VSL	INM	PTB	INRIM
Netherlands	Romania	Germany	Italy

Final Report of EURAMET.EM-S26

Supplementary Comparison

Inductance measurements of 100 mH at 1 kHz

EURAMET project 816

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Revision history

Draft A to Draft A2

A. Kölling (PTB) has been included as author

Section 6. Table 6: Average date of PTB is 19-03-2007
Section 6.4: The link to EUROMET.EM-S20 has been included

Section 7, p. 22, Discussion of the results: Comments from UMTS and DANIAmet-DPLE are included.

Section 9, p. 23: Conclusions have been included

Section 10, p. 23: Acknowledgements have been included

Annex A, p. 28: Dates corrected in the schedule: Table A-1.

Annex B, p. 29, Table B-1 $U(D_{\mathrm{EM\text{-}20}})$ corrected
As a result of this: $U(d) = 0.000\,69$ mH
and Table B-2 and Figure B-1 are also corrected for this change.

Annex F2 and F3 have been included
F4 is included to show the estimated effects of corrective actions on the comparison results

Several editorial changes.

Draft A2 to Draft B

INETI is replaced with IPQ

DANIAmet-DPLE is replaced with DANIAmet-NMI

Annex B, p.29, Equation B-3: $U(D_{\mathrm{EM20,i}})$ under the root sign is replaced with $U(D_{\mathrm{EM26,i}})$

Draft B to Final

No changes.

Table of contents

1. Introduction

After completion of the EUROMET.EM-S20 comparison on inductance measurements of 100 mH at 1 kHz [1], there was a need for a follow-up comparison to allow the remaining laboratories within the EUROMET region to participate in a comparison of this quantity. Therefore, it was decided to start a new comparison of this quantity as EUROMET project no. 816. From July 2007 all references to "EUROMET" have been changed to "EURAMET".

Metrology area, branch: Electricity and Magnetism, Inductance
Description: Inductance measurements of 100 mH at 1 kHz
BIPM KCDB reference: EURAMET.EM-S26
Time of measurements: September 2006 - October 2008
Status: Final report

Measurand: Inductance: 100 mH
Parameter(s): Frequency: 1000 Hz
Transfer device(s): Two 100 mH inductance standards, encased in a thermostatic controlled enclosure, provided by INRIM and PTB

Comparison type: Supplementary comparison
Consultative Committee: CCEM (Consultative Committee for Electricity and Magnetism)
Conducted by: EURAMET (European Metrology Collaboration)
Other designation(s): EURAMET 816 (European Metrology Collaboration Project Number 816)

2. Participants and organisation of the comparison

2.1. Participants

In this comparison there are 16 participants. The acronyms of the laboratories and their countries are given in Table 1. A list of the full participants' details is given in Annex A.

Table 1. Participants in the comparison

Laboratory	Country		Laboratory	Country
SMD	Belgium		IPQ*	Portugal
DANIAmet-NMI*	Denmark		INM	Romania
PTB	Germany		SIQ	Slovenia
MKEH*	Hungary		NMI SA	South Africa
NML	Ireland		METAS	Switzerland
IAI SL	Israel		UME	Turkey
VSL	Netherlands		UMTS*	Ukraine
GUM	Poland		NPL	United Kingdom

*) During the course of this comparison some participants changed their name and/or acronym:
DANIAmet-NMI used to be DANIAmet-DPLE
MKEH used to be OMH
IPQ used to be INETI
UMTS used to be UKRCSM

2.2. Organisation of the comparison

During the course of the comparison, PTB performed several sets of measurements to monitor the behaviour of the travelling standards. All other participants only performed one set of measurements.

After receipt of the standards, each laboratory allowed them to stabilize for 4 days to one week. Then the laboratory had two weeks to perform the measurements. At least 3 days to one week was allowed for transport of the standards to the next participants.
The measurement schedule is given in Annex A.

2.3. Unexpected incidents

The travelling standards have been exposed to a severe shock during transport from NPL, United Kingdom to PTB, Germany. As a result of this, there is a significant step in the value of both inductors. The behaviour of the standards will be shown in section 5 of this report.

One of the travelling standards (sn. 18197 from PTB) was lost during transport from PTB, Germany to NMI SA, South Africa. Unfortunately, the standard has not been retraced.

During the course of the comparison, some small delays have occurred in the original schedule. At the end of the schedule, SIQ, Slovenia has been included as an additional participant. The complete, actual schedule is given in Annex A.

3. Travelling standard and measurement instructions

3.1. Description of the standards

3.1.1 The INRIM inductance standard (sn. 13975)

The travelling standard provided by INRIM (Figure 1) is a modified GR1482-L 100 mH inductance standard. The standard is enclosed in a temperature controlled wooden box.

Figure 1. The travelling standard provided by INRIM

The standard is designed as a 4 terminal pair (4TP) impedance and is therefore equipped with 4 coaxial MUSA BPO connectors (Figure 2 and Figure 3). The connectors are indicated with IH and IL for the *current high* and *current low* respectively, and VH and VL for the *potential high* and *potential low* respectively.

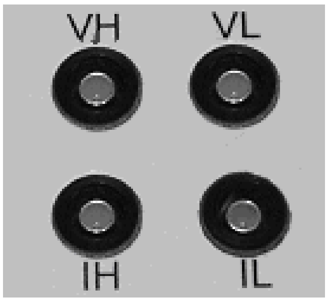

Figure 2. 4TP BPO connectors on the travelling standard.

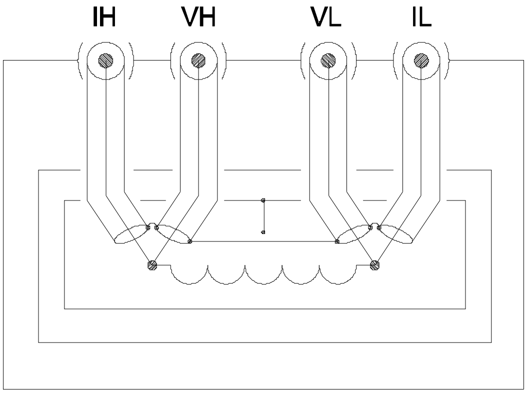

Figure 3. Schematic diagram of the internal 4TP connection of the travelling standard.

There are two banana sockets on the standard indicated with +12V (red) and 0V (black) (Figure 4). This is the 12 V power supply input for the thermostatic enclosure. The internal temperature of the enclosure is measured by PT100 resistance thermometer that can be accessed through the LEMO connector indicated with PT100 (Figure 5).

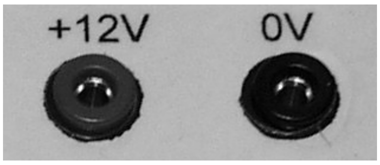

Figure 4. Banana socket for 12 V DC input of thermostatic enclosure.

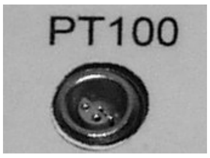

Figure 5. LEMO socket for measurement of the internal temperature: R_{PT100}.

3.1.2 Accessories with the INRIM inductance standard

In the transport case with the INRIM inductance standard, several accessories are provided. All 2-terminal (2T) measurements must be performed using the provided 4/2 adapter (Figure 6 and Figure 7). This adapter should be placed directly on the IH and IL BPO connectors of the standard. During the 2T measurement, the shorting bar (shown in Figure 6) must always be connected between the low, L, and ground, G, banana terminals of the adapter.

