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Magnetic properties comparison of mass standards among seventeen national metrology institutes

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Abstract
The ubiquitous technology of magnetic force compensation of gravitational forces acting on artifacts on the pans of modern balances and comparators has brought with it the problem of magnetic leakage from the compensation coils. Leaking magnetic fields, as well as those due to the surroundings of the balance, can interact with the artifact whose mass is to be determined, causing erroneous values to be observed. For this reason, and to comply with normative standards, it has become important for mass metrologists to evaluate the magnetic susceptibility and any remanent magnetization that mass standards may possess. This paper describes a comparison of measurements of these parameters among seventeen national metrology institutes. The measurements are made on three transfer standards whose magnetic parameters span the range that might be encountered in stainless steel mass standards.

(Some figures in this article are in colour only in the electronic version)

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Participating laboratories

Laboratory	Acronym	Country
Centro Nacional de Metrologia	CENAM	Mexico
National Physical Laboratory	NPL	United Kingdom
Center for Measurement Standards, Industrial Technology Research Institute	CMS/ITRI	Taiwan
Institute for National Measurement Standards, National Research Council	INMS/NRC	Canada
Korea Research Institute of Standards and Science	KRISS	Korea
Bureau International des Poids et Mesures	BIPM	International
National Metrology Laboratory	CSIR-NML	South Africa
Swedish National Testing and Research Institute	SP	Sweden
Bundesamt für Metrologie	METAS	Switzerland
Physikalisch-Technische Bundesanstalt	PTB	Germany
Standards, Productivity and Innovation Board	SPRING Singapore	Singapore
Instituto Nacional de Metrologia	INMETRO	Brazil
Laboratoire national de métrologie et d'essais	LNE	France
Centro Español de Metrologia	CEM	Spain
National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology	NMIJ /AIST	Japan
Measurement Standards Laboratory of New Zealand	MSL	New Zealand
Nederlands Meetinstituut, Van Swinden Laboratorium	NMi-VSL	The Netherlands

1. Introduction

This comparison, piloted by the National Research Council of Canada (NRC), concerns the measurement of magnetic susceptibility (χ) and remanent magnetization (M) of one kilogram mass standards. Many national metrology institutes (NMIs), including the NRC, are newcomers to measurement of magnetic properties. Several, but not all, use apparatus, standards and magnets supplied by the Bureau International des Poids et Mesures (BIPM) and employ the formulae and techniques developed by one of us (RSD) [1,2,8]. It was time to see how well various NMIs agree among themselves. This is particularly true of those laboratories, such as NRC, which have idiosyncratic structures used to position test objects over calibrated magnets, use a wide variety of balances or whose test magnets have not been calibrated at the BIPM.

Since many NMIs are 'traceable' to the BIPM, they are, in a sense, in a similar position to mass traceability to the International Prototype of the Kilogram with the difference that comparisons might be expected to show the degree of covariance among laboratories, rather than any strictly defensible traceability to SI base units. Nevertheless, any such comparison would alert outliers to the general consensus, a valuable service in itself.

Not enough confidence existed, however, to propose such an exercise as a key comparison, but there was a consensus that it was time that some reassurance should be available to those who are measuring susceptibility and remanent magnetization.

2. Protocol

Seventeen NMIs participated in this project, representing several regional metrology organizations (RMOs), including a number of institutes that are not members of the Consultative Committee for Mass and Associated Quantities (CCM). There was clear willingness to participate in a comparison and at the same time a natural reluctance to embarrassing exposure if something were seriously wrong with a laboratory's measurements. Therefore, to maximize participation and minimize fears of embarrassment, a pilot comparison that would not absorb a lot of valuable time was agreed upon.

NRC prepared three transfer standards of nominal one kilogram mass: a cylinder of minimum surface area, with a flat bottom, and weights of standard form with recesses as specified by the Organisation Internationale de Métrologie Légale (OIML) and by ASTM International (formerly American Society for Testing and Materials). All of the transfer standards were monolithic. They were selected from a field of well characterized weights that spanned a wide range of χ and M values. Characterization followed established NRC procedures, which are essentially those supplied by the BIPM. These transfer standards were circulated among participants who reported measured values of susceptibility and remanent magnetization along with associated uncertainties.

Three additional control pieces were also characterized. They were of the same nominal types as the transfer standards, made by the same manufacturers, and were sequestered at NRC to be used to ensure continuity of measurement procedures at the pilot laboratory and to detect any changes that might occur in the travelling standards depicted in figure 1.

NRC acted as a clearing house for data and assigned a letter code to each laboratory. When the data became available for initial distribution, each participating laboratory had its own code but no others. The aim here was to allow each participant to compare its performance with others and to assess its own level of compliance.

