

A comparison of primary platinum-iridium kilogram mass standards among eighteen European NMIs

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Abstract

The kilogram is unique among the base SI units in being the only one defined by an artefact rather than with relation to naturally occurring physical constants. A major problem with maintaining the traceability of the mass scale is the inherent instability of the kilogram artefacts. National standard kilograms accrete surface contamination over time which leads to an increase in their mass values. Without reference to the international prototype kilogram it is difficult to assess the magnitude of this mass gain and the traceability of measurements is compromised to some extent. This comparison examined the values of the national standard kilogram of 18 European NMIs, each of which uses an algorithm to predict the mass gain of their national standard. The results have been used to evaluate the accuracy of these algorithms and also to recommend a best-fit algorithm for the modelling of mass gain of national standard kilograms.

Key Words: Mass gain, kilogram, SI units, national standards.

1. Introduction

The kilogram is unique among the base SI units in being the only one defined by an artefact rather than with relation to naturally occurring physical constants. This imposes a unique set of problems relating to the maintenance and traceability of the mass scale worldwide. All mass measurements must be ultimately traceable to the International Prototype of the Kilogram (K) held at the BIPM (Bureau International des Poids et Mesures). This traceability is achieved via copies of the Prototype held by National Measurement Institutes (NMIs) and maintained by the periodic re-verification of these copies by the BIPM. A major problem with maintaining this traceability is the inherent instability of the kilogram artefacts. The national copies of K accrete surface contamination over time which leads to an increase in their mass values. Without reference to K it is difficult to assess the magnitude of this mass gain and the traceability of measurements is compromised to some extent.

The purpose of this project was to compare the values of the national copies of the prototype of 18 European NMIs. While the results obtained can be used to demonstrate equivalence between the participants, the main objective of the work is to calculate the relative mass gains of the national copies, to analyse this data, and to draw conclusions about the relative stabilities of the kilograms. Each

participating NMI uses an algorithm to predict the mass gain of their national standard. The results gained from this comparison have been used to evaluate the accuracy of these algorithms.

2. Participants

The participating laboratories are listed in Table 1. The National Physical Laboratory acted as the pilot for this exercise. Additionally, the BIPM provided traceability for the reference and travelling standards both before and after the comparison.

Laboratory		Country
Bundesamt für Eich- und Vermessungswesen	BEV	Austria
Metrology Division, FPS Economy	SMD	Belgium
Czech Metrological Institute	CMI	Czech Republic
Danish Institute of Fundamental Metrology	DFM	Denmark
Mittatekniikan keskus	MIKES	Finland
Institut National de Métrologie	BNM-INM	France
Physikalisch-Technische Bundesanstalt	PTB	Germany
National Office of Measures	OMH	Hungary
Istituto di Metrologia "G Colonnetti"	IMGC	Italy
Nederlands Meetinstituut-Van Swinden Laboratorium	NMi VSL	Netherlands
Justervesenet	JV	Norway
Central Office of Measures	GUM	Poland
Slovak Institute of Metrology	SMU	Slovakia
Centro Español de Metrologia	CEM	Spain
SP Measurement Technology	SP	Sweden
Swiss Federal Office of Metrology and Accreditation	METAS	Switzerland
Tübitak Ulusal Metroloji Enstitüsü	UME	Turkey
National Physical Laboratory	NPL	United Kingdom

Table 1: List of Participating Laboratories

3. Mass standards

Two platinum-iridium kilograms were used as the travelling mass standards for this comparison; these had the designations 55 and 651. Kilogram 55 is an official copy of the International Prototype and was manufactured in 1950, calibrated as part of the second verification in 1953 allocated to the PTB in 1954. Kilogram 651 is an underweight copy produced in 1979 and calibrated and supplied to the NPL in 1982. NPL platinum-iridium kilogram A was used as a reference standard against which to monitor the stability of the travelling standards. The stability of the transfer and reference standards had been monitored over periods of 10 to 20 years before the start of the comparison. Kilograms 55 and A showed good stability (drift less than 3 micrograms per year, typical of primary mass standards). Kilogram 651 showed a consistent mass loss of 10 micrograms per year. While not ideal the fact that the mass loss was consistent and could therefore be predicted meant that kilogram 651 could be used in this comparison.