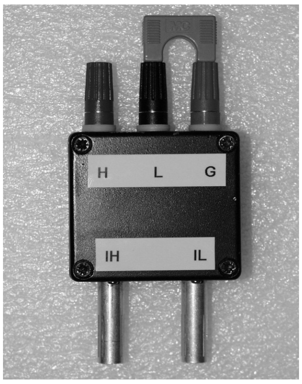

Figure 6. 4/2 adapter with shorting bar

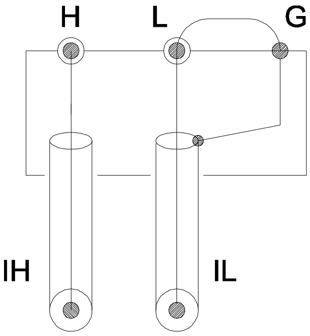

Figure 7. Schematic diagram of the 4/2 adapter

In order to power the thermostatic enclosure, a 12 V dc power supply is provided (Figure 8). It requires 220 V / 240 V ac, 50 Hz line power at the input.

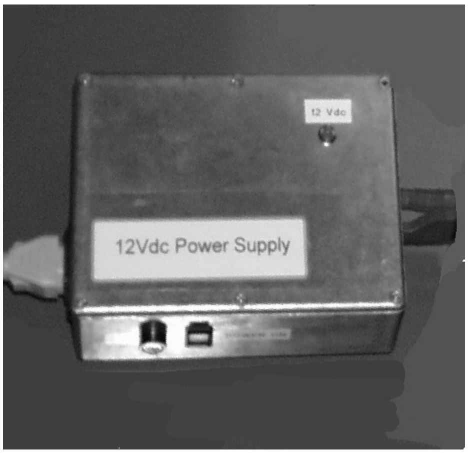

Figure 8. Power supply 12 V dc

Four BPO dust caps are provided to cover the connectors of the inductor when they are not used.

A 4-wire shielded R_{PT100} cable with LEMO-connector is provided to measure the resistance of the internal thermometer. The connections should be made as follows:

Red = high-current terminal, IH;
Black = low-current terminal, IL;
Yellow = high-voltage terminal, VH;
Green = low-voltage terminal, VL.

3.1.3 The PTB inductance standard (sn. 18197)

The thermostatically controlled inductance standard (Figure 9) consists of a commercial inductance standard GR1482-L. It is built in a thermostat with an electronic controller. This construction guarantees a constant operating temperature. The standard has three terminals (high, low and ground) with a removable ground strap to connect the low-terminal with ground (Figure 10).

There are two LEMO connectors.

- The two-terminal one (Figure 11) is the connection of the 24 V dc power supply. The thermostat is supplied by a 24 V DC-uninterruptible power system (UPS). Between the measurements the UPS must be connected to the line.
- The internal temperature of the standard is measured by a 10 kΩ NTC resistor that can be accessed through the four-terminal LEMO connector (Figure 12).

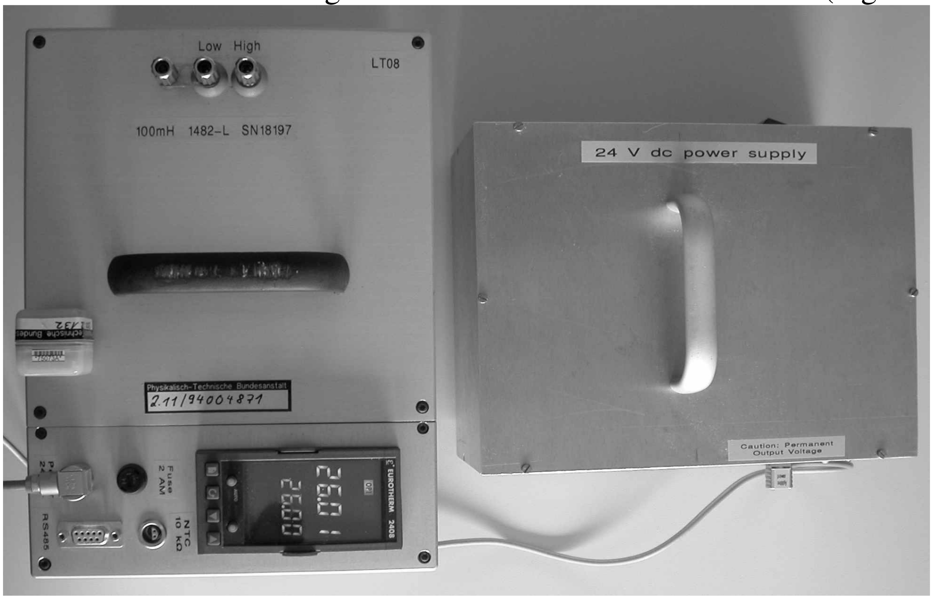

Figure 9. The travelling standard provided by PTB and the UPS

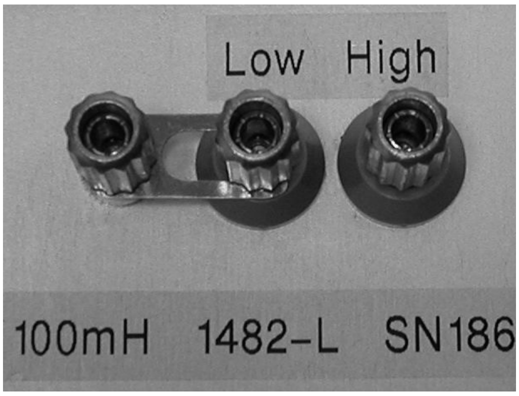

Figure 10. Terminals of the PTB standard: Jack-top binding posts on ¾-in. spacing with removable ground strap

Figure 11. 2-terminal LEMO socket for the 24 V DC power supply of the thermostat.

Figure 12. 4-terminal LEMO socket for measurement of the internal temperature R_{NTC} of the thermostat.

The electronic heating controller works automatically. It has a protection against wrong operation.

3.1.4 Accessories with the PTB inductance standard

The transport case of the PTB standard contains several accessories:

- Two 12V lead-acid batteries (non-disposable) for the transport without external power supply
- Cable set with fuse (2 A) and temperature switch (placed on the standard) to connect the transport batteries with the standard
- 24 V DC-uninterruptible power system (UPS) for measurement,
- cable set for the UPS and a line adapter for different socket-outlets with grounding contact,
- DC/DC converter 12 V / 24 V to supply the standard in a car
- cable set for the DC/DC converter
- 1 data logger to control the ambient temperature and humidity on transport,
- infrared adapter to connect the data logger to the computer,
- CD with software to read out the data loggers,
- 4-wire shielded cable with LEMO-connector to measure the resistance of the internal thermometer (NTC-resistor).
  Red = high-current terminal, IH; Blue = low-current terminal, IL;
  White = high-voltage terminal, VH; Black = low-voltage terminal, VL.

3.2. Quantities to be measured and conditions of measurement

The impedance of the travelling standard between the high and low connector can be modelled as a series connection of an ideal inductor L_s and an ideal resistor R_s. The complex impedance, Z, is given by $Z = R_s + j\omega L_s$, with $\omega = 2\pi f$ and f is the frequency.
The measurand in this comparison is the self-inductance, L_s, expressed in the unit of henry (H). The value of L_s should be determined with a sinusoidal excitation current with an effective value of 1 mA and a frequency, f, of 1 kHz.
The mandatory measurement in this comparison is to determine the value of L_s by means of a two-terminal connection of the travelling standard: the standard is connected between the high and low terminal and the case of the standard is connected to the low terminal.

