

- The harmonisation campaign 1999
- The quality-assurance-tests in the period 2000 to 2002 and
- The harmonisation campaign 2002

The remaining differences $\Delta_{harm,meter\ i}$ for the harmonisation campaigns are the residue of the single data in Fig.11 with respect to the linear approximation H_{1999} and H_{2001}. But for the quality-assurance-tests in the period 2000 to 2002 the values $\Delta_{harm,meter\ i}$ are directly determined as the difference $C_{NMi,meter\ i} - C_{PTB,meter\ i}$. In Fig. 12 the results are plotted in a “Youden” graph.

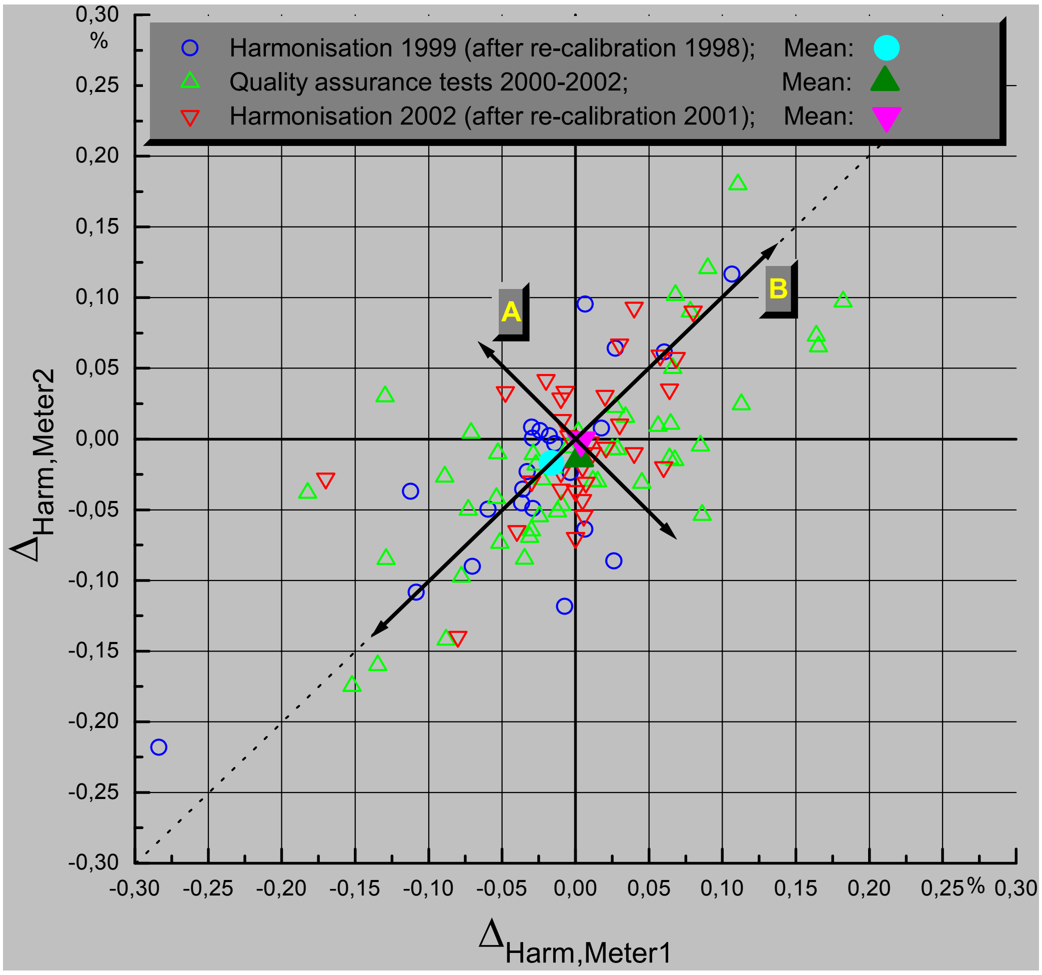

Figure . 12: Youden graph of the remaining differences $\Delta_{harm,meter\ i}$ based on the two meters of each transfer package after application of harmonisation between NMi-VSL and PTB. The relation of the spread spans A and B to the statistical meaning you will find in the text.

First of all we can look in Fig. 12 to the overall averages of data for the three different groups of measurements. Of course, the average for the harmonisation campaigns has to be close to zero because this is the analytical condition of the residue calculation. But more important is the average of the results determined within the quality-assurance-test, which were determined physically in the intercomparisons. This value is also very clause to zero what means that the harmonised reference value did not shift during the period of 2000 to 2002. This means also that the facilities[2] involved in the intercomparisons did not shift! As mentioned above we found for ***pigsar*** a common shift Δ_{ref} in the calibration values of the working standards from re-calibration to re-calibration. Based on the results of Fig. 10 we are able to say now that this Δ_{ref} is generated in the calibration process and is not a drift of ***pigsar*** over time!