4. Comparison Protocol

The protocol followed was similar to that which has been adopted for CCM regional key comparisons in the EUROMET area. The two transfer standards were circulated among the participating laboratories, returning to NPL for stability checks after each series of measurements. Each measurement series comprised either three or four laboratories. Participants had one month in which to complete their measurements.

5. Calibration of standards

Prior to the start of the comparison both of the transfer standards and the stability standard were calibrated by the BIPM. The weights were returned to NPL, compared with each other and then transported to the first participating laboratory.

Between each series of three or four measurements by the participating laboratories the two travelling standards were returned to NPL where their stability was checked against the reference standard.

After the completion of the comparison the travelling standards were checked against the reference standard at NPL and all three weights were again calibrated by the BIPM.

A step change in the value of kilogram 55 was noted between the third and fourth participants. On examining the weight when it returned to the pilot laboratory it was clear the weight had been damaged. This was taken into account when analysing the data.

6. Analysis

6.1 Reference values

The results from the participants, from the NPL stability checks and from the BIPM calibration values were analysed. Three potential reference values were considered;

1. Using only the BIPM data
2. Using the BIPM and NPL data
3. Using all consistent data

Consistent data was regarded as that data having a normalised deviation from the reference value of less than 2.0 (calculated using standard uncertainties).

The step change noted in the value of kilogram 55 was taken into account when calculating the reference value for this weight.

Since the NPL reference standard A and the travelling standards were calibrated at the BIPM before and after the comparison there is a strong correlation between the stability measurements made at NPL and the calibration of the weights at the BIPM. For this reason a correlation coefficient of $r=0.9$ between the NPL and the BIPM measurements has been assumed. Additionally, since each participating laboratory is directly traceable to the BIPM there can be assumed to

be some correlation between the measured values and the BIPM value (and between individual measured values). However, this correlation will depend on a number of factors, such as when the national standard of each participant was calibrated. For this reason no correlation coefficient for the participants' data was included.

The results of the three analysis methods were evaluated and the reference values calculated from each method agreed within the combined uncertainties. As they provide more fundamental reference values the values calculated from only the BIPM measurements were used.

6.2 Participant's data

The participants' results and uncertainties ($k=1$) with relation to the reference values are shown in Figures 1 and 2. Values have been "excluded" where the result had a normalised deviation from the reference value of greater than 2.0 (calculated using standard uncertainties).

It can be seen that the majority of the results are in agreement with the reference value (when the results are expressed at $k=2$ uncertainty). More of the measurements of kilogram 651 disagree with the reference value. The most obvious explanations for this are either that the relatively large discrepancy of the weight from nominal (over 11 mg) made it difficult for some laboratories to calibrate or that the model for the drift is in error.

