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A Collaboration Between Ten National Measurement Institutes To Measure The Mass Of Two One Kilogram Mass Standards

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ABSTRACT

A comparison has been carried out in which ten Western European national metrology institutes have determined the mass difference between a pair of 1 kg mass standards and assigned mass values to each of the weights. The results obtained illustrate that the measurements of the participants agree to within their quoted uncertainties (for a coverage factor of k=2), so demonstrating the metrological equivalence of mass measurements using stainless steel 1 kg standards in each of these institutes.

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1. INTRODUCTION

The third periodic verification of National Prototypes of the Kilogram took place at the International Bureau of Weight and Measures (BIPM) during the period 1988 To 1992 [1]. Each of the countries that possess National Prototypes of the Kilogram submitted their national standard to the BIPM for re-verification.

The process of transferring a national mass scale from a platinum-iridium (Pt-Ir) standard, such as a National Prototype, to a stainless steel standard introduces a large source of uncertainty due to the difference in air buoyancy experienced by weights of differing densities [2],[3]. It was agreed that a comparison would be carried out between Western European national measurement institutes (NMIs), under the auspices of EUROMET, to establish metrological equivalence in the measurement of stainless steel 1 kg mass standards in these institutes. This comparison, EUROMET Project 215, involves the assignment of mass values to two 1 kg mass standards and the determination of the mass difference between them.

The participants in the comparison are:-

Belgium	Service de la Métrologie (SMB)
Denmark	Danish Institute of Fundamental Metrology (DFM)
Finland	Centre for Metrology and Accreditation (MIKES)
France	Bureau National de Métrologie - Laboratoire National d'Essais (LNE)
Germany	Physikalisch-Technische Bundesanstalt (PTB)
Italy	Istituto de Metrologia "G Colonnetti" (IMGC)
Norway	Justervesenet (JV)
Spain	Centro Español de Metrologia (CEM)
Sweden	Sveriges Provnings (SP)
United Kingdom	National Physical Laboratory (NPL)

The results obtained by each of these institutes, and their respective uncertainties are described here along with a summary of the equipment used in the measurements.

The National Physical Laboratory acted as the pilot laboratory for this comparison, making regular measurements on the mass standards, both before and during the comparison, in order to monitor their stability. The analysis of the results has been carried out by the NPL and the IMGC.

2. MEASUREMENTS

2.1 ARTEFACTS

Four 1 kg mass standards were used during this comparison. Two of the weights, denoted as INM 10 and INM 11 throughout this report, were provided by the Bureau National de Métrologie - Institute National de Métrologie (BNM-INM) of France. These weights are cylindrical in shape, having a diameter equal to their height, and are manufactured from alacrite[1]. INM 10 has the number 10 etched on its vertical surface for the purpose of

[1] Composition of alacrite: 55 % cobalt, 20 % chromium, 15 % tungsten, 10 % nickel

identification while INM 11 is etched with a number 11. As may be seen from Table 2.1 these two weights have similar physical properties.

The second pair of weights, denoted as PTB B and PTB C, was supplied by the PTB of Germany. These weights are integral knobbed weights of the shape recommended in the International Organization for Legal Metrology Recommendation 111 [4] and are manufactured from austenitic stainless steel[2]. These weights are stamped with the letters B and C respectively on their top surfaces. Once more these two weights have similar physical properties.

WEIGHT	INM 10	INM 11	PTB B	PTB C
PROPERTY				
Density (kg m^{-3})	9 148.39 ± 0.2	9 146.66 ± 0.2	8 037.44 ± 0.07	8 037.45 ± 0.07
Coefficient of cubic thermal expansion (10^{-6} °C^{-1})	39.3 ± 0.2	39.3 ± 0.2	45.7 ± 0.3	45.7 ± 0.3
Height of centre of gravity (mm)	26	26	35.6	35.6
Magnetic Susceptibility	0.001 27	0.001 27	0.003	0.004

Table 2.1: Physical Properties Of The Weights

All of the data shown in Table 2.1 have been supplied by the laboratory which owns the relevant weight.

Weights PTB B and INM 10 were selected to be kept at NPL throughout the period of the comparison to act as monitoring standards. PTB C and INM 11 were circulated amongst the participants for measurements and are referred to as the transport standards.

2.2 CIRCULATION SCHEME

The transport standards were circulated around the participants in a series of four ‘petals’. Each petal consists of the pilot laboratory making measurements before and after two or three of the participant laboratories make measurements. A period of two months was assigned for each laboratory, including the pilot laboratory, to make its measurements. The dates of the measurements made by each laboratory are given in Appendix 1.

It should be noted that the three laboratories in the penultimate petal of the comparison, PTB, IMGC and NPL, also took part in a world-wide ‘Key Comparison’ of 1 kg weights organised by the Consultative Committee for Mass (CCM). It was agreed that a better overlap between these two comparisons would be achieved if these three laboratories made their measurements sequentially. With this exception the measurement order was arranged so that the transportation distance between any two successive laboratories was minimised.

2.3 TRANSPORTATION

Each participant laboratory was charged with the delivery of the transport standards to the next

[2] Composition of PTB weights: 19 - 20 % chromium, 24 - 25 % nickel, 4.5 % molybdenum, 1 - 1.5 % copper, 0.3 % silicon, 0.002 % carbon, remainder iron

laboratory. This was done either by air or overland transport. When the standards were transported by air they were carried in the cabin as hand luggage. The storage cases were packed inside a thermally insulated carrying case during transportation. Appendix 2 gives details of the transportation dates and methods used to transport the weights between laboratories.

3. MEASUREMENTS

3.1 PILOT LABORATORY ACTIVITY

The pilot laboratory compared each of the transport standards with its matching monitoring standard over a fourteen month period prior to the start of the comparison. The mass value of each of the four weights was determined by comparison with NPL's reference standards on receipt from its owner, immediately prior to the start of the circulation of the transport standards, and at the end of the comparison.

The comparison scheme shown in Table 3.1 was used to compare all four of the weights at the start and end of the comparison and on each occasion that the transport standards were returned to the pilot laboratory. These comparisons were carried out on a Mettler HK1000MC comparator using its two weight comparison mode.

Weighing No	Weight on Station 1	Weight on Station 3
1	PTB B + 1 mg	PTB C
2	PTB B	PTB C
3	PTB C	PTB B
4	PTB C	INM 10
5	PTB C	INM 11
6	PTB B	INM 11
7	PTB B	INM 10
8	INM 11	INM 10
9	INM 10	INM 11
10	INM 10 + 2 mg	INM 11

Table 3.1: Pilot Laboratory Weighing Scheme

The 1 mg and 2 mg weights used in the first and final comparison are intended to check the scale sensitivity of the comparator. Weighings 2 and 3, and also 8 and 9, check whether there is any systematic error introduced by changing the relative locations of the test weights on the weight exchanger.

3.2 PARTICIPANT LABORATORY ACTIVITY

Each of the participant laboratories was required to measure the mass difference between the transport standards and assign mass values to each of them. The assignment of the mass values was carried out using stainless steel reference standards that are traceable to the participant laboratory's official copy of the Prototype of the Kilogram. The mass difference between the two transport standards was carried out by direct comparison of the two weights.

