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Report on the CCM WG TG1 pilot comparison to measure water vapour sorption on stainless steel mass standards

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ABSTRACT

This report summarises the results of a comparison to measure the water vapour sorption correction on stainless steel masses when they are transferred between moist air and vacuum. A set of three sorption artefacts consisting of an integral 1 kg cylindrical stainless steel mass and two 1 kg cylindrical stainless steel stack weights with different surface areas was circulated among the participants. This report also summarises the results of the measurement of the absolute mass of the integral artefact in vacuum.

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1 INTRODUCTION

The Consultative Committee for Mass and Related Quantities (CCM) set up Task Group 1 (TG1) with the aim of investigating ways of performing mass comparisons in vacuum with the minimum combined standard uncertainty. Mass comparisons in vacuum are required to provide traceability to both the Watt balance [1] and X-ray crystal density [2] methods of redefining the kilogram in terms of a fundamental physical constant. When mass artefacts are exposed to vacuum, the layer of water molecules covering their surface is desorbed, and then re-adsorbed when they are returned to humid air. Measurement of this sorption of water molecules to/from a mass artefact is vital so that corrections can be applied allowing the absolute value and repeatability of masses measured in vacuum to be related to masses measured in air with the lowest possible uncertainty.

The aim of this study was to develop a protocol for measuring the sorption correction of a set of three artefacts and to perform a pilot comparison between participating institutes to evaluate the protocol. The three sorption artefacts consisted of an integral 1 kg cylindrical stainless steel mass (71DD), a 1 kg cylindrical stainless steel stack made up of two disc masses with three spacers (Stack 1), and a 1 kg cylindrical stainless steel stack made up of four disc masses with nine spacers (Stack 2). This report also summarises the results of absolute mass measurements made on the integral artefact in vacuum.

NPL was the pilot laboratory and provided the transfer standards. The comparison was split into two petals since the volumes of the stainless steel artefacts were re-measured by hydrostatic weighing in water after the third set of sorption measurements at NPL. The participating laboratories of both petals are listed in Table 1.

Previous work on evaluating the sorption effects on stainless steel mass artefacts has been undertaken by Davidson [3], Picard and Fang [4] and Schwartz [5] and the measured sorption values, surface roughness values and vacuum pressure levels are summarised in Table 2. The relative humidity of the measurements in air was 50 % RH for the NPL and PTB measurements and 40 % RH for the BIPM measurements. Two sets of measurements were performed at PTB, one using cleaned stainless steel artefacts and the second using uncleaned artefacts.

Table 1: List of participating laboratories

Petal 1	
Bureau International des Poids et Mesures	BIPM
Centro Español de Metrología	CEM
L'Istituto Nazionale di Ricerca Metrologica	INRIM
Laboratoire National de Métrologie et d'Essais	LNE
Swiss Federal Office of Metrology	EJPD
National Physical Laboratory	NPL
Physikalisch-Technische Bundesanstalt	PTB
Petal 2	
Laboratoire National de Métrologie et d'Essais	LNE
National Physical Laboratory	NPL
Physikalisch-Technische Bundesanstalt	PTB
Ulusal Metrologi Enstitüsü	UME

Table 2: Published stainless steel sorption values and surface roughness of the artefacts used

Institute	**Sorption value / µg cm^{-2}**	**Surface roughness / µm**	**Pressure / Pa**
NPL	-0.154	0.034 to 0.042 (R_Z)	10^{-4}
BIPM	-0.040	0.01 (R_q)	0.1
PTB (cleaned surface)	-0.024	0.077 to 0.177 (R_Z)	0.1
PTB (uncleaned surface)	-0.058	0.077 to 0.177 (R_Z)	0.1

2 DESCRIPTION OF THE TRANSFER STANDARDS

The construction of the three sorption artefacts is shown in Figure 1, and information on the artefacts is given in Table 3. The surface roughness of the stainless steel artefacts was measured previously by Davidson [3] and is given in Table 2. It is worth noting that the surface condition of the artefacts has deteriorated since Davidson measured the surface roughness and the values given in Table 2 are no longer representative over the whole surface of the artefacts. The spacers were manufactured from the same stainless steel material as the other artefacts and had a length equal to 10 mm and a diameter equal to 2 mm.

