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REPORT

EUROMET Project Reference No. 345

INTERCOMPARISON OF 10 pF AND 100 pF CAPACITANCE STANDARDS.

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February 1999

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National Physical Laboratory

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Abstract

An intercomparson of 10 pF and 100 pF capacitance standards has taken place within the framework of EUROMET. The intercomparison piloted by NPL, has involved seventeen laboratories, including several who are members of other regional organisations. The results presented in this report appear to show that there are significant differences between some laboratories' representation of the farad. However, the agreement demonstrated by the intercomparison provides confidence in maintaining traceability for the farad either via a calculable capacitor or via a quantum Hall reference standard and the consensus value of the von Klitzing constant (R_{K-90}).

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1 INTRODUCTION

1.1 Key for acronyms used.

CCEM	Comité Consultatif d'Électricité et Magnétisme
CIPM	Comité International des Poids et Mesures
CGPM	Conférence Générale des Poids et Mesures
BIPM	Bureau International des Poids et Mesures

1.2 A number of international committees organise and monitor intercomparisons of the primary measurement standards to ensure that all industrial and scientific measurements are on a sound common basis world-wide. The CCEM, under the direction of the CIPM which consists of individuals elected by the CGPM, is the committee responsible for ensuring universally uniform electrical measurement standards. The CGPM consists of delegates from all member states who have signed the treaty of the Convention du Mètre.

1.3 Several key quantities have been identified by the CCEM, the value of 10 pF capacitors being one, for assessing by audit the world-wide credibility of individual national laboratory capabilities and providing the evidence for mutual recognition of their measurements and calibration certificates. Auditing capacitance reveals to what extent there are divergences in their representations of the farad.

1.4 To make the amount of work associated with audit intercomparisons manageable, separate intercomparisons are undertaken by the regional organisations of EUROMET (Europe), COOMET (the former Eastern block), SIM (Inter-American Metrology System) which includes NORAMET (North America), APMP (Asia & Pacific) and SADCMET (Southern African States). World-wide co-ordination will be attained through a CCEM intercomparison between participants from laboratories in each region. The regional intercomparisons too will include participants from some other regions. So there is therefore a very desirable redundancy in the network of CCEM and regional intercomparisons.

2 PARTICIPANTS

2.1 Table 1 lists the participants and their associated regional organisation. As can be seen all the different regional organisations have been represented in this intercomparison.

2.2 The role of NPL as the pilot laboratory was to provide the capacitance standards, investigate their stability under likely transportation conditions, to make periodic measurements of their SI value during the intercomparison and to schedule the visits of the capacitors to each participant. Finally, NPL was responsible for collating and interpreting the measurement results and publishing a report at the end of the three year programme.

2.3 Table 1: List of participating laboratories, countries of origin and regional organizations.

Laboratory	**Country**	**Regional Organization**
NPL - National Physical Laboratory - Pilot	UK	EUROMET
BEV - Bundesamt für Eich- und Vermessungswesen	Austria	EUROMET
BIPM - Bureau International des Poids et Mesures (The working laboratory of the CIPM)	International	-
BNM-LCIE - Bureau National de Métrologie, Laboratoire Central des Industries Électriques	France	EUROMET
CEM - Centro Español de Metrología	Spain	EUROMET
CMI - Czech Metrological Institute	Czech Republic	EUROMET
CSIR - Council for Scientific and Industrial Research	South Africa	SADCMET
CSIRO-NML - Commonwealth Scientific and Industrial Research Organization - National Measurement Laboratory	Australia	APMP
GUM - Glowny Urzad Miar	Poland	COOMET
IEN - Instituto Elettrotecnico Nazionale	Italy	EUROMET
NIST - National Institute of Standards and Technology	USA	SIM/NORAMET
NMi - Nederlands Meetinstituut	Netherlands	EUROMET
OFMET - Office Fédéral de Métrologie	Switzerland	EUROMET
PTB - Physikalisch-Technische Bundesanstalt	Germany	EUROMET
SP - SP, Sveriges Provnings och Forskningsinstitut	Sweden	EUROMET
UME - Ulusal Metroloji Enstitüsü	Turkey	EUROMET
VTT - VTT Automation, Measurement Technology	Finland	EUROMET

3 CAPACITANCE STANDARDS

3.1 Two Andeen-Hagerling model AH11A capacitance modules having nominal values of 10 pF (S/N 01031) and 100 pF (S/N 01032) were used for the intercomparison. The modules are mounted in a frame (model AH1100, S/N 00010) which provides the electrical power, via a ribbon cable, to operate the precision temperature-control oven which is part of each capacitance module. Each module contains a capacitor fabricated from a fused-silica disc which is sealed hermetically in a copper chamber and is thermally insulated from the outside case. These two capacitors have been modified with additional internal screening to convert them to a true two terminal-pair configuration.

3.2 The temperature of each module is controlled by a servo-system which uses the mean of the readings from two precision sensors to maintain a constant temperature. The difference in the temperature indicated by these two sensors is displayed on the front panel of the frame as ‘Drift (ppm)’ rather than as a temperature. This drift is the equivalent difference in parts per million (ppm) of the capacitance value calculated from these divergent temperature indications and is intended to be a reassurance that the temperature control is functioning correctly.

3.3 The temperature of the frame is displayed on the front panel as the “Chassis Temp. (° C)”. It should stay constant at a value within the operating range of 10 °C to 40 °C whilst measurements are made.

3.4 The ‘high and ’low’ outputs of the capacitors appear as BNC connectors on the module and these are connected via cables to MUSA connectors on the front panel of the frame. MUSA to BNC adapters are sent with the capacitors to enable those few participants who employ BNC-terminal cables to measure the standards.

3.5 Before sending the capacitors to the first laboratory a number of measurements and tests were carried out to check their suitability for this intercomparison. The frame and inner travelling packing case were subjected to mechanical shocks similar to those expected during transit by air freight to each laboratory. No significant changes in value were detected for either capacitor. Measurements were carried out at a number of different voltages applied across the capacitors and with the frame subjected to various laboratory temperatures in the range 18 °C to 27 °C. Both these tests again resulted in no detectable changes in the value of either capacitor greater than 1 part in 10^8.

