EUROMET Project 427, EUROMET.EM-S7

Final report

"Comparison of AC and DC Conductivity Standards"

May 2009

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1. Introduction

This project is closely related to the EC project ‘Conductivity’ which started in October 2000, where one objective was to establish agreement between existing and new DC and AC methods of conductivity measurement. After delays in receiving results and uncertainties the status of the comparison for Euromet project 427 was reviewed in December 2008 with an aim of finalising the report in 2009.

Towards the end of 2008 UME were asked to check the values they submitted in 2004. The following was received in an email dated 20/2/2009.

“We checked out our results but we could not interpret some parts of them. So, we decided to withdraw from the comparison. In addition, we will temporarily suspend the dc conductivity measurement from the CMC table.”

NPL, PTB and VSL agree to the withdrawal of UME as long as their CMC entry is suspended.

Boeing never provided uncertainties so their results have not been included.

See Appendix 1 for typical uncertainty budgets.

See Appendix 2 for the comparison protocol.

2. Travelling standards

2.1 Description: Four bar test specimens and four block test specimens have been produced as travelling standards. They have been carefully machined to avoid work hardening and they have been finished by diamond turning to provide a good finish and the minimum variation in dimensions.

The test specimen details are given in the following table:

Specimen Material	Bar size (mm)	Block size (mm)	Bar and block thickness (mm)	Approximate conductivity at 20 °C (MS/m)
Aluminium	600 x 80	80 x 80	10	36
Aluminium Alloy	600 x 80	80 x 80	10	22
Nordic gold (optional)	300 x 40	80 x 80	10	9
Titanium	600 x 80	80 x 80	10	2

2.2 Quantities to be measured: Participants should determine the conductivity of the bars/blocks by either a DC or AC technique (or both, if available). At NPL the bars have been measured by both AC and DC methods. The AC measurements were made at frequencies of 10, 30, 60 and 90 kHz. Only AC values measured at 60 kHz are used in this comparison.

3. Measurement methods

3.1 NPL

3.1.1 AC Conductivity Bridge

Prior to the start of the CONDUCTIVITY project, NPL provided calibration of AC conductivity reference standards using a toroidally wound mutual inductor method where the conductivity is calculated from the change in mutual resistance when a material is introduced into the inductor. Available standard materials covered the conductivity range of 11.5 to 59 MS/m, and the frequency range covered by the bridge is 10 to 100 kHz. Reference standard calibrations are carried out at the working frequency of commercial eddy current conductivity instruments at 60 kHz. This measurement system was established in the mid 1980s after the British Calibration Service approached NPL regarding differences between AC and DC methods and AC traceability. Figure 1 shows the toroidally wound mutual inductor and diecast box containing the T-network.

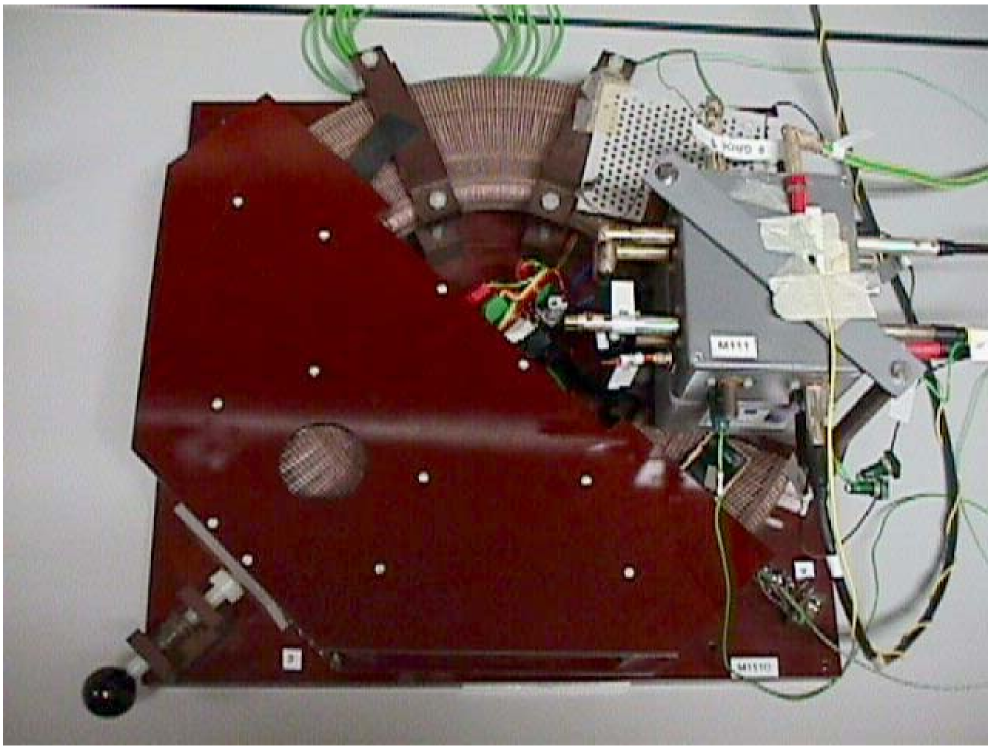
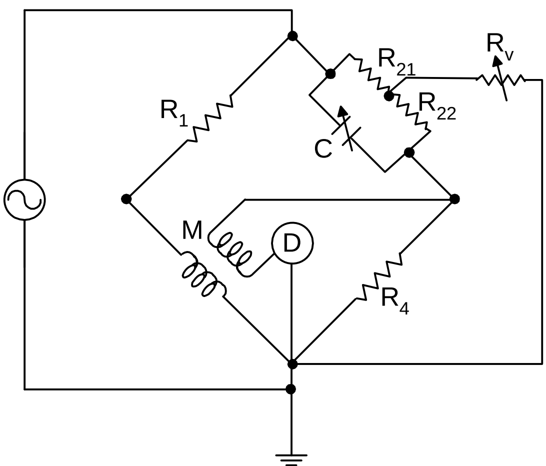


Figure 1.

The NPL primary standards are in the form of annuli and fabricated from non-ferromagnetic conducting material. The metal annuli are made in two parts, which allow them to be assembled as a complete ring within the coil former of the mutual-inductor bridge, also made in two sections. The dimensions of the rings are an outer diameter of 380 mm, an inner diameter of 220 mm and a thickness of 10 mm. This gives the annuli an 80 mm flat surface on which the probe of a transfer instrument can be used. Secondary reference standards for the calibration of commercial instruments are available in the form of 80 x 80 mm square blocks, which have a thickness of 10 mm. These blocks are calibrated against the rings using a comparator probe containing a mutual winding that replaces the toroidal mutual inductor in the bridge. Figure 2 shows an annuli ring standard and a secondary reference block.

Figure 2.

Circuit for the measurement of the ring standards



R_v = variable resistor

C = variable capacitor

$R_{21} = R_{22} = 10\ \text{k}\Omega$

$R_1 = 1\ \text{k}\Omega$

$R_4 = 10\ \Omega$

M = inductor

Figure 3.

