EUROMET Comparison

of a 10 mH Inductance Standard at 1 kHz

EUROMET.EM-K3

Final Report

by
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Summary

This report describes the organization, the equipment and the results of a EUROMET comparison of a 10 mH inductance standard at a frequency of 1 kHz which took place in 2006. The participants were PTB (Germany), INM (Romania) and NCM (Bulgaria). Comment: NCM is now BIM, Bulgarian Institute of Metrology

The participation of PTB made it possible to have a link to the key comparison CCEM-K3.

Although the methods of measurement differed in all participating laboratories, an agreement within the respective limits of uncertainty could be achieved by all participants. The results of each participant are referred to the Key Comparison Reference Value (KCRV), stated in the CCEM-K3 final report.

Contents

Introduction

The comparison was organized within the framework of Phare 2002 Project BG0201.12 “Strengthening of the National Conformity Assessment System – Technical Assistance for Standardization and Metrology”, EUROPE Aid/116486/D/SV/BG.
The comparison was linked to the corresponding CCEM comparison CCEM-K3 [1].
Three national metrology institutes took part in this comparison: PTB (Germany), NCM (Bulgaria) and INM (Romania).
PTB acted as the pilot laboratory and in this function was responsible for providing the travelling standard, the evaluation of the measurement results and the final report. NCM was responsible for the protocol.
The comparison was accomplished in accordance with the EUROMET Guidelines on Conducting Comparisons and CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons.

1. Participants and organization

1.1 Participants

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1.3 Time schedule

Starting date:	April 2006
First measurements at PTB:	From 16 to 20 February 2006
Measurements at INM:	From 12 June to 7 July 2006
Measurements at NCM:	From 24 July to 4 August 2006
Final measurements at PTB:	September 2006

1.4 Transportation

The travelling standard was taken as carry-on luggage by aeroplane from Germany to Romania. An NCM car was used for transportation from Romania to Bulgaria. Transportation of the standard back to Germany by car was organized by NCM. The standard was accompanied by an ATA – carnet in order to solve custom formalities.

2. Travelling standard

The travelling standard was an inductance standard with a nominal value of 10 mH. It is a General Radio 1482-H 10 mH inductance standard encased by a temperature-regulated enclosure.
The thermostated device together with a power supply unit guarantees a constant operating temperature during the transportation . A set of batteries (2 pieces, 6 V lead storage battery) or the car's supply system of 12 volt (in the case of transportation by car) was used.

2.1 Description of the standard

Table 1: Description of the standard

Type	GR 1482-H Inductance Standard
Manufacturer	General Radio, enclosure ASMW
Serial number	№01
Nominal value of inductance	10 mH ± 0.1%
Relative instability of inductance	< 1 μH/H per year
Nominal thermostatic temperature	30.0 °C± 0.2 K
Instability of thermostatic temperature with an instability of the ambient air temperature of 0.5 K	± 0.01 K per year
Dependence of the value of inductance on the ambient air temperature in the range from 18 °C to 28 °C	≤ 0.3 ppm per K
Measuring frequency	1 000 Hz
Measuring voltage	≤ 0.5 V
Effective resistance (DC) of the coil at an ambient air temperature of 23.0 °C ± 0.1 K	8.671 Ω
Width of the HIGH and LOW connecting terminals	19 mm
Connection system	Two terminals (case is internally connected with LOW terminal)
Power supply of thermostat: • power supply unit (230 V ± 10%; 50 Hz); • set of batteries (2 x 6 V); • 12 V supply system of a car	0.5 A at 12 V (DC)
Power cable	Red plug to be connected to plus, blue plug to be connected to minus
Dimensions of leather bag	470 mm x 300 mm x 400 mm
Total mass	Approx. 38 kg

2.2 Quantities to be measured

The quantities to be measured were:

- ***L:*** inductance of the standard (two terminals);
- ***R:*** DC resistance of the inductor coil;
- ***f:*** measurement frequency;
- T_{ext}**:** the temperature (°C) of the environment where the standard is measured.