3.6 The capacitors visited all the participants during a three year period and were returned to NPL for measurement between each visit to both build up a history and to monitor any unexpected changes in their values. They travelled by both air freight and road with no changes detected in value due to transportation.

4 MEASUREMENT DEFINING CONDITIONS

4.1 Measurement frequencies of 398 Hz, 796 Hz, 1 kHz, 1·233 kHz, 1·592 kHz, 2·466 kHz and 12·33 kHz were specified for the intercomparison. Each participant was required to measure the capacitors at 1 kHz or 1·592 kHz and could volunteer to undertake measurements at the other frequencies listed.

4.2 Instructions were issued to each participant to help avoid any confusion about the defining conditions of the measurement. These instructions stated that each capacitor was to be measured as a two terminal-pair impedance (or a four terminal-pair impedance by using T-junctions), as defined at the output ports. As a result of modifying the internal screening, the ‘high’ and ’low’ ports are interchangeable but account should be taken of any loading effect of the shunt capacitances presented by these ports on the measuring network.

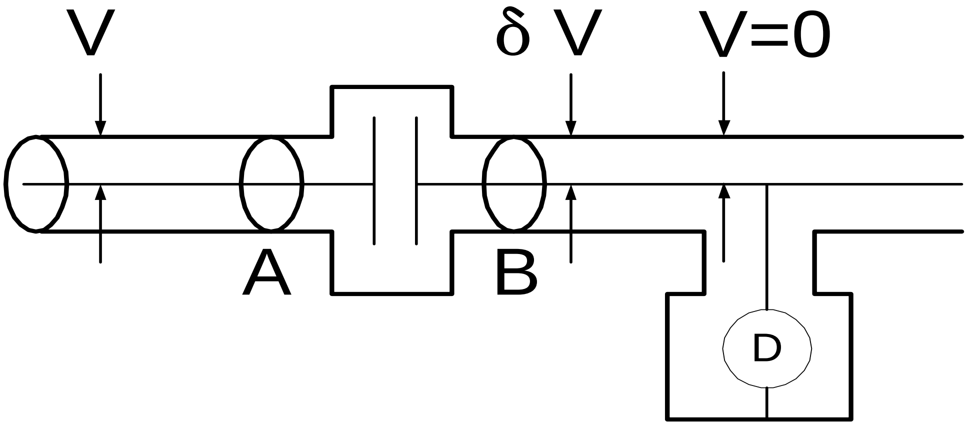

Figure 1

4.3 **Shunt capacitances**

4.3.1 A note on shunt capacitances was sent with the capacitors to all participants. It pointed out that additional shunt capacitances can be added to the coaxial connectors so that differences between the values of nominally equal capacitors can be correctly measured by substitution in a two terminal-pair bridge. ([1], p.35). It is assumed that the same bridge cables are used during substitution.

4.3.2 In detail the note stated that in order that the capacitors to be substituted appear identical to the bridge, the total shunt admittance of each standard at the connection A must be identical. See figure 1. Therefore if the connector A (usually designated the 'high' connector), is to be connected to the voltage ratio device of the bridge, the admittance of each standard looking into A with B short-circuited should be made identical, by using adjustable shunt capacitors.

4.3.3 Notice that if this is done, the standard is not reversible. To ensure reversibility, shunt capacitors must be added to both A and B, and adjusted with the other connector shorted. Then the input shunt admittances measured at A <u>or</u> B can be made the same for all the capacitors. This will also eliminate on substitution, the error caused by current diverted through the shunt admittance at B by δV.

4.4 To avoid problems with voltage coefficients, the maximum applied voltage was specified to be 100 volts rms across the 10 pF capacitor and 10 volts rms across the 100 pF capacitor. These voltages were to be used at 1 kHz and the higher frequencies, where possible.

4.5 When the capacitors arrive at a laboratory the frame housing them is energised and the "Oven Not Ready" light goes out after about an hour. The indicated "Chassis Temp.(°C)" would then be a few degrees above ambient, but would continue to rise as the whole instrument warms up. Both the "Chassis Temp. (°C)" and "'Drift (ppm)" should have been stable for at least 24 hours prior to a measurement. These parameters should then be recorded for each capacitor at the time of measurement.

5 RESULTS

5.1 As part of the measurement instructions participants were asked in reporting their results to include details of the traceability of their measurements and to express their results with reference to the von Klitzing constant $R_{K\text{-}90}$ where possible, to ensure that all results were expressed on a common basis. The internationally agreed value of $R_{K\text{-}90}$ is 25 812·807 Ω with a relative standard uncertainty of 2 parts in 10^7. Ref. [2].

5.2 The participating laboratories made measurements of these travelling capacitors in terms of either their own Calculable Capacitor or a quantum Hall reference standard, or have traceability to other laboratories. This meant that there were a number of independent measurements of these capacitors which enabled the representation of the farad in those countries to be compared.

5.3 At NPL the value of our primary standard 10 pF and 100 pF capacitors are determined in terms of the quantum Hall reference standard using a series of AC coaxial bridges with an overall relative combined uncertainty (1 σ) of 4·6 parts in 10^8. Full details of this traceability chain are given in section 1 of [3].

5.4 The results reported by the participants, at a frequency of 1·592 kHz unless otherwise indicated, are given in appendices 1 and 2, tables 7 and 8 and as graphs. The tables give the reported results from each participating laboratory (including two typical NPL results) with the values for each capacitor given as the relative difference in part per million (ppm) of its nominal value with an associated uncertainty in ppm. All the uncertainties quoted in this report are expanded uncertainties (U), having a coverage factor k=2 which provides a level of confidence of approximately 95%. Also in the tables is a 'Figure of Merit value', E, which is explained in detail in section 5.13 of this report.