The circuit diagram in Figure 3 shows the Heydweiller bridge and T-network selected for the measurement of the mutual resistance change when the inductor is empty and when the inductor has the material annuli inserted into the inductor. Since the mutual resistances to be measured are small there are a number of factors that can contribute errors in the measurement. These factors include the primary and secondary winding resistances, leakage inductances, self-capacitance of the windings and mutual capacitance between the windings. The bridge can be calibrated by determining the values of the discrete components making up the bridge and allowing for the multitude of corrections.

Circuit for the calibration of the Heydweiller bridge

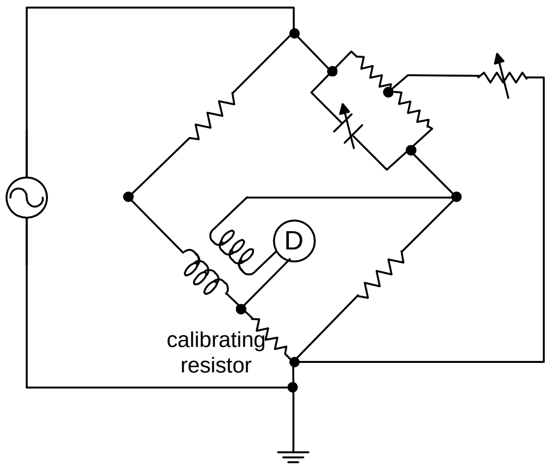


Figure 4.

The circuit diagram shown in Figure 4 shows the preferred approach for calibration of the bridge by measuring a known low value resistance that is inserted into the measuring arm of the bridge. The resistors constructed for the bridge calibration are co-axial, each consisting of a short length of Zeranin wire in a copper tube mounted on a co-axial plug. The measurements are of the difference between each resistor and a short circuit.

<u>3.1.2 Calculation of AC conductivity of ring standards</u>

The AC conductivity of each ring, σ, can be calculated using the following formula

$$\sigma = \frac{4\pi f(b+t)^2 \mu_o N^4}{R_m^{*2} l^2}$$

where:

σ = the conductivity of the ring in S/m
b = the mean width of the standard ring in m
t = the mean thickness of the standard ring in m
μ_o = the magnetic constant, $4\pi.10^{-7}$ H/m
N = the number of turns in winding = 30
R^*_m = the eddy current resistance

l = the mean circumference of the standard ring in m
f = frequency in Hz

This expression is derived using a one-dimensional approach and corrects for that part of the eddy-current path from one surface to the other. To do this a factor (b+t)/b has been used. This correction is only appropriate when the ratio t/δ is greater than 10. When t/δ is small curved paths are present and interference between upper and lower corners occur.

3.1.3 Calibration of reference blocks and bars

When calibrating reference blocks and bars the toroidal mutual inductor is replaced by a solenoidal mutual inductor designed to stand on the surface to be measured and at a well defined distance from the surface. The mutual inductance and resistance can then be measured with the same Heydweiller bridge used for the annular ring standards. A plot of the calibrated conductivities of the ring standards is made against the balance resistances, R_V and a spline fitted to the data points. The balance resistance of the material under test is measured and the conductivity value determined using the spline.

3.2 PTB

3.2.1 Calibrated Object

The calibrated objects are eighteen conductivity standards made from nine different materials, pure metals and metallic alloys. From each material two samples were calibrated, one sample having a bar geometry (600×80×10 mm^3) and one being a so called Van-der-Pauw (VdP) geometry which is a quadratic plate (80×80×10 mm^3).

3.2.2 Calibration Procedure

The DC conductivity of the bar shaped conductivity standards was determined by measurements of the resistance per unit length, using knife edges of known distance, and measurements of the thickness and width of the sample.

The DC conductivity of the VdP conductivity standards was determined by measurements of the so called VdP resistance and by measurements of the thickness of the plate. The terminus VdP resistance is defined as follows: If the edges of the square plate are clockwise numbered as 1, 2, 3, and 4, the VdP resistance is the ratio of the voltage drop across the edges 3-4 and the current through the edges 1-2. By a cyclic rotation of the current and voltage connections to the edges of the sample four different measurements can be made. Presumed a perfect sample (homogenous conductivity; square plate with the large surfaces being parallel) the four resistance measurements give equal results. Contact to the corners of the quadratic plates was made by pressing copper plates against each corner.

The method for the resistance measurements was the same for the bar samples and for the VdP samples: A current of 10 Ampere was given by a transconductance amplifier (Wavetek 4600) in connection with a calibrator (Datron 4000). This current was measured by means of a calibrated 10-mΩ resistance standard and a calibrated DVM

(Agilent 3458A). The voltages at the block were measured using a nanovoltmeter (NVM, Keithley 181, 2 mV range). The NVM was calibrated up to about 300 µV using a voltage which was generated by an appropriate current I_{cal} driven through the same 10-mΩ shunt. This current I_{cal} was calibrated using the above Agilent 3458A. Details concerning the model equation and the uncertainty are given in the appendix.
All measurements were traceable to the primary standards of PTB.

3.2.3 Environmental Conditions

During the calibration the conductivity standards under test were kept in an oil-bath at (20,00 ± 0,03) °C.

3.2.4 Measurement Conditions

The measuring current was (9,9975 ± 0,0003) A.

3.3 VSL

3.3.1 Introduction

Measurements have been performed on Set C, set B, and set A respectively. The measurement period was from 24 October 2002 up until 5 March 2003. No visible damage was seen on arrival of the sets of the standards.

3.3.2 Electrical measurement set-up

The electrical measurement set-up used was identical to that described in the CPEM 2002 paper and the final report of the CONDUCTIVITY project. The measurement current was 10 A in almost all cases, with a 15 µΩ shunt used as reference resistor. The value of this shunt was determined several times during the measurement period by comparing it with a calibrated 100 µΩ reference resistor using the same set-up. The shunt did not significantly change value in the measurement period, so the average value of all calibration measurements was taken as the reference value in the conductivity measurements.

Each sample was measured at least two times in order to check for reproducibility. A single measurement consisted of 10 – 20 ratio measurements for the bars and 40 ratio measurements for the blocks (each side 10 times). Between the different bar measurements, the knife-edge was repositioned to a slightly other location of the bar, but still near to the middle of the bar.
The measurements were completely automated.

With the block measurements, the contact resistance of the four contacts at the corners of the blocks was checked before each measurement. This appeared to be crucial in order to prevent excessive heating at the corners due to accidentally bad contacts (with contact resistances of a few mΩ instead of the normal 50 – 100 µΩ).

With the bar measurements, it appeared important to check the position of the knife-edge voltage contacts after the measurements. In a few occasions, the knife-edge had moved due to the oil flow in the oil bath. In all these cases, the measurement results were ignored and the measurement was repeated.

The model for the uncertainty calculations and an example uncertainty budget are given in appendix 1.