2.3 Measurement instructions

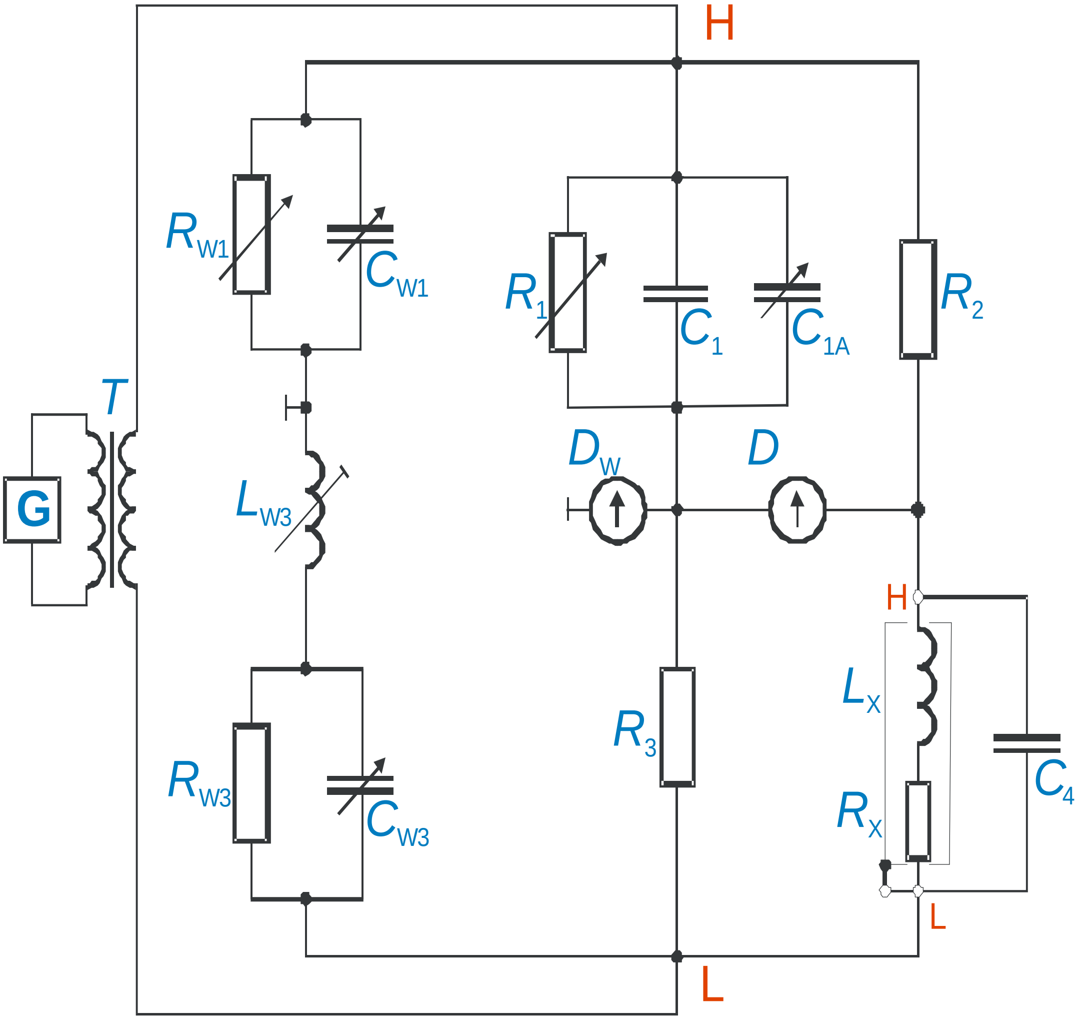
The measurements should be performed under the following conditions:

- Measurement frequency: 1000 Hz;
- Measuring voltage: <0.5 V (rms);
- Temperature of the environment: 23°C ± 1°C;
- Relative humidity: between 30 % and 70 %.

3. Description of measuring methods

3.1 Measuring method at PTB

Inductance measurements at PTB are carried out with a Maxwell-Wien Bridge. This bridge has the advantage, that to a first order the bridge equation (1) is independent of frequency. But measurements at a frequency of 1 kHz require an investigation of higher order effects, i.e., lumped impedances must be taken into account.



The main arms of the bridge contain, besides the DUT, represented by the element L_X and R_X, the fixed capacitor C_1, the variable capacitor C_{1A}, the two fixed resistors R_2 and R_3 and the variable resistor R_1.
The main bridge balance (equ. (3)) is achieved with components C_{1A} and R_1.
The bridge is adapted to the value of inductor L_X by exchanging C_1, R_2 and R_3.

$$L_X \approx C_1 \cdot R_2 \cdot R_3 \tag{1}$$

The impedance of the resistors can be characterized by

$$Z_n \approx R_n(f) \cdot (1 + j\omega\tau_n) \tag{2}$$

With the impedances Z_2 and Z_3 the bridge equation leads to

$$R_X + j\omega L_X = \frac{Z_2 Z_3 (1 + j\omega(C_1 + C_{1A}) Z_1)}{Z_1 - j\omega C_4 Z_2 Z_3 (1 + j\omega(C_1 + C_{1A}) Z_1)} \tag{3}$$

The capacitance C_4 characterizes only the stray capacitance at the bridge terminals. The inherent parallel capacitance of the inductor is not included in C_4.

To eliminate the main effects of the time constants τ_n, a zero-substitution method is employed: Inductor L_X is replaced by a relatively small inductor L_{X0}, and C_1 is removed. The value C_{1A0} for C_{1A} is obtained to balance the bridge. The Value C_{40} can be different to C_4 because of different connection to the main measurement.