Pre-printed sheets were provided for use by the participants to report their measurement results and record the following data:-

- Traceability of reference standards used
- Physical properties of the reference standards used
- Details of balance used
- Traceability of all ancillary equipment (eg air density measurement apparatus)
- Ambient atmospheric conditions at the time of each measurement
- A detailed uncertainty budget

4. RESULTS OF MEASUREMENTS

4.1 PILOT LABORATORY

4.1.1 Comparison of Standards

The weighing scheme shown in Section 3.1 was used by the Pilot Laboratory to compare the weights on each occasion that it made measurements during the period of the comparison. The results of these measurements are shown in Table 4.1.

Weights Compared	**11-10**	**11-B**	**11-C**	**10-B**	**10-C**	**B-C**
Measurement Date	**Mass Difference (µg)**					
January 1995	298	2819	3001	2519	2696	166
August 1995	295	2842	3003	2549	2715	164
January 1996	293	2844	3009	2548	2714	168
September 1996	280	2836	3010	2557	2734	173
June 1997	290	2848	3006	2562	2717	162
Spread	18	29	9	43	38	11

Table 4.1: Results of Comparisons of Standards Undertaken By The Pilot Laboratory

The values in Table 4.1 represent direct comparisons of each pair of weights. When one of the stainless steel standards has been compared with one of the alacrite weights a 20 mg weight has been added to the stainless steel weight to compensate for the difference in air buoyancy effect.

The results of the comparison of the two transport standards (11 and C) are good, with only a 9 µg variation in the measured mass difference over a thirty month period. The comparisons of the two stainless steel standards and the two alacrite standards also give reasonable results, with 11 µg and 18 µg variations in their respective mass differences.

On initial examination the comparison of the two monitoring standards (10 and B) is disappointing over the same 30 month period. However, if the result from January 1995 is not considered then the range in the mass difference is only 14 µg. The most likely cause of this anomaly is that there was some form of contamination on PTB B when the two weights were compared.

4.1.2 Assignment of Mass Values

Mass values were assigned to each of the four standards when they were received from their owners and at the start and finish of the comparison. The two weights comprising NPL weight set NPLW36 were used in the 1993 and 1994 calibrations and produced the values shown in the second and fourth columns of Table 4.2. The values shown in the sixth column are based on the calibration of the weights against one standard from each of weight sets NPLW 61 and NPLW 62.

Date	November 1993		November 1994		July 1997	
Weight	Deviation from 1 kg in µg	Uncertainty (k=1) in µg	Deviation from 1 kg in µg	Uncertainty (k=1) in µg	Deviation from 1 kg in µg	Uncertainty (k=1) in µg
INM 10	+2127	15	+2101	15	+2125	15
INM 11	+2430	15	+2404	15	+2415	15
PTB B	-419	15	-424	15	-426	15
PTB C	-590	15	-588	15	-588	15

Table 4.2: Mass Values Assigned To Standards By The Pilot Laboratory

The results indicate little measurable change in the mass value of each of these weights, as measured by the Pilot Laboratory, during the period November 1993 to July 1997. The results obtained in November 1994 for the two alacrite weights are lower than anticipated, but the Pilot Laboratory was having problems at this time with the performance of the mass comparator used in this work (the weight exchange mechanism was replaced immediately after this work was carried out). It should be noted that the July 1997 values are based on the value assigned to the United Kingdom's Prototype of the Kilogram, Kilogram 18, by the BIPM in October 1997. The earlier values are based on the value of Kilogram E, NPL's oldest precious metal standard, which was calibrated against Kilogram 18 in 1993 following the third re-verification [5]. None of these mass values have been used in calculating the reference values for the weights. Those calculations are based only on the data from the participants.

4.2 PARTICIPANT LABORATORY RESULTS

The results of the participant laboratories are presented here in several different forms. The mass value assigned to each of the weights by the participants is shown as well as an average mass value assigned to the pair of weights by each participant. These average results are used as an overall indication of the agreement between all of the laboratories in Table 4.7 shown in Section 4.2.4. Each set of data is summarised in Sections 4.2.2 to 4.2.5 along with information relating to the difference between each participant's results.

4.2.1 Assignment of Reference Values and Uncertainties

Reference values have been calculated for each of the weights, the average combined mass of the pair, and the difference between them. These reference values are based on the median of the results submitted by the participants. The median has been selected for this quantity due to its insensitivity to outlying results. It should be noted that none of the pilot laboratory results have been used in the calculation of the reference value, but those obtained by NPL as a participant have been included in the same manner as those obtained by the other participants.

The uncertainty in the median has been calculated as described by Müller [6]. This calculation is based on taking the median of absolute deviations from the median of the results reported by the participants, multiplying by 1.858 (derived in [6]) and dividing the answer by the square root of one less than the number of results.

$$s = \frac{1.858}{\sqrt{n-1}} MAD$$

where

s = uncertainty
n = number of results
MAD = median of absolute deviations from the median

4.2.2 Mass Difference Between The Transport Standards

The mass difference between the two transport standards obtained by each laboratory is shown in Table 4.3. These results, which are illustrated graphically in Figure 4.1, show a good agreement between all of the participants except for MIKES. With the exception of this laboratory the measurements in any two successive laboratories agree to within the quoted k=1 uncertainties. The error bars on the graph indicate k=2 uncertainties. The reference value is indicated by a solid line with the uncertainty (k=2) in this value being represented by broken lines.

Laboratory	Measurement Date	INM 11 -PTB C Mass Difference in µg	Uncertainty (k=1) in µg
Pilot	Jan 1995	3001	4.5
JV	Apr 1995	3005	12.5
SP	Jun 1995	3000	15*
Pilot	Aug 1995	3003	4.5
MIKES	Sep 1995	2988	5.8
DFM	Nov 1995	3015	2.2
Pilot	Jan 1996	3009	4.5
PTB	May 1996	3011.1	2.4
IMGC	June 1996	3011	3.5
NPL	Sep 1996	3010.8	4.5
Pilot	Sep 1996	3010	4.5
SMB	Nov 1996	3003	3.0
BNM-LNE	Jan 1997	3006	4.4
CEM	Feb 1997	3011.7	2.3
Pilot	Jun 1997	3009	4.4
Median	Not including pilot	3008.4	2.1
Median	Including pilot	3009.0	1.7

Table 4.3: Mass Difference Between The Transport Standards

The overall spread of the measurements is 15 µg if the anomalous result is not included in the analysis (or 27 µg if it is). This value is higher than the 9 µg observed by the pilot laboratory for the repeated comparison of this pair of weights, but is comparable with the observed stability of each transport standard against its matching monitoring standard. Hence it may be concluded that, with one exception, a good agreement was achieved for this part of the comparison.

A comparison of the results obtained by each pair of participants, and their combined uncertainties is shown in Table 4.4.