3.3.3 Environment

All measurements were performed with the samples in a temperature controlled oil bath, with the temperature close to 20 °C (typically 20.025 °C), so that the temperature corrections to the conductivity would be small. The heating of the sample due to the 10 A measurement current was negligible in the bar measurements, and at most 0.02 °C in the block measurements. In the block measurements 4 thermistors were placed at the respective corners of the sample, to monitor the temperature close to the contacts. In the bar measurements the thermistors were close to the measurement area of the bar, that is the location of the knife-edge.

The measurement set-up with the oil bath was located in a temperature and humidity controlled room, part of our Faraday cage, with measured temperature variation of (23.0 ± 0.2) °C and humidity variation of (45 ± 5) %.

4. Results

The following figures show the NPL AC conductivity measured at 60 kHz and the DC values determined by PTB and VSL. All measurements are reported for a temperature of 20 °C. The error bars show the 95 % measurement uncertainties. Tables 1 and 2 give the values plotted in these figures for the bars and blocks respectively.

A correction to the results submitted by VSL for the aluminium and alloy R bars was made in May 2009 since the thicknesses for these bars had been exchanged in the earlier analyses. All participants were in agreement that the data could be corrected since it was clear from the analyses spreadsheets that this had occurred.

See the table in section 2.1 for test specimen details.

Bar	NPL AC value	NPL Uncertainty	PTB DC value	PTB Uncertainty	VSL DC value	VSL Uncertainty
MS/m						
Aluminium	35.979	0.2519	35.828	0.0130	35.826	0.0250
Alloy R	22.491	0.1574	22.639	0.0170	22.618	0.0118
Nordic Gold			9.53	0.0030	9.521	0.0057
Titanium	2.182	0.0153	2.16	0.0010	2.1604	0.0019

Table 1. Conductivity values at 20 °C for the bars.

Block	NPL AC value	NPL Uncertainty	PTB DC value	PTB Uncertainty	VSL DC value	VSL Uncertainty
MS/m						
Aluminium	35.911	0.2514	35.786	0.0300	35.813	0.0217
Alloy R	22.465	0.1573	22.529	0.0270	22.524	0.0197
Nordic Gold	9.553	0.0669	9.529	0.0020	9.53	0.0045
Titanium	2.182	0.0153	2.173	0.0010	2.1739	0.0011

Table 2. Conductivity values at 20 °C for the blocks.

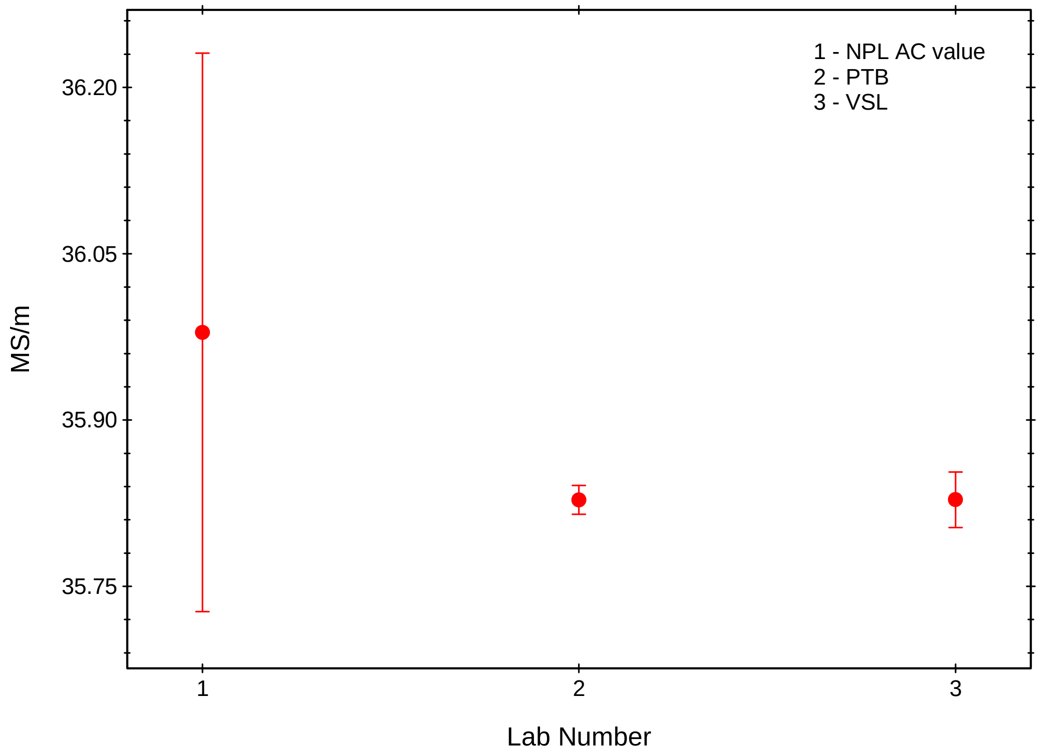


Figure 5. Aluminium bar.

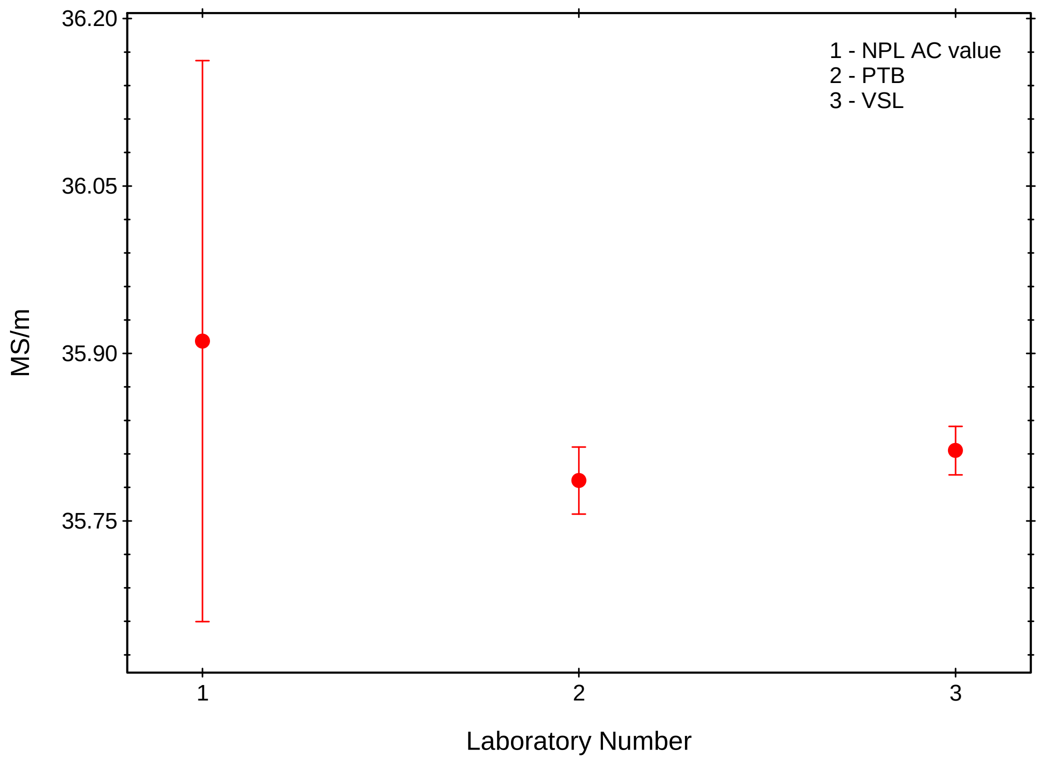


Figure 6. Aluminium block.