Besides the self-inductance, the participants have also been requested to measure and report the series resistance, R_s, (Ω) of the travelling standard and several parameters that may affect the inductance value:
- Frequency, f, (Hz)
- Current, I, (rms mA)
- Internal temperature of the standards, indicated by resistive sensors: R_PT100 or R_NTC (Ω)
- Ambient temperature (°C)
- Relative humidity (%)

4. Methods of measurement

Table 2 shows, for each laboratory, which type of measurement set-up is used to perform the measurements and how the traceability for the quantity is realised. A more detailed description of the measurement set-ups of the participants is provided in Annex C.

Table 2. Methods of measurement and traceability

Laboratory	Source of traceability	Measurement set-up
SMD	PTB	Substitution LCR meter
DANIAmet-NMI	DANIAmet-NMI	LCR Resonance bridge; *C* from NPL, *f* from PTB (DCF77)
PTB	PTB	Maxwell-Wien Bridge
MKEH	PTB	Owens-bridge to 10 mH
NML	NPL	Substitution LCR meter
IAI SL	NPL	Transformer ratio bridge 1:1
VSL	VSL	Transformer Resonance bridge; *C* from BIPM
GUM	GUM	Transformer Resonance bridge; *C* from BIPM
IPQ	PTB	Substitution LCR meter
INM	PTB	Substitution LCR meter
SIQ	NPL	Substitution LCR meter
NMI SA	UME Turkey	Substitution LCR meter
METAS	METAS	Sampling - Resistance
UME	UME	Maxwell-Wien Bridge
UMTS	UMTS	Quasi-reverberatory C-L transfer method
NPL	NPL	Transformer Resonance bridge; C from QHR

5. Behaviour of the travelling standards

PTB has performed repeated measurements on the travelling standards during the course of this comparison. From these measurements, the behaviour of the standards can be seen in Figure 13.

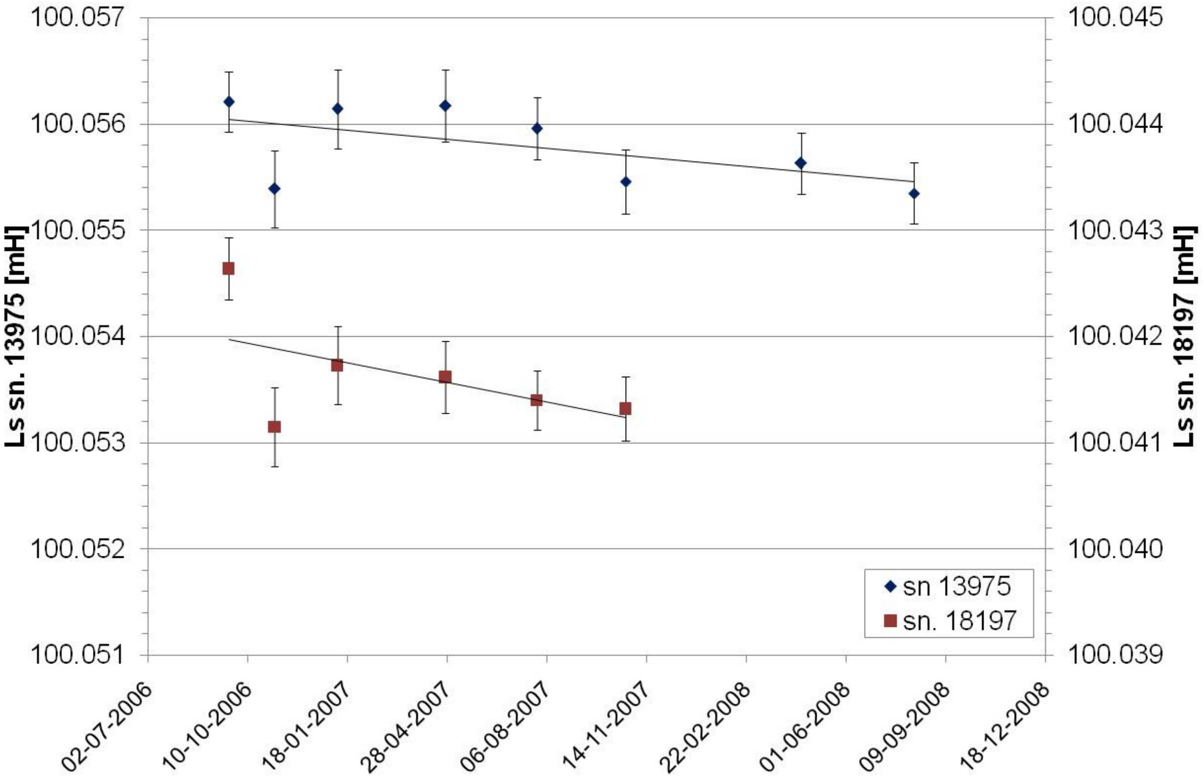

Figure 13. Behaviour of the travelling standards.

Both of the standards show a small drift.
For both standards, the value of the second measurement, in November 2006, is significantly lower than the other values. This deviation is most probably caused by a shock that the standards have experienced during transport from NPL to PTB. It seems that after a few months, the standards have recovered to their previous value and behaviour.

Despite the deviation in November 2006, the behaviour of the standards is approximate by a linear fit through all of the measurement points of PTB. This linear fit is given by:

$$y - y_0 = m \cdot (x - x_0) \qquad (1)$$

where:

x	(days)	:	a given date
x_0	(days)	:	the average date of the PTB measurements on one standard
y	(mH)	:	the inductance value given by the linear fit on date x
y_0	(mH)	:	the average inductance value of the PTB measurements on one standard
m	(mH/day)	:	the drift of the inductance value per day

For each of the travelling standards, the values of x_0, y_0 and m are given in Table 3.
In this table $u(y_0)$ and $u(m)$ are the standard uncertainties ($k = 1$) in y_0 and m respectively.

Table 3. Fit parameters for the behaviour of the travelling standards

Inductor	x_0	y_0 (mH)	$u(y_0)$ (mH)	m (mH/day)	$u(m)$ (mH/day)
sn. 13975	10-07-2007	100.055 79	0.000 12	-0.85×10^{-6}	0.50×10^{-6}
sn. 18197	19-03-2007	100.041 64	0.000 20	-1.84×10^{-6}	1.44×10^{-6}

6. Measurement results

6.1. Results of the participating institutes

The inductance values L_s and their expanded uncertainties $U(L_s)$ reported by the participants are given in Table 5 and Table 6.
Detailed uncertainty budgets from all participants are given in Annex D.
Each of the L_s values has been corrected for the drift of the standards.
The correction values δL_{s_drift} and the corrected inductance values L_{s_corr} are also given in the tables below, together with their corresponding uncertainties $U(\delta L_{s\_drift})$ and $U(L_{s\_corr})$.

$$L_{s\_corr} = L_s + \delta L_{s\_drift} \tag{2}$$

$$U\left(L_{s\_corr}\right) = \sqrt{\left(U\left(L_s\right)\right)^2 + \left(U\left(\delta L_{s\_drift}\right)\right)^2} \tag{3}$$

Note: For the PTB results, it is to be expected that there is a correlation between $U(L_s)$ and $U(\delta L_{s\_drift})$. For reasons of simplicity, these correlation have been ignored, which may result in a slightly overestimated value of $U(L_{s\_corr})$.
The corrected values are also presented in the graph in Figure 14.

The PTB result in this comparison is the average value of the individual results reported by PTB for each of the travelling standards. The averaged PTB results are given on the last line of Table 5 and Table 6.
The uncertainty of the averaged PTB result is calculated as a combined uncertainty of the individual results. It has been assumed that the contributions determined by a type B evaluation [2] are fully correlated between the individual results, whereas the contributions from the type A evaluation [2] are expected to be uncorrelated.