* SP has since re-calculated the k=1 uncertainty in this quantity to be 8.5 µg

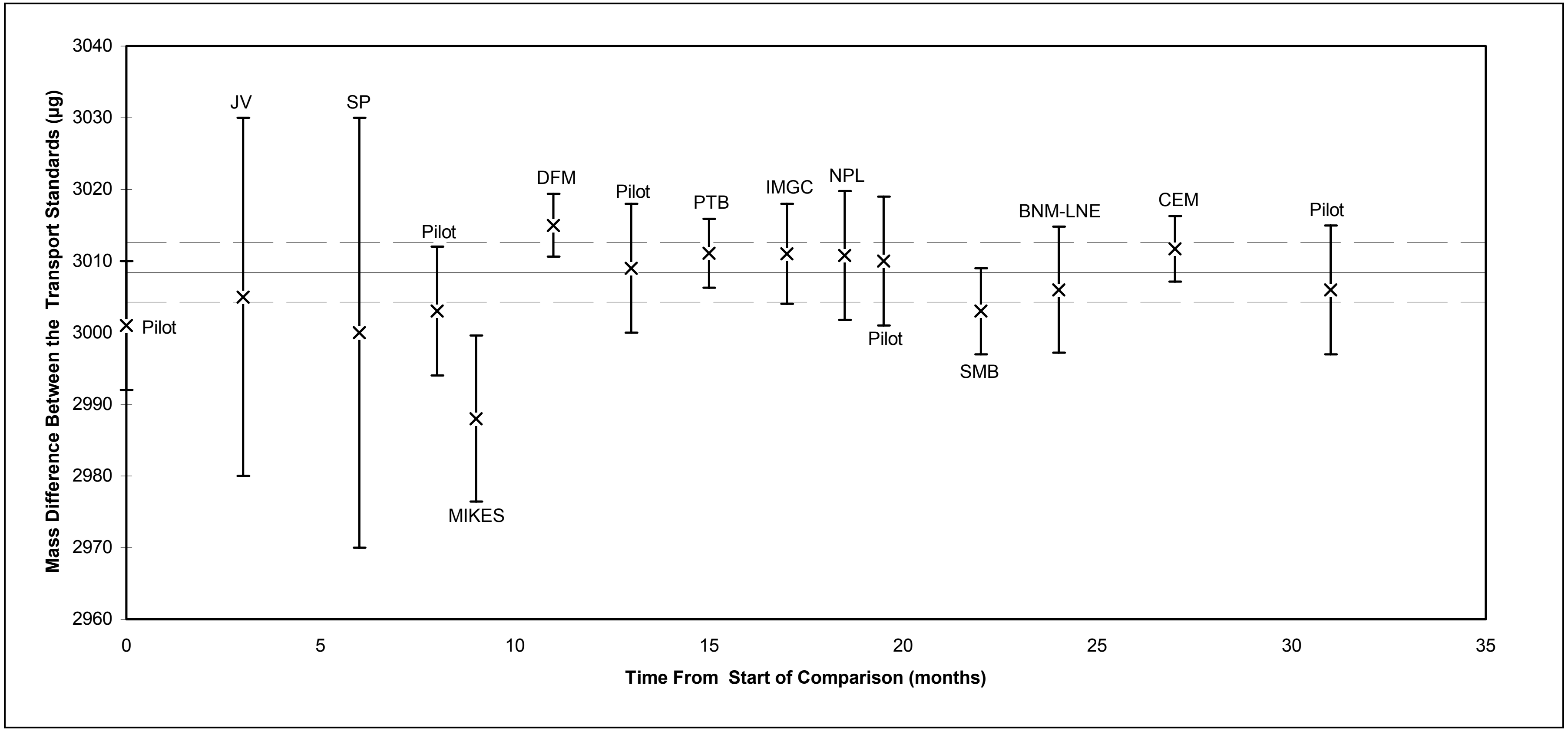

Figure 4-1: Mass Difference Between Transport Standards (Solid line: reference value, broken lines: uncertainty in reference value, all uncertainties at k=2)

Table 4.4 indicates the difference between the results obtained by each pair of participants. The combined uncertainties of each pair of laboratories (k=2) are indicated in parentheses next to the calculated offset. The numbers shown in the table below are in micrograms and represent the offset in the results between the laboratories shown in the relevant row and column. An example of how to read the table is that NPL obtained a result 4 μg lower than DFM for the comparison of the two transport standards. The combined uncertainty of this difference is 11 μg.

Laboratory	Reference	JV	SP	MIKES	DFM	PTB	IMGC	NPL	SMB	BNM-LNE	CEM
Reference		+3 (26)	+8 (31)	+20 (13)	-7 (7)	-3 (7)	-3 (9)	-2 (10)	+5 (8)	+2 (10)	-3 (7)
JV	-3 (26)		+5 (40)	+17 (28)	-10 (26)	-6 (26)	-6 (26)	-6 (27)	+2 (26)	-1 (27)	-7 (26)
SP	-8 (31)	-5 (40)		+12 (33)	-15 (31)	-11 (31)	-11 (31)	-11 (32)	-3 (31)	-6 (32)	-12 (31)
MIKES	-20 (13)	-17 (28)	-12 (33)		-27 (13)	-23 (13)	-23 (14)	-23 (15)	-15 (14)	-18 (15)	-24 (13)
DFM	+7 (7)	+10 (26)	+15 (31)	+27 (13)		+4 (7)	+4 (9)	+4 (11)	+12 (8)	+9 (10)	+3 (7)
PTB	+3 (7)	+6 (26)	+11 (31)	+23 (13)	-4 (7)		0 (9)	0 (11)	+8 (8)	+5 (11)	-1 (7)
IMGC	+3 (9)	+6 (26)	+11 (31)	+23 (14)	-4 (9)	0 (9)		0 (12)	+8 (10)	+5 (12)	-1 (9)
NPL	+2 (10)	+6 (27)	+11 (32)	+23 (15)	-4 (11)	0 (11)	0 (12)		+8 (11)	+5 (13)	-1 (11)
SMB	-5 (8)	-2 (26)	+3 (31)	+15 (14)	-12 (8)	-8 (8)	-8 (10)	-8 (11)		-3 (11)	-9 (8)
BNM-LNE	-2 (10)	+1 (27)	+6 (32)	+18 (15)	-9 (10)	-5 (11)	-5 (12)	-5 (13)	+3 (11)		-6 (10)
CEM	+3 (7)	+7 (26)	+12 (31)	+24 (13)	-3 (7)	+1 (7)	+1 (9)	+1 (11)	+9 (8)	+6 (10)	

TABLE 4.4: Comparison Of Results Obtained By The Participants For The Comparison Of The Transport Standards (All values in μg)

4.2.3 Assignment of Mass Value to PTB C

The mass values assigned to transport standard PTB C by each participating laboratory are shown in Table 4.5 and graphically in Figure 4.2. The median, indicated on the graph by a solid line, is considered as the reference value with its uncertainty being indicated by broken lines. The pilot laboratory results are for information only and have not been included in the evaluation of the reference value.

The agreement between the results is excellent with the results of all the laboratories agreeing to within the quoted k=2 uncertainties, which is a good result for an artefact standard being circulated throughout Western Europe over a thirty month period.