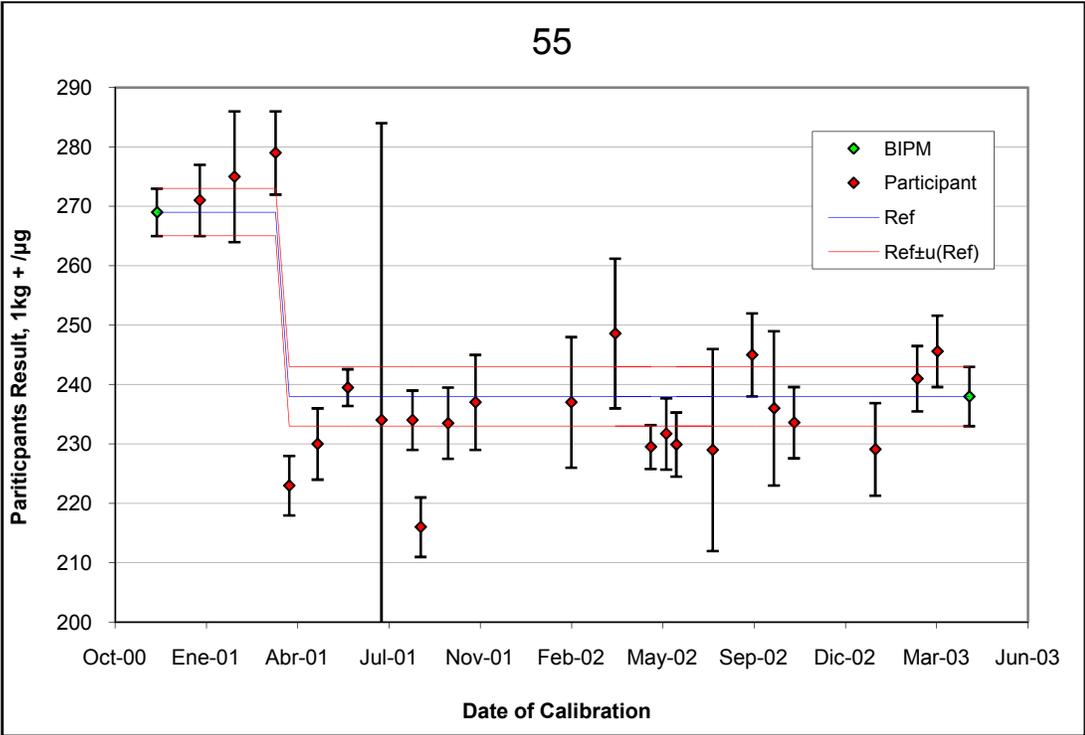


Figure 1: Participants' results relative to the reference value for kilogram 55

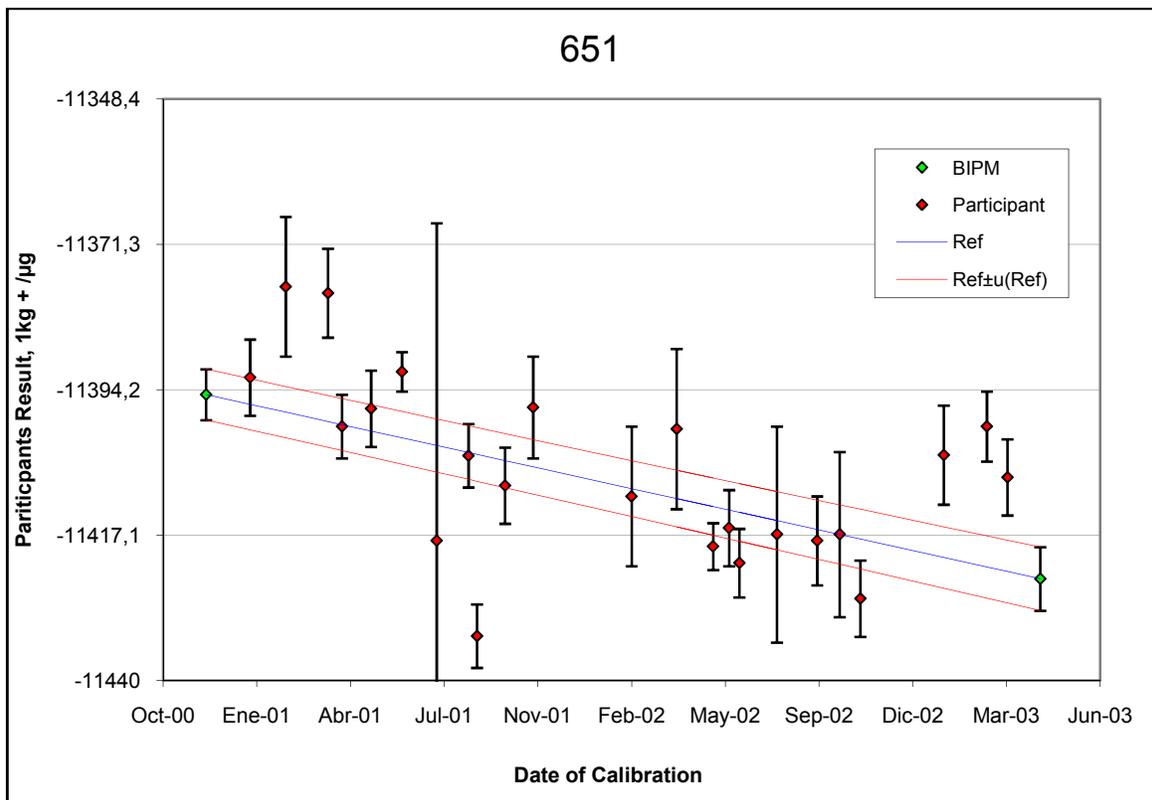


Figure 2: Participants' results relative to the reference value for kilogram 651.

6.3 Analysis of mass gain algorithms

Table 2 summarises the algorithms used by the participating laboratories to predict the mass gain of their national prototype. In order to check the accuracy of the algorithms, the results of the comparison were analysed with respect to the time elapsed since the national prototype was last cleaned and calibrated at the BIPM.

Participant	Algorithm
NPL	$m = m_{(1991)} + 0.356\ 097 \times t^{0.511\ 678} \mu\text{g}$ (t in days)
SMD	$m = m_{(1991)} + 3.0 \mu\text{g/year}$
NMi	Data fit - approximates $m = m_{(1997)} + 1.2 \mu\text{g/year}$
CEM	Note 1
GUM	$m = m_{(1990)} + 2.2632 \mu\text{g/year}$
CMI	None
PTB	$m = m_{(1996)} + 3.064 \mu\text{g/year}$
SMU	None
OMH	$m = m_{(1990)} + 1 \mu\text{g/year} + 0.0368 \mu\text{g/day}$
BEV	$m = m_{(1990)} + 10 \mu\text{g} + (n - 1) \times 1.4 \mu\text{g}$ (n in years)
IMGC	Compromise between estimated drift and consistency of two standards