In the calculation of the results, the reported inductance values have not been normalized to a common reference temperature. It has been assumed that the standard's temperature has been sufficiently stable in the temperature controlled enclosure. Whereas most participants performed the measurements at an ambient temperature of about 23 °C, one laboratory (NPL) reported a temperature of about 20 °C. However, the readings from the internal temperature sensors in the standards at NPL are not significantly different from the values reported in other laboratories.

Furthermore, effects from current deviations from the specified 1 mA, and frequency deviations from 1 kHz have been ignored in the computation of the results.
Effects of current level dependence have not been evaluated, but from experience it is known that there is no significant effect on the inductance value as long as the power dissipation in the inductor doesn't produce any heating of the standard.
For this type of standard, the inductance value is typically proportional to the frequency squared. A typical value of frequency dependence for a 100 mH standard is about 2×10^{-11} H/Hz^2, which results in a deviation of about 1.2 µH/H for a frequency offset of 3 Hz.

All reported values of the internal temperature of the standards, the ambient temperature and relative humidity, the measurement current and frequency are provided in Annex E.

6.2. Reference value

To establish a link between this comparison and the EUROMET.EM-S20 comparison, it is easiest to determine a reference value from the results of laboratories that have participated in both comparisons. In this case there are two laboratories that participated in both comparisons: PTB (Germany) and GUM (Poland). However, GUM in this comparison used another measurement set-up than in the previous comparison, which may result in systematic differences. Therefore, the reference value, *RV*, is determined only from the PTB results.

A *RV* is calculated for each of the travelling standards.
RV is taken to be equal to the averaged PTB result, and the uncertainty in *RV*, *U*(*RV*) is equal to the uncertainty in the averaged PTB result. The *RV*'s are given in Table 4.

Table 4. Reference values

Travelling Standard	*RV* (mH)	$U(RV)$ ($k = 2$) (mH)
sn. 13975	100.055 79	0.000 49
sn. 18197	100.041 64	0.000 69

Table 5. Measurement results with drift corrections on travelling standard sn. 13975
The reported uncertainties are expanded uncertainties ($k = 2$).

Laboratory	Country	average date	L_s mH	$U(L_s)$ mH	$\delta L_{s\_\mathrm{drift}}$ mH	$U(\delta L_{s\_\mathrm{drift}})$ mH	L_{s_corr} mH	$U(L_{s\_\mathrm{corr}})$ mH
PTB1	Germany	21-09-2006	100.05621	0.00028	-0.00025	0.00039	100.05596	0.00048
NPL	United Kingdom	16-10-2006	100.05540	0.00420	-0.00023	0.00039	100.05517	0.00422
PTB2	Germany	06-11-2006	100.05539	0.00036	-0.00021	0.00039	100.05518	0.00053
UMTS	Ukraine	26-11-2006	100.05170	0.00200	-0.00019	0.00039	100.05151	0.00204
PTB3	Germany	08-01-2007	100.05614	0.00037	-0.00016	0.00039	100.05598	0.00054
IPQ	Portugal	24-01-2007	100.05180	0.00420	-0.00014	0.00039	100.05166	0.00422
SMD	Belgium	10-02-2007	100.05700	0.00236	-0.00013	0.00039	100.05687	0.00239
DANIAmet-NMI	Denmark	28-02-2007	100.07130	0.00490	-0.00011	0.00039	100.07119	0.00492
VSL	Netherlands	14-03-2007	100.05640	0.00260	-0.00010	0.00039	100.05630	0.00263
PTB4	Germany	26-04-2007	100.05617	0.00034	-0.00006	0.00039	100.05611	0.00052
GUM	Poland	13-05-2007	100.05550	0.00360	-0.00005	0.00039	100.05545	0.00362
MKEH	Hungary	06-06-2007	100.17900	0.02070	-0.00003	0.00039	100.17897	0.02070
INM	Romania	05-07-2007	100.06400	0.00800	0.00000	0.00039	100.06400	0.00801
PTB5	Germany	27-07-2007	100.05596	0.00029	0.00001	0.00039	100.05597	0.00049
METAS	Switzerland	14-08-2007	100.06399	0.00154	0.00003	0.00039	100.06402	0.00159
UME	Turkey	07-09-2007	100.05680	0.00160	0.00005	0.00039	100.05685	0.00165
NML	Ireland	02-10-2007	100.06350	0.02300	0.00007	0.00039	100.06357	0.02300
PTB6	Germany	24-10-2007	100.05546	0.00030	0.00009	0.00039	100.05555	0.00050
NMI SA	South Africa	01-02-2008	100.05800	0.00900	0.00017	0.00039	100.05817	0.00901
IAI SL	Israel	11-05-2008	100.05700	0.02000	0.00026	0.00039	100.05726	0.02000
PTB7	Germany	17-04-2008	100.05563	0.00029	0.00024	0.00039	100.05587	0.00049
SIQ	Slovenia	11-07-2008	100.06100	0.06000	0.00031	0.00039	100.06131	0.06000
PTB8	Germany	08-08-2008	100.05535	0.00029	0.00034	0.00039	100.05569	0.00049
PTB	Germany	10-07-2007	100.05579				100.05579	0.00049

Table 6. Measurement results with drift corrections on travelling standard sn. 18197
The reported uncertainties are expanded uncertainties (k = 2).

Laboratory	Country	average date	L_s mH	$U(L_s)$ mH	$\delta L_{s\_\text{drift}}$ mH	$U(\delta L_{s\_\text{drift}})$ mH	L_{s_corr} mH	$U(L_{s\_\text{corr}})$ mH
PTB1	Germany	21-09-2006	100.04264	0.00029	-0.00033	0.00063	100.04231	0.00069
NPL	United Kingdom	16-10-2006	100.04100	0.00420	-0.00028	0.00063	100.04072	0.00425
PTB2	Germany	06-11-2006	100.04115	0.00037	-0.00025	0.00063	100.04090	0.00073
UMTS	Ukraine	26-11-2006	100.03710	0.00200	-0.00021	0.00063	100.03689	0.00210
PTB3	Germany	08-01-2007	100.04173	0.00037	-0.00013	0.00063	100.04160	0.00073
IPQ	Portugal	24-01-2007	100.03730	0.00420	-0.00010	0.00063	100.03720	0.00425
SMD	Belgium	10-02-2007	100.04290	0.00244	-0.00007	0.00063	100.04283	0.00252
DANIAmet-NMI	Denmark	28-02-2007	100.05720	0.00490	-0.00004	0.00063	100.05716	0.00494
VSL	Netherlands	14-03-2007	100.04190	0.00260	-0.00001	0.00063	100.04189	0.00267
PTB4	Germany	26-04-2007	100.04162	0.00034	0.00007	0.00063	100.04169	0.00071
GUM	Poland	13-05-2007	100.04090	0.00360	0.00010	0.00063	100.04100	0.00365
MKEH	Hungary	06-06-2007	100.18800	0.02070	0.00014	0.00063	100.18814	0.02071
INM	Romania	05-07-2007	100.05400	0.00800	0.00020	0.00063	100.05420	0.00802
PTB5	Germany	27-07-2007	100.04140	0.00028	0.00024	0.00063	100.04164	0.00069
METAS	Switzerland	14-08-2007	100.04207	0.00153	0.00027	0.00063	100.04234	0.00165
UME	Turkey	07-09-2007	100.04250	0.00160	0.00031	0.00063	100.04281	0.00172
NML	Ireland	02-10-2007	100.04920	0.02300	0.00036	0.00063	100.04956	0.02301
PTB6	Germany	24-10-2007	100.04132	0.00030	0.00040	0.00063	100.04172	0.00070
PTB	Germany	19-03-2007	100.04164				100.04164	0.00069