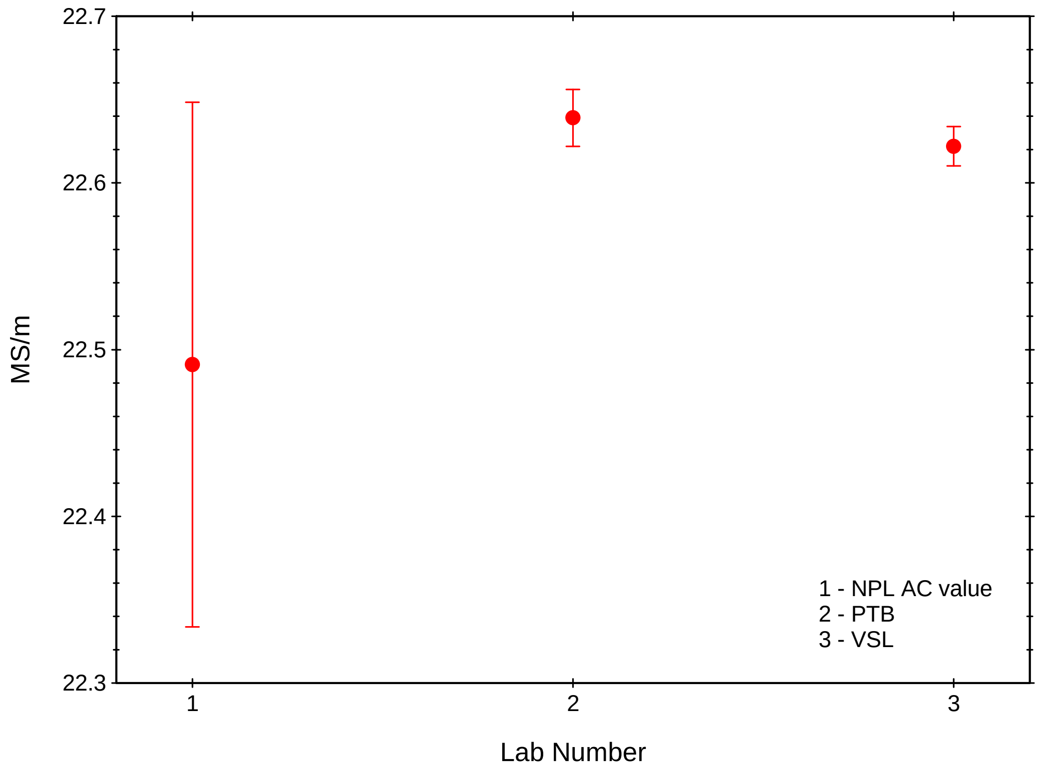


Figure 7. Aluminium alloy bar.

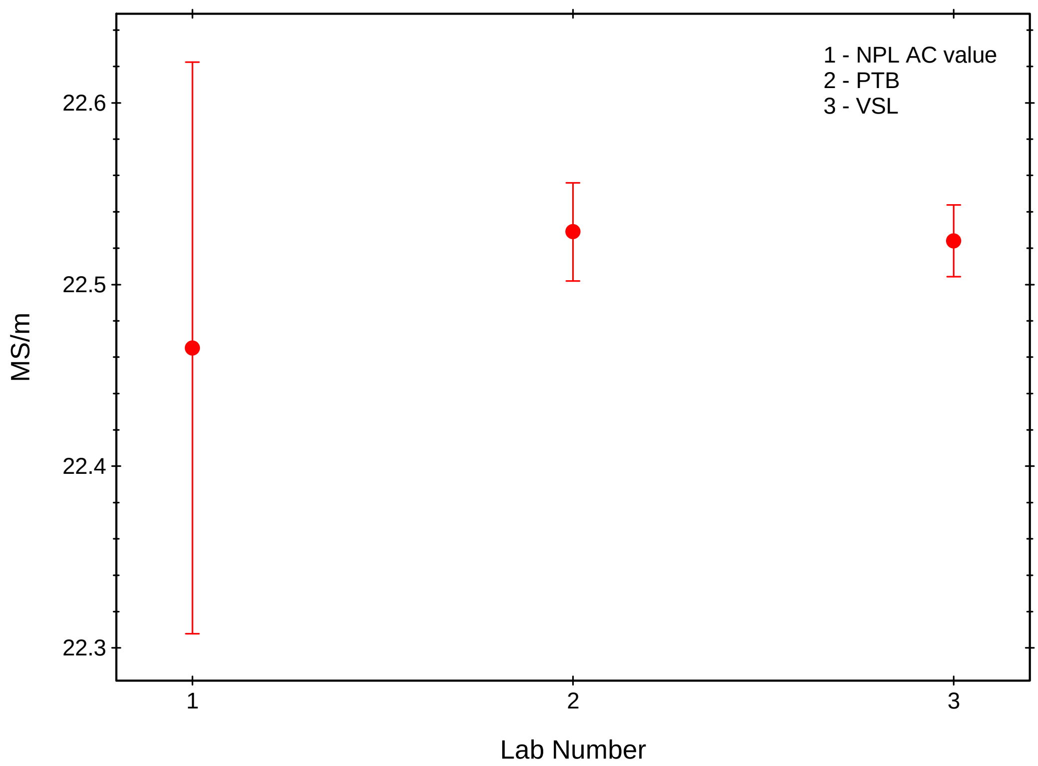


Figure 8. Aluminium alloy block.

No AC measurements were possible on the Nordic gold bar since the 50% reduction in the width and the length of this bar due to lack of material meant that the comparator probe of the NPL system was too large for the surface of the bar.