5.5 The reported values from each laboratory have been plotted on the graphs with their associated uncertainty using a mean measurement date for each laboratory's results. The NPL values are plotted as dots between each symbol with an uncertainty shown for clarity for two typical results only. The laboratories reporting results at 1 kHz were only able to measure at this frequency, but this does not invalidate any conclusions because the change in value of the 10 pF and 100 pF capacitors between 1·592 kHz and 1 kHz is much less than the quoted uncertainties of these laboratories.

5.6 BNM-LCIE have reported two results for each capacitor although only one has an uncertainty attached. The result with the uncertainty bars shown is traceable to their quantum Hall effect standard and quadrature bridge system which has an evaluated uncertainty budget. The other result is traceable to their calculable capacitor, but as this system is still being evaluated the results are for information only.

5.7 In order to make fair comparison with those laboratories (NPL, BIPM and BNM-LCIE), who have measured the capacitors directly in terms of a quantum Hall reference standard a second, larger, uncertainty bar has been plotted. This is because their results have been expressed in terms of the consensus value of the von Klitzing constant R_{K-90} of 25 812·807 Ω so a second uncertainty has been calculated, denoted by a ✭ in tables 7 and 8, which includes the 2σ relative uncertainty of 4 parts in 10^7 for R_{K-90}.

5.8 **Traceability**

5.8.1 The traceability route for the primary standard of capacitance for each laboratory is given in table 2. The majority of the laboratories obtain their unit of capacitance from a calculable capacitor either directly or via another laboratory.

5.8.2 Table 2: Traceability route for each participating laboratory.

Laboratory	Country	Traceability Route
NPL - Pilot	UK	DC QHR
BEV	Austria	PTB (Calculable Capacitor)
BIPM	-	QHR (Measured at 1 Hz)
BNM-LCIE	France	DC QHR & Calculable Capacitor
CEM	Spain	NIST & PTB (Calculable Capacitor)
CMI	Czech Republic	VNIIM ✢[i] (Calculable Capacitor)
CSIR	South Africa	NPL (DC QHR), ITRI ✢[ii] & NMi (Calculable Capacitor)
CSIRO-NML	Australia	Calculable Capacitor
GUM	Poland	PTB (Calculable Capacitor)
IEN	Italy	NIST (Calculable Capacitor)
NIST	USA	Calculable Capacitor
NMi	Netherlands	Calculable Capacitor
OFMET	Switzerland	NPL (DC QHR)
PTB	Germany	Calculable Capacitor
SP	Sweden	BIPM (QHR)
UME	Turkey	PTB (Calculable Capacitor)
VTT	Finland	SP & NPL (DC QHR)

✢ - [i] VNIIM - D.I. Mendeleyev Institute for Metrology, Russian Federation.
- [ii] ITRI - Industrial Technology Research Institute, Taiwan.

5.9 **Significant parameters**

5.9.1 Certain significant parameters namely, ambient laboratory temperature, applied voltage, 'Chassis temp. (°C)' and 'Drift (ppm)' as displayed on the frame, were recorded during each laboratory's measurements. The values reported are given in table 3.

5.9.2 Table 3: Significant parameters.

Laboratory	**Ambient Laboratory Temperature °C**	**Applied Voltage**		**Values reported as displayed on the frame.**		
				Chassis Temp. °C	**Drift (ppm)**	
		S/N 01031 10 pF	**S/N 01032 100 pF**	**Range °C**	**S/N 01031 10 pF**	**S/N 01032 100 pF**
NPL	20·0 ± 0·5	100	10	26·8	0·066 ± 0·001	0·095 ± 0·001
PTB	23·0 ± 0·3	50	10	27·6	0·058	0·096
NIST	20·0	100	10	25·4	-	-
OFMET	20·0 ± 1	100	10	25·7 ± 1	0·067 ± 0·001	0·101 ± 0·001
BEV	22·9	50	50	30·9	-	-
IEN	23·0	100	10	28·3 to 28·6	0·056	0·094
NMi	23·0 ± 0·5	10	10	28·5 to 28·6 ± 0·1	0·057 ± 0·001	0·098 ± 0·001
SP	23·0 ± 0·5	100	10	28·1	0·058	0·100
CSIR	24·0 ± 1	15	15	29·1 to 30·9	0·055	0·099
BNM-LCIE	20·0 ± 0·5	30	30	25·1	0·073	0·102
CSIRO-NML	20·2 ± 0·5	100	10	27·0	0·065 to 0·074	0·100 to 0·109
NIST	20·0	100	10	25	0·068	0·101
VTT	23·0 ± 1	15	7·5	27·9 to 28·3	0·058	0·097
GUM	23·0 ± 0·5	90	10	28·6 to 30·3	0·049 to 0·055	0·095 to 0·097
CEM	22 to 23	15	15	28·7	0·054 to 0·061	0·099 to 0·100
PTB	23·0 ± 0·3	50	10	29·9	0·057	0·102
BIPM	23·0 ± 0·5	100	10	30·5 ± 0·2	0·056 ± 0·001	0·104 ± 0·001
CMI	22·5 ± 0·5	15	15	29·2	0·058	0·102
NPL	20·0 ± 0·5	100	10	27·3	0·070 ± 0·001	0·101 ± 0·001
UME	23 ± 0·5	15	10	31·2	0·051	0·097

5.9.3 As can be seen the ambient temperature ranged from 20 °C to 24 °C but as the temperature of the capacitors is controlled at a much higher temperature this should not affect their values. As different voltages were also applied to the capacitors by each laboratory, the capacitors were measured over a range of different voltages and temperatures prior to the commencement of this exercise (see section 3.5). No effect on their values due to the voltage applied or ambient temperature within this range was detected.

5.9.4 As the stability of the capacitors depends on the whole temperature control circuitry it is important to monitor both the 'Chassis Temp. (°C) and 'Drift (ppm)' indicators which are described in detail in sections 3.2 and 3.3. The variations reported in chassis temperature were from 25 °C to 30 °C, well within the operating specification of the frame. The maximum rate of change of capacitance over the whole three year period was 0·021 ppm/year for the 10 pF capacitor and 0·011 ppm/year for the 100 pF capacitor. These were much less than the 0·3 ppm/year limit of the manufacturer's specification.