It is important to note at this point that NRC was a participant in this exercise and its measurements are to be interpreted only as a means of detecting changes that may have occurred in the travelling standards.

The dimensions of the transfer standards are listed in table 1. It seemed prudent to make the measurement of the form of the standards covariant by supplying the same

Figure 1. Transfer Standards. The control standards are visually indistinguishable from the transfer standards.

Table 1. Dimensions of the transfer standards.

Standards' component dimensions/mm	1 OIML	C&CA	[52]
Cylindrical part			
Cylinder diameter	47.9	53.4	53.9
Cylinder height	60.5	53.6	55.1
Base recess			
Maximum recess diameter	41.4	48.0	0.0
Minimum recess diameter	35.5	44.2	0.0
Recess depth	2.17	0.70	0.0
Knob			
Knob diameter	43.1	25.4	0.0
Knob neck diameter	27.3	11.6	0.0
Overall height of artifact	82.9	76.7	55.1

dimensions to all participants. Uncertainties attributed to all artifact dimensions are taken to be zero for the same reason.

3. Execution

Because of the relatively large number of participants, the comparison was to be performed in two Petals with the standards returning to NRC for reassessment, along with the controls, about midway through the exercise. The transfer and control standards were to be measured before and after Petal 1 and at the end of Petal 2. This plan was altered through a misunderstanding; one laboratory interpreted the protocol as 'calibration as for a client' and demagnetized the three standards because the magnetization levels of two of the transfer weights were higher than the usual ones for each grade. The results before and after degaussing have both been reported by the laboratory. The standards had been chosen for a range of both remanent magnetization and susceptibility that might be encountered by an NMI, so this action was significant enough in effect to break the exercise into three Petals rather than two, at least as far as remanent magnetization is concerned. The results are therefore discussed as belonging to Petal 1a, before degaussing, Petal 1b, after degaussing, and the members of Petal 2.

While the degaussing event was disconcerting at the time, as we shall see, there were also some interesting results due to it.

4. Results

In the presentation of the results, the median is used as the reference value in every case, as in many CCM key comparisons. Its uncertainty is calculated by means of the procedure outlined by Müller [3]. The median is robust in its resistance to 'dragging' by outliers but presents problems under conditions of high dispersion coupled with small numbers of data. For this reason, and for information only, tabulated data include mean values and their uncertainties. All uncertainties are combined using the accepted ISO methods [4].

The NRC measurements are the only ones identified since they are used as a means of detecting relative changes in the properties of the transfer standards. They are as follows: Q1 before Petal 1a, Q2 after Petal 1b and Q3 after Petal 2. Measurements of susceptibility and remanent magnetization made on the controls are designated C1 before Petal 1a, C2 after Petal 1b and C3 after Petal 2. These control results are tabulated with the transfer standards data *but do not contribute to the analysis*. They are used only to assess the consistency of the NRC measurements with time.

The laboratory that demagnetized the transfer standards is the only one that has been allocated two code letters, P and O. It supplied values for χ and M as received (P) and after demagnetization (O). The former results contribute to Petal 1a and the latter to Petal 1b. The demagnetization decision was driven by the laboratory's experience with standards that had been magnetized during transport by air. As we shall see, their suspicions may well have been justified.

In general, and in accordance with naïve expectation, degaussing does not seem to have affected the measurement of magnetic susceptibility.

Only absolute values of the remanent magnetization are listed in this paper. This decision was taken for several reasons. First, the sign of the polarity of this parameter is not of primary importance in assessing its effect on mass measurement, which is, after all, the root cause of this project. Second, there is always the question of whether or not 'north' has been properly assigned to the test magnet(s) by each participant. Third, particularly in the case of the cylindrical artifact [52], is the question of inversion. In fact a number of participants submitted two sets of results for [52], upright and inverted, while for others the sign was not explicitly stated. Only the ASTM artifact, C&CA, could not easily be inverted. Finally, as will be seen, the dispersion of values for this measurand is large enough that to include signed values would have made its analysis even more intractable than it is.

The numerical results for the 1 OIML artifact are given in table 2. Its magnetic susceptibility is plotted in figure 2 and its remanent magnetization in figure 3.

The zero value for the uncertainty ascribed to the median value for the susceptibilities reported for Petal 1b and shown in table 2 is not an error. It is an artifact of the calculation of median uncertainties when, as can happen for small data sets, there are $2n + 1$ measurements and at least $n + 1$ of these have the median value. The median of the absolute deviations of the measurements from the median value is, in fact, zero in this case. It is because of this limitation in the procedure that the mean values are also shown for information. This problem is a price that is paid for robustness against outliers. This robustness is of particular value in the treatment of remanent magnetization.