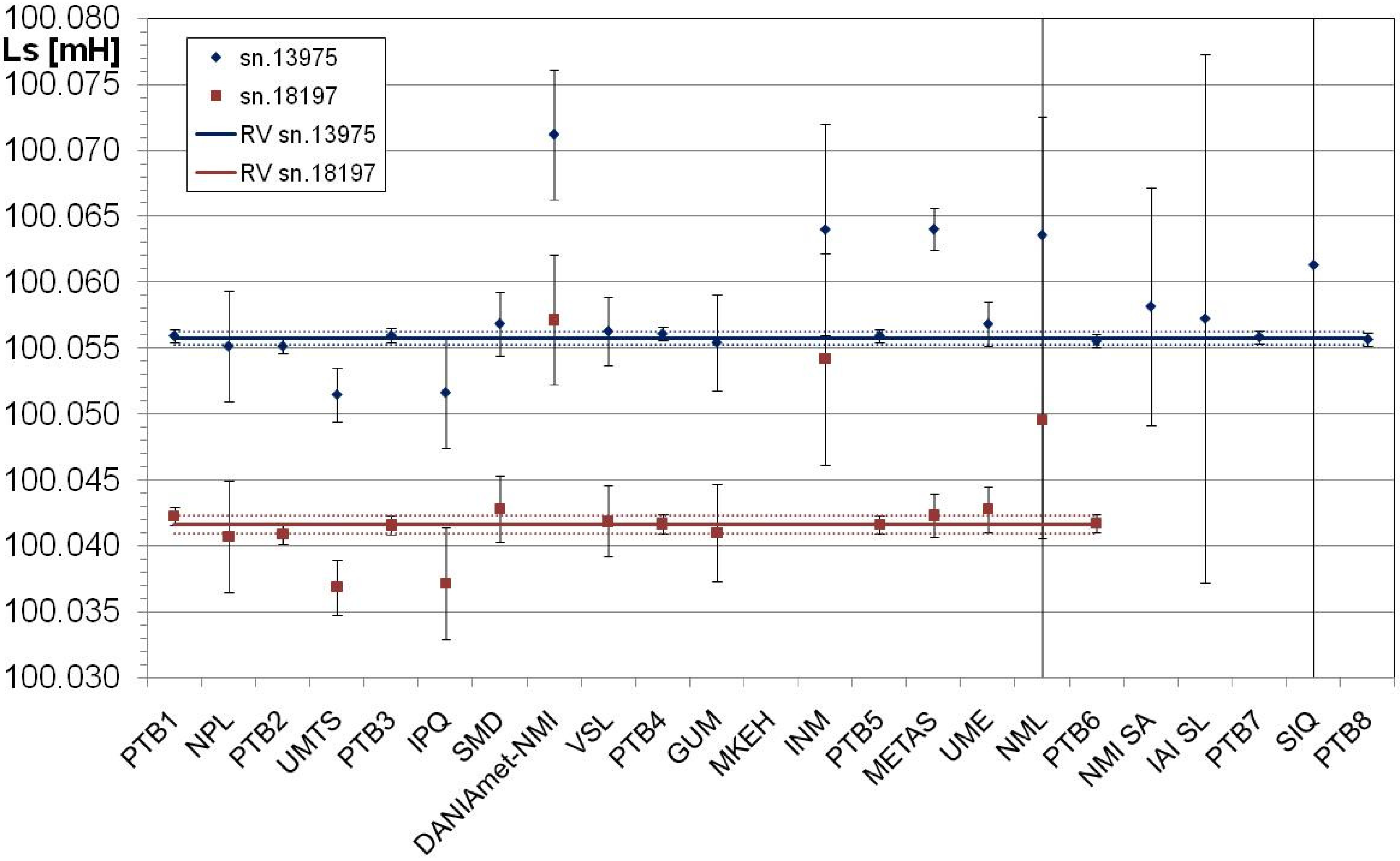

Figure 14. Inductance values measured by the participants and corrected for drift of the standards
(The Reference Values are indicated with full lines. The expanded uncertainties in the reference values are shown as dotted lines.)

6.3. Degrees of equivalence

For each participant, *i*, and each travelling standard, *k*, the degree of equivalence, $D_{i,k}$, with respect to the reference value is determined as:

$$D_{i,k} = L_{\mathrm{s}\_i,k} - RV_k \tag{4}$$

with the corresponding uncertainty $U(D_{i,k})$:

$$U(D_{i,k}) = \sqrt{\left(U\left(L_{\mathrm{s}\_i,k}\right)\right)^2 + \left(U\left(RV_k\right)\right)^2 - 2 \cdot r_{i,k} \cdot U\left(L_{\mathrm{s}\_i,k}\right) \cdot U\left(RV_k\right)} \tag{5}$$

where $r_{\mathrm{i,k}}$ is the correlation coefficient between laboratory result and the *RV*.
Correlations between the results from the laboratories and the reference value have been ignored ($r_{i,k} = 0$) in the computation of $U(D_{i,k})$, except for the case of PTB. From the selection of the *RV*, it is obvious that there is a full correlation ($r_{\mathrm{PTB},k} = 1$) between the uncertainty of the PTB result and the uncertainty in *RV*.

For some other laboratories, there is a correlation between their result and the *RV* because they obtain their traceability from PTB. By ignoring these correlations, the values of $U(D_\mathrm{i})$ can be slightly overestimated, but this effect is expected to be less than 5 % of the uncertainty value.

For those laboratories that performed measurements on two travelling standards, the overall degree of equivalence, D_i, is calculated as the average value of two individual standards:

$$D_i = \frac{D_{i,1} + D_{i,2}}{2} \tag{6}$$

with the uncertainty:

$$U(D_i) = \sqrt{\left(\frac{U(D_{i,1})}{2}\right)^2 + \left(\frac{U(D_{i,2})}{2}\right)^2 + 2 \cdot r_{1,2} \cdot \frac{U(D_{i,1})}{2} \cdot \frac{U(D_{i,2})}{2}} \tag{7}$$

In this equation, a full correlation, $r_{1,2} = 1$, is assumed between $U(D_{i,1})$ and $U(D_{i,2})$, which can result in a slightly overestimated value of $U(D_i)$.

Additionally, the performance indicator E_n is calculated as:

$$E_\mathrm{n} = \frac{D_i}{U(D_i)} \tag{8}$$

All degrees of equivalence and the E_n values are given in Table 7.
The values of D_i with the uncertainties are also plotted in Figure 15 and Figure 16.

6.4. Link to the EUROMET.EM-S20 comparison

The results of this comparison are to be linked to the EUROMET.EM-S20 comparison [1], which was organized by the Istituto Nazionale de Ricerca Metrologica (INRiM) in Italy, and the measurements were performed in 2002 and 2003.
A complete calculation of the link and its results is given in Annex B.
The link is determined from the results of laboratories that have participated in both comparisons. Two laboratories, PTB and GUM, have participated in both comparison, but GUM did not use the same measurement set-up in both comparisons. Therefore, it was decided to use only the PTB results to determine the link.