METAS	$m = m_{(1991)} + 0.037 \mu\text{g/day (first 18 months)} + 1.205\mu\text{g/year (subsequent)}$
JV	$m = m_{(2001)} + 10 \mu\text{g} + 1 \mu\text{g/year}$
DFM	$m = m_{(1991)} + 0.00191 t + 0.0113 \sqrt{t} \mu\text{g (t in days)}$
SP	$m = m_{(1991)} + 3.2 \mu\text{g} + (n - 0.25) \times 1 \mu\text{g (n in years)}$
MIKES	$m = m_{(2001)} + 6 \mu\text{g (year 1)} + 5 \mu\text{g/year (subsequent)}$
BNM-INM	None
UME	$m = m_{(1993)} + 10 \mu\text{g}$

Table 2: Participant results and uncertainties and mass gain algorithms used

Note 1: CEM algorithm

$$m(t) = m + \left[m_3 + \frac{m_1 - 10\mu\text{g}}{n_1 - 1} \times (n - 1) + \frac{m_2}{n_1} \times n \right]$$

$m(t)$ - calculated mass

m - mass at last calibration

m_1 - mass loss due to cleaning (last calibration)

m_2 - mass diff. between last two calibrations (after

cleaning)

m_3 - 10 μg (first year mass gain)

n - years since last calibration

n_1 - Years between last two calibrations

The results of the participants' measurements on the two transfer standards, with respect to the time since their national prototype was calibrated, are plotted in Figures 3 and 4. Only results from participants who had the national standards cleaned before they were last calibrated are included.