The numerical results for the C&CA artifact are given in table 3. Its magnetic susceptibility is plotted in figure 4 and its

Table 2. Results and expanded uncertainties ($k = 2$) for 1 OIML are those reported by the participants.

Petal	Lab code	Susceptibility χ	$U(\chi)$	Remanent magnetization/(A m^{-1}) M	$U(M)$
1a	Q1	3.43E−03	2.80E−04	6.20E−02	4.80E−02
	C1	3.53E−03	2.69E−04	1.73E−01	1.12E−02
	G	3.30E−03	4.00E−04	7.00E−02	1.00E−01
	D	3.68E−03	4.80E−04	2.00E−01	—
	S	3.30E−03	4.00E−04	1.00E−02	1.00E−01
	J	3.20E−03	4.00E−04	5.00E−02	1.60E−01
	N	3.27E−03	3.00E−04	3.20E−02	3.00E−02
	U	3.14E−03	6.00E−05	2.42E−02	1.40E−02
	P	3.23E−03	6.40E−04	2.43E+00	4.40E−01
Median		3.29E−03	1.01E−04	5.60E−02	4.01E−02
Mean		3.32E−03	1.19E−04	3.60E−01	5.93E−01
1b	O	3.23E−03	6.40E−04	6.30E−01	7.40E−02
	A	3.40E−03	1.60E−03	9.23E−01	4.80E−02
	L	3.31E−03	5.20E−04	7.78E−01	8.60E−02
	V	3.40E−03	8.00E−04	7.85E−01	2.40E−02
	Q2	3.40E−03	2.82E−04	7.99E−01	5.56E−02
	C2	3.48E−03	2.71E−04	2.34E−01	1.35E−02
Median		3.40E−03	0.00E+00	7.85E−01	2.66E−02
Mean		3.35E−03	6.85E−05	7.83E−01	9.31E−02
2	R	2.16E−03	2.20E−04	9.44E−01	1.16E−01
	T	3.30E−03	4.00E−04	7.00E−01	2.00E−01
	E	3.27E−03	1.56E−04	9.73E−01	3.00E−02
	B	2.10E−03	2.00E−04	6.24E−01	6.00E−02
	F	3.98E−03	3.60E−04	7.40E−01	6.60E−02
	H	2.40E−03	2.00E−04	7.90E−01	7.00E−02
	Q3	3.41E−03	2.80E−04	8.08E−01	5.42E−02
	C3	3.50E−03	2.71E−04	2.45E−01	1.43E−02
Median		3.27E−03	1.11E−03	7.90E−01	1.40E−01
Mean		2.95E−03	5.47E−04	7.97E−01	9.53E−02
Global median		3.30E−03	8.72E−05	—	—
Global mean		3.20E−03	2.06E−04	—	—

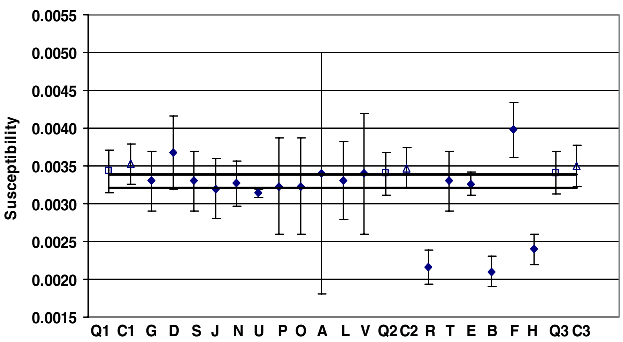

Figure 2. Magnetic susceptibility for 1 OIML. Uncertainty bars and median limits, indicated by horizontal lines, $k = 2$. Data C1, C2 and C3 represent control standard measurements.

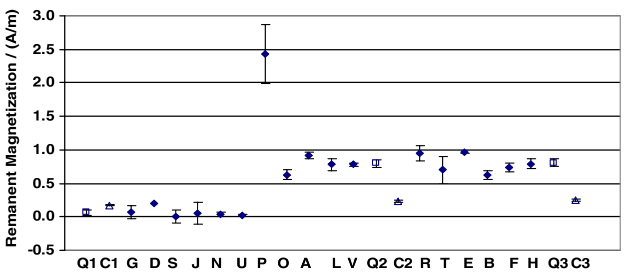

Figure 3. The remanent magnetization for 1 OIML. Uncertainty bars $k = 2$. Data C1, C2 and C3 represent control standard measurements.

remanent magnetization in figures 5 and 6. Data labelled Q1 to Q3 are NRC data for the transfer artifact and data labelled C1 to C3 are NRC data for the similar control standard.