5.9.5 Since the capacitance modules did not have any method of measuring their temperature directly it was not possible to correct for any temperature variations. Even though the capacitance changes caused by temperature change is specified to be not more than 0·01 ppm/°C, it would have been beneficial to be able to correct the capacitance values to a standard temperature because this would have eliminated from the results any short-term variations due to temperature.

5.10 **Results at optional frequencies**

5.10.1 Results for the measurements carried out on the capacitors measured at other frequencies are given in tables 4 & 5. Only a small number of laboratories undertook these optional measurements so the reported values are given as the difference between each laboratory's 1·592 kHz value (or 1 kHz value denoted by *, if no 1·592 kHz result reported) minus their value at each frequency. The uncertainty quoted at these frequencies is that associated expanded uncertainty (U) quoted by that laboratory for the measurement at that frequency. The was done to eliminate the time-dependence of the capacitors so as to make it easier to compare each laboratory's results.

5.10.2 As can be seen, the differences between measurements made at 1·592 kHz and at each of the other frequencies are small and in most cases are within the associated uncertainties.

5.10.3 Table 4: Frequency-dependence results for capacitor S/N 01031 - 10 pF.

The values quoted are each laboratories capacitance value at 1·592 kHz - the value at each frequency in ppm of the 10 pF nominal value, together with their associated expanded uncertainty (U) in ppm at each frequency.

Laboratory	398 Hz	796 Hz	1 kHz	1·233 kHz	2·466 kHz	12·33 kHz
NPL	+ 0·10 ± 0·5 ppm	+0·10 ± 0·10 ppm	+ 0·02 ± 0·10 ppm	0·0 ± 0·10 ppm	+0·05 ± 0·5 ppm	+0·50 ± 3·0 ppm
BEV	-	-	+ 0·27 ± 1·4 ppm	-	-	-
BIPM	-	-	- 0·015 ± 0·084 ppm	-	-	-
CEM *	-3·9 ± 12·0 ppm	-	-	-	-	-
CSIRO	-	-	- 0·069 ± 0·078 ppm	-	-	-
GUM	-	-	-1·0 ± 1·0 ppm	-	-	-
BNM-LCIE	+ 0·13 ± 0·074 ppm	+ 0·05 ± 0·058 ppm	-	-	-	-
NMi	- 0·03 ± 1·2 ppm	0·0 ± 1·2 ppm	+ 0·01 ± 1·2 ppm	-	- 0·06 ± 1·2 ppm	-
PTB Nov 95 PTB Feb 98	-	-	- 1·23 ± 0·6 ppm - 1·49 ± 0·6 ppm	- 0·73 ± 0·4 ppm	+ 0·97 ± 0·4 ppm	+ 0·17 ± 0·8 ppm

* Difference from their value measured at 1 kHz.

5.10.4 Table 5: Frequency-dependence results for capacitor S/N 01032 - 100 pF

The values quoted are each laboratories capacitance value at 1·592 kHz - the value at each frequency in ppm of the 100 pF nominal value, together with their associated expanded uncertainty (U) in ppm at that frequency.

Laboratory	398 Hz	796 Hz	1 kHz	1·233 kHz	2·466 kHz	12·33 kHz
NPL	- 0·90 ± 0·5 ppm	- 0·50 ± 0·10 ppm	- 0·33 ± 0·10 ppm	- 0·20 ± 0·10 ppm	+ 0·34 ± 0·5 ppm	+1·96 ± 3·0 ppm
BEV	-	-	+ 0·88 ± 1·4 ppm	-	-	-
BNM-LCIE	+ 0·12 ± 0·074 ppm	+ 0·01 ± 0·058 ppm	-	-	-	-
BIPM	-	-	+ 0·001 ± 0·084 ppm	-	-	-
CEM *	+0·0 ± 12·0 ppm	-	-	-	-	-
CSIRO	-	-	- 0·061 ± 0·078 ppm	-	-	-
NMi	+1·83 ± 2·5 ppm	+ 0·84 ± 2·5 ppm	+ 0·53 ± 2·5 ppm	-	- 0·45 ± 2·5 ppm	-
PTB	-	-	+ 0·51 ± 1·6 ppm	+ 0·31 ± 0·8 ppm	- 0·49 ± 1·4 ppm	-7·99 ± 5·2 ppm

* Difference from their value measured at 1 kHz.

5.11 **Dissipation Factor**

5.11.1 Dissipation Factor measurements for the capacitors are given in table 6. As can be seen the Dissipation Factor of both capacitors is very small and all results are in agreement when their associated uncertainties are taken into account.

5.11.2 Table 6: Dissipation Factor measurement results.

Laboratory	Frequency	Dissipation Factor	Expanded Uncertainty (U)
NPL 10 pF	398 Hz	0·0 x 10^{-6}	± 7 x 10^{-6}
	776 Hz, 1 kHz, 1·233 kHz, 1·592 kHz & 2·466 kHz	1·0 x 10^{-6}	± 6 x 10^{-6}
	12·33 kHz	10 x 10^{-6}	± 10 x 10^{-6}
NPL 100 pF	398 Hz	1 x 10^{-6}	± 8 x 10^{-6}
	796 Hz, 1 kHz, 1·233 kHz 1·592 kHz & 2·466 kHz	0·0 x 10^{-6}	± 7 x 10^{-6}
	12·33 kHz	7 x 10^{-6}	± 10 x 10^{-6}
BIPM 10 pF & 100 pF	1·592 kHz	- 0·3 x 10^{-6} Difference (10 pF - 100 pF).	± 2·0 x 10^{-6}
CEM 10 pF	400 Hz	<1·0 x 10^{-6}	-
	1 kHz	< 0·4 x 10^{-6}	± 30 x 10^{-6}
CEM 100 pF	400 Hz	< 0·3 x 10^{-6}	-
	1 kHz	< 0·1 x 10^{-6}	± 30 x 10^{-6}
CMI 10 pF	1 kHz	0·9 x 10^{-6}	± 0·5 x 10^{-6}
CMI 100 pF	1 kHz	0·5 x 10^{-6}	± 0·6 x 10^{-6}
PTB 10 pF	1 kHz 1·233 kHz & 1·592 kHz 2·466 kHz	8·8 x 10^{-6} 8·7 x 10^{-6} 8·4 x 10^{-6}	± 6 x 10^{-6} ± 6 x 10^{-6} ± 6 x 10^{-6}
PTB 100 pF	1 kHz 1·233 kHz 1·592 kHz 2·466 kHz	7·6 x 10^{-6} 7·4 x 10^{-6} 7·0 x 10^{-6} 6·1 x 10^{-6}	± 6 x 10^{-6} ± 6 x 10^{-6} ± 6 x 10^{-6} ± 6 x 10^{-6}
VTT 10 pF & 100 pF	1 kHz	0·0 x 10^{-6}	± 10·0 x 10^{-6}