Laboratory	Measurement Date	Mass of PTB C (Deviation from 1 kg in µg)	Uncertainty (k = 1) in µg
Pilot	Jan 1995	-591	16
JV	Apr 1995	-577	23.5
SP	Jun 1995	-589	25*
Pilot	Aug 1995	-589	16
MIKES	Sep-Oct 1995	-596	17.2
DFM	Nov 1995	-571	20
Pilot	Jan 1996	-593	16
PTB	May 1996	-589	14.8
IMGC	Jun-Aug 1996	-559	13.6
NPL	Sep 1996	-572	14.4
Pilot	Sep 1996	-598	16
SMB	Nov 1996	-599	21
BNM-LNE	Jan-Feb 1997	-591	18
CEM	Mar-Apr 1997	-600	17
Pilot	Jun 1997	-587	16
Median	Not including pilot	-589	6.5
Median	Including Pilot	-589	3.5

Table 4.5: Mass Values Assigned to the Weight PTB C

The differences between the mass values assigned to this weight by the participants are shown in Table 4.6 along with the combined uncertainty of each pair of laboratories' measurements. It may been seen from the table that all of the laboratories' measurements agree to within their combined uncertainties for a coverage factor of k=2.

* SP has since re-calculated the k=1 uncertainty in this quantity to be 18 µg

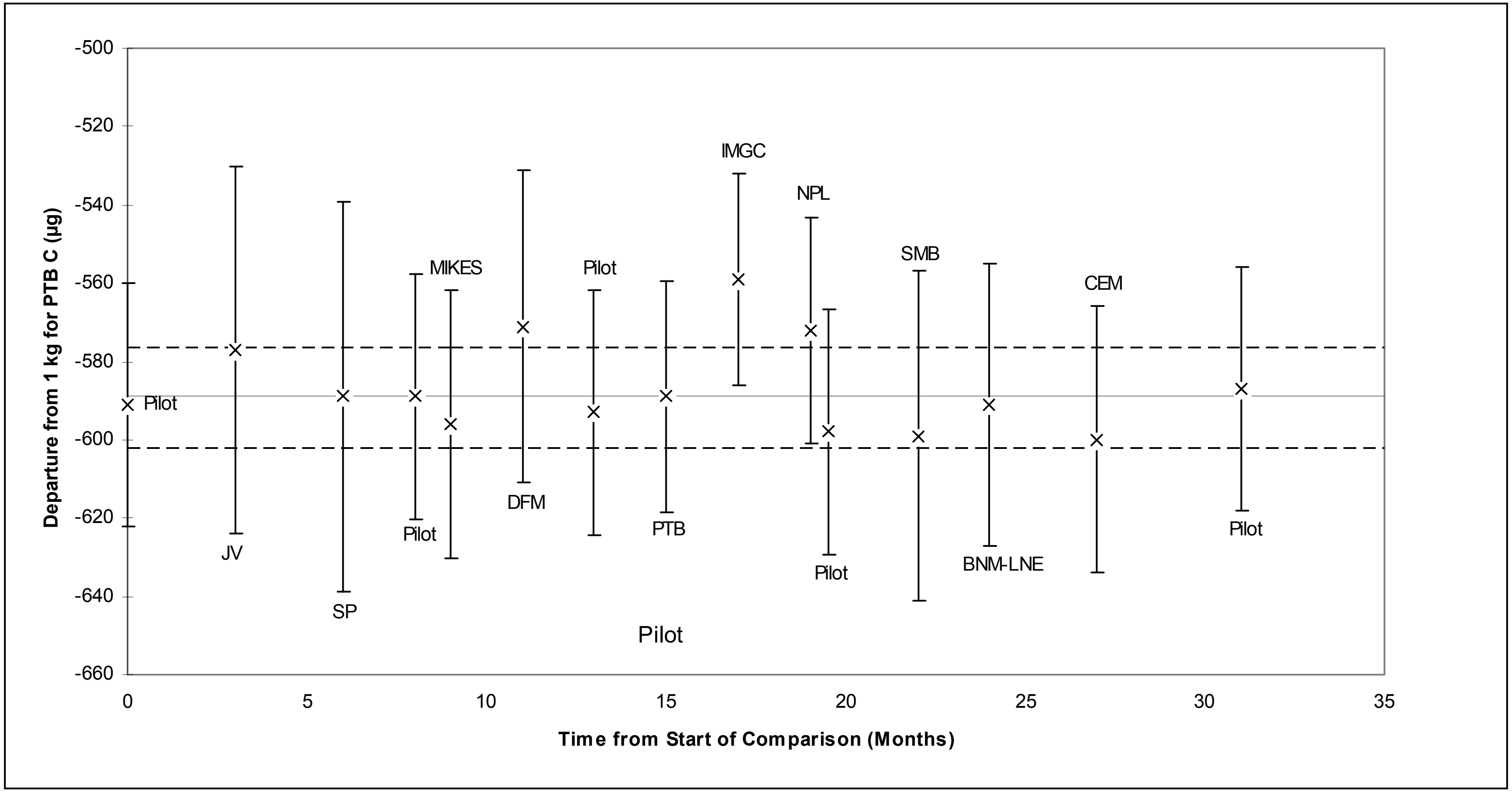

Figure 4-2: Mass Values Assigned to Weight PTB C (Solid line: reference value, broken lines: uncertainty in reference value, all uncertainties at k=2)

Table 4.6 indicates the difference between the results obtained by each pair of participants. The combined uncertainties of each pair of laboratories (k=2) are indicated in parentheses next to the calculated offset. The numbers shown in the table below are in micrograms and represent the offset in the results between the laboratories shown in the relevant row and column. An example of how to read the table is that NPL obtained a result 1 µg lower than DFM for the assignment of a mass value to weight PTB C. The combined uncertainty of this difference is 50 µg.

Laboratory	Reference	JV	SP	MIKES	DFM	PTB	IMGC	NPL	SMB	BNM-LNE	CEM
Reference		-12 (49)	0 (52)	+7 (37)	-18 (42)	0 (33)	-30 (31)	-17 (32)	+10 (44)	+2 (39)	+11 (37)
JV	12 (49)		+12 (69)	+19 (59)	-6 (62)	+12 (56)	-18 (55)	-5 (56)	+22 (63)	+14 (60)	+23 (58)
SP	0 (52)	-12 (69)		+7 (61)	-18 (64)	0 (59)	-30 (57)	-17 (58)	+10 (66)	+2 (62)	+11 (61)
MIKES	-7 (37)	-19 (59)	-7 (61)		-25 (53)	-7 (46)	-37 (44)	-24 (45)	+3 (55)	-5 (50)	+4 (49)
DFM	+18 (42)	+6 (62)	+18 (64)	+25 (53)		+18 (50)	-12 (49)	+1 (50)	+28 (58)	+20 (54)	+29 (53)
PTB	0 (33)	-12 (56)	0 (59)	+7 (46)	-18 (50)		-30 (41)	-17 (42)	+10 (52)	+2 (47)	+11 (46)
IMGC	+30 (31)	+18 (55)	+30 (57)	+37 (44)	+12 (49)	+30 (41)		+13 (40)	+40 (50)	+32 (46)	+41 (44)
NPL	+17 (32)	+5 (56)	+17 (58)	+24 (45)	-1 (50)	+17 (42)	-13 (40)		+27 (51)	+19 (47)	+28 (45)
SMB	-10 (44)	-22 (63)	-10 (66)	-3 (55)	-28 (58)	-10 (52)	-40 (50)	-27 (51)		-8 (56)	+1 (54)
BNM-LNE	-2 (39)	-14 (60)	-2 (62)	+5 (50)	-20 (54)	-2 (47)	-32 (46)	-19 (47)	+8 (56)		+9 (50)
CEM	-11 (37)	-23 (58)	-11 (61)	-4 (49)	-29 (53)	-11 (46)	-41 (44)	-28 (45)	-1 (54)	-9 (50)	

TABLE 4.6: Comparison of Mass Values Assigned To PTB C By The Participants (All values in µg)

4.2.4 Assignment of a Mass Value to INM 11

The transport standard INM 11 is a more challenging weight to calibrate than PTB C as it has a density of 9 150 kg m^{-3}, rather then a density of approximately 8 000 kg m^{-3} (the usual density of mass standards). The results obtained, together with the quoted uncertainties and the assigned reference value are shown in Table 4.7 and Figure 4.3. The pilot laboratory results are for information only and have not been used in the evaluation of the reference value.