This procedure results in the model equation that approximates L_X within the uncertainties of the calibration.

$$\begin{aligned} L_X = {} & (C_1 + C_{1A}) R_2 R_3 - C_{1A0} R_2 R_3 + L_{X0} \\ & - \omega^2 R_2 R_3 C_1 \tau_2 \tau_3 \\ & - \omega^2 R_2^2 R_3^2 (C_4 (C_1 + C_{1A})^2 - C_{40} C_{1A0}^2) \\ & + (C_4 - C_{40}) \frac{R_2^2 R_3^2}{R_1^2} \end{aligned} \tag{4}$$

A potential problem in Maxwell-Wien Bridge circuits is that of stray capacitance between either connecting point of the null detector and ground potential. The best solution for solving this problem is to insert a Wagner earth. This voltage divider is designed to have the same voltage ratio and phase shift as each side of the bridge. These circuit elements have the index “W”. Because the midpoint of the Wagner divider is directly grounded, the Wagner balance forces the null detector to be at virtual ground potential, without a direct connection between the detector and the ground.

3.2 Reference standard and the traceability to the SI at PTB

The reference standards are represented by the components C_1, R_2 and R_3. The capacitor C_1 is traceable to the Thompson-Lampard Capacitor of PTB. The two resistors are traceable to the quantized Hall resistance via calculable AC/DC transfer resistors of PTB.

3.3 Measuring method at INM

The equivalent series inductance of the standard inductor is measured in two-terminal connection by substitution against the equivalent series inductance of one 10 mH reference standard using a digital LCR-meter, type HP 4284 A.

The DC resistance of the inductor coil is measured directly in four-terminal connection using a digital multimeter, type Keithley 2001.

This procedure results in the model equation that approximates L_X within the uncertainties of the calibration.

$$L_X = \left(L_S + \Delta L_{\text{Scurrent}} + \delta L_{\text{Sdrift}} + \delta L_{\text{ST}}\right) \cdot K \cdot K_C - \delta L_{\text{XT}} \quad ^{1} \tag{5}$$

3.4 Reference standard and the traceability to the SI at INM

The 10 mH reference standard (serial number 8602) used is an inductor built in INM in 1986.
This inductor is included in the group of transfer standards used to provide traceability on a regular basis. The last external calibration of this standard was performed in December 2005 in INRIM, Italy.

3.5 Measuring method at NCM

A 1:1 substitution method with inductance bridge model GR 1632 A is used. The travelling and reference standards (L and L_S) are measured in turn in two-wire connection using five decades of the bridge. The last digit of the measured values (missing in the uncertainty budget table) is estimated by de-balancing the bridge with a step of the last decade in plus and in minus. The measurements are made at 1000 Hz.

This procedure results in the model equation that approximates L_X within the uncertainties of the calibration.

$$L = (L_S + \delta L_D + \delta L_{TS}) \cdot l_K \cdot \bar{l} - \delta L_T \quad * \tag{6}$$

All conditions mentioned in section 4 “Measuring instructions” from the Technical Protocol are observed.

3.6 Reference standard and the traceability to the SI at NCM

The reference standard (L_S) model GR 1482 H, Ser. № 17982, is part of the national group standard. The value of the national standard is traceable to PTB. The last calibration was in 2003.

4. Measurement results

4.1 Results of the participants and degree of equivalence with respect to CRV

Table 2 reports the measured inductance and uncertainty given by NCM, INM and PTB, along with the degrees of equivalence D_i and their expanded uncertainty U_{Di} for the participants NCM and INM.
The drift of the travelling standard was neglected, because the change between the first and second measurement in PTB was very small, especially compared with the uncertainties claimed by NCM and INM. In the following calculations, the mean value of the first and second PTB result, PTB_{mean}, was taken into account. For the associated expanded uncertainty, the two PTB results were looked at, as if they were the results of two different measurements with a correlation coefficient of 1.
The degree of equivalence D_i is given with respect to the PTB_{mean} value, which is taken as the comparison reference value (CRV):

$$D_i = L_i - L_{\text{PTB}_{\text{mean}}} \tag{7}$$

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[1] See a description of the single components in Appendix A

with the expanded uncertainty :

$$U_{\mathrm{D_i}} = \sqrt{U_{\mathrm{i}}^{\;2} + U_{\mathrm{PTB}}^{2}} \tag{8}$$

Table 2: Results of the participants

participants	measured inductance, L_X	expanded uncertainty, $U(L_\mathrm{X})$	degree of equivalence, D	expanded uncertainty, U_D
	mH	mH	µH/H	mH
PTB$_\mathrm{1st}$	10.00456	$6.4 \cdot 10^{-5}$		-
NCM	10.0044	$40 \cdot 10^{-5}$	-12.5	$40 \cdot 10^{-5}$
INM	10.0043	$60 \cdot 10^{-5}$	-22.5	$60 \cdot 10^{-5}$
PTB$_\mathrm{2nd}$	10.00449	$5.1 \cdot 10^{-5}$		-
PTB$_\mathrm{mean}$	**10.004525**	**$5.7 \cdot 10^{-5}$**		