5.12 The graphs in appendix 1 (Figure 1) and appendix 2 (Figure 2) show the drift characteristics of the two capacitors. Both the 10 pF and 100 pF capacitors appear to be approaching a steady value exponentially as shown by the dotted line. Investigations into the scatter of the NPL results have shown that there does not appear to be any contribution due to the mechanical shock or temperature cycling which occurs during travelling, as there is no correlation between the first and subsequent measurements after each return of the capacitors to NPL. Also, whilst taking the measurements, we observed no noise that might otherwise have accounted for the scatter of the results, so it does appear that the short-term stability of the capacitors is not perfect. Another possibility for the cause of the scatter could be temperature fluctuations of the capacitors. As mentioned previously, there is no means provided to measure the actual temperature of the capacitors so unfortunately the results cannot be corrected for temperature variations.

5.13 **Figure of Merit, E**

5.13.1 Part of the guidelines recently issued by EUROMET entitled ‘Guidelines for the organisation of comparisons’ No. 3:1 insist the analysis of results should include calculation of a ‘Figure of merit’

$$E_i = \frac{x_i - X_r}{\sqrt{U^2_i + U^2_r}}$$

E to assist in identifying discrepant results. The E value is calculated using the following equation:
where: E_i is the figure of merit between the reference value and that of the i^{th} laboratory.
x_i is the reported measurement result.
X_r is the reference value.
U_i is the total uncertainty of the reported result.
U_r is the total uncertainty of the reference value.

5.13.2 As the values of the capacitors are time-dependent they were measured before and after each visit so that a drift curve for each one could be established. Each laboratory's reported results were then plotted on a mean measurement date and the difference from the drift curve calculated. The reference value and its associated uncertainty was then calculated from the mean of these differences weighted by their stated variances. The NPL data was also taken on the same basis as if it were a single measurement. The reference values were then plotted and shown as a curve having its y coordinates displaced by the same amount along its length from the drift curve. The E value for each laboratory was then calculated using equation **(1)** above. The reference value and its associated uncertainty has been represented on each graph by a solid line with uncertainty bars. To enable all the results to be compared on an equal footing, as described in section 5.7, the larger uncertainty for NPL, BNM-LCIE and BIPM (which includes the 2 σ relative uncertainty of 4 parts in 10^7 of the consensus value of R_{K-90}) has been used. The resulting E value for each laboratory is given in tables 7 and 8.

5.13.3 In table 7 there are two laboratories where the E value is somewhat greater than 1. However it should be noted that the claimed uncertainty of these laboratories' measurement is very small, and this will increase the likelihood of obtaining a higher E value. Also, as noted in 5.12, the short-term stability of the capacitors is in question so an increased E value could occur by chance. The E values for the 100 pF capacitor, table 8, are all one or less indicating a slightly better overall agreement with the reference value.

5.14 The graphs also show that there is good agreement between the NPL results and the reference value for the 10 pF capacitor whereas there is a discrepancy between them for the 100 pF capacitor. This becomes even more obvious if the extra 2σ relative uncertainty of 4 parts in 10^7 for $R_{K\text{-}90}$ which has been added to the NPL uncertainty is disregarded as being common to the NPL 10 pF and 100 pF results. The cause of the discrepancy is not clear as laboratories use different routes for their measurements (QHR and Calculable Capacitor) and as such arrive at the values of the 10 pF and 100 pF from different directions. In the past, intercomparisons were only carried out at the 10 pF level so that possible discrepancies of this kind were not addressed. There is clearly a need for further investigation in the future.

5.15 To compare each laboratory's 10:1 measurement ratio a chart has been drawn (Figure 3 in Appendix 3) which shows the 10:1 measured ratio for each laboratory at 1·592 kHz (or 1 kHz for those laboratories who did not make a measurement at 1·592 kHz). The results have been calculated using equation (2).

$$R_i = (x_i 100 - X_r 100) - (x_i 10 - X_r 10)$$

where: R_i is the 10:1 measurement ratio for the ith laboratory.

x_{i100} is the reported measurement result for the 100 pF capacitor by the ith laboratory.

X_{r100} is the reference value for the 100 pF capacitor.

x_{i10} is the reported measurement result for the 10 pF capacitor by the ith laboratory.

X_{r10} is the reference value for the 10 pF capacitor.

6 CONCLUSION

This intercomparison has proved to be a most interesting exercise involving participants from laboratories around the world and from BIPM. The results appear to show that there are perhaps some significant differences between each laboratory's representation of the farad. These discrepancies do highlight the importance of carrying out intercomparisons on a regular basis to monitor each laboratory's capabilities and measurement methods. It is fortunate that in the laboratories taking part where the unit of capacitance has been determined directly by a laboratory, it has been done by either via a calculable capacitor or via a quantum Hall reference standard and the consensus value of $R_{K\text{-}90}$. The agreement demonstrated by the results of this intercomparison gives confidence in both methods of maintaining traceability.

7 REFERENCES

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8.2 A special thanks must go to all the laboratories who participated in this intercomparison for their hard work in measuring the capacitors so promptly, their assistance in keeping the intercomparison on schedule and for their helpful comments and suggestions in finalizing this report.