Table 7. Degrees of equivalence and E_n values

Laboratory	$D_{i,1}$ sn.13975 mH	$U(D_{i,1})$ mH	$D_{i,2}$ sn. 18197 mH	$U(D_{i,2})$ mH	D_i mH	$U(D_\mathrm{i})$ mH	E_n
PTB1	0.00017	0.00048	0.00067	0.00069	0.00042	0.00059	0.7
NPL	-0.00062	0.00425	-0.00093	0.00430	-0.00077	0.00427	-0.2
PTB2	-0.00061	0.00051	-0.00074	0.00071	-0.00067	0.00061	-1.1
UMTS	-0.00428	0.00210	-0.00475	0.00221	-0.00452	0.00215	-2.1
PTB3	0.00020	0.00052	-0.00004	0.00071	0.00008	0.00061	0.1
IPQ	-0.00413	0.00425	-0.00444	0.00430	-0.00429	0.00427	-1.0
SMD	0.00108	0.00244	0.00119	0.00261	0.00114	0.00253	0.4
DANIAmet-NMI	0.01540	0.00494	0.01552	0.00499	0.01546	0.00496	3.1
VSL	0.00051	0.00267	0.00025	0.00276	0.00038	0.00272	0.1
PTB4	0.00032	0.00050	0.00004	0.00070	0.00018	0.00060	0.3
GUM	-0.00034	0.00365	-0.00064	0.00372	-0.00049	0.00369	-0.1
MKEH	0.12318	0.02071	0.14650	0.02072	0.13484	0.02072	6.5
INM	0.00821	0.00802	0.01255	0.00805	0.01038	0.00804	1.3
PTB5	0.00019	0.00049	-0.00001	0.00069	0.00009	0.00059	0.2
METAS	0.00823	0.00166	0.00070	0.00179	0.00446	0.00173	2.6
UME	0.00106	0.00172	0.00117	0.00185	0.00112	0.00179	0.6
NML	0.00778	0.02301	0.00792	0.02302	0.00785	0.02301	0.3
PTB6	-0.00024	0.00049	0.00008	0.00069	-0.00008	0.00059	-0.1
NMI SA	0.00239	0.00902			0.00239	0.00902	0.3
IAI SL	0.00147	0.02001			0.00147	0.02001	0.1
PTB7	0.00008	0.00049			0.00008	0.00049	0.2
SIQ	0.00552	0.06000			0.00552	0.06000	0.1
PTB8	-0.00010	0.00049			-0.00010	0.00049	-0.2
PTB	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.0

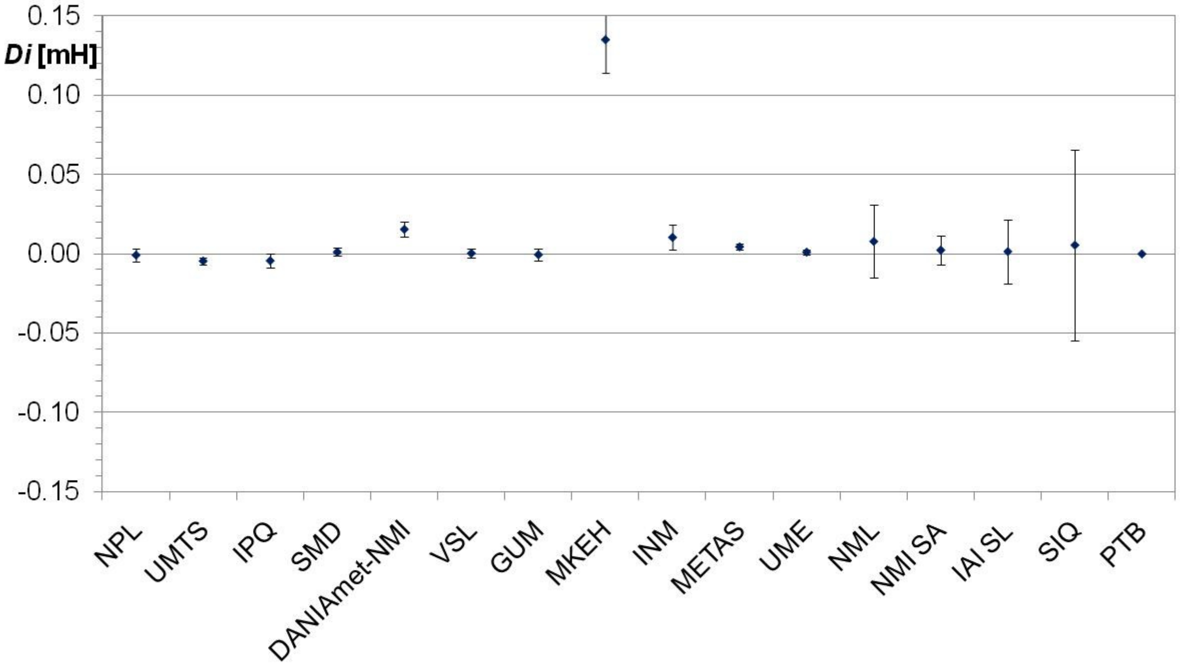

Figure 15. Degrees of equivalence

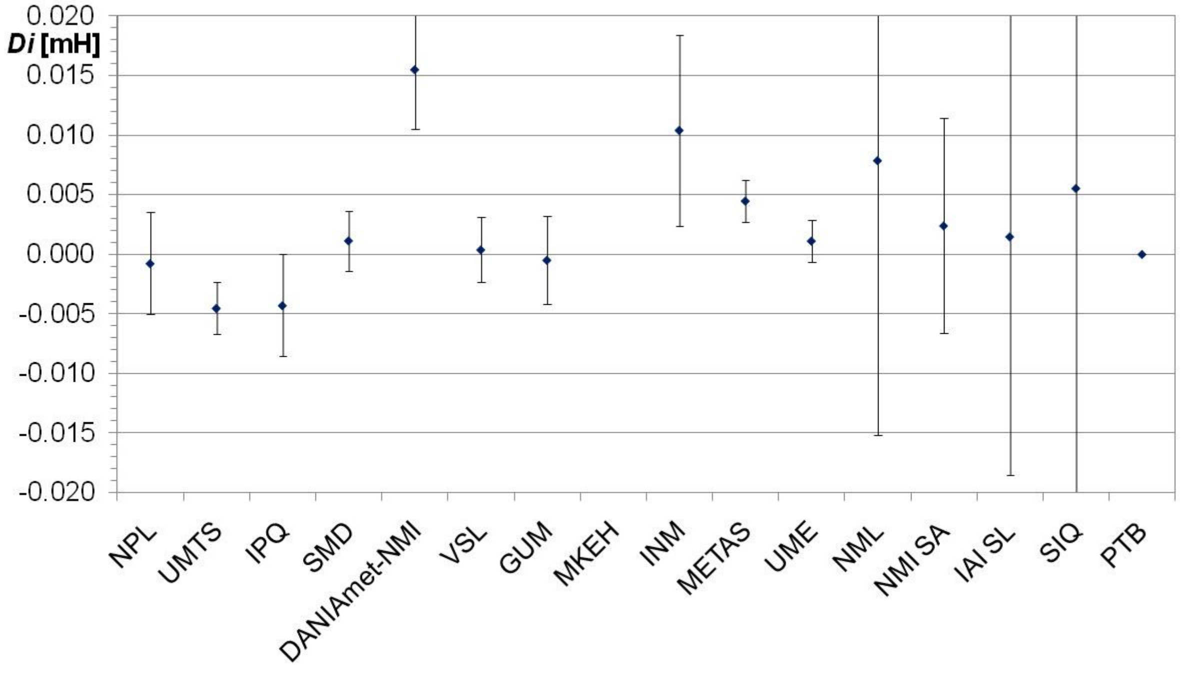

Figure 16. Degrees of equivalence (zoom)

7. Discussion of the results

The results of this comparison show that 10 out of 16 participants are in agreement with the reference value. The consistency of the results with the reference value was tested with a χ^2 test. The χ^2 test fails if the result of MKEH is included. Since the MKEH result is an obvious outlier, the χ^2 test was repeated without this result. Then the test passes.