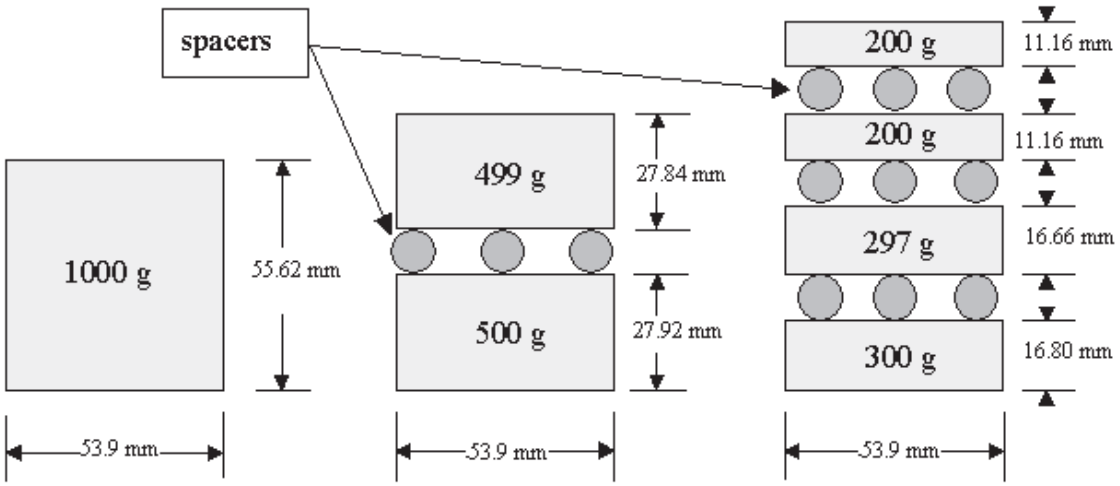

Figure 1: Diagram of the three stainless steel sorption artefacts

Table 3: Information on the transfer standards

Identification	Nominal mass / g	Material	Density at 20 °C /g cm^{-3}	Density uncertainty (k = 1) / g cm^{-3}	Volume at 20 °C / cm^3	Surface area / cm^2	Height / mm	Alpha / 10^{-6} °C^{-1}	Beta / 10^{-9} °C^{-2}
71DD	1000	Steel	7.888	0.000 2	126.771 9	140.02	55.62	45	0
Stack 1									
500	500	Steel	7.888	0.000 2	63.388 0	92.73	27.92	45	0
499	499	Steel	7.888	0.000 2	63.260 5	92.86	27.84	45	0
3 spacers	1	Steel	7.915	0.002 0	0.126 3	2.69	1.99	45	0
Sum						188.28	57.75		
Stack 2									
300	300	Steel	7.888	0.000 3	38.031 0	74.17	16.80	45	0
297	297	Steel	7.888	0.000 2	37.651 3	73.93	16.66	45	0
200(1)	200	Steel	7.888	0.000 5	25.354 1	64.61	11.16	45	0
200(2)	200	Steel	7.888	0.000 2	25.354 5	64.61	11.16	45	0
9 spacers	3	Steel	7.915	0.002 0	0.379 0	8.06	5.97	45	0
Sum						285.38	61.75		

3 SUMMARY OF THE COMPARISON

3.1 PETAL 1

The schedule of the comparison in Petal 1 is shown in Table 4. None of the transfer standards were cleaned prior to the start of the comparison or by the participants. The transfer standards were previously cleaned by wiping with lens cleaning tissue and ethanol three years prior to the start of the comparison. All of the transfer standards were wrapped in acid free tissue paper and placed in a sealed lightweight case containing moist air at ambient temperature and pressure during transport between laboratories.

Three mass differences were obtained for each measurement in air and in vacuum:

- 71DD versus Stack 1
- 71DD versus Stack 2
- Stack 1 versus Stack 2

Each participant performed repeat measurements on the artefacts in air and in vacuum. This allowed evaluation of the repeatability of the air to vacuum transfer mass change due to reversible water sorption.

Table 4: Petal 1 Schedule

Laboratory	End date of measurements
NPL 1	20 October 2008
BIPM	16 January 2009
LNE	6 April 2009
PTB	27 October 2009
NPL 2	3 February 2010
METAS	19 June 2010
CEM	22 February 2011
INRIM	26 April 2011
NPL 3	27 May 2011

3.2 PETAL 2

The schedule of the comparison in Petal 2 is shown in Table 5. Prior to circulation all of the stainless steel transfer standards were cleaned using the following two-stage process:

1. The first cleaning stage consisted of washing in solvent in an ultrasonic bath. The solvent used was reagent grade ethanol (purity of at least 99.8 %). Each transfer standard was placed in turn in ethanol within the ultrasonic bath for a period of 5 minutes. The ultrasonic cleaning process was then repeated with the other transfer standards and the small spacers used to separate the stack.
2. The second stage involved rinsing in distilled water. Distilled water was poured over each transfer standard in copious amounts for about 5 minutes. Each transfer standard was left to

dry in air with large water droplets removed using clean lens tissue paper. This cleaning process was repeated with the other transfer standards and with the small spacers.

No further cleaning of the transfer standards was performed after the initial cleaning. The transfer standards were transported between laboratories using the same procedure as Petal 1 and the same measurements were made by each participant as for Petal 1 (see § 3.1).

Table 5: Petal 2 Schedule

Laboratory	End date of measurements
NPL A	20 February 2012
UME	29 April 2012
PTB	12 July 2012
LNE	26 October 2012
NPL B	7 January 2013

4 RESULTS OF THE COMPARISON

4.1 MASS DIFFERENCES AND STANDARD UNCERTAINTIES

The average mass differences and standard uncertainties in both air and vacuum reported by the participants for Petal 1 and Petal 2 are given in Table 8 and Table 9, respectively. Two mass differences in air are shown for each measurement; the first value is the uncorrected mass difference in air and the second value is the mass difference in air corrected to a humidity of 50 % RH. The formula used to correct to a humidity of 50 % RH is that reported by Schwartz [6] for uncleaned artefacts.

Where:

$$\alpha_h = \mathbf{80} \times \delta_h \ \mathbf{ng \cdot cm^{-2}} \quad (1)$$

Where: α_h = humidity correction

δ_h = humidity difference to 50 % RH

4.2 SORPTION VALUES AND UNCERTAINTIES

4.2.1 Sorption values

The average sorption values calculated from each participant's data and standard uncertainties for Petal 1 and Petal 2 are given in Table 11 and Table 12 respectively. In both petals only the second set of results for the pilot laboratory (NPL 2 or NPL B) have been included in the calculation of the median sorption value.

All the sorption values have been adjusted so they represent the correction going from air with a humidity of 50 % RH to vacuum. The sorption values have been calculated using the following formula:

$$\text{Sorption } (\mu g\ cm^{-2}) = \frac{m_{AIRVAC}}{A} \times 1000 \quad (2)$$

Where: $m_{AIRVAC} =$ Mass difference in vacuum – mass difference in air (mg)

$A =$ Surface area difference (cm^2)

The signs of the sorption values are negative and represent the correction required when going from air to vacuum.

4.2.2 Standard uncertainty calculation

The standard uncertainties of the calculated sorption coefficients have been calculated from the uncertainties in air and uncertainties in vacuum supplied by the participants, and from the uncertainty in the surface area of the artefacts. From equation (2) the uncertainty in the sorption correction may be expressed as follows:

$$u_{sorption}\ (k=1)(\mu g\ cm^{-2}) = \sqrt{{C_1}^2 {U_{mAIRVAC}}^2 + {C_2}^2 {U_A}^2} \quad (3)$$

Where: $u_{sorption} =$ Uncertainty in the calculated sorption coefficient

$u_{mAIRVAC} =$ Uncertainty in vacuum – air mass difference (mg)

$u_A =$ Surface area difference uncertainty (cm^2)

$C_1 = A^{-1}$

$C_2 = -m_{AIRVAC} \times A^{-2}$

The uncertainty in the surface area difference of the artefacts (u_A) was calculated to be equal to ± 3.5 cm^2, ± 4.0 cm^2 and ± 4.2 cm^2 for Stack1 – 71DD, Stack2 – 71DD and Stack2 – Stack1 respectively. Uncertainty components calculated for the NPL 2 results are shown in Table 6.