A1 APPENDIX 1

Table 7: Capacitor S/N 01031 - 10 pF.

Laboratory	Mean Date	Reported Value ppm †	Expanded Uncertainty (U) ppm †	Reference Value ppm †	Expanded Uncertainty (U) ppm †	Figure of Merit Value. E
NPL	1/8/95	-3·11	± 0·10	-	-	-
			± 0·412 ✯	-3·20	± 0·037	+ 0·20
PTB	5/11/95	-2·93	± 0·10	-3·05	± 0·037	+ 1·12
NIST	22/1/96	-2·83	± 0·04	-2·90	± 0·037	+ 1·27
OFMET	15/3/96	-3·0 at 1 kHz	± 62·0	-2·80	± 0·037	+ 0·00
BEV	14/5/96	-2·3	± 1·4	-2·70	± 0·037	+ 0·29
IEN	17/7/96	-2·29	± 0·8	-2·60	± 0·037	+ 0·39
NMi	13/10/96	-3·04	± 1·2	-2·47	± 0·037	- 0·48
SP	7/12/96	-3·0 at 1 kHz	± 1·8	-2·40	± 0·037	- 0·33
CSIR	12/2/97	-2·0 at 1 kHz	± 2·5	-2·32	± 0·037	+ 0·13
BNM-LCIE	13/5/97	-2·12 (QHR)	± 0·052	-	-	-
			± 0·403 ✯	-2·23	± 0·037	+ 0·27
		-1·76 (Cal.Cap)	-	-	-	-
CSIRO	25/6/97	-2·181	± 0·078	-2·19	± 0·037	- 0·10
NIST	18/8/97	-2·21	± 0·04	-2.15	± 0·037	-1·12
VTT	23/9/97	-3·05 at 1 kHz	± 1·5	-2·13	± 0·037	- 0·61
GUM	3/11/97	-2·5	± 0·8	-2·10	± 0·037	- 0·50
CEM	15/12/97	-2·1 at 1 kHz	± 3·0	-2·08	± 0·037	-0·01
PTB	21/2/98	-2·19	± 0·10	-2·05	± 0·037	- 1·32
BIPM	28/4/98	-1·998	± 0·074	-	-	-
			± 0·407 ✯	-2·02	± 0·037	-0·05
CMI	16/6/98	-2·26 at 1 kHz	± 0·4	-2·01	± 0·037	- 0·62
NPL	5/8/98	-1·88	± 0·10	-	-	-
			± 0·412 ✯	-1·97	± 0·037	+ 0·20
UME	22/9/98	-1·69	± 1·6	-2·01	± 0·037	+ 0·20

† - ppm signifies parts per million of the 10 pF nominal value of the capacitor.
✯ - uncertainty calculated which includes the 2 σ relative uncertainty of 4 parts in 10^7 for $R_{K\text{-}90}$.

A1 APPENDIX 1 (continued)

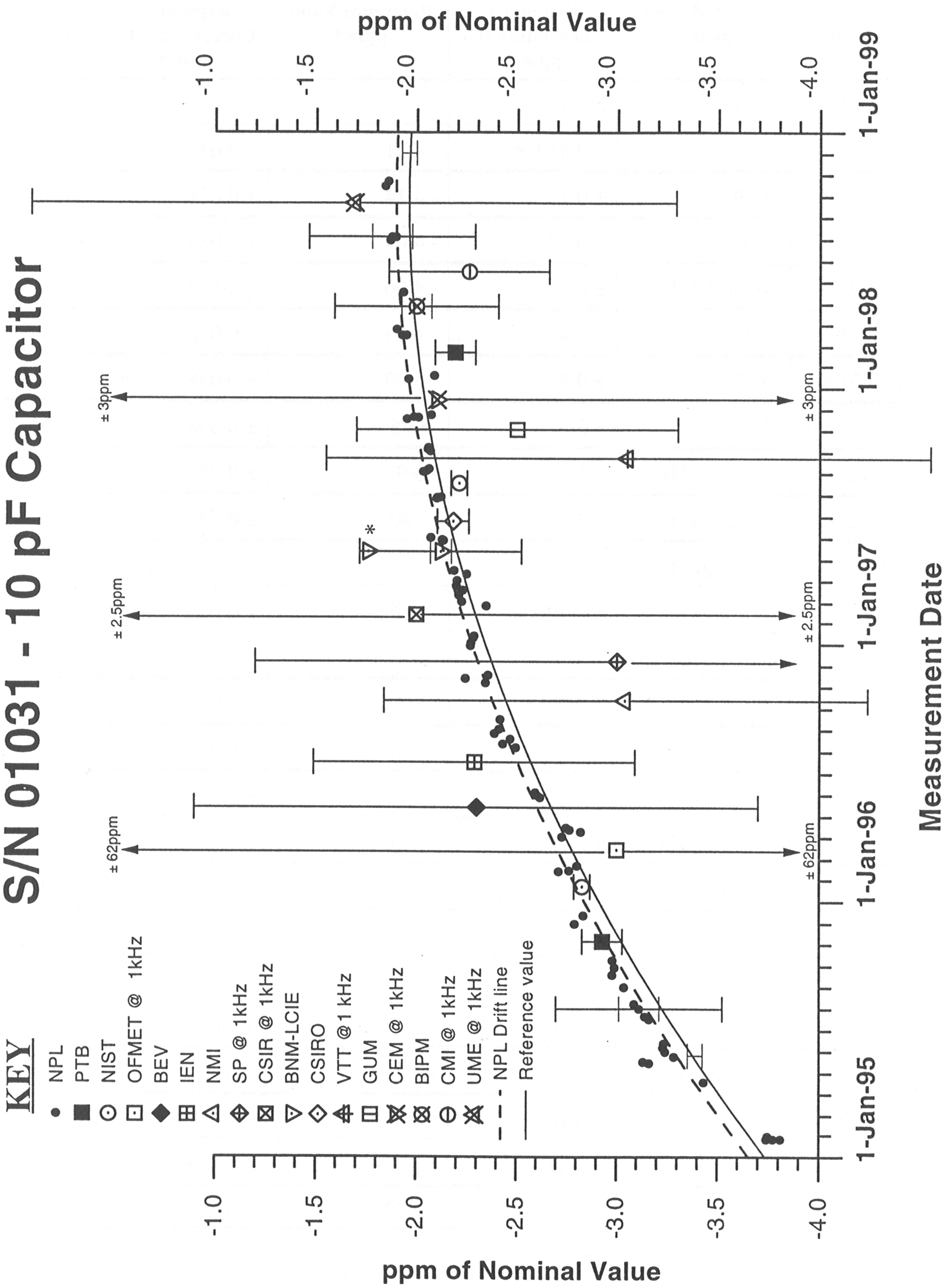

Figure 1: The results of measuring the 10 pF capacitor with associated 2σ uncertainty bars by various laboratories, expressed as the relative difference in parts per million (ppm) from the nominal 10 pF value.