Laboratory N reports inclusion of an uncertainty component associated with deviation from the assumption that the magnetic susceptibility χ is much less than 1. This would particularly have an effect on their results for C&CA because it has a large value for χ.

The numerical results for the [52] artifact are given in table 4. Its magnetic susceptibility is plotted in figure 7 and its remanent magnetization in figure 8. Data labelled Q1 to Q3 are NRC data for the transfer artifact and data labelled C1 to C3 are NRC data for the similar control standard.

5. Median values for susceptibility and remanent magnetization

The effect of the demagnetization event on the properties of the transfer standards may be assessed by comparing the median values of susceptibility and remanent magnetization for Petals 1a, 1b and 2. The effects on susceptibility are shown in table 5 and figures 9–11. The effects on remanent magnetization are shown in table 6 and figures 12–14.

Table 3. Results and expanded uncertainties ($k = 2$) for C&CA are those reported by the participants.

Petal	Lab code	Susceptibility χ	$U(\chi)$	Remanent magnetization/(A m^{-1}) M	$U(M)$
1a	Q1	3.03E−01	1.89E−02	3.97E+00	1.87E+00
	C1	2.10E−01	3.60E−04	1.39E+00	8.31E−02
	G	2.69E−01	2.60E−02	4.00E+00	8.00E+00
	D	3.04E−01	4.00E−02	3.00E+00	—
	S	2.95E−01	5.40E−02	4.00E−01	3.40E+00
	J	2.70E−01	1.60E−02	2.30E+00	2.60E+00
	N	2.82E−01	1.62E−01	3.30E+00	2.60E+00
	U	2.52E−01	1.06E−02	3.70E+00	4.00E+00
	P	2.53E−01	3.00E−02	2.20E+02	3.80E+01
Median		2.76E−01	3.02E−02	3.50E+00	7.18E−01
Mean		2.79E−01	1.48E−02	3.01E+01	5.43E+01
1b	O	2.64E−01	3.00E−02	2.00E−01	2.40E+00
	A	3.10E−01	1.60E−01	1.45E+01	1.72E+01
	L	2.70E−01	2.80E−02	4.06E+00	2.80E−01
	V	2.89E−01	5.40E−02	2.28E+00	2.14E+00
	Q2	3.07E−01	1.99E−02	1.02E+01	9.00E+00
	C2	2.11E−01	3.61E−04	1.32E+00	8.38E−02
Median		2.89E−01	3.61E−02	4.06E+00	7.33E+00
Mean		2.88E−01	1.87E−02	6.25E+00	5.31E+00
2	R	2.52E−01	2.60E−02	5.80E−01	7.62E+00
	T	2.65E−01	3.80E−02	1.17E+01	8.00E+00
	E	2.56E−01	1.42E−02	1.95E+02	1.48E+01
	B	2.96E−01	2.60E−02	1.69E+01	3.00E+00
	F	2.82E−01	1.12E−02	9.45E+01	6.62E+00
	H	2.58E−01	1.80E−02	1.11E+01	3.20E+00
	Q3	3.05E−01	1.98E−02	9.26E+01	1.28E+01
	C3	2.12E−01	3.56E−04	1.32E+00	7.95E−02
Median		2.65E−01	2.02E−02	1.69E+01	2.53E+01
Mean		2.74E−01	1.59E−02	6.03E+01	5.40E+01
Global median		2.76E−01	1.69E−02	—	—
Global mean		2.79E−01	9.21E−03	—	—

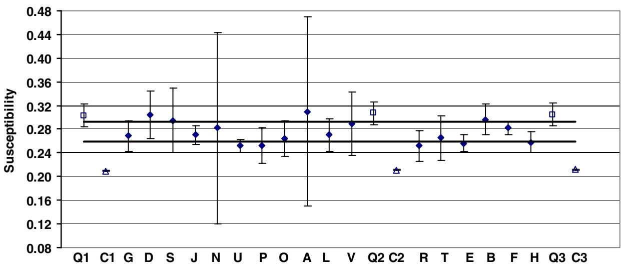

Figure 4. Magnetic susceptibility for C&CA. Uncertainty bars and median limits, indicated by horizontal lines, $k = 2$. Data C1, C2 and C3 represent control standard measurements.