Furthermore we want to analyse the spread of data in Fig. 12 evaluate the reproducibility of transfer meters and test facilities. For that purpose we use an analytical method described by Pöschel in paper [13] which allows us to split the parts of facilities and meters. In paper [13] the preconditions for application are given (what is mainly the independence of the facilities and meters).

For the calculations two auxiliary values are determined:

$$\Delta_{+} = \Delta_{Harm,Meter\ 1} + \Delta_{Harm,Meter\ 2}$$

$$\Delta_{-} = \Delta_{Harm,Meter\ 1} - \Delta_{Harm,Meter\ 2}$$

As shown in [13], the empirical variances s^2 of the auxiliary values Δ_+ and Δ_- are related with the variances of meters and harmonised reference value as follows:

$$s_{+}^{2} = s_{Meter\ 1}^{2} + s_{Meter\ 2}^{2} + 4s_{\Delta_{Harm}}^{2}$$

$$s_{-}^{2} = s_{Meter\ 1}^{2} + s_{Meter\ 2}^{2}$$

The values s^2_+ and s^2_- find their geometrical interpretation in Fig. 10 as the spread spans A and B in following relation: $A = 2s_-$ and $B = \sqrt{2}s_+$

From the fact that both meters of a transfer package are turbine meters and that the facilities operate with the same physical methods (working standards are also

[2] Note that in the quality-assurance-tests not only the facilities Bergum and ***pigsar*** are involved but also the facility Westerbork. The calibration of this facility is derived from Bergum. It works at a pressure of about 60 bar. Due to these facts (additional facility and comparison 50 bar with 60 bar) we got a little higher scatter of the data in Fig. 11.

turbine meters, equivalent pressure and temperature measurement) we can assume:

$$s^2_{Meter\ 1} + s^2_{Meter\ 2} = 2s^2_{Meter} \quad \text{and}$$

$$s^2_{\Delta_{Harm}} = s^2_{\text{repro,fac}\,1} + s^2_{\text{repro,fac}\,2} = 2s^2_{\text{repro,fac}}$$

Therefore we get from our estimates s^2_+ and s^2_- following estimates for the reproducibility (standard deviation) of the transfer meters and the test facilities:

$$s_{meter} = \frac{1}{\sqrt{2}}\sqrt{s^2_-} \quad \text{and}$$

$$s_{repro,fac} = \frac{1}{\sqrt{8}}\sqrt{s^2_+ - s^2_-}$$

Results are given in Table 2.

Table 2: Estimates $s_{\text{repro,fac}}$ and s_{meter}

Campaign	$s_{\text{repro,fac}}$	s_{meter}
Harmonisation 1999	0.031	0.025
Quality assurance tests	0.046	0.030
Harmonisation 2002	0.025	0.024

Hence we get from the analysis of harmonisation data a reproducibility of our test facilities of $U_{\text{repro,facility}} = 2s_{\text{repro,fac}} \approx 0{,}06$ % and for the transfer meters $U_{\text{repro,transfer meter}} = 2s_{\text{meter}} \approx 0{,}05$ %. The quality-assurance-test included one more test facility (Westerborg) which operates at 60 bar (leads to a comparison of 50 to 60 bar instead of 50 to 50 bar as mentioned for the harmonisation), so that we got here some little higher values.

CONCLUSION for the reliability of this harmonization process

With the analysis of data determined at ***pigsar*** (progression of calibration values at ***pigsar***) and data of the intercomparisons within the harmonisation we found reliable estimates for the reproducibility of the test facility ***pigsar*** as well as the transfer meters.

It has to be emphasise that both approaches leads to the same statements:

- Reproducibility of ***pigsar*** as a whole: $U_{\text{repro,pigsar}} \approx 0{,}06$ % and
- Reproducibility of a commercial available transfer meter: $U_{\text{repro,transfer meter}} \approx 0{,}05$ %.
- The drift of the harmonised reference value over three years is equal to zero within the statistical significance level, compare Figure 12.

CONCLUSION FOR INDUSTRIE, SCOCIETY and METROLOGY

As National institutes for Measurement Standards, NMi-VSL as well as PTB, have a function to provide society with reliable sources of traceability. A prerequisite to this function is the ability to generate and to improve the reference values themselves as well as the knowledge about reference values of high-pressure gas-flow measurements.
The minimization of observed differences between ***pigsar*** and NMi-VSL together with the realization of enhanced stability in Reference Values is of economic importance. Improved uncertainties are a distinct additional benefit of the Harmonization process.

HARMONIZATION AGREEMENT

The agreement on harmonization between PTB and NMi VSL is open to others. Other National Metrology Institutes or even other calibration laboratories that operate a demonstrated, independently realized set of reference values, are acceptable. All prerequisite conditions are to be met and an additional decrease in harmonized uncertainty together with a gain in stability should be offered.

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