Laboratory	Date	INM 11= 1 kg +	Uncertainty (k=1)
Pilot	Jan 1995	2411	16
JV	Apr 1995	2428	21.5
SP	Jun 1995	2411	28*
Pilot	Aug 1995	2408	16
MIKES	Sep-Oct 1995	2393	17.1
DFM	Nov 1995	2444	20
Pilot	Jan 1996	2406	16
PTB	May 1996	2422	13.2
IMGC	Jun-Aug 1996	2451	13.9
NPL	Sep 1996	2432	14.9
Pilot	Sep 1996	2393	16
SMB	Nov 1996	2401	21
BNM-LNE	Dec 1996-Feb 1997	2415	18
CEM	Mar-Apr 1997	2412	17.1
Pilot	Jun 1997	2403	16
Median	Not including pilot	2418.5	7.3
Median	Including pilot	2411	4.0

Table 4.7: Mass Values Assigned to Weight INM 11 (All numbers in μg)

The spread of these results is 58 μg, which is larger than the 41 μg obtained for the other transport standard. This additional spread is related to the results of the comparison of the two standards. MIKES obtained a value which was lower than all of the other participants for comparing the standards, but the value assigned to PTB C is comparable with the reference value for that weight. This would imply that that a problem occurred during the measurement of INM 11 but not PTB C. The measurement on INM 11 made by MIKES is no further from the reference value than those made by DFM and IMGC, but those two institutes appear to have assigned values to both of the transport standards that are systematically offset relative to the reference value. This means that both of these institutes measured the difference between the two transport standards to be similar to most of the other participants.

* SP has since re-calculated the k=1 uncertainty in this quantity to be 18 μg

One explanation for problems in measuring this weight is that it has an unusual density which means that a larger air buoyancy correction must be applied during its calibration than during the calibration of the other transport standard. However, this is an unlikely explanation as, unless the air density instrumentation had either been changed, or re-calibrated and assigned grossly different corrections, a laboratory would assign an incorrect mass value to its stainless steel standards when calibrating them against a Pt-Ir standard. Hence an incorrect value would also be assigned to PTB C.

The offsets between the mass values assigned to INM 11, along with their combined uncertainty, between each pair of participants is shown in Table 4.8.

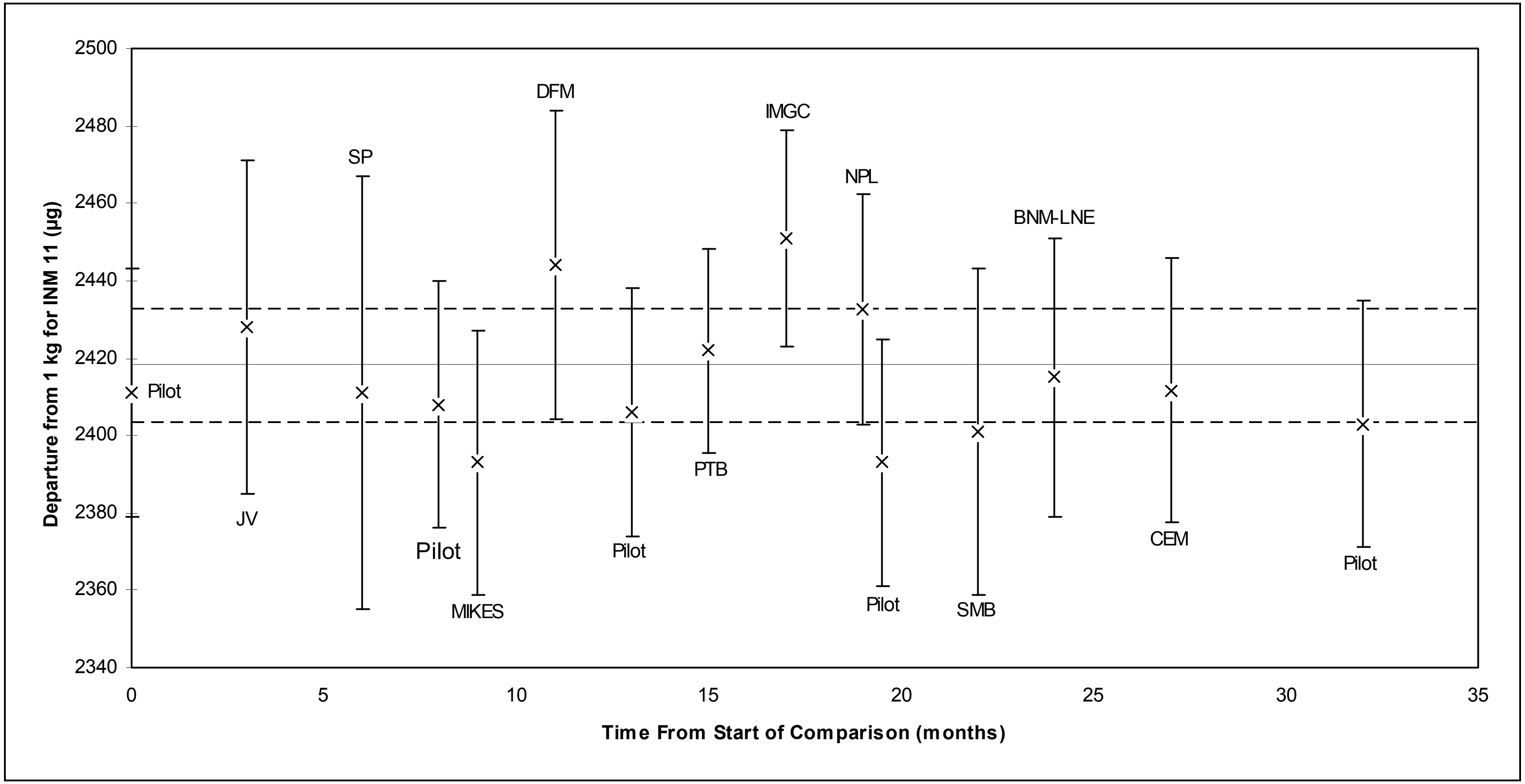

Figure 4-3: Mass Values Assigned to Weight INM 11 (Solid line: reference value, broken lines: uncertainty in reference value, all uncertainties at k=2)

Table 4.8 indicates the difference between the results obtained by each pair of participants. The combined uncertainties of each pair of laboratories (k=2) are indicated in parentheses next to the calculated offset. The numbers shown in the table below are in micrograms and represent the offset in the results between the laboratories shown in the relevant row and column. An example of how to read the table is that NPL obtained a result 12µg lower than DFM for the assignment of a value to weight INM 11. The combined uncertainty of this difference is 50 µg.