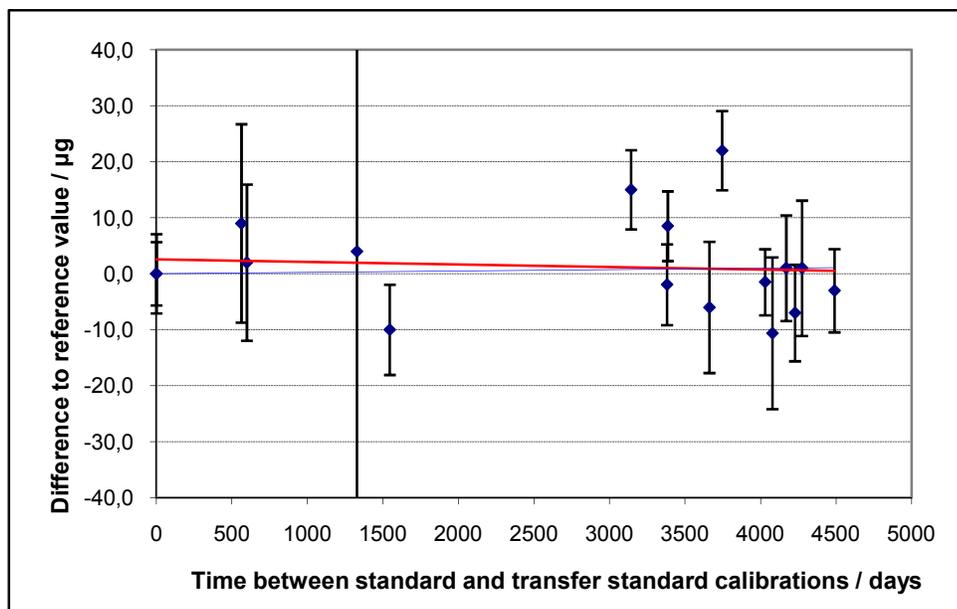


Figure 3: Results for kilogram 55 with respect to time since national prototype calibration (values corrected by participants for drift in national prototype).

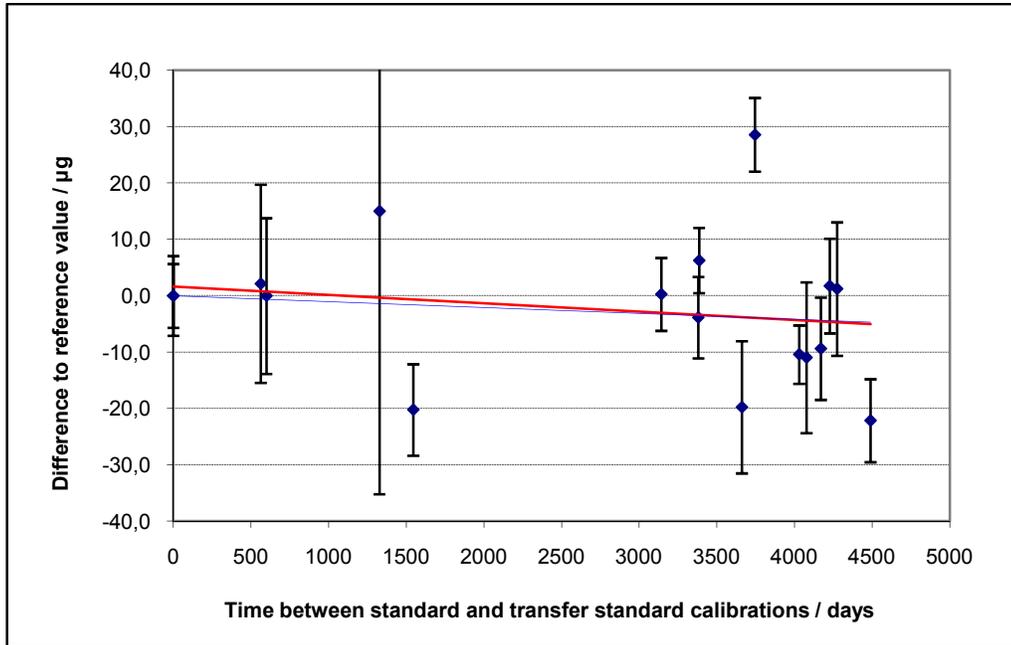


Figure 4: Results for kilogram 651 with respect to time since national prototype calibration (values corrected by participants for drift in national prototype).