4.2 Link to the CCEM-K3 and degree of equivalence with respect to KCRV

The link for NCM and INM results to the key comparison reference value of CCEM-K3 is made via the PTB measurements, as PTB or PTB (ASMW) respectively participated in both comparisons. The applied travelling standard was one of the two standards that are used in the CCEM-K3 comparison. In the meantime this standard was always kept under thermostated condition. PTB has a history of the measurement values of this standard from the first measurements at ASMW up to now. The actual measuring system of PTB achieves lower uncertainties (see table 2) then the systems of ASMW and PTB that are used during the CCEM comparison. Measurements based on the mentioned standard history shows that this PTB system has an exact accordance with the old ASMW measuring system. To compare the results of NCM/INM with results of the participants in the key comparison CCEM-K3, the Key Comparison Reference Value (KCRV), stated in the CCEM-K3 final report was referred to. The degree of equivalence $D_\mathrm{K3,NCM/INM}$ and expanded uncertainty $U_\mathrm{K3,NCM/INM}$ of NCM/INM with respect to KCRV is calculated as follows:

$$D_\mathrm{K3,NCM/INM} = D_\mathrm{NCM/INM} + D_\mathrm{K3,PTB} \tag{9}$$

$$U_\mathrm{K3,NCM/INM} = \sqrt{U^2_{\mathrm{D_{NCM/INM}}} + U^2_{\mathrm{D_{K3/PTB}}}} \tag{10}$$

where $D_\mathrm{K3,PTB}$ and $U_\mathrm{K3,PTB}$ are the degree of equivalence and its expanded uncertainty of PTB (ASMW) with respect to KCRV. The degree of equivalence and expanded uncertainty of NCM/INM with respect to KCRV are given in Table 3.

Table 3: Degree of equivalence and expanded uncertainty of NCM/INM with respect to KCRV

participants	degree of equivalence, $D_\mathrm{K3,NCM/INM}$ in µH/H	expanded uncertainty, $U_\mathrm{K3,NCM/INM}$ in µH/H	degree of equivalence, $D_\mathrm{K3,PTB}$ in µH/H	expanded uncertainty, $U_\mathrm{K3,PTB}$ in µH/H
NCM	-16	41	-3	8
INM	-26	61	-3	8

4.3 Correlation

The result of INM is correlated to the KCRV (section 5.1), because the reference standard of INM was calibrated at INRIM, Italy (IEN at the time of CCEM-K3).
The result of NCM is correlated to the CRV and the KCRV, because the reference standard of NCM was calibrated at PTB.
The uncertainties of the INM and NCM reference values are the largest contributions to the uncertainty budgets. They are traced back via the INRIM and PTB standards to the SI. The reason for the large uncertainties is that these standards are not thermostated, so that the temperature coefficient of the standards which is not correlated with the INRIM or PTB measurements had the biggest influence on the uncertainties. Therefore, the effect of correlation was neglected.

5. Measurement uncertainty

A detailed uncertainty analysis and an uncertainty budget in accordance with the ISO Guide to the Expression of Uncertainty in Measurement is given in Appendix A.

6. Conclusion

The comparison EUROMET.EM-K3 was organized with the main objective of showing the international equivalence of the as-maintained units of inductance at NCM and INM. To calculate the degree of equivalence of the results of NCM and INM they were linked to CCEM-K3. The results obtained show very good agreement with the reference value within the expanded uncertainties.

7. Reference

[1] H. Eckhard, “Final Report of CCEM-K3: International Comparison of 10 mH Inductance Standards at 1 kHz”, published online in the *Key Comparison Data Base:* http://kcdb.bipm.fr

Appendix A Summary of uncertainty budgets

Acronym of institute: PTB

Date: September 2006

Remarks: Because of the two measurement periods we have to give two different groups of results.

Model equation

$$
\begin{aligned}
L_{\mathrm{X,A/B}} = {} & (C_{\mathrm{1H}} - C_{\mathrm{1A0}}) R_2 R_3 + L_{\mathrm{X0}} + TypB_{\mathrm{T}} \\
& - \omega^2 R_2 R_3 C_1 (k_2 + k_3 - \tau_2 \tau_3) \\
& - \omega^2 R_2^2 R_3^2 (C_{\mathrm{4H}} C_{\mathrm{1H}}{}^2 - C_{40} C_{\mathrm{1A0}}^2) \\
& + (C_{\mathrm{4H}} - C_{40}) \frac{R_2^2 R_3^2}{R_1^2}
\end{aligned}
$$

$$
\begin{aligned}
C_{\mathrm{1H}} &= C_1 + C_{\mathrm{1A}} \\
\omega &= 2\pi f \\
C_{\mathrm{1A}} &= c_{\mathrm{1A}} (1 + TypB_{\mathrm{C}}) \\
C_{\mathrm{1A0}} &= c_{\mathrm{1A0}} (1 + TypB_{\mathrm{C}}) \\
R_1 &= r_1 (1 + TypB_{\mathrm{R1}}) \\
L_{\mathrm{X0}} &= l_{\mathrm{X0}} (1 + TypB_{\mathrm{L}})
\end{aligned}
$$