Laboratory	Reference	JV	SP	MIKES	DFM	PTB	IMGC	NPL	SMB	BNM-LNE	CEM
Reference		-10 (46)	+8 (58)	+26 (38)	-26 (43)	-4 (31)	-32 (32)	-14 (34)	+18 (45)	+4 (39)	+7 (38)
JV	+10 (46)		+17 (71)	+35 (55)	-16 (59)	+6 (51)	-23 (52)	-4 (53)	+27 (61)	+13 (57)	+16 (55)
SP	-8 (58)	-17 (71)		+18 (66)	-33 (69)	-11 (62)	-40 (63)	-22 (64)	+10 (70)	-4 (67)	-1 (66)
MIKES	-26 (38)	-35 (55)	-18 (66)		-51 (53)	-29 (44)	-58 (45)	-40 (46)	-8 (55)	-22 (50)	-19 (49)
DFM	+26 (43)	+16 (59)	+33 (69)	+51 (53)		+22 (48)	-7 (49)	+12 (50)	+43 (58)	+29 (54)	+32 (53)
PTB	+4 (31)	-6 (51)	+11 (62)	+29 (44)	-22 (48)		-29 (39)	-10 (40)	+21 (50)	+7 (45)	+10 (44)
IMGC	+32 (32)	+23 (52)	+40 (63)	+58 (45)	+7 (49)	+29 (39)		+18 (41)	+50 (51)	+36 (46)	+39 (45)
NPL	+14 (34)	+4 (53)	+22 (64)	+40 (46)	-12 (50)	+10 (40)	-18 (41)		+32 (52)	+18 (47)	+21 (46)
SMB	-18 (45)	-27 (61)	-10 (70)	+8 (55)	-43 (58)	-21 (50)	-50 (51)	-32 (52)		-14 (56)	-11 (55)
BNM-LNE	-4 (39)	-13 (57)	+4 (67)	+22 (50)	-29 (54)	-7 (45)	-36 (46)	-18 (47)	+14 (56)		+3 (50)
CEM	-7 (38)	-16 (55)	+1 (66)	+19 (49)	-32 (53)	-10 (44)	-39 (45)	-21 (46)	+11 (55)	-3 (50)	

TABLE 4.8: Comparison of Mass Values Assigned To INM 11 By The Participants (All values in µg)

4.2.5 Combined Results

An additional parameter that may be considered is the mean of the mass values assigned to the pair of weights by each laboratory. This offers an overall figure for the assignment of mass to the pair of weights by each participant which may be used to compare the overall results of all the laboratories. Table 4.9 shows the values obtained in this manner. The uncertainties displayed in this table are the arithmetic mean of the uncertainties quoted for each weight by the laboratory in question. Once more the median of the results is taken to be the reference value for this quantity.

Laboratory	Date	Mean = 1 kg + (μg)	Uncertainty (k=1)
Pilot	Jan 1995	910	16
JV	Apr 1995	925.5	22.5
SP	Jun 1995	911.0	26.5*
Pilot	Aug 1995	909.5	16
MIKES	Sep-Oct 1995	898.5	17.2
DFM	Nov 1995	936.5	20
Pilot	Jan 1996	906.5	16
PTB	May 1996	916.5	14
IMGC	Jun-Aug 1996	946.0	13.8
NPL	Sep 1996	930.2	14.7
Pilot	Sep 1996	897.5	16
SMB	Nov 1996	901.0	21
BNM-LNE	Dec 1996-Feb 1997	912.0	18
CEM	Mar-Apr 1997	905.8	17.1
Pilot	Jun 1997	908	16
Median	Not including pilot	914.2	7.6
Median	Including pilot	910	4.2

Table 4.9: Mean Mass Values Of The Two Transport Standards (All numbers in μg)

A comparison between all the participants results is shown in Table 4.10. From this it can be seen that all of the ten participants agree with the reference value to within the quoted uncertainties for a coverage factor of k=2.

* The re-calculated SP uncertainties mean that this uncertainty (k=1) should read 18 μg

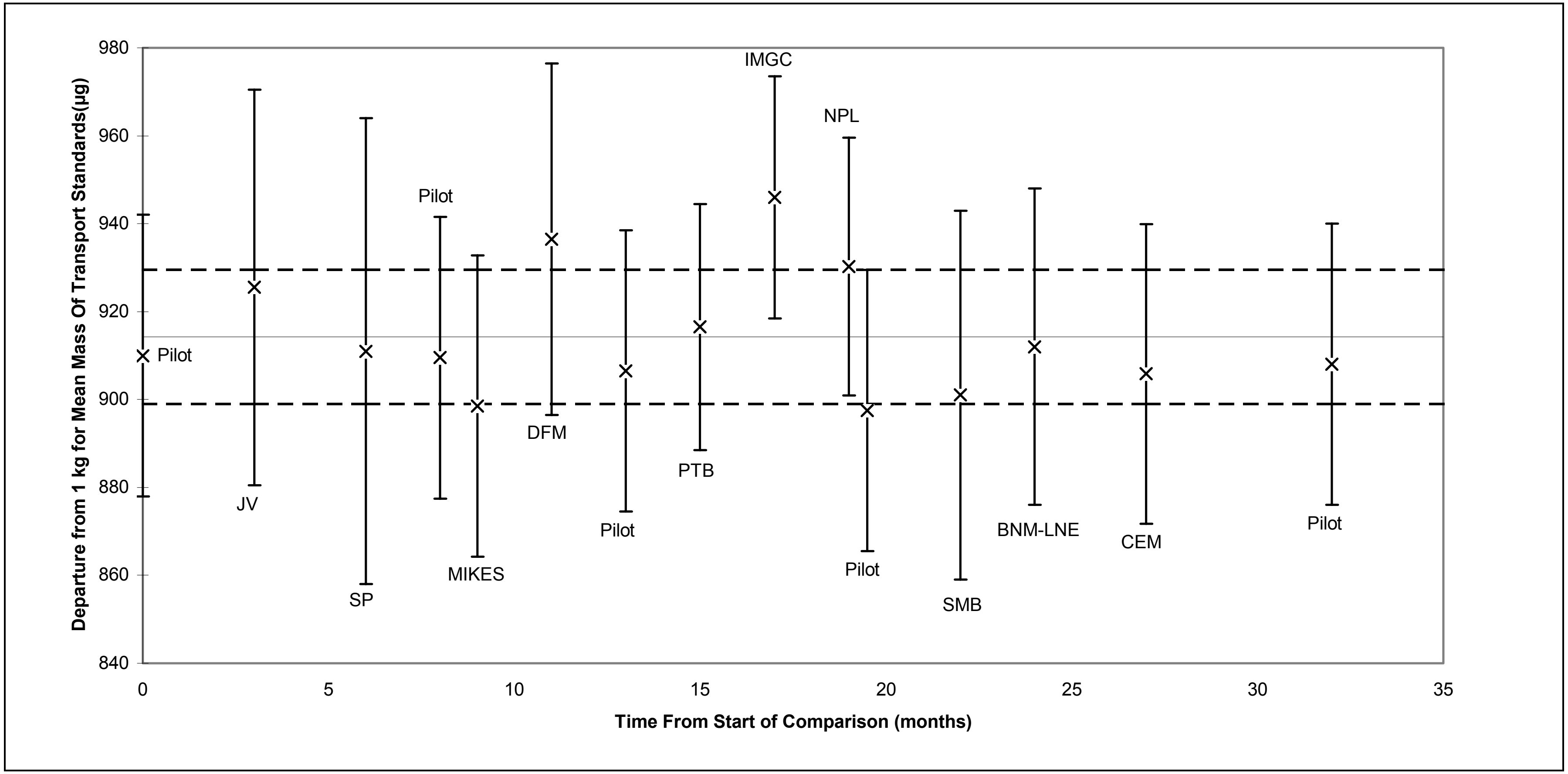

Figure 4-4: Mean Combined Mass Values Assigned to The Transport Standards(Solid line: reference value, broken lines: uncertainty in reference value, all uncertainties at k=2)