Table 6: Uncertainty components for NPL 2 Results

	Standard uncertainty (71DD - Stack1) / µg cm^{-2}	Standard uncertainty (71DD - Stack2) / µg cm^{-2}	Standard uncertainty (Stack1 - Stack2) / µg cm^{-2}
u_{mVAC}	**0.024**	**0.008**	**0.014**
u_{wAIR}	0.031	0.010	0.015
$u_{\rho AIR}$	0.002	0.001	0.002
u_V	0.050	0.017	0.022
u_{mAIR}	**0.059**	**0.020**	**0.027**
u_A	**0.019**	**0.005**	**0.005**
$u_{sorption}$	**0.066**	**0.022**	**0.031**

Where: u_{mVAC} = Uncertainty due to the vacuum mass measurement

u_{wAIR} = Uncertainty due to the air weighing

$u_{\rho AIR}$ = Uncertainty due to the air density measurement

u_V = Uncertainty due to the volume of the artefacts

u_{mAIR} = Combined uncertainty due to the air mass measurement

The largest uncertainty component in Table 6 is due to the mass measurement in air, which in turn is mainly due to the uncertainty in the volume of the artefacts.

The uncertainty in the median value has been calculated according to the "Median of the Absolute Deviations" or MAD method described by Müller [7].

The median sorption values and standard uncertainties for Petal 1 and Petal 2 are shown graphically in Figure 2 and Figure 3 respectively. The three solid lines represent the median value of all the sorption values reported by the participants (For the NPL data only the NPL 2 or NPL B values are used in the calculation of the median sorption values).

4.2.3 Equivalence of the results

The equivalence of the participants' results has been evaluated by calculating the normalised error E_n, which takes into account both the result and the uncertainty. The normalised error was calculated using the following formula:

$$E_{n=}\frac{V_{lab}-V_{median}}{\sqrt{U_{lab}^2+U_{median}^2}} \quad (4)$$

Where the subscript *lab* refers to the participants' values and uncertainties and the subscript *median* refers to the median value and median uncertainty calculated from all the participants' values. The uncertainty values used are expanded uncertainties ($k = 2$).

Calculated E_n values for the results from Petal 1 and Petal 2 are given in Table 13 and Table 14 respectively. The results are considered equivalent if the absolute values of the normalised errors are less than 1. For Petal 1 all of the calculated E_n values are less than 1 and therefore the results are equivalent. For Petal 2 all of the calculated E_n values are less than 1 apart from the NPL A and UME results for the comparison of Stack 2 and 71DD which are greater than 1 and are therefore not equivalent to the results of the other participants.

4.3 ABSOLUTE MASS IN VACUUM OF KILOGRAM 71DD

The participants also calculated the absolute mass in vacuum of the integral 1 kg stainless steel artefact identified as 71DD. The results of these measurements are given in Table 10 and are shown in Figure

4. The blue diamonds are the results from Petal 1 and the red squares are the results from Petal 2. The solid green line represents the median values of the participants' results for each leg of the comparison but does not include the NPL 1 and NPL 3 results in the Petal 1 median nor the NPL A result in the Petal 2 median. These NPL results were excluded from the median calculation so that the median value would not be biased towards the NPL results. The sorption artefacts were contaminated in vacuum between the LNE result and the PTB result in Petal 1which would explain the gain in mass of 71DD observed by PTB and confirmed by the NPL2 result. LNE confirmed that a vacuum gauge in the LNE vacuum system was responsible for the contamination. It is interesting that following the NPL2 result the mass value of 71DD appears to have returned to its pre-contaminated value. This was probably a result of additional contamination desorbing from the surface of 71DD during an exposure to vacuum.

4.4 EFFECT OF DIFFERENT VACUUM PRESSURE LEVELS

The vacuum pressure levels during the sorption measurements were recorded by the participants' and are given in Table 7. The effect of the vacuum pressure level on the sorption measured by each participant is shown in Figure 5. According to the results shown in Figure 5 there does not appear to be any correlation between the level of vacuum in the participants' apparatus and the sorption value measured over the range of vacuum pressures from 0.000 43 Pa to 0.05 Pa.

Table 7: Participant measured pressure levels

Participant	Pressure / Pa
BIPM	0.002 5
LNE	0.04
PTB	0.01
NPL	0.000 5
EJPD	0.001
CEM	0.05
INRIM	0.000 43

5 VOLUME RE-DETERMINATION OF THE SORPTION ARTEFACTS

Following the completion of the third set of NPL measurements (NPL3) the volumes of all the artefacts were re-measured by hydrostatic weighing. The new and original volumes for the artefacts are given in Table 15. All of the new volumes for the artefacts agree with the original volumes, provided to the participants, within the expanded uncertainty of the volume measurements.
Revised average sorption values correcting for the new volumes of the artefacts along with the original sorption values are shown in Figure 6. For clarity only the error bars of the original sorption values are shown in Figure 6 as the uncertainty of the new sorption values is very similar to that of the original values. Within the expanded uncertainty of the measurements the revised sorption values agree with

the original values. Agreement between the three pairs of artefacts was improved using the new values as the sorption values calculated for artefact pair 71DD – Stack2 were shifted towards the other values.

6 CONCLUSIONS

All of the participants successfully measured sorption values for the three pairs of stainless steel artefacts used as transfer standards in this comparison. The equivalence of the participants' results was assessed by calculating the normalised error E_n. All of the calculated E_n values for the participants' results in Petal 1 were less than one which indicated that the results were all equivalent within the expanded uncertainty of the measurements. The calculated E_n values for the participants' results in Petal 2 were also less than one, apart from the NPL A and UME values for the comparison of Stack2 versus 71DD. This poor agreement may have been due to instability in the artefacts following density measurements and cleaning prior to the NPL A measurements.

The sorption values calculated for the three combinations of stainless steel sorption artefacts in both Petals were all higher than the values reported by Schwartz and Picard and Fang. Although the Stack2 versus 71DD and Stack2 versus Stack1 results for Petal 1 show good agreement with the results reported previously by Davidson, the other sorption results for Petal 1 and Petal 2 are significantly higher than the numbers reported by Davidson.