For those laboratories that are not in agreement with the reference value, there is in most cases a systematic deviation for both travelling standards. In the case of METAS, for one standard the value is in agreement with the reference value and the other one is not. After the comparison, METAS investigated this deviation by performing additional measurements on the travelling standard for which the deviation was observed. It was found that the bridge was sensitive to a leakage current from the inductors thermostat to ground through its power supply. From the test measurements, a correction was estimated. The corrected result is shown in Annex F1.

For the disagreement of the UMTS results with respect to the reference value, there are two different causes. First of all, UMTS reported that one of the uncertainty contributions had been underestimated. Furthermore, the UMTS results are adversely affected by the behaviour of the standards. In October 2006, both travelling standards showed a jump in the inductance value of about 10 µH/H. This was most probably caused by a shock during transport of the standards. From the reference measurements in November 2006 and January 2007, it was observed that the inductance values recovered, more or less, to their previous values. The measurements at UMTS were performed at a time when the standards had not yet fully recovered, which affects the results of UMTS.
Comments on the results of UMTS are given in Annex F2.

The disagreement of the results of DANIAmet-NMI has been, most probably, related to the reference standard that was used in this laboratory for this comparison. Detailed comments are given in Annex F3.

The participants in this comparison have reported four different techniques to realize the traceability of the unit of inductance.
Traditional techniques are the Maxwell-Wien bridge and the LC resonance technique. The Maxwell-Wien bridge appears to yield the lowest uncertainties.
A quite modern technique is the sampling bridge, comparing the inductor with a resistor. In terms of uncertainty, this technique is at about the same level as the LC resonance bridges, but may be further improved in the future.
Laboratories that do not have their own realization of the unit of inductance, obtain the traceability from another laboratory, usually through the calibration of one or more inductors. These calibrated reference inductors are then used in a substitution measurement to calibrate the travelling standards. It is interesting to see that there is a large variety in reported uncertainties from laboratories that use this technique.

8. Conclusions

A comparison was organized of measurements of self-inductance at a nominal value of 100 mH at a frequency of 1 kHz. This comparison is identified as EURAMET.EM-S26 and was carried out as EURAMET project no. 816. The results from 10 out of 16 participants are in agreement with the reference values.

In this comparison, the participants report four different methods to realize the traceability of the unit of inductance. The results from these different methods are in good agreement within the reported uncertainties.

The results of this comparison have been linked to the results of the EUROMET.EM-S20 comparison.

Transport of travelling standards remains a critical issue in the organization comparisons. In this comparison, the inductance values showed a step, most probably due to a severe shock during transport. Later in the comparison, one of the travelling standards was lost during transport and has not been found again.

9. Acknowledgements

The authors of this report would like to acknowledge the co-operation and contributions from all participants in this comparison.

10. References

[1] L. Callegaro, "EUROMET.EM-S20: Intercomparison of a 100 mH inductance standard (Euromet Project 607)", Metrologia, 44, Tech. Suppl., 01002, 2007.
[2] OIML, "Evaluation of measurement data – Guide to the expression of uncertainty in measurement (GUM)", OIML G 1-100 Edition 2008 (E) / JCGM 100:2008.

Annex A. List of participants and schedule

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Table A-1. Measurement schedule of the comparison

Institute	Country	Measurements		Travelling standard	
		Start date	End date	sn. 13975	sn. 18197
PTB1	Germany	26-06-2006	24-09-2006	yes	yes
NPL	United Kingdom	02-10-2006	16-10-2006	yes	yes
PTB2	Germany	23-10-2006	29-10-2006	yes	yes
UMTS	Ukraine	14-11-2006	26-11-2006	yes	yes
PTB3	Germany	27-11-2006	07-01-2007	yes	yes
IPQ	Portugal	19-01-2007	29-01-2007	yes	yes
SMD	Belgium	02-02-2007	14-02-2007	yes	yes
DANIAmet-NMI	Denmark	26-02-2007	02-03-2007	yes	yes
VSL	Netherlands	19-03-2007	01-04-2007	yes	yes
PTB4	Germany	16-04-2007	29-04-2007	yes	yes
GUM	Poland	07-05-2007	20-05-2007	yes	yes
MKEH	Hungary	28-05-2007	10-06-2007	yes	yes
INM	Romania	01-07-2007	12-07-2007	yes	yes
PTB5	Germany	16-07-2007	29-07-2007	yes	yes
METAS	Switzerland	08-08-2007	20-08-2007	yes	yes
UME	Turkey	28-08-2007	17-09-2007	yes	yes
NML	Ireland	26-09-2007	09-10-2007	yes	yes
PTB6	Germany	11-10-2007	26-10-2007	yes	yes
NMI SA	South-Africa	28-01-2008	08-02-2008	yes	no
IAI SL	Israel	11-05-2008	11-05-2008	yes	no
PTB7	Germany	27-03-2008	17-04-2008	yes	no
SIQ	Slovenia	11-07-2008	11-07-2008	yes	no
PTB8	Germany	21-07-2008	08-08-2008	yes	no

Annex B. Link to EUROMET.EM-S20

The results of this comparison are to be linked to the EUROMET.EM-S20 comparison [1], which was organized by INRIM, and the measurements were performed in 2002 and 2003. The link is determined from the results of laboratories that have participated in both comparisons. Two laboratories, PTB and GUM, have participated in both comparison, but GUM did not use the same measurement set-up in both comparisons. Therefore, it was decided to use only the PTB results to determine the link.

A summary of the results of the EUROMET.EM-S20 comparison is given in Table B-1. D_{EM20} is the degree of equivalence with respect to the reference value of EUROMET.EM-S20, RV_{EM20}. The corresponding uncertainty $U(D_{\mathrm{EM20}})$ is not given in the comparison report [1], but has been estimated from the uncertainties $U(L_{\mathrm{S}})$ and the uncertainty in the reference value $U(RV_{\mathrm{EM20}})$, taking into account the correlations from the computation of the reference value as the weighted mean of the results.

Table B-1. Summary of results of EUROMET.EM-S20

Lab	L_{S} mH	$U(L_{\mathrm{S}})$ mH	D_{EM20} mH	$U(D_{\mathrm{EM20}})$ mH
IEN	100.05266	0.00070	-0.00062	0.00077
PTB	100.05314	0.00063	-0.00014	0.00069
SP	100.05361	0.00060	0.00033	0.00066
GUM	100.06007	0.00700	0.00679	0.00701
CMI	100.05395	0.00110	0.00067	0.00116
NCM	100.05305	0.01300	-0.00023	0.01301
RV_{EM20}	100.05328	0.00042		

The results of the EURAMET.EM-S26 comparison are to be expressed in relation to the RV_{EM20}. For this purpose the degrees of equivalence of comparison EURAMET.EM-S26, now indicated by D_{EM26}, will be corrected by a correction d. This correction d is determined from the results of the linking laboratory PTB in both comparisons:

$$d = D_{\mathrm{EM20,PTB}} - D_{\mathrm{EM26,\,PTB}} \qquad \text{(B-1)}$$

d = -0.000 14 mH and $U(d)$ = 0.000 69 mH

The corrected results for the participants in EURAMET.EM-S26 in terms of RV_{EM20} are then given by:

$$D_{\mathrm{EM20},i} = D_{\mathrm{EM26},i} + d \qquad \text{(B-2)}$$

with the uncertainty:

$$U\left(D_{\mathrm{EM20},i}\right) = \sqrt{\left(U\left(D_{\mathrm{EM26},i}\right)\right)^2 + \left(U\left(d\right)\right)^2} \qquad \text{(B-3)}$$

In equation (11) effects of correlation are neglected because they are expected to be very small.