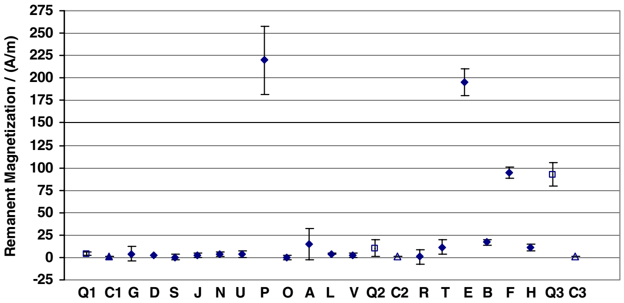

Figure 5. Remanent magnetization for C&CA. Uncertainty bars $k = 2$.

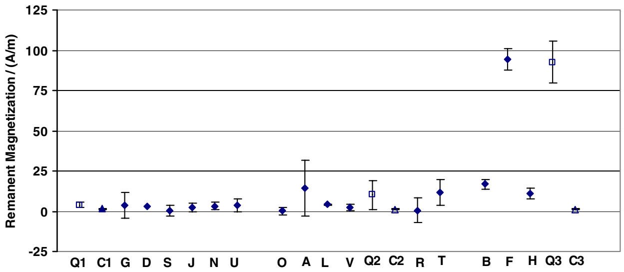

Figure 6. Remanent magnetization for C&CA with the ordinate scaled to emphasize dispersion for smaller data; two data are lost as a result. Uncertainty bars $k = 2$. Data C1, C2 and C3 represent control standard measurements.

Based on the values of the medians it is apparent that there were no statistically significant variations in the magnetic susceptibilities of the transfer standards among the three Petals, in accordance with naïve expectation.

It is also evident that there were no statistically significant changes in the remanent magnetization measured for C&CA and [52], in spite of the degaussing event. It is true, however, that any changes would be masked by the increase in the dispersion of the measured values of M in Petal 2 compared with Petals 1a and 1b. There was a pronounced and persistent increase in the remanent magnetization of the standard 1 OIML, which started this interchange with the lowest value of M of the three transfer standards.

Table 4. Results and expanded uncertainties ($k = 2$) for [52] are those reported by the participants.

Petal	Lab code	Susceptibility		Remanent magnetization/(A m^{-1})	
		χ	$U(\chi)$	M	$U(M)$
1a	Q1	3.08E−02	3.86E−03	6.60E+00	3.00E+00
	C1	4.84E−02	4.18E−03	2.92E+00	2.16E+00
	G	3.30E−02	8.00E−03	6.70E+00	2.80E+00
	D	3.18E−02	4.20E−03	1.30E+01	—
	S	3.37E−02	4.00E−03	7.20E+00	4.00E−01
	J	2.80E−02	2.00E−03	3.60E+00	2.20E+00
	N	2.97E−02	3.40E−03	3.54E+00	3.60E−01
	U	2.90E−02	2.60E−03	4.89E+00	1.20E+00
	P	3.79E−02	1.56E−02	3.03E+01	1.26E+01
Median		3.13E−02	2.87E−03	6.65E+00	3.45E+00
Mean		3.17E−02	2.23E−03	9.48E+00	6.31E+00
1b	O	3.12E−02	3.20E−03	8.40E−01	3.60E−01
	A	3.20E−02	6.00E−03	2.40E+00	5.80E+00
	L	3.15E−02	3.00E−03	1.70E−01	3.40E−01
	V	3.17E−02	8.60E−03	1.70E−01	4.40E−01
	Q2	3.22E−02	4.50E−03	1.14E+00	1.52E+00
	C2	4.67E−02	3.50E−03	2.31E+00	1.63E+00
Median		3.17E−02	5.70E−04	8.40E−01	1.27E+00
Mean		3.17E−02	3.54E−04	9.44E−01	8.21E−01
2	R	3.19E−02	3.40E−03	3.81E+00	1.16E−01
	T	4.10E−02	6.00E−03	2.40E+00	1.20E+00
	E	2.94E−02	1.80E−03	3.35E+01	6.80E−02
	B	3.28E−02	3.40E−03	1.50E+00	1.66E+00
	F	2.83E−02	8.40E−04	1.68E+01	1.00E+00
	H	3.19E−02	2.00E−03	3.20E−01	1.50E+00
	Q3	3.42E−02	6.22E−03	1.68E+01	1.00E+00
	C3	4.77E−02	2.54E−03	2.88E+00	1.22E+00
Median		3.19E−02	3.57E−03	3.81E+00	5.41E+00
Mean		3.28E−02	3.13E−03	1.07E+01	9.27E+00
Global median		3.19E−02	9.59E−04	—	—
Global mean		3.21E−02	1.37E−03	—	—

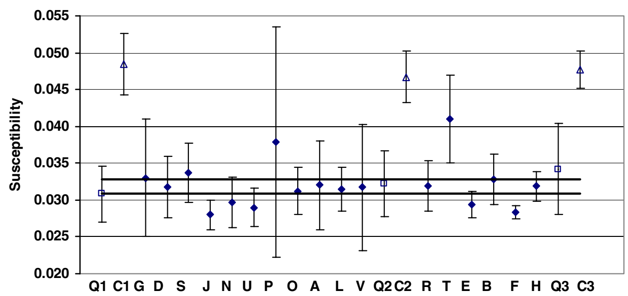

Figure 7. Magnetic susceptibility for [52]. Uncertainty bars and median limits, indicated by horizontal lines, $k = 2$. Data C1, C2 and C3 represent control standard measurements.