Definition of quantities

quantity	**unit**	**definition**
$L_{\mathrm{XA/B}}$	H	inductance of travelling standard
C_1	F	capacitance of capacitor C_1
C_{1A}	F	capacitance of capacitor C_{1A}
c_{1A}	F	observations of capacitor C_{1A}
C_{1A0}	F	entire capacitance of zero-substitution
c_{1A0}	F	observations of capacitor C_{1A0}
C_{1H}	F	entire capacitance of main measurement
C_{40}	F	capacitance of bridge terminals in the zero-substitution
C_{4H}	F	capacitance of bridge terminals in the main measurement
f	Hz	frequency of measurement
k_2	s^2	frequency coefficient of resistor R_2
k_3	s^2	frequency coefficient of resistor R_3
L_{x0}	H	inductance of small air coil L_{X0}
l_{xO}	H	observations of small air coil L_{X0}
R_1	Ω	value of decade resistor R_1
r_1	Ω	observations of decade resistor R_1
R_2	Ω	value of resistor R_2
R_3	Ω	value of resistor R_3

quantity	**unit**	**definition**
$TypB_C$[2]		takes into account the uncertainty of the capacitance meter
$TypB_L$[1]		takes into account the uncertainty of the inductance meter
$TypB_{R1}$[1]		takes into account the uncertainty of the decade resistor R_1
$TypB_T$[1]	H	takes into account the uncertainty of the temperature stability of the travelling standard
ω	s^{-1}	radian frequency of measurement
π		time constant of resistor R_2
τ_2	s	time constant of resistor R_3
τ_3	s	frequency coefficient of resistor R_3

Uncertainty budget of the **first** measurement period

quantity	**value**	**standard uncertainty**	**degrees of freedom**	**sensitivity coefficient**	**uncertainty contribution**	**index**
C_1	$1.000023240\cdot10^{-9}$ F	$276\cdot10^{-18}$ F	26	$10\cdot10^{6}$	$2.8\cdot10^{-9}$ H	0.8 %
C_{1A}	$1.19118\cdot10^{-12}$ F	$1.73\cdot10^{-15}$ F	4			
c_{1A}	$1.19118\cdot10^{-12}$ F	$1.73\cdot10^{-15}$ F	4	$10\cdot10^{6}$	$17\cdot10^{-9}$ H	8.9 %
C_{1A0}	$1.12176\cdot10^{-12}$ F	$2.06\cdot10^{-15}$ F	4			
c_{1A0}	$1.12176\cdot10^{-12}$ F	$2.06\cdot10^{-15}$ F	4	$-10\cdot10^{6}$	$-21\cdot10^{-9}$ H	22.2 %
C_{1H}	$1.00121442\cdot10^{-9}$ F	$1.75\cdot10^{-15}$ F	4			
C_{40}	$100\cdot10^{-15}$ F	$577\cdot10^{-15}$ F	∞	-76	$-44\cdot10^{-12}$ H	0.0 %
C_{4H}	$200\cdot10^{-15}$ F	$577\cdot10^{-15}$ F	∞	-3900	$-2.2\cdot10^{-9}$ H	0.5 %
f	1000.500 Hz	0.289 Hz	∞	$-1.4\cdot10^{-12}$	$-410\cdot10^{-15}$ H	0.0 %
k_2	$100.0\cdot10^{-18}$ s^2	$57.7\cdot10^{-18}$ s^2	∞	$400\cdot10^{3}$	$23\cdot10^{-12}$ H	0.0 %
k_3	$100.0\cdot10^{-18}$ s^2	$57.7\cdot10^{-18}$ s^2	∞	$400\cdot10^{3}$	$23\cdot10^{-12}$ H	0.0 %
L_{X0}	$4.07000\cdot10^{-6}$ H	$5.87\cdot10^{-9}$ H	∞			
l_{X0}	$4.07\cdot10^{-6}$ H	$2.07\cdot10^{-24}$ H	4	0.0	0.0 H	0.0 %
R_1	$1.148560\cdot10^{6}$ Ω	664 Ω	∞			
r_1	$1.1485600\cdot10^{6}$ Ω	24.5 Ω	4	$-13\cdot10^{-18}$	$-320\cdot10^{-18}$ H	0.0 %
R_2	999.94214 Ω	$1.42\cdot10^{-3}$ Ω	5200	$10\cdot10^{-6}$	$14\cdot10^{-9}$ H	35.8 %
R_3	10000.14037 Ω	$9.82\cdot10^{-3}$ Ω	1200	$1.0\cdot10^{-6}$	$9.8\cdot10^{-9}$ H	24.7 %
$TypB_C$	0.0	$57.7\cdot10^{-6}$	∞	$690\cdot10^{-9}$	$40\cdot10^{-12}$ H	0.0 %
$TypB_L$	0.0	$1.44\cdot10^{-3}$	∞	$4.1\cdot10^{-6}$	$5.9\cdot10^{-9}$ H	3.6 %
$TypB_R$	0.0	$577\cdot10^{-6}$	∞	$-15\cdot10^{-12}$	$-8.8\cdot10^{-15}$ H	0.0 %
$TypB_T$	0.0 H	$5.77\cdot10^{-9}$ H	∞	1.0	$5.8\cdot10^{-9}$ H	3.5 %
ω	6286.33 s^{-1}	1.81 s^{-1}	∞			
π	3.1415926535898					
τ_2	$800\cdot10^{-12}$ s	$2.02\cdot10^{-9}$ s	∞	$-320\cdot10^{-6}$	$-640\cdot10^{-15}$ H	0.0 %
τ_3	$800\cdot10^{-12}$ s	$2.02\cdot10^{-9}$ s	∞	$-320\cdot10^{-6}$	$-640\cdot10^{-15}$ H	0.0 %
L_A	0.0100045577 H	$30.9\cdot10^{-9}$ H	49			