* BNM-LCIE value from their Calculable Capacitor

A2 APPENDIX 2

Table 8: Capacitor S/N 01032 - 100 pF

Laboratory	Mean Date	Reported Value ppm †	Expanded Uncertainty (U) ppm †	Reference Value ppm †	Expanded Uncertainty (U) ppm †	Figure of Merit Value. E
NPL	1/8/95	-3·93	± 0·10	-	-	-
			± 0·412 ✯	- 4·21	± 0·038	+ 0·63
PTB	5/11/95	-4·09	± 0·12	- 4·14	± 0·038	+ 0·42
NIST	22/1/96	-4·08	± 0·04	- 4·09	± 0·038	+ 0·24
OFMET	15/3/96	-4·3 at 1 kHz	± 6·6	- 4·06	± 0·038	- 0·04
BEV	14/5/96	-2·71	± 1·4	- 4·03	± 0·038	+ 0·94
IEN	17/7/96	-3·67	± 0·8	- 3·99	± 0·038	+ 0·40
NMi	14/10/96	-2·37	± 2·5	-3·95	± 0·038	+ 0·63
SP	7/12/96	-3·5 at 1 kHz	± 1·7	- 3·92	± 0·038	+ 0·25
CSIR	12/2/97	-4·0 at 1 kHz	± 3·0	-3·90	± 0·038	- 0·03
BNM-LCIE	13/5/97	-3·77 (QHR)	± 0·052	-	-	-
			± 0·403 ✯	-3.86	± 0·038	+ 0·23
		-3·39 (Cal. Cap)	-	-	-	-
CSIRO	25/6/97	-3·788	± 0·078	- 3·84	± 0·038	+ 0·64
NIST	18/8/97	-3·86	± 0·04	- 3·83	± 0·038	- 0·49
VTT	23/9/97	-3·42 at 1 kHz	± 1·5	- 3·81	± 0·038	+ 0·26
GUM	3/11/97	-3·4 at 1 kHz	± 2·2	- 3·80	± 0·038	+ 0·18
CEM	15/12/97	-4·1 at 1 kHz	± 3·0	- 3·79	± 0·038	- 0·10
PTB	21/2/98	-3·91	± 0·12	- 3·78	± 0·038	- 1·01
BIPM	28/4/98	-3·753	± 0·074	-	-	-
			± 0·407 ✯	- 3·75	± 0·038	+ 0·00
CMI	16/6/98	-4·11 at 1 kHz	± 0·6	- 3·75	± 0·038	- 0·59
NPL	5/8/98	-3·49	± 0·10	-	-	-
			± 0·412 ✯	- 3·77	± 0·038	+ 0·63
UME	22/9/98	-3·544	± 1·7	- 3·72	± 0·038	+ 0·11

†- ppm signifies parts per million of the 100 pF nominal value of the capacitor.
✯ - uncertainty calculated which includes the 2σ relative uncertainty of 4 parts in 10^7 for $R_{K\text{-}90}$.

A2 APPENDIX 2 (continued)