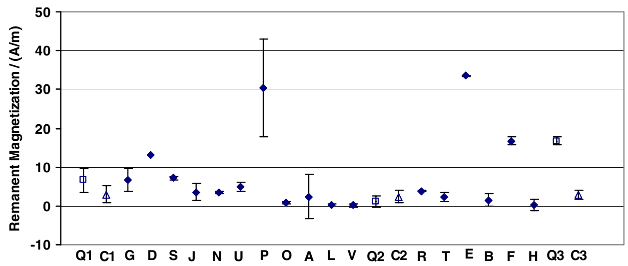

Figure 8. Remanent magnetization for [52]. Uncertainty bars $k = 2$. Data C1, C2 and C3 represent control standard measurements.

6. Conclusions

6.1. Susceptibility

In the general sense, and in congruity with intralaboratory experience, the magnetic susceptibilities of the three standards seem to have remained fairly constant within the uncertainties imposed on the medians. The overall uncertainties and dispersions associated with χ values are consistent with those reported for a comparison among five European laboratories reported by Davis *et al* [5]. Although degaussing produced large changes in remanent magnetization, there appears to have been no associated effect on the susceptibility of any of the transfer standards. The medians of all petals are statistically indistinguishable in spite of the effects due to a small number of outliers.

The susceptibilities of all three controls showed no changes with time, verifying the consistency of the measurements made on the transfer standards by the pilot laboratory.

6.2. Remanent magnetization

At the outset of any discussion of the measurement of the remanent magnetization of the transfer standards it should be noted that within the Petals 1a, 1b and 2 the dispersion of

Table 5. Medians of susceptibility for transfer standards.

	1 OIML		C&CA		[52]	
Petal	χ	$U(\chi)$	χ	$U(\chi)$	χ	$U(\chi)$
1a	3.29E−03	1.01E−04	2.76E−01	3.02E−02	3.13E−02	2.87E−03
1b	3.40E−03	0.00E+00	2.89E−01	3.61E−02	3.17E−02	5.70E−04
2	3.27E−03	1.11E−03	2.65E−01	2.02E−02	3.19E−02	3.57E−03

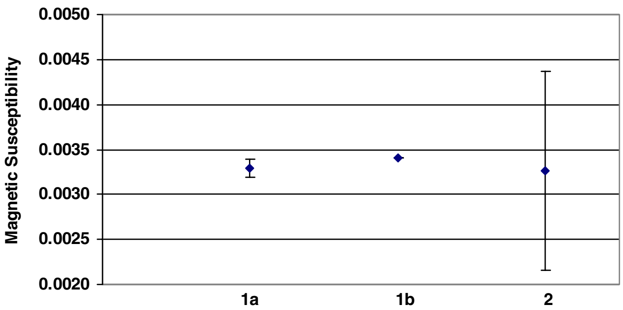

Figure 9. Medians of magnetic susceptibility for 1 OIML.

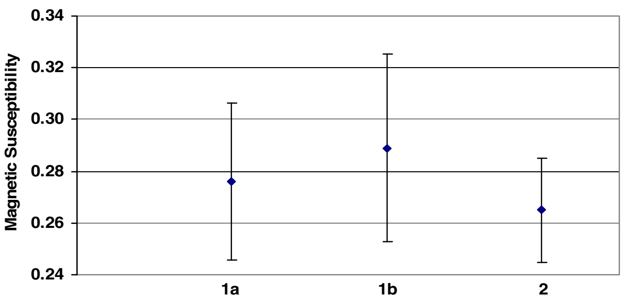

Figure 10. Medians of magnetic susceptibility for C&CA.