The absolute mass in vacuum of the integral kilogram artefact (71DD) was also measured by the participants. In Petal 1, the results from PTB and NPL2 were discrepant from the other values by about 40 μg. This was attributed to known contamination in vacuum between the measurement at LNE and the measurement at PTB. All of the other participants' results for the integral kilogram were in good agreement. In Petal 2, the absolute mass in vacuum of 71DD was in good agreement apart from the NPL A value which was about 80 μg lower than the other results. This may have been due to 71DD rapidly gaining mass due to contamination of its surface after cleaning (and the subsequent NPL A mass determination) and then stabilising by the time it was measured at UME.

Vacuum pressure levels during the sorption measurements were supplied by the participants' and ranged from 0.000 425 Pa to 0.05 Pa. Examination of the data showed that there was no correlation between the vacuum pressure level used during a participant's sorption measurements and the resulting sorption value.

At the end of Petal 1 the volumes of the artefacts were measured again. All of the new volumes for the artefacts agreed with the original volumes supplied to the participants within the expanded uncertainty

of the measurements. Agreement between the three pairs of artefacts was improved using the new volume values as the values calculated for artefact pair 71DD – Stack2 were shifted towards the values of the other artefact pairs. This change in calculated sorption values indicated that the volume uncertainty of the artefacts is a significant component in the uncertainty of the sorption measurements and so it is vital that volume measurements of sorption artefacts have as small an uncertainty as possible. This is supported by the uncertainty analysis for the NPL 2 results in Table 6 which showed that the principal source of uncertainty was due to the volume uncertainty of the artefacts. The use of sorption artefacts that have a stack of just two discs should also be avoided as the uncertainty in the sorption values are more sensitive to the volume uncertainty component due to the smaller surface area difference to the integral artefact.

In conclusion the main aim of this pilot study was met as a protocol has been developed for measuring the sorption correction of a set of artefacts and it was evaluated successfully by performing a two-petal pilot comparison between participating institutes.

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8 TABLES OF RESULTS

Table 8: Average mass differences reported for the transfer standards with standard uncertainties (k = 1) for Petal 1

	Δm (Stack1 – 71DD) / mg			Δm (Stack2 – 71DD) / mg			Δm (Stack2 – Stack1) / mg		
Participant	Air	Air (50 % RH)	Vacuum	Air	Air (50 % RH)	Vacuum	Air	Air (50 % RH)	Vacuum
NPL 1	0.145 3	0.145 3	0.132 5	-0.131 6	-0.131 8	-0.155 6	-0.277 5	-0.277 6	-0.288 1
BIPM	0.142 0	0.142 3	0.130 2	-0.146 4	-0.145 4	-0.165 6	-0.288 5	-0.287 8	-0.295 8
LNE	0.133 6	0.133 5	0.124 0	-0.133 5	-0.133 8	-0.156 5	-0.267 1	-0.267 3	-0.280 5
PTB	0.140 1	0.140 3	0.129 5	-0.101 1	-0.100 1	-0.121 6	-0.241 1	-0.240 5	-0.251 1
NPL 2	0.146 8	0.147 1	0.134 0	-0.077 7	-0.077 0	-0.101 0	-0.221 3	-0.220 8	-0.233 2
EJPD	0.167 1	0.167 1	0.159 2	-0.052 8	-0.052 8	-0.074 2	-0.219 9	-0.219 9	-0.233 2
CEM	0.138 9	0.138 9	0.126 6	-0.091 0	-0.090 9	-0.114 2	-0.229 7	-0.229 6	-0.240 9
INRIM	0.136 8	0.137 1	0.125 3	-0.101 7	-0.100 7	-0.122 8	-0.238 4	-0.237 8	-0.249 7
NPL 3	0.141 0	0.141 6	0.131 0	-0.102 4	-0.100 6	-0.118 7	-0.243 1	-0.241 9	-0.249 6
	$U_{\Delta m}$ (Stack1 – 71DD) / mg			$U_{\Delta m}$ (Stack2 – 71DD) / mg			$U_{\Delta m}$ (Stack2 – Stack1) / mg		
Participant	Air	Air (50 % RH)	Vacuum	Air	Air (50 % RH)	Vacuum	Air	Air (50 % RH)	Vacuum
NPL 1	0.002 8	0.002 8	0.001 2	0.002 9	0.002 9	0.001 2	0.002 6	0.002 6	0.001 4
BIPM	0.003 5	0.003 5	0.000 5	0.004 0	0.004 0	0.000 4	0.003 3	0.003 3	0.000 5
LNE	0.003 5	0.003 5	0.001 2	0.004 0	0.004 0	0.003 7	0.003 1	0.003 1	0.002 4
PTB	0.004 0	0.004 0	0.001 0	0.004 0	0.004 0	0.001 0	0.004 0	0.004 0	0.001 0
NPL 2	0.002 8	0.002 8	0.001 2	0.002 9	0.002 9	0.001 0	0.002 6	0.002 6	0.001 6
EJPD	0.003 2	0.003 2	0.000 5	0.003 2	0.003 2	0.000 5	0.003 2	0.003 2	0.000 5
CEM	0.001 2	0.001 2	0.000 7	0.001 2	0.001 2	0.000 7	0.001 2	0.001 2	0.000 7
INRIM	0.003 4	0.003 4	0.000 4	0.003 9	0.003 9	0.000 4	0.003 0	0.003 0	0.000 4
NPL 3	0.002 8	0.002 8	0.000 5	0.002 9	0.002 9	0.000 4	0.002 6	0.002 6	0.000 4

Table 9: Average mass differences reported for the transfer standards with standard uncertainties (k = 1) for Petal 2