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[2] The quantity (value = 0) does not make a contribution to the value of L_S but rather to the uncertainty.

Uncertainty budget of the **second** measurement period

quantity	**value**	**standard uncertainty**	**degrees of freedom**	**sensitivity coefficient**	**uncertainty contribution**	**index**
C_1	$1.000023240\cdot10^{-9}$ F	$276\cdot10^{-18}$ F	26	$10\cdot10^{6}$	$2.8\cdot10^{-9}$ H	1.2 %
C_{1A}	$1.20880\cdot10^{-12}$ F	$1.19\cdot10^{-15}$ F	2			
c_{1A}	$1.20880\cdot10^{-12}$ F	$1.18\cdot10^{-15}$ F	2	$10\cdot10^{6}$	$17\cdot10^{-9}$ H	-4.5 %
C_{1A0}	$1.15363\cdot10^{-12}$ F	$1.32\cdot10^{-15}$ F	2			
c_{1A0}	$1.15363\cdot10^{-12}$ F	$1.32\cdot10^{-15}$ F	2	$-10\cdot10^{6}$	$-13\cdot10^{-9}$ H	4.9 %
C_{1H}	$1.00123204\cdot10^{-9}$ F	$1.22\cdot10^{-15}$ F	2			
C_{40}	$100\cdot10^{-15}$ F	$577\cdot10^{-15}$ F	∞	-76	$-44\cdot10^{-12}$ H	0.0 %
C_{4H}	$200\cdot10^{-15}$ F	$577\cdot10^{-15}$ F	∞	-3900	$-2.2\cdot10^{-9}$ H	0.8 %
f	1000.500 Hz	0.289 Hz	∞	$-1.4\cdot10^{-12}$	$-410\cdot10^{-15}$ H	0.0 %
k_2	$100.0\cdot10^{-18}$ s^2	$57.7\cdot10^{-18}$ s^2	∞	$400\cdot10^{3}$	$23\cdot10^{-12}$ H	0.0 %
k_3	$100.0\cdot10^{-18}$ s^2	$57.7\cdot10^{-18}$ s^2	∞	$400\cdot10^{3}$	$23\cdot10^{-12}$ H	0.0 %
L_{X0}	$4.05500\cdot10^{-6}$ H	$6.53\cdot10^{-9}$ H	52			
l_{X0}	$4.05500\cdot10^{-6}$ H	$2.89\cdot10^{-9}$ H	2	1.0	$2.9\cdot10^{-9}$ H	0.9 %
R_1	$1.149537\cdot10^{6}$ Ω	664 Ω	∞			
r_1	$1.1495367\cdot10^{6}$ Ω	19.2 Ω	2	$-13\cdot10^{-18}$	$-250\cdot10^{-18}$ H	0.0 %
R_2	999.94562 Ω	$1.41\cdot10^{-3}$ Ω	5200	$10\cdot10^{-6}$	$14\cdot10^{-9}$ H	51.0 %
R_3	10000.19615 Ω	$9.82\cdot10^{-3}$ Ω	1200	$1.0\cdot10^{-6}$	$9.8\cdot10^{-9}$ H	35.6 %
$TypB_C$	0.0	$57.7\cdot10^{-6}$	∞	$550\cdot10^{-9}$	$32\cdot10^{-12}$ H	0.0 %
$TypB_L$	0.0	$1.44\cdot10^{-3}$	∞	$4.1\cdot10^{-6}$	$5.9\cdot10^{-9}$ H	5.2 %
$TypB_R$	0.0	$577\cdot10^{-6}$	∞	$-15\cdot10^{-12}$	$-8.7\cdot10^{-15}$ H	0.0 %
$TypB_T$	0.0 H	$5.77\cdot10^{-9}$ H	∞	1.0	$5.8\cdot10^{-9}$ H	5.0 %
ω	6286.33 s^{-1}	1.81 s^{-1}	∞			
π	3.1415926535898					
τ_2	$800\cdot10^{-12}$ s	$2.02\cdot10^{-9}$ s	∞	$-320\cdot10^{-6}$	$-640\cdot10^{-15}$ H	0.0 %
τ_3	$800\cdot10^{-12}$ s	$2.02\cdot10^{-9}$ s	∞	$-320\cdot10^{-6}$	$-640\cdot10^{-15}$ H	0.0 %
L_B	0.0100044907 H	$25.7\cdot10^{-9}$ H	2500			