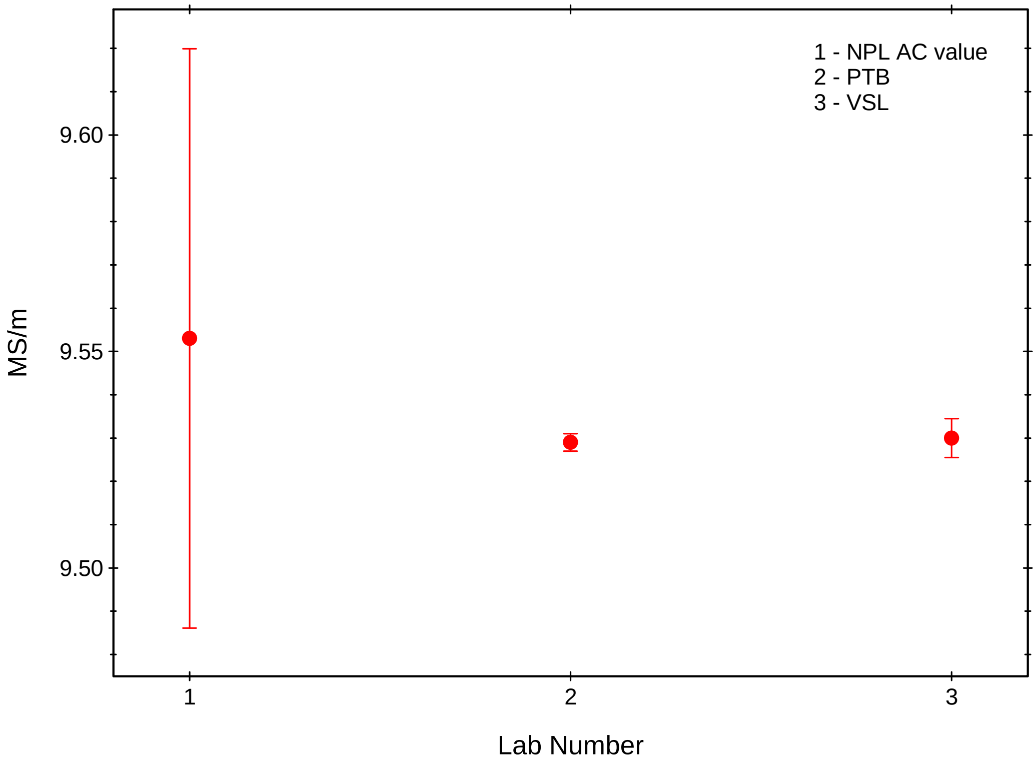


Figure 9. Nordic gold block.

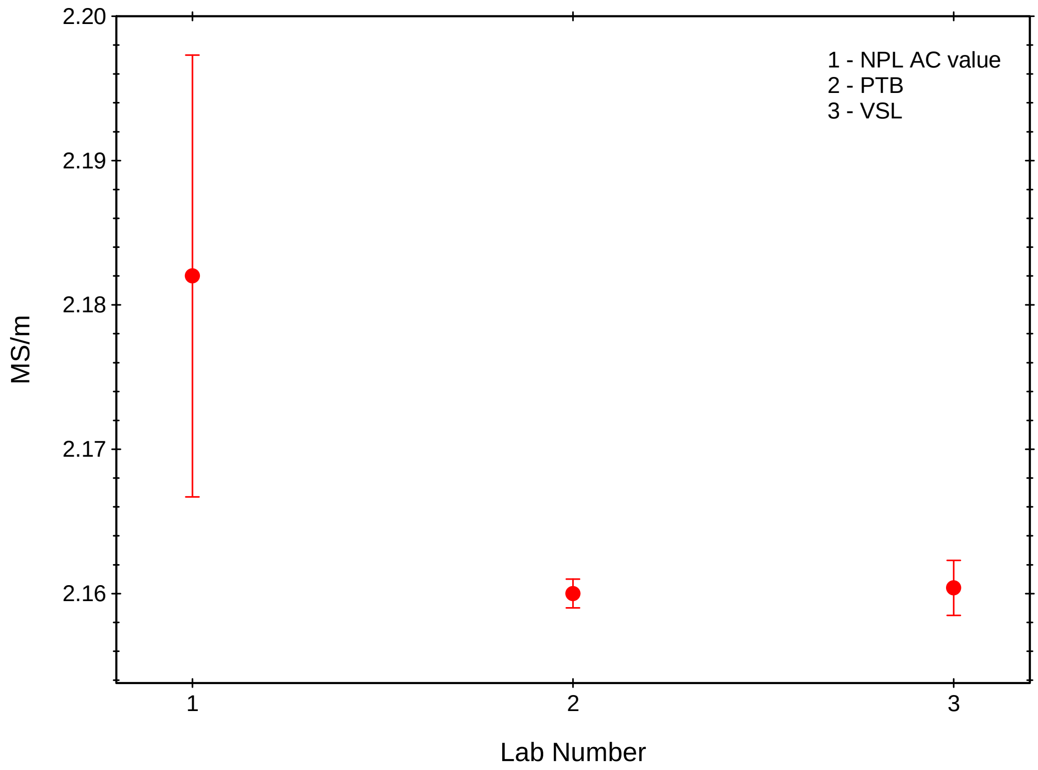


Figure 10. Titanium bar.

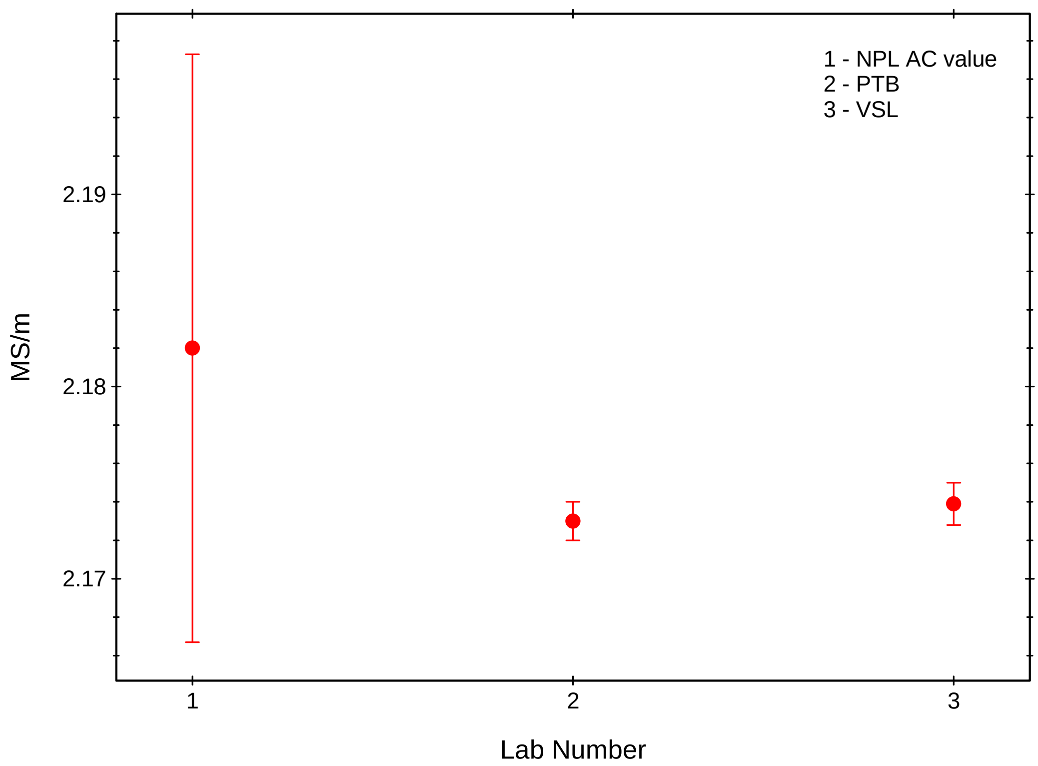


Figure 11. Titanium block.