	Δm (Stack1 – 71DD) / mg			Δm (Stack2 – 71DD) / mg			Δm (Stack2 – Stack1) / mg		
Participant	Air	Air (50 % RH)	Vacuum	Air	Air (50 % RH)	Vacuum	Air	Air (50 % RH)	Vacuum
NPL A	-0.143 8	-0.143 9	-0.157 0	-1.641 6	-1.641 8	-1.685 3	-1.501 1	-1.501 2	-1.527 4
UME	-0.135 6	-0.135 8	-0.147 5	-1.696 3	-1.696 9	-1.713 4	-1.552 4	-1.552 8	-1.565 8
PTB	-0.163 9	-0.163 5	-0.176 1	-1.698 4	-1.697 5	-1.725 7	-1.534 6	-1.533 9	-1.549 6
LNE	-0.172 2	-0.172 3	-0.180 2	-1.684 5	-1.684 8	-1.718 7	-1.512 3	-1.512 5	-1.538 5
NPL B	-0.148 0	-0.148 1	-0.160 4	-1.675 7	-1.676 0	-1.707 8	-1.527 2	-1.527 3	-1.547 4
	$U_{\Delta m}$ (Stack1 – 71DD) / mg			$U_{\Delta m}$ (Stack2 – 71DD) / mg			$U_{\Delta m}$ (Stack2 – Stack1) / mg		
Participant	Air	Air (50 % RH)	Vacuum	Air	Air (50 % RH)	Vacuum	Air	Air (50 % RH)	Vacuum
NPL A	0.002 8	0.0028	0.000 8	0.002 9	0.002 9	0.000 7	0.002 6	0.002 6	0.000 6
UME	0.003 5	0.003 5	0.000 9	0.004 3	0.004 3	0.000 8	0.003 1	0.003 1	0.000 9
PTB	0.003 5	0.003 5	0.001 0	0.004 0	0.004 0	0.001 0	0.003 1	0.003 1	0.001 0
LNE	0.003 8	0.003 8	0.001 5	0.004 3	0.004 3	0.004 1	0.003 5	0.003 5	0.002 7
NPL B	0.002 8	0.002 8	0.000 8	0.002 9	0.002 9	0.001 6	0.002 6	0.002 6	0.001 1

Table 10: Absolute mass in vacuum reported for kilogram 71DD with standard uncertainties (k = 1)

Petal 1		
Participant	71DD absolute mass in vacuum / g	71DD mass uncertainty in vacuum / mg
NPL 1	1 000.001 543	0.007
BIPM	1 000.001 537	0.006
LNE	1 000.001 539	0.011
PTB	1 000.001 588	0.007
NPL2	1 000.001 588	0.007
EJPD	1 000.001 532	0.030
CEM	1 000.001 548	0.012
INRIM	1 000.001 546	0.009
NPL 3	1 000.001 562	0.007
Median[1]	**1 000.001 546**	**0.007**
Petal 2		
Participant	71DD absolute mass in vacuum / g	71DD mass uncertainty in vacuum / mg
NPL A	1 000.000 976	0.007
UME	1 000.001 061	0.015
PTB	1 000.001 045	0.007
LNE	1 000.001 058	0.011
NPL B	1 000.001 069	0.010
Median[2]	**1 000.001 060**	**0.006**

1 Only the second set of results for the pilot laboratory (NPL2) has been included in the calculation of the median sorption value
2 Only the second set of results for the pilot laboratory (NPLB) has been included in the calculation of the median sorption value

Table 11: Average sorption values for the transfer standards and standard uncertainties (k = 1) for Petal 1

	Average sorption (Stack1 – 71DD) / µg cm^{-2}		Average sorption (Stack2 – 71DD) / µg cm^{-2}		Average sorption (Stack2 – Stack1) / µg cm^{-2}	
	Corrected to 50 % RH	Standard Uncertainty	Corrected to 50 % RH	Standard Uncertainty	Corrected to 50 % RH	Standard Uncertainty
NPL 1	-0.267	0.066	-0.163	0.022	-0.104	0.031
BIPM	-0.251	0.075	-0.139	0.028	-0.083	0.035
LNE	-0.198	0.078	-0.161	0.037	-0.143	0.041
PTB	-0.225	0.087	-0.148	0.029	-0.109	0.043
NPL 2	-0.272	0.066	-0.165	0.022	-0.126	0.032
EJPD	-0.172	0.068	-0.153	0.023	-0.142	0.034
CEM	-0.265	0.034	-0.167	0.011	-0.120	0.015
INRIM	-0.251	0.073	-0.156	0.027	-0.125	0.032
NPL 3	-0.220	0.061	-0.128	0.020	-0.084	0.027
Median value[3]	**-0.251**	**0.016**	**-0.156**	**0.006**	**-0.125**	**0.023**
Standard Deviation	**0.037**		**0.010**		**0.021**	

Table 12: Average sorption values for the transfer standards and standard uncertainties (k = 1) for Petal 2

	Average sorption (Stack1 – 71DD) / µg cm^{-2}		Average sorption (Stack2 – 71DD) / µg cm^{-2}		Average sorption (Stack2 – Stack1) / µg cm^{-2}	
	Corrected to 50 % RH	Standard Uncertainty	Corrected to 50 % RH	Standard Uncertainty	Corrected to 50 % RH	Standard Uncertainty
NPL A	-0.287	0.063	-0.300	0.022	-0.269	0.030
UME	-0.243	0.077	-0.114	0.030	-0.134	0.034
PTB	-0.259	0.078	-0.194	0.029	-0.161	0.034
LNE	-0.187	0.085	-0.247	0.041	-0.277	0.047
NPL B	-0.261	0.063	-0.225	0.024	-0.210	0.030
Median value[4]	**-0.251**	**0.010**	**-0.209**	**0.029**	**-0.186**	**0.023**
Standard Deviation	**0.037**		**0.069**		**0.064**	

3 Only the second set of results for the pilot laboratory (NPL2) has been included in the calculation of the median sorption value
4 Only the second set of results for the pilot laboratory (NPLB) has been included in the calculation of the median sorption value

Table 13: Absolute Normalised Error (E_n) values calculated from the participants' results for Petal 1 (k = 2)

	E_n (Stack1 – 71DD)	E_n (Stack2 – 71DD)	E_n (Stack2 – Stack1)
NPL 1	0.08	0.10	0.22
BIPM	0.00	0.22	0.43
LNE	0.24	0.06	0.17
PTB	0.11	0.10	0.14
NPL 2	0.11	0.13	0.02
EJPD	0.39	0.03	0.18
CEM	0.09	0.19	0.06
INRIM	0.00	0.00	0.00
NPL 3	0.16	0.41	0.47

Table 14: Absolute Normalised Error (E_n) values calculated from the participants' results for Petal 2 (k = 2)

	E_n (Stack1 – 71DD)	E_n (Stack2 – 71DD)	E_n (Stack2 – Stack1)
NPL A	0.18	1.23	0.92
UME	0.04	1.13	0.54
PTB	0.04	0.19	0.25
LNE	0.28	0.37	0.79
NPL B	0.05	0.21	0.27

Table 15: Volumes measured for the stainless steel sorption artefacts at the end of the comparison