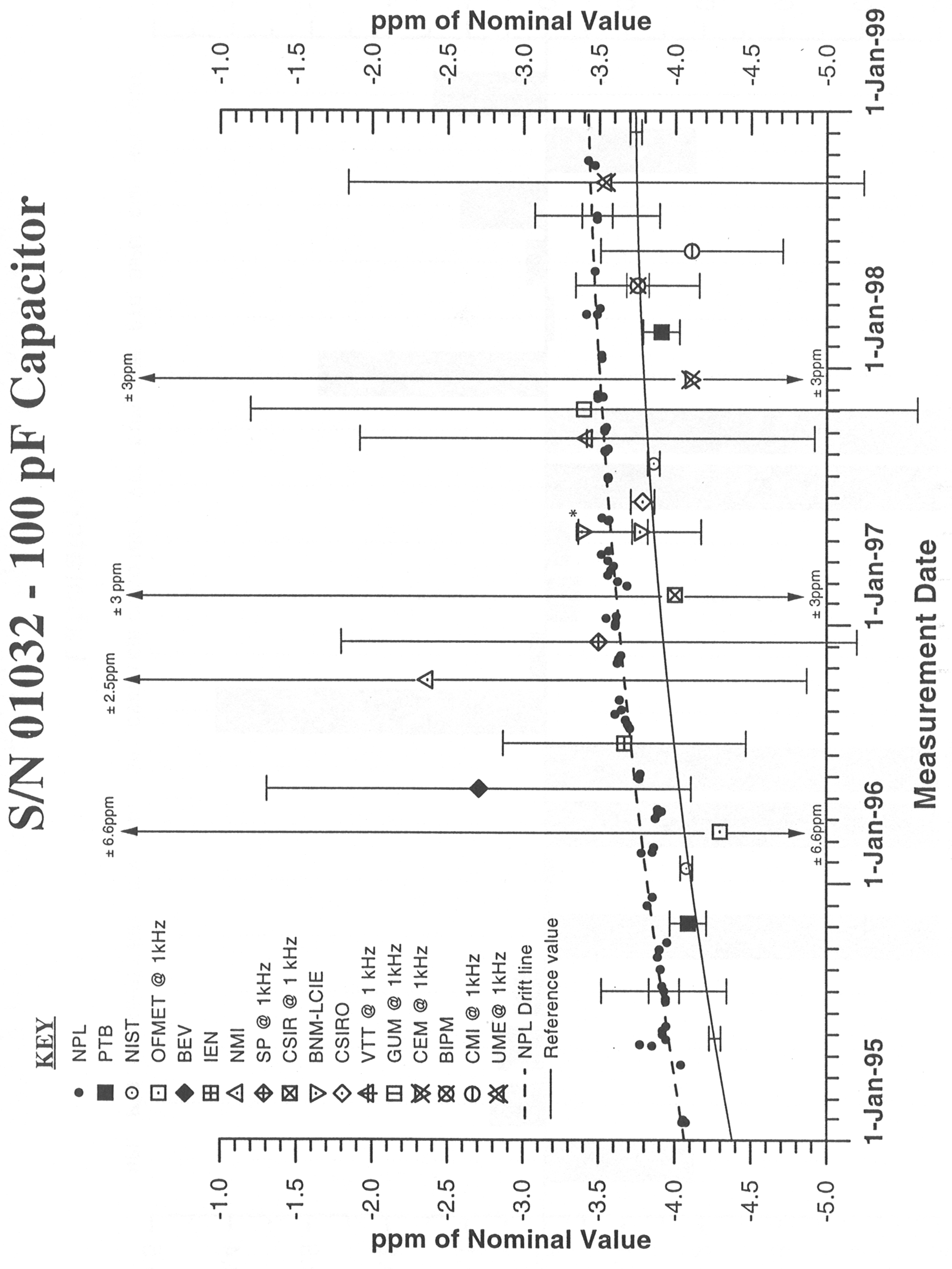

Figure 2: The results of measuring the 100 pF capacitor with associated 2σ uncertianty bars by various laboratories, expressed as the relative difference in parts per million (ppm) from the nominal 100 pF value.

* BNM-LCIE value from their Calculable Capacitor

A3 APPENDIX 3

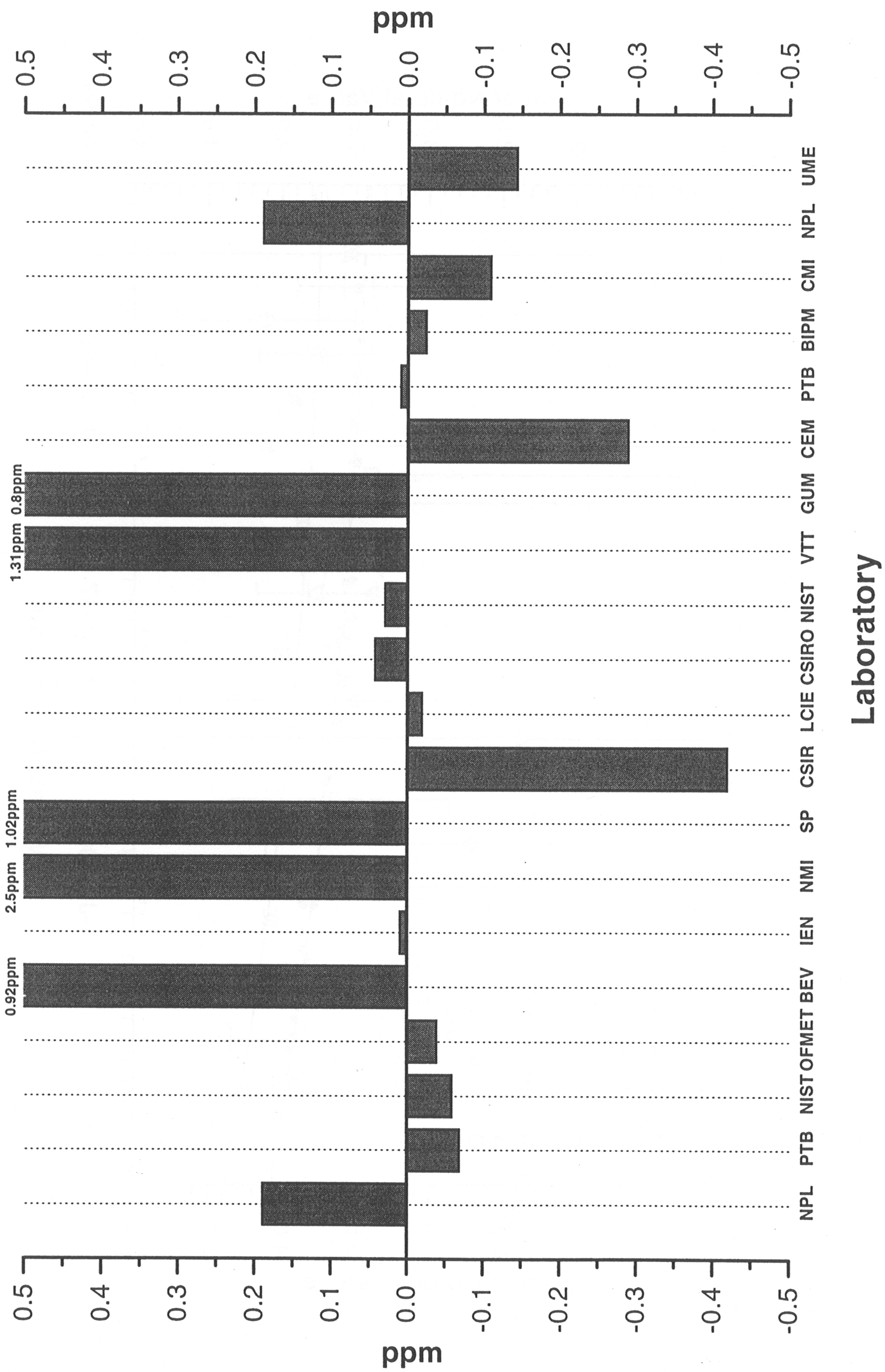

Figure: 3 The 10:1 measurement ratio (100pF-10pF) for each laboratory.