Table 4.10 indicates the difference between the results obtained by each pair of participants. The combined uncertainties of each pair of laboratories (k=2) are indicated in parentheses next to the calculated offset. The numbers shown in the table below are in micrograms and represent the offset in the results between the laboratories shown in the relevant row and column. An example of how to read the table is that NPL obtained a result 6 μg lower than DFM for the assignment of a mean mass value to the pair of transport standards. The combined uncertainty of this difference is 50 μg.

Laboratory	Reference	JV	SP	MIKES	DFM	PTB	IMGC	NPL	SMB	BNM-LNE	CEM
Reference		-11 (48)	+3 (56)	+16 (38)	-22 (43)	-2 (32)	-32 (32)	-16 (33)	+13 (45)	+2 (40)	+8 (38)
JV	11 (48)		+14 (70)	+27 (57)	-11 (61)	+9 (53)	-20 (53)	-5 (54)	+24 (62)	+14 (58)	+20 (57)
SP	-3 (56)	-14 (70)		+12 (64)	-26 (67)	-6 (60)	-35 (60)	-19 (61)	+10 (68)	-1 (65)	+5 (64)
MIKES	-16 (38)	-27 (57)	-12 (64)		-38 (53)	-18 (45)	-48 (44)	-32 (46)	-2 (55)	-14 (50)	-7 (49)
DFM	+22 (43)	+11 (61)	+26 (67)	+38 (53)		+20 (49)	-10 (49)	+6 (50)	+36 (58)	+24 (54)	+31 (53)
PTB	+2 (32)	-9 (53)	+6 (60)	+18 (45)	-20 (49)		-30 (40)	-14 (41)	+16 (51)	+4 (46)	+11 (45)
IMGC	+32 (32)	+20 (53)	+35 (60)	+48 (44)	+10 (49)	+30 (40)		+16 (41)	+45 (51)	+34 (46)	+40 (44)
NPL	+16 (33)	+5 (54)	+19 (61)	+32 (46)	-6 (50)	+14 (41)	-16 (41)		+29 (52)	+18 (47)	+24 (45)
SMB	-13 (45)	-24 (62)	-10 (68)	+2 (55)	-36 (58)	-16 (51)	-45 (51)	-29 (52)		-11 (56)	-5 (55)
BNM-LNE	-2 (40)	-14 (58)	+1 (65)	+14 (50)	-24 (54)	-4 (46)	-34 (46)	-18 (47)	+11 (56)		+6 (50)
CEM	-8 (38)	-20 (57)	-5 (64)	+7 (49)	-31 (53)	-11 (45)	-40 (44)	-24 (45)	+5 (55)	-6 (50)	

TABLE 4.10: Differences between the participants in the mean of the mass values assigned to each of the two transport standards (all values in μg)

5. UNCERTAINTY ESTIMATES

Uncertainty estimates were provided by each of the laboratories for all of the measurements that they carried out. Each laboratory calculated its measurement uncertainties in the manner that it would normally make such calculations. As would be anticipated, the major contributions were considered in a similar manner by each participant with the only differences being in the smaller contributions, which tend not to be significant. All of the uncertainties quoted in this section are for a coverage factor of k=1.

5.1 MASS STANDARDS

The uncertainty in the values of the mass standards that were used in the comparison ranged from 13.0 μg to 20 μg, typical of the uncertainties that would be expected for such stainless steel mass standards. All of the standards used were traceable to the official copy of the Prototype of the Kilogram held in that particular country.

5.2 TRANSPORT STANDARD VOLUME

The information relating to the uncertainty in the density of each of the transport standards was provided by the owner of each weight and is shown in Table 2.1. From these figures the uncertainty in the volume of PTB C may be calculated to be 0.0011 cm^3 while that for INM 11 is 0.0024 cm^3. The volume uncertainty is multiplied by the air density at the time of the calibration of the weight to give the equivalent uncertainty in mass units. The figures quoted for this contribution by the participants range from 0.6 μg to 2.4 μg when considering PTB C and that for INM 11 was from 0.7 μg to 3.4 μg. It should be noted that some participants combined the uncertainty in the volume of their own standards with that in the test weight to give a larger figure.

5.3 PARTICIPANT STANDARD VOLUME

There is an uncertainty in the volume of the weights used as mass standards by each participating laboratory that may be considered in the same manner as discussed in Section 5.2. However, if the uncertainty in the volume of the standard has already been included in its own calibration it will be possible to ignore this contribution. A further option that has been considered by one participant is that the uncertainty in the volume of the standard should be multiplied by the difference in air density at the time of calibration of the standard from that at the time when it is used as a standard.

5.4 AIR DENSITY MEASUREMENT

All of the laboratories involved in this comparison have used the empirical equation recommended by the CIPM [7], [8] to calculate the air density at the time of making measurements on the transport standards. There is an uncertainty associated with this equation, as well as with the measurement of the temperature, air pressure, humidity and carbon dioxide concentration, which are the quantities fed into the equation to calculate air density.

5.5 ADDITIONAL WEIGHTS

The high density, and hence low volume, of INM 11 means it experiences approximately 20 mg less upthrust from the air than a stainless steel weight. Most laboratories have taken this into account when comparing INM 11 with their own standards and PTB C by adding a 20 mg standard to the stainless steel weight. This means that only a small part of the mass comparator's measurement window is used in the comparison process. There is an uncertainty associated with the mass of such additional weights.

5.6 MASS COMPARATOR

There are uncertainties associated with the mass comparators used in this comparison which may be broken down into the following categories.

5.6.1 Sensitivity Error

The mass difference between two weights under comparison is usually indicated by an electronic scale on the comparator in use. Often there is a linear error in this scale which some laboratories have taken into account in their uncertainty budgets. Others have minimised the problem by matching the apparent mass of the weights under comparison using additional weights (see Section 5.5).

5.6.2 Weight Exchanger Anomalies

Many of the mass comparators used in this comparison have automatic mechanisms that allow for the automatic comparison of several weights. Some of these mechanisms are prone to influencing the results of a comparison such that the measured mass difference is dependent on the relative location of the weights. Several participants who were aware of this potential problem with their comparator made comparisons with the weights in many different positions on the exchanger in order to eliminate the effects of this problem, while others have made an allowance for it in the uncertainty budgets.

5.6.3 Long Term Repeatability

Some laboratories have included a component in the uncertainty budget to take into account the reproducibility of the mass comparator used. The remainder have considered that making several measurements, including the repositioning of the weights on the weight exchange mechanism, during the comparison means this contribution is accounted for in the standard deviation of all the measurements (see Section 5.7).