The results broadly confirm that the algorithms used by the participants model the mass gain of their national prototypes correctly. While there is a reasonably large spread on the drift compensated results (particularly for kilogram 651), fitting both sets of data gives a drift co-efficient which is very small, indicating that there is minimal error on the collective algorithms. Linear best-fit lines have been added to the graphs and these show negligible departure from the expected result (along the y axis). The red lines represent the fit of all the data the blue lines have been constrained to go through the origin. There is a small slope on the fitted line for kilogram 651 (equal to -0.4 micrograms per year). It is probable this is a function of the difficulty of calibrating this weight (it was significantly under 1 kilogram in nominal mass) and thus of the larger spread in the measurement data.

By removing the mass gain algorithms from the individual results reported by the participants the mass gains of the individual national standards, with respect to time since cleaning, can be examined.

The results of the uncorrected participants' measurements on the two transfer standards, with respect to the time since their national prototype was calibrated, are plotted in Figures 5 and 6.

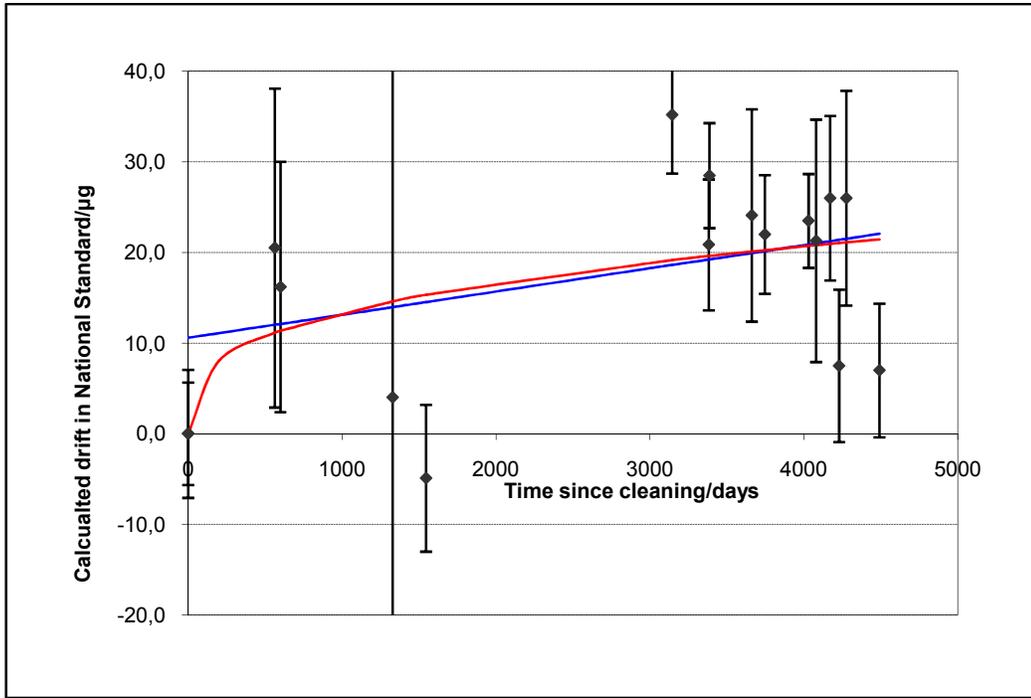


Figure 5: Results for kilogram 55 with respect to time since national prototype cleaning (results uncorrected for drift in national prototype)