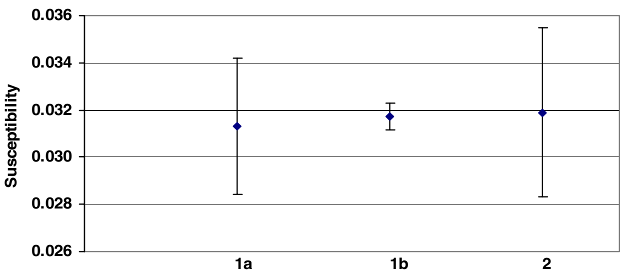

Figure 11. Medians of magnetic susceptibility for [52].

the values of M is such as to render any statistical analysis problematic. For this reason the tabulated values of the medians M which are displayed in figures 12–14 serve only to provide a rough comparison of the values of M during each petal. The difficulty here is exacerbated by the fact that the purpose of this project was specifically to compare the abilities of the participating laboratories to measure both χ and M. To discuss the reasons for some of the dramatic changes we have seen in M, therefore, is tantamount to using the thing to be proved in the proof.

However, if it is reasonably assumed that the same observed data are used in the calculation of M as are used in the calculation of χ then the logical dilemma vanishes. Since the values of χ are well behaved, on the whole, it may be logically concluded that the measurements of M are equally well managed by the participants. We are then left with the prospect that the measured changes in M are real, not the product of any participants' errors, and, if that is so, that changes in M are driven by external magnetic fields. For the purposes of the metrologist it does not matter, for the moment, whether these fields are generated by ground or air transportation equipment. What does matter is that in order to effect not only magnetic properties comparisons but mass comparisons themselves, the transfer standards must be hand carried between participating laboratories in order to ensure that the remanent magnetization does not change. This project demonstrates that the stability of the state of magnetization of transfer standards cannot be assumed in unescorted transit.

It has been suggested that comparative measurement of M should include initial demagnetization of the transfer standards by each participating laboratory. Unfortunately, such a procedure would entail the deconvolution of two separate procedures—demagnetization followed by the measurement of M. Few of the participants in the present experiment have degaussing facilities, and even if all of them did the only way in which such a procedure could be adequately controlled would be through a star distribution pattern, rather than the two (or three) petals planned in this case. Such an experiment might be profitably carried out in the future, but it must be emphasized that the observed changes in M were unanticipated. Ironically, one of the most valuable results of the present project may well be the documentation of the changes that may occur in M during unescorted transport.

The degaussing which ended Petal 1a did not always seem to have the intended effect. The 1 OIML artifact had its low median value of M increase dramatically by a factor of 14 and that increase remained constant throughout Petals 1b and 2. The NRC measurements for this standard agree very well with those of the medians of all participants. This standard had the lowest initial values of both χ and M. We note that even the increased magnetization is still below the limit for OIML class E1 weights [7].

For C&CA, the remanent magnetization increased, rather than decreased, but by only 16% due to degaussing, based on the median values. This observation is, however, misleading, since it is only the very large dispersion of data among the participants in Petals 1b and 2 that might lead one to this conclusion. In this case, as with 1 OIML, degaussing did not achieve its desired effect.

For the [52] standard, degaussing actually reduced the remanent magnetization by a factor of 7.9 compared with Petal 1a, as intended. However, there was an unexplained rise by a factor of 8.6 in M during Petal 2. Repeated measurements at NRC over a period of seven months after the end of the interchange confirm both the validity and the stability of this change. The dramatic increase in the dispersion of M data reported by participants in Petal 2, as contrasted with

Table 6. Medians of remanent magnetization for transfer standards for transfer standards ($\mathrm{A\,m^{-1}}$).

	1 OIML		C&CA		[52]	
Petal	M	$U(M)$	M	$U(M)$	M	$U(M)$
1a	5.60E−02	4.01E−02	3.50E+00	7.18E−01	6.65E+00	3.45E+00
1b	7.85E−01	2.66E−02	4.06E+00	7.33E+00	8.40E−01	1.27E+00
2	7.90E−01	1.40E−01	1.69E+01	2.53E+01	3.81E+00	5.41E+00

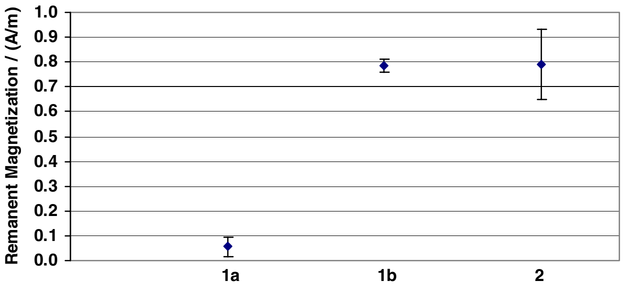

Figure 12. Medians of remanent magnetization for 1 OIML.