Acronym of institute: INM

Date: July 2006

Remarks:

Model equation

$$L_X = \left(L_S + \Delta L_{Scurrent} + \delta L_{Sdrift} + \delta L_{ST}\right) \cdot K \cdot K_C - \delta L_{XT}$$

Definition of quantities

quantity	unit	definition
L_S	H	certificate value of the reference standard
$\Delta L_{Scurrent}$	H	correction for the different measurement current of the reference standard
δL_{Sdrift}	H	time drift of the reference standard
δL_{ST}	H	correction for the temperature variation of the reference standard
δL_{XT}	H	correction for the temperature variation of the unknown inductance
K_c		correction factor given by systemic effects of the measurement circuit (finite resolution of the LCR-meter, undesired couplings, variation of inductance of the measurement cables, etc.)
K		ratio between the indicated value of the unknown inductance and the indicated value of the reference standard inductor
L_X	H	inductance of travelling standard

Uncertainty budget

quantity X_i	estimate x_i	standard uncertainty $u(x_i)$	probability distribution	degrees of freedom	sensitivity coefficient c_i	uncertainty contribution $u_i(L)$
L_S	10.00204 mH	0.00015 mH	normal	∞	1	0.00015 mH
$\Delta L_{Scurrent}$	-0.00017 mH	0.00001 mH	rectangular	∞	1	0.00001 mH
δL_{Sdrift}	0.00002 mH	0.00015 mH	rectangular	∞	1	0.00015 mH
δL_{ST}	0.00008 mH	0.00001 mH	normal	8	1	0.00001 mH
δL_{XT}	0.00000 mH	0.00000 mH	rectangular	∞	-1	-0.00000 mH
K_c	1.00000	0.00002	triangular	∞	10 mH	0.00016 mH
K	1.000230	0.000001	normal	29	10 mH	0.00001 mH
L_x	10.00427 mH					0.00027 mH

Acronym of institute: NCM

Date: September 2006

Remarks:

Model equation

$$L = (L_S + \delta L_D + \delta L_{TS}) \cdot l_K \cdot \bar{l} - \delta L_T$$

Definition of quantities

quantity	**unit**	**definition**
L_S	H	certificate value of the reference standard
δL_D	H	time drift of the reference standard
δL_{TS}	H	correction for the temperature variation of the reference standard
δL_T	H	correction for the temperature variation of the unknown inductance
l_K		correction factor given by systemic effects of the measurement circuit
$\bar{l}$		ratio between the indicated value of the unknown inductance and the indicated value of the reference standard inductor
L	H	inductance of travelling standard

Uncertainty budget

quantity X_i	estimate x_i	standard uncertainty $u(x_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(L)$
L_S	9.9999 mH	1.50E-04 mH	normal	1.0	1.50E-04 mH
δL_D	-0.0002 mH	1.16E-04 mH	normal	1.0	1.16E-04 mH
δL_{TS}	3.00E-05 mH	1.73E-05 mH	rectangular	1.0	1.73E-05 mH
δL_T	0.0000 mH	3.46E-05 mH	rectangular	-1.0	-3.46E-05 mH
l_K	1.000 000	2.45E-06	triangular	10.0000 mH	2.45E-05 mH
$\bar{l}$	1.00046	5.60E-07	normal	10.0000 mH	5.60E-06 mH
L	10.0044 mH				1.95E-04 mH

Appendix B Technical protocol

The original text of the TECHNICAL PROTOCOL below was edited.

TECHNICAL PROTOCOL

EUROMET project 889

EUROMET.EM-K3

Trilateral comparison of a 10 mH inductance standard

June 2006

1. Introduction

The comparison is organized within the framework of Phare 2002 Project BG0201.12 “Strengthening of the National Conformity Assessment System – Technical Assistance for Standardization and Metrology”, EUROPE Aid/116486/D/SV/BG.
Three national institutes of metrology are taking part in this comparison: PTB (Germany), NCM (Bulgaria) and INM (Romania).
PTB is responsible for providing the travelling standard and the evaluation of the measurement results.
NCM is responsible for the protocol and the final report.
It is planned to complete this comparison in September 2006.

2. Description of travelling standard

2.1. The travelling standard is an inductance standard having the nominal value of 10 mH. It is constructed starting from a General Radio 1482-L 10 mH inductance standard, encased in a thermostated enclosure.

The thermostatic device guarantees a constant operating temperature using a power supply unit. During the transportation a set of batteries (8 pieces, LR 20 type) or the car’s supply system of 12 volt (in the case of transportation by car) can be used.