5. Discussion

For the DC measurements on the blocks the PTB and VSL values agree. Referring to Table 1 there is a small, but significant, unresolved difference between the DC conductivity values for the Nordic gold bar. This difference is significant given the (relatively small) uncertainties that PTB and VSL have given for their measurements of this material in this comparison, which is 0.03% and 0.06% respectively. However, when the 0.08% uncertainty of the present CMC of PTB is used in the analysis of the results, the difference is not significant with respect to the combined PTB-VSL measurement uncertainty.
In general, the DC measurement results on blocks agree slightly better than those of the bars, which leads to the conclusion that DC measurements on blocks are slightly preferred to those on bars. This is probably because measurements on blocks require fewer physical measurements and the same volume of material contributes to the measurements. Another reason could be that the volume of material contributing to the measurement may be different for the bars since laboratories will probably use knife-edges with a different spacing. If the material properties are not homogeneous, this will contribute to a difference in the measured conductivity..

For all cases the uncertainty for AC conductivity measurements is considerably larger than that for DC measurements. Referring to the NPL uncertainty budget on page 18 it can be seen that the reasons for this are large contributions due to aspects concerned with AC measurements such as corrections due to the eddy current path and the calibration of the bridge.

From Figure 10 there is a significant difference between the measured AC and DC conductivities for the titanium bar.

For all other conductivities and geometries the results agree within the measurement uncertainties.

Possible reasons for the observed difference between the AC and DC measured conductivities for the titanium bar are:

1) The skin depth in the material makes the AC measurement surface sensitive. For DC measurements the current is through the volume of the material.
2) DC measurements on bars are made along the length and for the AC measurements the current is in circular paths on the surface.

When considering 1), if the conductivity of the material is not uniform through the thickness then there will be a difference between the AC and DC determined values due to the difference in the volume of the material involved. Non-uniform conductivity through the thickness is most probably due to work hardening of the surface. This work hardening could happen as the result of the rolling required to obtain the thickness of the parent sheet. This leaves the surface of the material stressed and this changes the conductivity. Some aluminium alloys are heat-treated after rolling to obtain the required temper condition and this will relieve the stress to some extent.

Point 2) will contribute to AC/DC differences if the conductivity is dependent on direction. A considerable number of the conductivity coupons that are used to calibrate commercial conductivity measuring instruments are calibrated using primary standards measured at DC. A circular cross section bar for which the conductivity has been determined at DC will be sectioned into disk coupons. Possible differences between AC and DC measured conductivities could be due to the poor material uniformity introduced in 1) and the conductivity anisotropy of 2). Since the current paths for AC methods are circular different conductivities will contribute to the measured value. As for 1), a possible cause of anisotropy is the rolling stage used in producing the parent plate. In the production of rods extrusion is involved and this could contribute to anisotropy.

Measurement methods are required to discriminate between 1) and 2). For 1) the measurement method requires sensitivity to depth through the thickness. For the AC method used at NPL the measurement frequency can be selected. Shown in Figure 12 is the skin depth for a material with a conductivity of 16.5 %IACS at frequencies from 1 kHz to 100 kHz. The skin depth is the distance at which the magnitude of the current reduces to 1/e (= 36.8%) of the value at the surface.

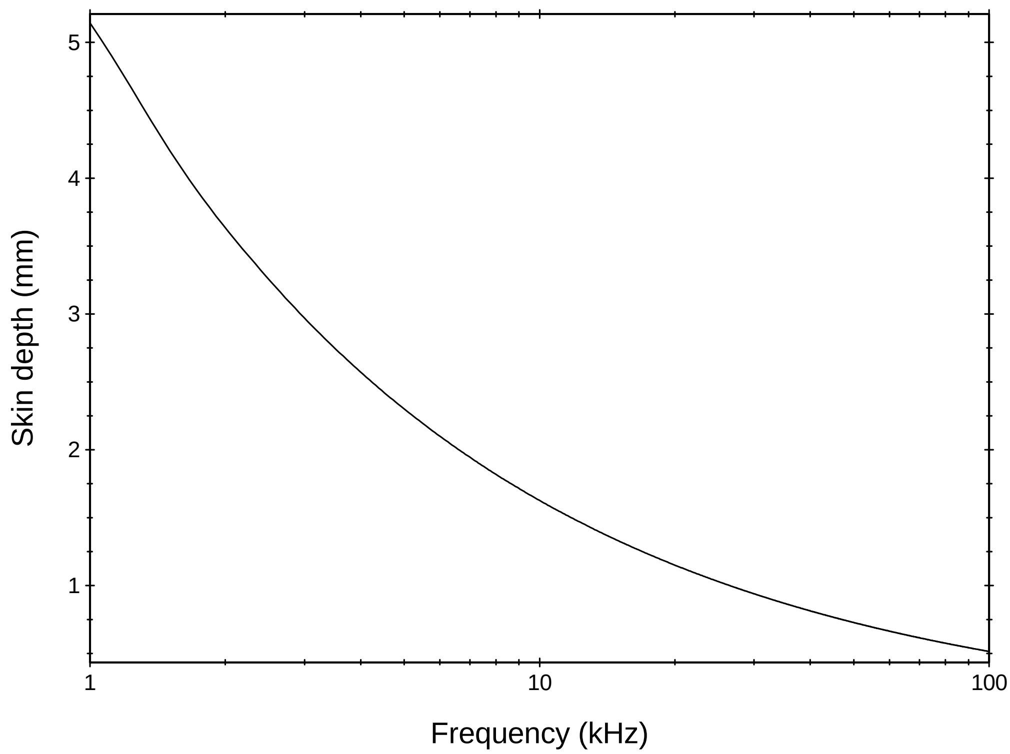


Figure 12 Skin depth versus frequency for material with a conductivity of 16.5 %IACS.

Measurements at high frequency are therefore sensitive to the surface material and measurements at lower frequencies approach the DC condition of current through the whole volume of the material.

For 2) contributions due to anisotropy can be investigated using DC Van der Pauw measurements. For this technique the resistance used to calculate the conductivity is the average of two resistance values. The individual resistance values are determined in such a way that the current flows in two roughly orthogonal directions. This is closer to the current path for the AC method than the current direction for DC bar measurements. If anisotropy is present there will be a difference in the two resistance values. Another possible cause of a difference for these blocks is the length of the sides. When a significant difference occurs the geometry should be checked to eliminate this as the cause. By comparing the DC conductivity value of a block to that of a bar when these are made from the same material could demonstrate if this discrimination is possible.

For Figures 10 and 11 titanium has a significant difference of 0.6% between the block and bar DC conductivity values (Bar value lower than that of the block). For the titanium block the VSL Van der Pauw two resistance values differed by 3.6% and anisotropy therefore exists. The AC conductivity value for the block and bar agree well and this agreement is believed to be due to the circulating current direction that occurs for both measurements. For the AC bar measurement the current also flows in a direction at right angles to the DC current and for all angles between these and the effect of the anisotropy is reduced compared to the DC measurement. The remaining difference between the AC and DC measured values for the block could be due to the material uniformity through the thickness. For titanium it can be concluded that both poor conductivity uniformity through the thickness and anisotropy contribute to the difference between the AC and DC measured conductivity values.