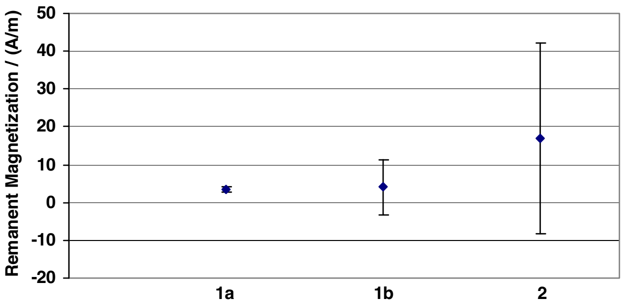

Figure 13. Medians of remanent magnetization for C&CA.

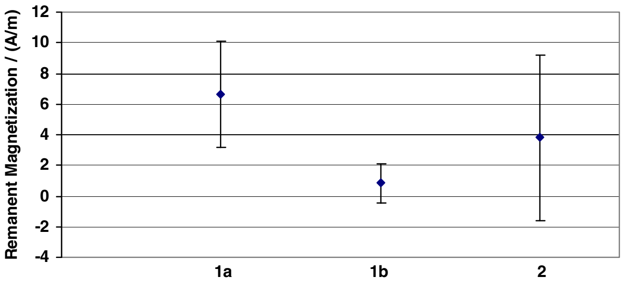

Figure 14. Medians of remanent magnetization for [52].

those of Petals 1a and 1b, is clearly apparent in the graphed data. This artifact seems to have reverted approximately to its pre-demagnetization value for remanent magnetization. Any remarks on the remanent magnetization of [52] must be qualified by the very large dispersion of its measurements among the participating laboratories. This dispersion implies that magnetization of [52] is highly localized in the artifact, which is made of 316 stainless steel. This condition seems to parallel that described by Davis [6] for standards involved in EUROMET Project 324.

It might be supposed that the large dispersion exhibited by the remanent magnetization of the transfer standards might be due to induction by the test magnets used by the participants. However, the data provided by the participants render this conclusion unlikely. The values of the moments of the magnets employed and the separations between the magnets and the transfer standards (Zo) are shown in table 7.

Table 7. Moments and offsets for test magnets.

Petal	Lab code	Moment/ ($\mathrm{A\,m^2}$)	Offset (Zo)/mm 1 OIML	C&CA	[52]
1a	Q1	0.0914	20.07	19.80	19.80
	G	0.1245	31.00	31.00	31.00
	D	0.0897	17.23	17.23	17.23
	S	0.1220	26.66	31.64	31.64
	J	0.0904	14.20	29.30	19.20
	N	0.1225	21.92	21.92	21.92
	U	0.0827	25.02	25.01	25.02
	P	0.0879	27.50	27.50	27.50
1b	O	0.0879	27.50	27.50	27.50
	A	0.0837	17.37	17.37	17.37
	L		24.40	24.30	24.30
	V	0.0776	21.93	21.91	21.95
	Q2		19.18	19.19	19.19
2	R	0.1240	22.09	22.11	22.10
	T	0.0905	42.30	42.30	42.30
	E	0.0390	18.80	20.80	18.80
	B	0.0915	20.90	20.90	20.90
	F	0.1070	19.64	19.64	19.64
	H	0.0909	19.70	19.70	19.70
	Q3		19.17	19.17	19.19
Median		0.0905	21.41	21.92	21.41
Mean		0.0943	22.31	23.91	23.31

In table 7 only one value for the moment of the magnet used by the pilot laboratory is included to avoid skewing the median and mean values. The same magnet was used for all measurements made by the pilot.

The experience of laboratory P&O regarding magnetization of stainless steel standards during air travel may also account for the wide dispersion of M values in Petals 1b and 2. The ratio of magnetic moment to $(\mathrm{Zo})^3$ provides a measure of the maximum exposure of the transfer standards to applied magnetic field strength. If induced magnetization were to be expected due to the measurement process, it would be reasonable to suppose that such induction would have occurred in the laboratories using the maximum field strength relative to the other participants (Laboratory J for 1 OIML, Laboratory D for the two other transfer standards). The data show nothing exceptional in the results of these laboratories and thus give no support to the hypothesis that the samples have been altered by the measurement process.

Finally, it might be concluded that degaussing of mass standards should be done with circumspection since the process does not always achieve the desired effect. Since the standards travelled unaccompanied and at least three padlocks were cut off the container by various customs officers in possession of a universal key (aka bolt cutter) we may never know the true cause of the changes. The magnetic properties of the transfer standards and their controls were last measured on 2006-05-14. At that time there had been no significant change in any of them since the conclusion of Petal 2. They were consistent with the tabulated values and uncertainties shown for Q3 and C3 in this paper.

The controls for all three transfer standards exhibited no discernible changes in remanent magnetization over the duration of this comparison, validating the stability of the measurement process and procedure used by the pilot laboratory.

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