Identification	Nominal mass / g	New Volume at 20 °C /cm^3	Original Volume at 20 °C / cm^3	Volume Difference / cm^3	New Volume Uncertainty (k = 1) / cm^3	New Alpha / 10^{-6} °C^{-1}	New Beta / 10^{-9} °C^{-2}
71DD	1000	126.773 0	126.771 9	**0.001 1**	0.001 9	45.6	0
Stack 1							
500	500	63.388 0	63.388 0	**0.000 0**	0.001 0	45.6	0
499	499	63.259 4	63.260 5	**-0.001 1**	0.001 0	45.6	0
3 spacers	1	0.126 3	0.126 3	**0.000 0**		45.6	0
Stack 2							
300	300	38.031 2	38.031 0	**0.000 2**	0.000 6	45.6	0
297	297	37.651 0	37.651 3	**-0.000 3**	0.000 6	45.6	0
200(1)	200	25.354 5	25.354 1	**0.000 4**	0.000 4	45.6	0
200(2)	200	25.354 3	25.354 5	**-0.000 2**	0.000 4	45.6	0
9 spacers	3	0.379 0	0.379 0	**0.000 0**		45.6	0

9 FIGURES

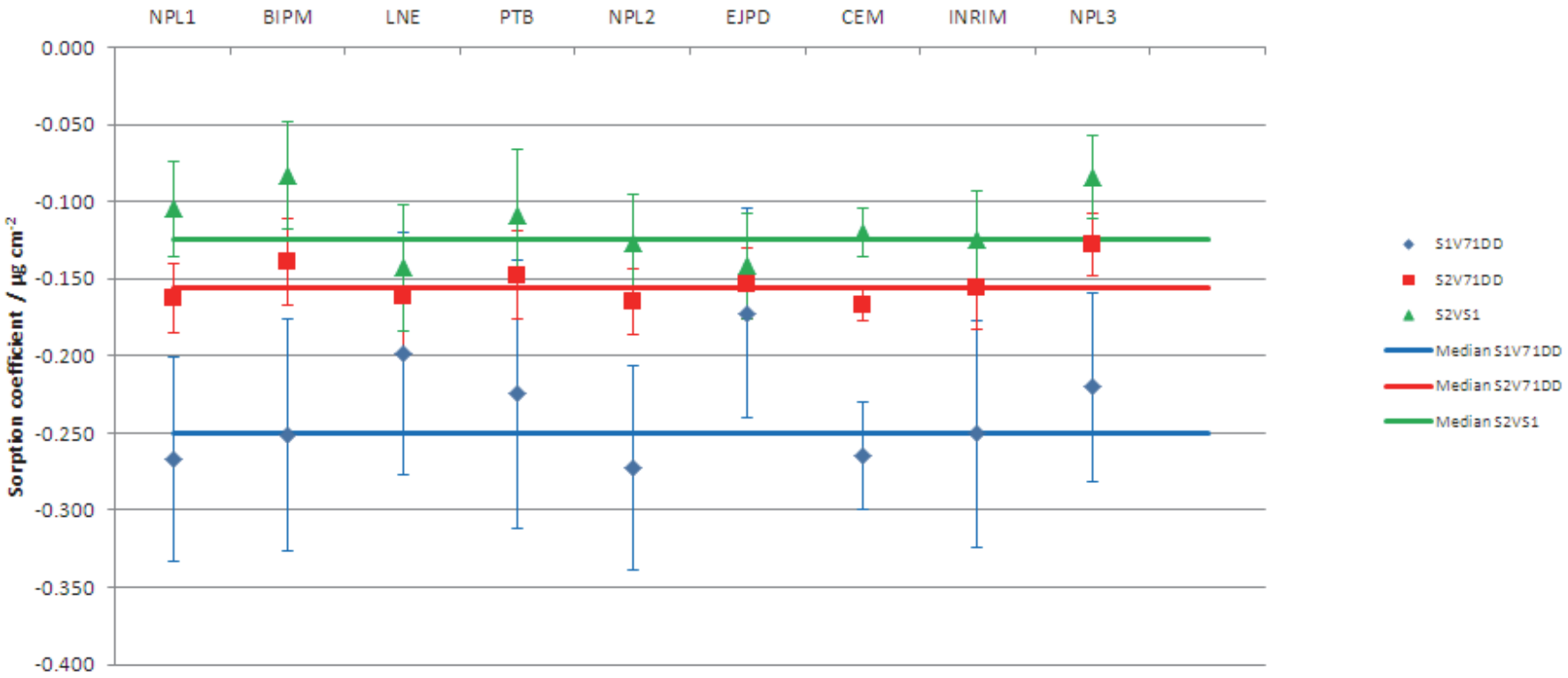

Figure 2: Sorption values for the transfer standards in Petal 1, error bars represent the standard uncertainty ($k = 1$)