2.2. Specifications

Nominal value of inductance	10 mH ± 0.1%
Relative instability of inductance	< 1 ppm per year
Nominal thermostatic temperature	30.0 °C± 0.2 K
Instability of thermostatic temperature with an instability of the ambient air temperature of 0.5 K	±0.01 K per year
Dependence of the value of inductance on the ambient air temperature in the range from 18 °C to 28 °C	≤ 0.3 ppm per K
Measuring frequency	1 000 Hz
Measuring voltage at the standard	≤ 0.5 V
Effective resistance (DC) of the coil at an ambient air temperature of 23.0 °C ± 0.1 K	№01 – 8.671 Ω
Width of the HIGH and LOW connecting terminals	19 mm
Connection system	Two terminals (case is internally connected with LOW terminal)
Power supply of thermostat: • power supply unit (230 V ± 10%; 50 Hz); • set of batteries (2 x 6 V); • 12 V supply system of a car	0.5 A at 12 V (DC)
Power cable	Red plug to be connected to plus, blue plug to be connected to minus
Dimensions of leather bag	470 mm x 30 mm x 400 mm
Total mass	Approx. 38 kg

2.3. Accessories
- Power supply unit;
- Set of batteries (2 pieces);
- 1 adapter cable for connection to a 12 V car supplies system

3. Quantities to be measured

- ***L:*** inductance of the standard (two terminals);
- ***R:*** DC resistance of the inductor coil;
- ***f:*** measurement frequency;
- **T_{ext}:** the temperature (°C) of the environment where the standard is measured.

4. Measurement instructions

4.1. Measurements should be performed under the following conditions:

- Measurement frequency: 1000 Hz;
- Measuring voltage: 0.5 V (rms);
- Temperature of the environment: 23°C ± 1°C;
- Relative humidity: between 30 % and 70 %.

4.2. Set-up of the standard:

Under laboratory conditions the standard is supplied by the power supply unit. The red lamp signals readiness for operation. The green lamp indicates that the heater of the thermostat is switched on.
In order to avoid electromagnetic interference during inductance measurement, the power supply unit must be placed as far as 2 meters away from the inductance bridge and may be switched off during the inductance measurements, but for no longer than 5 minutes.
The participating laboratories are asked to follow the Operating Instructions of the travelling standard.

5. Reporting of results

A report should be sent to the pilot laboratory within one month after the measurements are completed. The report should include:

- Description of the measurement method;
- The reference standard;
- The traceability to the SI;
- The results of the quantities to be measured (list of section 3);
- The associated standard uncertainties, the effective degrees of freedom and the expanded uncertainties;

The measurement frequency, the applied voltage and the environment conditions must also be reported.

6. Uncertainty of measurement

The uncertainty must be calculated following the ISO “Guide to the expression of uncertainty in measurement” (GUM), 1995 and the complete uncertainty budget must be reported.

7. Transportation

The travelling standard must be transported in the travel leather bag and protected from mechanical loads, vibration etc. A transport box suitable for transport by plane or car is provided. This box is equipped with tilt and squeeze indicators. It has to be handled carefully and kept the right way up. The travel box contains the following items:

- leather bag,
- inductance standard,
- power supply unit,
- set of two batteries (6 V lead storage battery, Hoppecke) with connection cable and fuse,
- spare fuse,
- 1 adapter cable for connection to a 12 V car supply system,
- mechanical temperature recorder (Metrawatt Thermoscript 838012),
- spare strip charts for the temperature recorder (initially 3 coils),
- operating instructions of the travelling standard (this document),
- operating instructions for the temperature recorder (in German, in case of difficulties consult PTB),

When it is transported by car, the standard must be connected by the adapter cable to the 12 V power system of the car. Carrying the standard by air or rail requires the connection to the set of batteries. The batteries have to be charged with an appropriate power supply (not included in the box). Standard 4 mm banana plugs can be used to connect the batteries.

During transport the temperature recorder has to be switched on. If the operation of this recorder has to be interrupted or if a new strip chart coil is used, the date and time of both the stop and start of operation have to be written on the paper by hand. The total recording time per coil is about 30 days.

The transport box always has to be carried and kept upright. It internally contains internal eyelets which shall be used to fix the leather bag inside the box.

8. Participants

Table 1. List of participants and contact information.

Laboratory address	Contact name, e-mail
Physikalisch-Technische Bundesanstalt (PTB) Electricity Division, FB 2.1 Bundesallee 100 38116 Braunschweig GERMANY	Jürgen Melcher Juergen.Melcher@ptb.de
National Centre of Metrology (NCM) 52-B G. M. Dimitrov Str. 1797 Sofia BULGARIA	Petya Aladzhem ncm@sasm.orbitel.bg
National Institute of Metrology (INM) sos. Vitan Barzesti 11 sector 4, 042122 Bucuresti ROMANIA	Anca Nestor anca.nestor@inm.ro

9. Schedule

Table 2. List of the participants, measurement dates and report dates.

Laboratory	Measurement dates	Report date
PTB - Germany	April 2006	
INM - Romania	12 - 29 May 2006	June 2006
NCM - Bulgaria	2 - 16 June 2006	July 2006
PTB - Germany	July 2006	