6. Conclusions

DC conductivity measurements on blocks are slightly preferred to those on bars, given the slightly better overall agreement in PTB and VSL measurement values on blocks. This probably is related to the reduced number of dimensional measurements needed for the blocks and the better defined measurement geometry.

It is clear that the origin of differences between the AC and DC measured values of conductivity are not easy to interpret. What can be concluded is that if the DC measured value for the conductivity was used to calibrate a commercial conductivity measurement instrument working at 60 kHz then a discrepancy could be introduced due to this calibration in all subsequent measurements.

It is important to emphasise that even when there is correct agreement between DC and AC conductivity values the uncertainty cannot be lower than that of the AC method. It is not possible to say if the AC and DC values agree to a level better than the combined uncertainty of the individual methods. Since the uncertainty for the AC method is considerably higher than the DC techniques this dominates the level of agreement that can be achieved. If instruments that work at AC are calibrated using conductivity reference materials that are measured at DC, the evaluation of the uncertainty for the calibration of the mentioned instruments should include a contribution from the possible difference between AC and DC measurements. It is also recommended that the calibration certificates for DC calibrations of conductivity standards should contain a sentence which states that for the calibration of eddy current meters by means of these DC calibrated standards one has to take into account an additional contribution from the possible difference between AC and DC measurements.

Appendix 1: Uncertainty Budgets

NPL

Uncertainty budget for ring calibrations

Ring Standards Uncertainty								
Source of uncertainty	Reference	Value (±%)	Type	Prob.Dist.	Divisor	C_i	u_i (±%)	V_i or V_{eff}
Dimensions of ring	Paper ref.2	0.03	B	normal	2	1	0.015	inf
Calculation of average path length of of eddy currents	Paper ref.2	0.02	B	rectangular	1.7321	1	0.012	inf
Skin effect correction	Interpolation from paper ref.2	0.17	B	rectangular	1.7321	1	0.098	inf
Errors caused by capacitance between windings	Interpolation from paper ref.2	0.10	B	rectangular	1.7321	1	0.058	inf
Bridge calibration error		0.15	B	normal	2	1	0.075	inf
Bridge resolution		0.02	B	rectangular	1.7321	1	0.012	inf
Temperature measurement		0.12	B	rectangular	1.7321	1	0.069	inf
Repeatability of measurement		0.235	A	normal	1	1	0.235	inf
Combined uncertainty							0.281	
Expanded uncertainty			k=2				0.563	
The expanded uncertainty is rounded up to ± 0.6%								

VSL

The model used for the conductivity σ is: $\dfrac{1}{\sigma} = \rho = \dfrac{\pi}{\ln(2)}\, d\, R_{ref}\;\, r\;\, f(r)\, (1 + \delta r_{th})\, (1 + \delta r_{lin})\, (1 + \delta r_T)\, (1+\delta_{cont})$

Parameter	Value		Uncertainty		Sensitivity coefficient		Uncertainty distribution	Uncer-tainty [nΩm]
Thickness d of the sample	10059.4	μm	1.00	μm	$2.78 \cdot 10^{-6}$	Ω	normal	$2.78 \cdot 10^{-3}$
Contact size δ_{cont}	0		$4.62 \cdot 10^{-7}$		$2.79 \cdot 10^{-2}$	μΩm	rectangular	$1.29 \cdot 10^{-5}$
Reference resistor R_{ref}	14.9665	μΩ	$4.49 \cdot 10^{-4}$	μΩ	$1.87 \cdot 10^{+3}$	μm	normal	$8.38 \cdot 10^{-4}$
Measured ratio r	$4.09317 \cdot 10^{-2}$		$3.27 \cdot 10^{-6}$		$6.82 \cdot 10^{-1}$	μΩm	normal	$2.23 \cdot 10^{-3}$
Correction factor f(r)	1		$5.77 \cdot 10^{-6}$		$2.79 \cdot 10^{-2}$	μΩm	rectangular	$1.61 \cdot 10^{-4}$
Residual thermal voltages δr_{th}	0		$1.15 \cdot 10^{-4}$		$2.79 \cdot 10^{-2}$	μΩm	rectangular	$3.23 \cdot 10^{-3}$
Non-linearity nV-meter δr_{lin}	0		$5.77 \cdot 10^{-5}$		$2.79 \cdot 10^{-2}$	μΩm	rectangular	$1.61 \cdot 10^{-3}$
Temperature effect sample δr_T	$-1.85 \cdot 10^{-4}$		$8.00 \cdot 10^{-5}$		$2.79 \cdot 10^{-2}$	μΩm	normal	$2.23 \cdot 10^{-3}$
Resistivity ρ:	27.926	nΩm			Total uncertainty:			$5.60 \cdot 10^{-3}$
					Total expanded uncertainty (k=2):			$1.12 \cdot 10^{-2}$

Final result: conductivity σ = (35.809 ± 0.014) MS/m

PTB

sample uncertainty budget for Van der Pauw measurement for copper-germanium

	value	u	C_i	$C_i \cdot u$	$(C_i \cdot u)^2$	ν	u^4/ν
d	9,95840 mm	$9 \cdot 10^{-5}$	1	$9 \cdot 10^{-5}$	$8{,}10 \cdot 10^{-09}$	4	$1{,}64 \cdot 10^{-17}$
U_1	5,3716 µV	$1{,}1 \cdot 10^{-4}$	1	$1{,}1 \cdot 10^{-4}$	$1{,}21 \cdot 10^{-08}$	3	$4{,}88 \cdot 10^{-17}$
U_2	5,3872 µV	$1{,}3 \cdot 10^{-4}$	1	$1{,}3 \cdot 10^{-4}$	$1{,}69 \cdot 10^{-08}$	3	$9{,}52 \cdot 10^{-17}$
U_3	5,3703 µV	$9{,}4 \cdot 10^{-5}$	1	$9{,}4 \cdot 10^{-5}$	$8{,}84 \cdot 10^{-09}$	3	$2{,}60 \cdot 10^{-17}$
U_4	5,3861 µV	$7{,}5 \cdot 10^{-5}$	1	$7{,}5 \cdot 10^{-5}$	$5{,}62 \cdot 10^{-09}$	3	$1{,}05 \cdot 10^{-17}$
I	9,9975 A	$1{,}5 \cdot 10^{-5}$	1	$1{,}5 \cdot 10^{-5}$	$2{,}25 \cdot 10^{-10}$	∞	0
k_{NVM} (1)	0,99985	$4{,}3 \cdot 10^{-4}$	1	$4{,}3 \cdot 10^{-4}$	$1{,}85 \cdot 10^{-07}$	∞	0
k_{NVM} (2)	1	$2 \cdot 10^{-5}$	1	$2 \cdot 10^{-5}$	$4{,}00 \cdot 10^{-10}$	∞	0
k_{edge}	1	0	1	0	0	∞	0
$k_{T\text{-}oil}$	1	$5{,}2 \cdot 10^{-5}$	1	$5{,}2 \cdot 10^{-5}$	$2{,}70 \cdot 10^{-09}$	∞	0
k_r	1	0	1	0	0	∞	0
k_{flat}	1	$3{,}2 \cdot 10^{-9}$	1	$3{,}2 \cdot 10^{-9}$	$1{,}02 \cdot 10^{-17}$	∞	0
		$4{,}90 \cdot 10^{-04}$			$2{,}40 \cdot 10^{-07}$	$\nu_{eff} = 291$	$1{,}97 \cdot 10^{-16}$
	$k = 2$	$9{,}79 \cdot 10^{-04}$					