5.7 SPREAD OF RESULTS

The spread of the results contributing to the final values assigned to each quantity have been included in the uncertainty budget of every participant. There is some variation between the different laboratories, with some using the sample standard deviation of their measurements while others have used the standard uncertainty as a measure of this quantity.

5.8 OTHER SOURCES

Many other minor sources of uncertainty have also been considered by various participants. These all have negligible influence on the final uncertainty quoted for each quantity and are summarised below:-

- The uncertainty in the determination of the height of the centre of gravity of the weights
- The uncertainty in the measurement of the gradient in the local gravitational field
- The effect of changes in relative humidity on weights having different surface areas
- Magnetic interaction between the weight and the mass comparator
- Dust contamination

6. SUMMARY

The values assigned to each of the two mass standards show that the measurements made by all of the participants agree with the reference mass value for the standards to within their quoted uncertainties (k=2). Eight of the ten participants assigned a mass value to the stainless steel weight that agrees with the reference value to within the quoted k=1 uncertainties while seven of the participants assigned values to the alacrite weight that are within the quoted k=1 uncertainty.

It may be concluded that measurements made in all of these laboratories on stainless steel 1 kg standards were metrologically equivalent at the time of this comparison (for a k=2 coverage factor).

7. PROPOSED FUTURE WORK

A further EUROMET project which involves the comparison of Pt-Ir 1 kg standards has been agreed with the aim of establishing whether there are systematic offsets in the way that some NMIs treat the value assigned to their national copy of the Prototype of the Kilogram. Such standards were cleaned at the BIPM prior to being calibrated at the time of the third verification of National Prototypes of the Kilogram. It is well documented that Pt-Ir prototypes gain mass following cleaning [1]. Several of the participants have used mathematical models to predict the magnitude of this mass gain while others have not taken it into account. The purpose of the Pt-Ir comparison will be to establish whether this difference in approaches leads to significant differences in value that various NMIs assign to their national copy of the Prototype of the Kilogram. The importance of the Pt-Ir comparison is further demonstrated by a problem that arose at the IMGC at the time of this comparison. Shortly after submitting its results, the IMGC became aware that, following an attempt to clean its official copy of the kilogram (number 62), it had a problem with its assigned value. It is almost certain that the results of the IMGC would have been much closer to the reference value had this problem, which has now been addressed, not occurred.

A second additional 1 kg comparison, using 1 kg stainless steel weights, will be organised under the auspices of EUROMET. This will allow NMIs that did not participate in this exercise to demonstrate metrological equivalence with the participants of this comparison, and hence the CCM 'Key Comparison' at 1 kg.

8. REFERENCES

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APPENDIX 1: MEASUREMENT DATES

Laboratory	INM 11- PTB C	PTB C	INM 11
Pilot	12/01/95-22/01/95		
JV	30/04/95-03/05/95	08/05/95-10/05/95	04/05/95-16/05/95
SP	11/06/95-21/06/95	11/06/95-21/06/95	11/06/95-21/06/95
Pilot	14/08/95-23/08/95		
MIKES	15/09/95-18/09/95	26/09/95-10/10/95	18/09/95-09/10/95
DFM	10/11/95-17/11/95	10/11/95-17/11/95	10/11/95-17/11/95
Pilot	12/01/96-21/01/96		
PTB	15/04/96-24/05/96	15/04/96-24/05/96	15/04/96-24/05/96
IMGC	12/06/96	12/06/96-13/08/96	12/06/96-13/08/96
NPL	28/08/96-04/09/96	28/08/96-20/09/96	28/08/96-24/09/96
Pilot	09/09/96-18/09/96		
SMB	25/11/96	25/11/96	25/11/96
BNM-LNE	31/12/96-30/01/97	30/12/96-10/02/97	02/01/97-10/02/97
CEM	24/02/97-27/02/97	13/03/97-07/04/97	13/03/97-07/04/97
Pilot	28/05/97-08/06/97		

APPENDIX 2: TRANSPORTATION DETAILS

Date	Transportation	Carrier	From	To	Comments
31/03/95	Air	I Severn (NPL)	NPL	JV	
29-30/05/95	Road	T Myklebust (JV)	JV	SP	INM 11 filter not sealed
05/06/95	Air	L Pendrill (SP)	SP	NPL	
12/09/95	Air	I Severn (NPL)	NPL	MIKES	
17/10/95	Air	H Kajastie (MIKES)	MIKES	DFM	
13/12/95	Air	H Simonsen (DFM)	DFM	NPL	
26/03/96	Air	S Davidson (NPL)	NPL	PTB	
27/05/96 28/05/96	Road to BIPM Air IMGC	M Glaser (PTB) M Mosca (IMGC)	PTB	IMGC	Journey via BIPM, Paris
19/08/96	Air	W Bich (IMGC)	IMGC	NPL	PTB C not fully clamped
21/10/96	Air	D Rayner (NPL)	NPL	SMB	
27/11/96	Rail	G Bairy (SMB)	SMB	BNM-LNE	
12/02/97	Air	T Madec (BNM-LNE)	BNM-LNE	CEM	
23/04/97	Air	M Redondo (CEM)	CEM	NPL	

APPENDIX 3: AIR DENSITY DURING MEASUREMENTS

Laboratory	Minimum	Maximum	Mean
Pilot	1.1696	1.2253	1.1915
JV	1.2073	1.2145	1.2105
SP	1.1672	1.1755	1.1703
Pilot	1.1852	1.1984	1.1930
MIKES	1.188	1.219	1.204
DFM	1.1505	1.1978	1.18
Pilot	1.1777	1.2157	1.20163
PTB	1.1881	1.1902	1.1892
IMGC	1.1651	1.1656	1.1654
NPL	1.1977	1.2111	1.2044
Pilot	1.1985	1.2173	1.2098
SMB	1.17109	1.17118	1.17114
BNM-LNE	1.18556	1.21991	1.20074
CEM	1.0529	1.0529	1.0529
Pilot	1.1811	1.2175	1.1990

Table A3.1: Air density during comparison of transport standards (all values in kg m^{-3})

Laboratory	Minimum	Maximum	Mean
JV	1.1909	1.1981	1.1931
SP	1.1672	1.1755	1.1703
MIKES	1.174	1.204	1.190
DFM	1.1505	1.1978	1.18
PTB	1.1881	1.1902	1.1892
IMGC	1.148	1.180	1.165
NPL	1.1951	1.2111	1.2031
SMB	1.17100	1.17118	1.17108
BNM-LNE	1.18542	1.21470	1.19880
CEM	1.0501	1.0501	1.0501

Table A3.2: Air density during determination of mass of PTB C (all values in kg m^{-3})

Laboratory	Minimum	Maximum	Mean
JV	1.1789	1.2027	1.1921
SP	1.1672	1.1755	1.1703
MIKES	1.196	1.270	1.204
DFM	1.1505	1.1978	1.18
PTB	1.1881	1.1902	1.1892
IMGC	1.148	1.180	1.165
NPL	1.1977	1.2111	1.2044
SMB	1.17112	1.17119	1.17116
BNM-LNE	1.18736	1.21606	1.20219
CEM	1.0501	1.0501	1.0501

Table A3.3:Air density during determination of mass of INM 11 (all values in kg m^{-3})