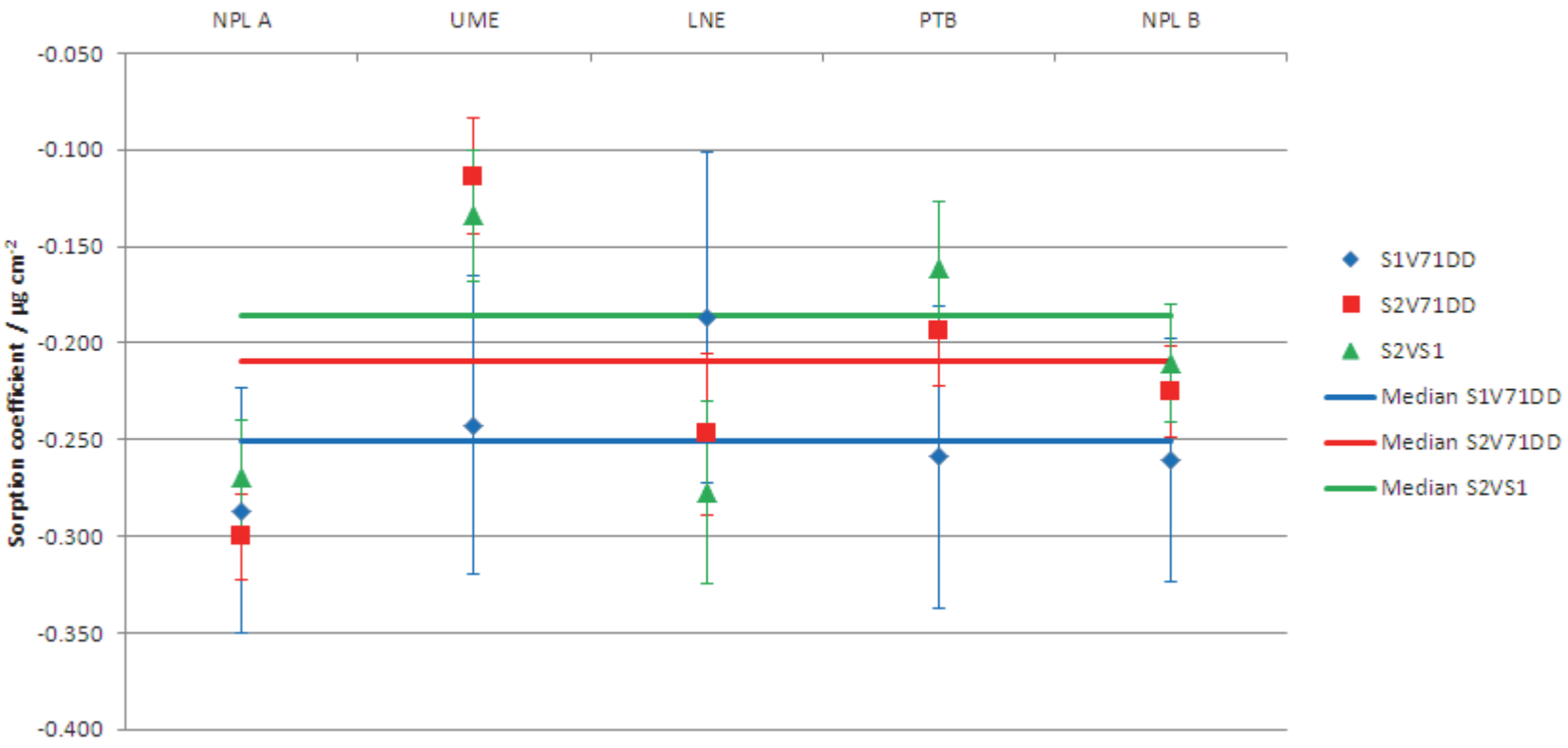

Figure 3: Sorption values for the transfer standards in Petal 2, error bars represent the standard uncertainty (k = 1)

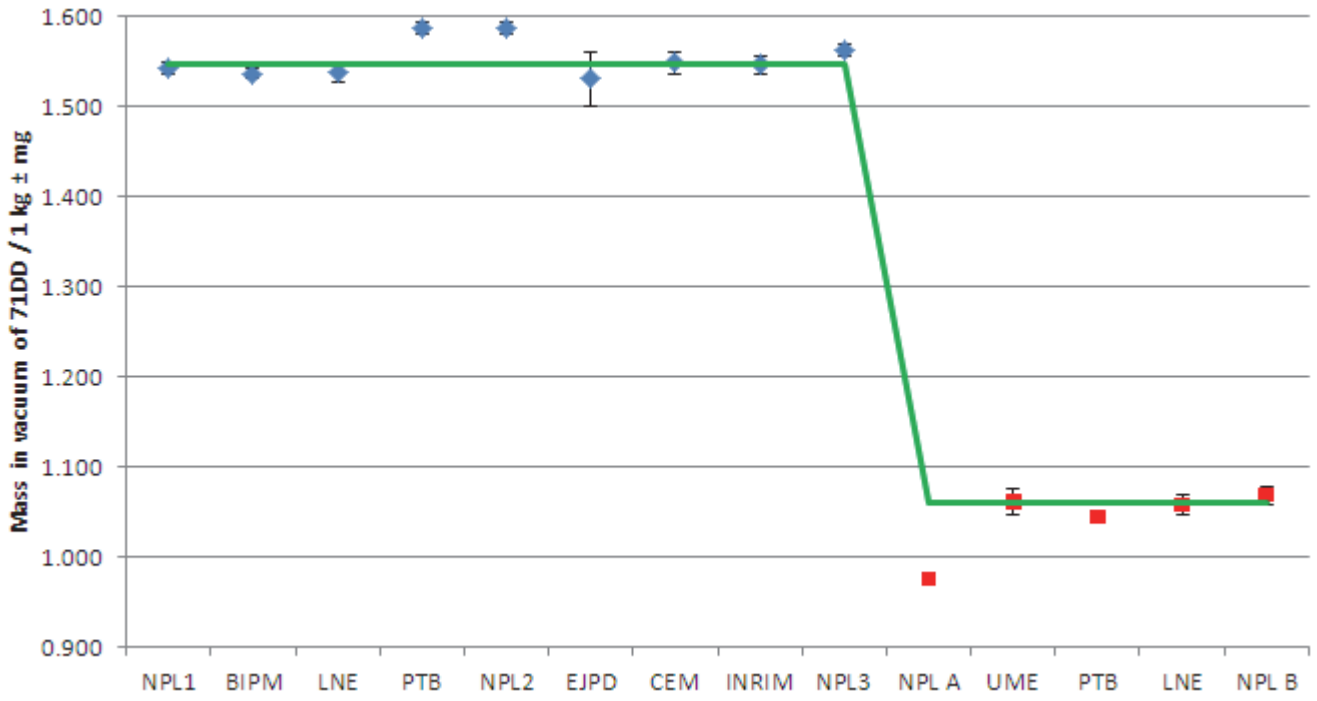

Figure 4: Mass in vacuum of 71DD, error bars represent the standard uncertainty ($k = 1$). The blue diamonds are the results from Petal 1 and the red squares are the results from Petal 2. The solid green line represents the two median values of the participants' data for Petal 1 and Petal 2.