result: (41,187 ± 0,040) MS/m

sample uncertainty budget for bar shaped sample measurement for copper-germanium

	value	u	C_i	$C_i \cdot u$	$(C_i \cdot u)^2$	ν	u^4/ν
d	10,0614 mm	$7{,}9 \cdot 10^{-5}$	1	$7{,}9 \cdot 10^{-5}$	$6{,}24 \cdot 10^{-09}$	14	$2{,}78 \cdot 10^{-18}$
U_1	30,1780 µV	$1{,}2 \cdot 10^{-5}$	1	$1{,}2 \cdot 10^{-5}$	$1{,}44 \cdot 10^{-10}$	10	$2{,}07 \cdot 10^{-21}$
U_2*	60,0471 µV	$2{,}6 \cdot 10^{-5}$	1	0	0	10	0
U_3	90,2079 µV	$7 \cdot 10^{-6}$	1	$7 \cdot 10^{-6}$	$4{,}90 \cdot 10^{-11}$	10	$2{,}40 \cdot 10^{-22}$
l_1	100,200 mm	$1{,}7 \cdot 10^{-5}$	1	$1{,}7 \cdot 10^{-5}$	$2{,}89 \cdot 10^{-10}$	∞	0
l_2	200,054 mm	$1{,}7 \cdot 10^{-5}$	1	$1{,}7 \cdot 10^{-5}$	$2{,}89 \cdot 10^{-10}$	∞	0
l_3	299,129 mm	$1{,}7 \cdot 10^{-5}$	1	$1{,}7 \cdot 10^{-5}$	$2{,}89 \cdot 10^{-10}$	∞	0
B	80,0497 mm	$6 \cdot 10^{-5}$	1	$6 \cdot 10^{-5}$	$3{,}60 \cdot 10^{-09}$	4	$3{,}24 \cdot 10^{-18}$
I	9,9975 A	$1{,}5 \cdot 10^{-5}$	1	$1{,}5 \cdot 10^{-5}$	$2{,}25 \cdot 10^{-10}$	∞	0
k_{NVM} (1)	0,99985	$7{,}6 \cdot 10^{-5}$	1	$7{,}6 \cdot 10^{-5}$	$5{,}86 \cdot 10^{-09}$	∞	0
k_{NVM} (2)	1	$5 \cdot 10^{-5}$	1	$5 \cdot 10^{-5}$	$2{,}5 \cdot 10^{-09}$	∞	0
$k_{T\text{-}oil}$	1	$5{,}2 \cdot 10^{-5}$	1	$5{,}2 \cdot 10^{-5}$	$2{,}70 \cdot 10^{-09}$	∞	0
k_{tilt}	1	$1{,}4 \cdot 10^{-4}$	1	$1{,}4 \cdot 10^{-4}$	$1{,}96 \cdot 10^{-08}$	∞	0
		$2{,}03 \cdot 10^{-04}$			$4{,}12 \cdot 10^{-08}$	$\nu_{eff} = 281$	$6{,}02 \cdot 10^{-18}$
	$k = 2$	$4{,}06 \cdot 10^{-04}$					

* excluded from evaluation due to poor insulation of one knife edge

result: (41,194 ± 0,017) MS/m

Appendix 2: Comparison Protocol.

7. Travelling standards

7.1 Description: Four bar test specimens and four block test specimens have been produced as travelling standards. They have been carefully machined to avoid work hardening and they have been finished by diamond turning to provide a good finish and the minimum variation in dimensions.

The test specimen details are given in the following table:

Specimen Material	Bar size (mm)	Block size (mm)	Bar and block thickness (mm)	Approximate conductivity at 20 °C (MS/m)
Aluminium	600 x 80	80 x 80	10	36
Aluminium Alloy	600 x 80	80 x 80	10	22
Nordic gold (optional)	300 x 40	80 x 80	10	9
Titanium	600 x 80	80 x 80	10	2

7.2 Quantities to be measured: Participants should determine the conductivity of the bars/blocks by either a DC or AC technique (or both, if available). Dimensions of the bars/blocks will be provided. At NPL the bars have been measured by both AC and DC methods. The AC measurements were made at frequencies of 10, 30, 60 and 90 kHz. Only AC values measured at 60 kHz are used in this comparison.

8. Organisation

8.1 Co-ordinator: National Physical Laboratory
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8.2 Participants: One month has been allowed for each participant and includes transportation time to the next participant.

Laboratory	Period of measurements
NPL (Co-ordinator)	October 2002 – March 2003
PTB	October 2002 – March 2003

VSL	October 2002 – March 2003
NPL (Co-ordinator)	October 2002 – March 2003
UME*	October 2003
Boeing+	November 2003
NPL (Co-ordinator)	December 2003

* - Withdraw from comparison with agreement of NPL, PTB and VSL.
+ - Uncertainties were not received.

See Appendix 2 for participant details.

9. Measurements instructions

9.1 Methods of measurement: The measurand is the electrical conductivity. It should be measured at 20 degrees Celsius. Any deviation from this temperature must be reported and the conductivity corrected to 20 degrees Celsius using temperature coefficients which will be circulated with the standards.

Each participant should use their own DC or AC method. For an AC method, the frequency must be reported.

10. Measurement uncertainty

10.1 Main Uncertainty contributions: Each participant should evaluate all the contributions for their particular measurement technique.

10.2 Reported uncertainty budgets: The uncertainties in the measurement should be calculated in accordance with the ISO Guide to the Expression of Uncertainties in Measurement, stating the k-factor (at 95% confidence level) and the number of degrees of freedom. An uncertainty budget must be included in the report.

11. Measurement report

11.1 Time constraints: The report should be sent to the pilot laboratory within 6 weeks of completing measurements (BIPM Guidelines).

11.2 Content of the report: In addition to the results and associated uncertainty for each result, the report should contain a brief description of the measurement technique and all relevant defining conditions such as temperature, frequency, date of measurement etc.

A statement should be included describing traceability to the SI. If traceability is taken from another NMI then this should be clear in the report and the uncertainty budget.

12. Participants

Laboratory and address	Contact name, e-mail and fax
PTB Bundesallee 100 D-38116 Braunschweig Germany	Peter Warnecke* peter.warnecke@ptb.de +49 531 592 2105
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UME Tübitak, UME PO Box 21 Gebze, Kocaeli 41470 Turkey	Levent Sözen* Levent.sozen@ume.tubitak.gov.tr +90 (262) 646 59 14
The Boeing Company PO Box 3707 MC 2T-40 Seattle WA 98124-2207 United States	Joseph Rook Joseph.c.rook@boeing.com +1 206 544 5907

* Indicates members of support group