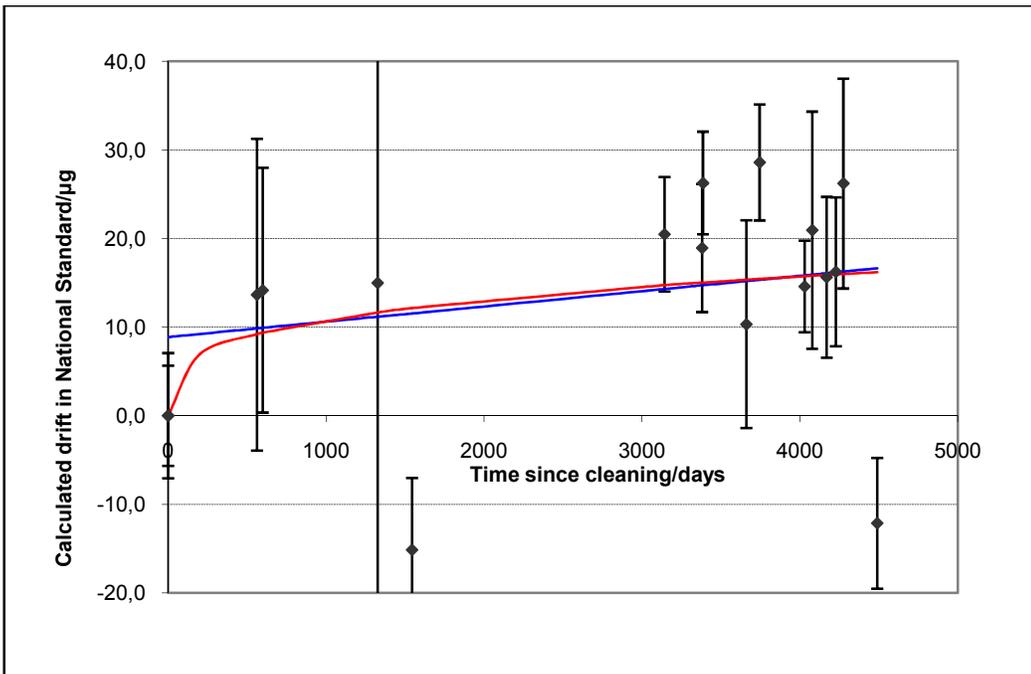


Figure 6: Results for kilogram 651 with respect to time since national prototype calibration (values uncorrected for drift in national prototype)

Two best-fit models have been added to the graphs. The first (green line) is of the form:

$$m(t) = m(t_0) + A + B(t) \dots \dots \dots (1)$$

Where A is the initial rapid mass gain of the national standard and B is a constant representing the subsequent linear mass gain as a function of time t. This is the form of model used by the majority of participants.

The second (red line) is of the form:

$$m(t) = m(t_0) + A(t)^B \dots\dots\dots(2)$$

Where A and B are constants and t is the time since the calibration of the national prototype.

It can be seen that after a year the two models produce very similar solutions for the mass gain of the kilogram it is probable that the second (red) model produces a better fit for the mass gain over the first year. This model was produced by NPL based largely on data gathered over the first two years after the cleaning of the kilogram.

Combining the data for the two transfer standards the following solutions for the two mass gain models (1) and (2) can be derived;

$$\text{Mass gain} = 1.562 \text{ } 0 \text{ t}^{0.295 \text{ } 992} \text{ (with t in days)} \dots\dots\dots(3)$$

for the exponential model and

$$\text{Mass gain} = 9.7 \text{ } \mu\text{g} + 0.8 \text{ } \mu\text{g/year} \dots\dots\dots(4)$$

for the linear model.

These, in effect, represent the best-fit solutions for all the available data and so is the best estimate for the mass gain algorithms (taking the mass gain of all the cleaned kilograms of the participants). Both models give an average residual of 2.0 micrograms (difference between the fit and the measured value). For a number of participants the linear model is reassuringly near the most popularly adopted mass gain algorithm (+10 μg for the first year followed by a subsequent gain of + 1μg/year).

7. Conclusions

Although the main aim of the comparison was not a demonstration of the participating laboratories ability to calibrate platinum-iridium kilogram mass standards there is generally good agreement between the results of the participants. Individual laboratories will be able to draw their own conclusions about their results.

Examining the algorithms used by the individual NMIs to correct for the mass gain of their national prototype kilograms shows that there is no bias to the data and that, taken as a whole, the various algorithms used represent good models of the mass gain of the respective national prototypes. Again, individual laboratories can draw conclusions regarding their own algorithms. Looking at the data uncorrected for the changes in the national prototypes, the results can be modelled

using the widely accepted algorithm of rapid mass gain, after cleaning and BIPM, over the first few months followed by a linear mass gain model. From the analysis of this data, the values calculated are 8.4 micrograms for the rapid mass gain after cleaning followed by 1.1 microgram per year linear mass gain.

8. Acknowledgements

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