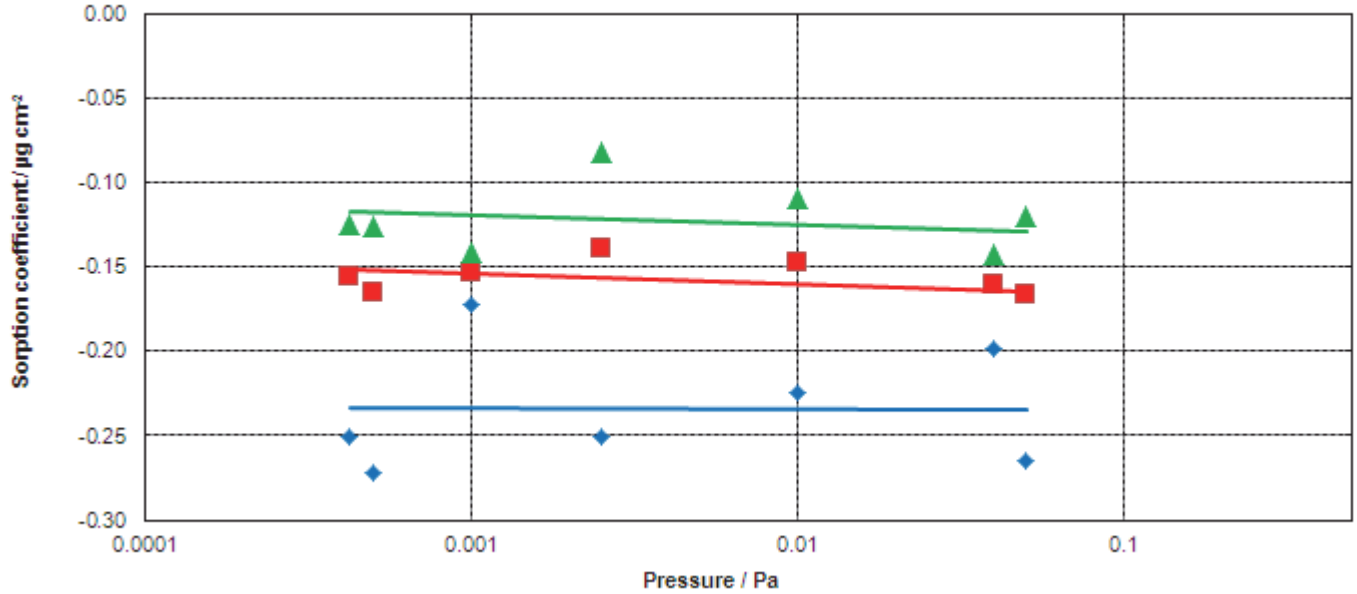

Figure 5: Participants' sorption values versus vacuum pressure for S1 V 71DD (blue diamonds), S2 V 71DD (red squares) and S2 V S1 (green triangles).

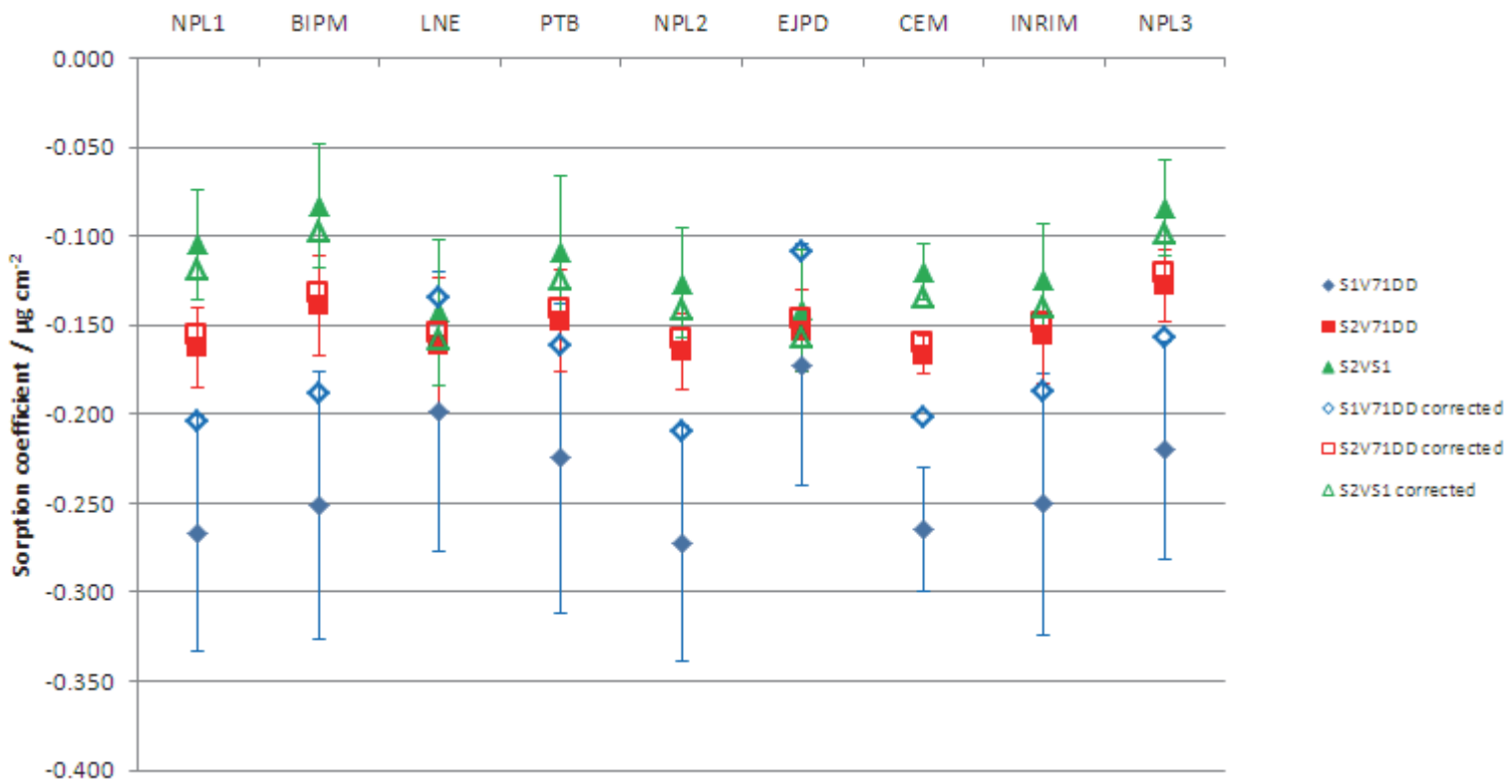

Figure 6: Sorption values for the transfer standards, error bars represent the standard uncertainty (k = 1). Closed markers represent values calculated using the original volumes, open markers represent values calculated using the revised volumes.