The results from all participants in terms of RV_{EM20} are shown in Table B-2 and Figure B-1.

Table B-2. Degrees of equivalence of all participants in EUROMET.EM-S20 and in EURAMET.EM-S26 with respect to RV_{EM20} with the expanded uncertainty (95% coverage factor)

Lab	D_{EM20} mH	$U(D_{\mathrm{EM20}})$ mH	D_{EM26} mH	$U(D_{\mathrm{EM26}})$ mH	D_{EM20} mH	$U(D_{\mathrm{EM20}})$ mH
IEN	-0.00062	0.00077			-0.00062	0.00077
PTB	-0.00014	0.00069			-0.00014	0.00069
SP	0.00033	0.00066			0.00033	0.00066
GUM	0.00679	0.00701			0.00679	0.00701
CMI	0.00067	0.00116			0.00067	0.00116
NCM	-0.00023	0.01301			-0.00023	0.01301
NPL			-0.00077	0.00427	-0.00091	0.00433
UMTS			-0.00452	0.00215	-0.00466	0.00226
IPQ			-0.00429	0.00427	-0.00443	0.00433
SMD			0.00114	0.00253	0.00100	0.00262
DANIAmet-NMI			0.01546	0.00496	0.01532	0.00501
VSL			0.00038	0.00272	0.00024	0.00281
GUM			-0.00049	0.00369	-0.00063	0.00375
MKEH			0.13484	0.02072	0.13470	0.02073
INM			0.01038	0.00804	0.01024	0.00807
METAS			0.00446	0.00173	0.00432	0.00186
UME			0.00112	0.00179	0.00098	0.00192
NML			0.00785	0.02301	0.00771	0.02302
NMI SA			0.00239	0.00902	0.00225	0.00905
IAI SL			0.00147	0.02001	0.00133	0.02002
SIQ			0.00552	0.06000	0.00538	0.06001

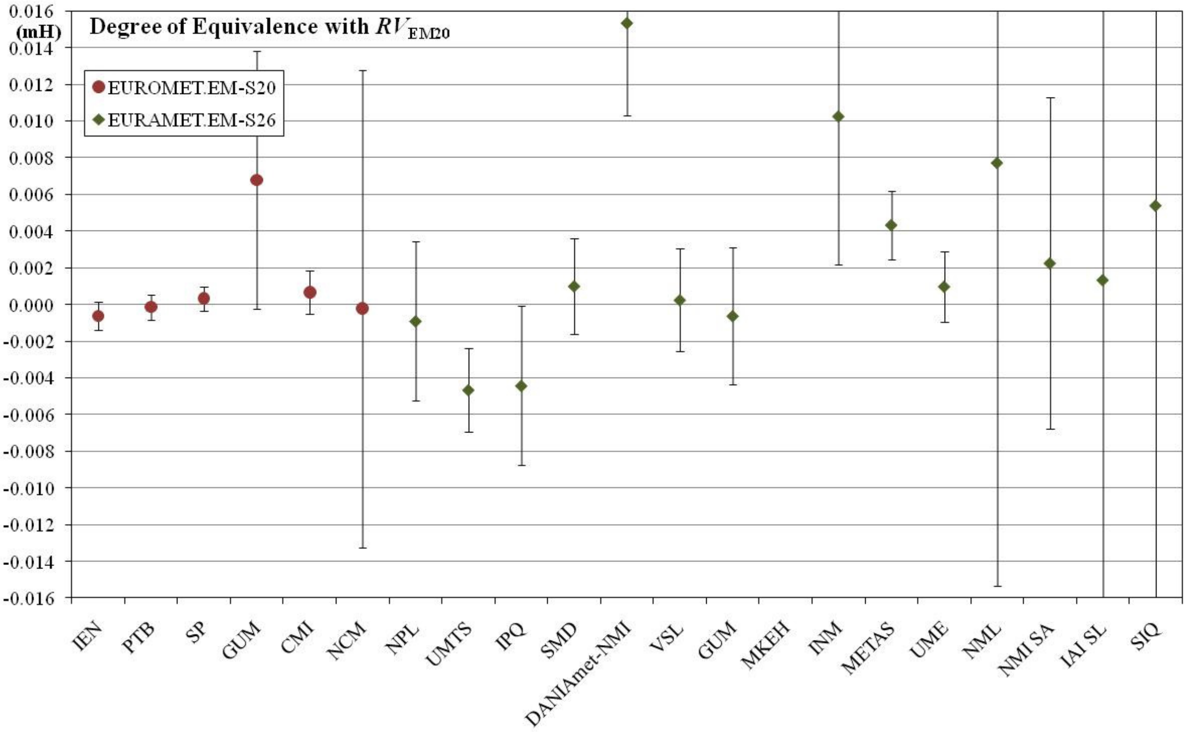


Figure B-1. Degrees of equivalence of all participants in EUROMET.EM-S20 (red markers) and in EURAMET.EM-S26 (green markers) with respect to RV_{EM20} with the expanded uncertainty (95% coverage factor)

Annex C. Methods of measurement

C.1 SMD (Belgium)

The method used to obtain the measurement results of the inductance value is by comparison of the travelling standard with a traceable and calibrated reference standard. A commercial LCR bridge is used to obtain the inductance values.

The device under test (X1 or X2) and the reference standard (S1 or S2) are connected to the LCR bridge following a scheme –SXXS-.
The inductance is connected by a two-terminal method as shown in Figure C.1-1:

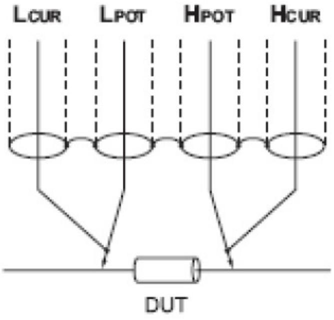


Figure C.1-1. Two-terminal method

The wires come with the LCR bridge and connect directly to the front panel.

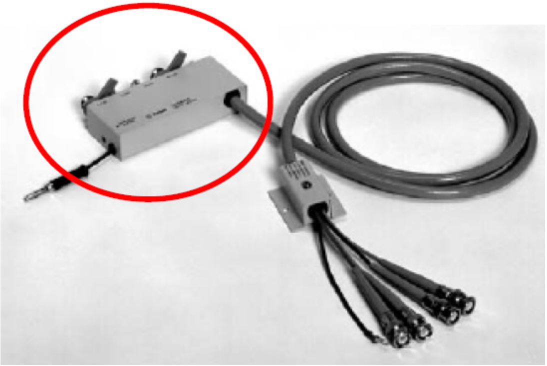


Figure C.1-2. Wires used for the measurements

Figure C.1-3. The front panel of an Agilent E4980 LCR bridge.

The LCR bridge was connected to a controller using a GPIB interface. In house developed software is used to execute the measurements.

C.2 DANIAmet-NMI (Denmark)

The measurement of inductance is realized by connecting a variable capacitor in parallel with the inductor, thus establishing a resonance circuit as shown in fig. C.2-1. R_C and R_P denote the parallel resistance of the variable capacitor with value C_r at resonance and the parallel inductance L_P respectively. The LCR-meter, a Quad Tech 7400, is used to detect the resonance, and the counter (a HP 53132 A) disciplined by the 10 MHz output of a DCF-77 receiver is used to measure the frequency of the test signal of the LCR-meter. The test signal of the LCR-meter was set to 1 mA, 1 kHz as requested in the technical protocol for this intercomparison.

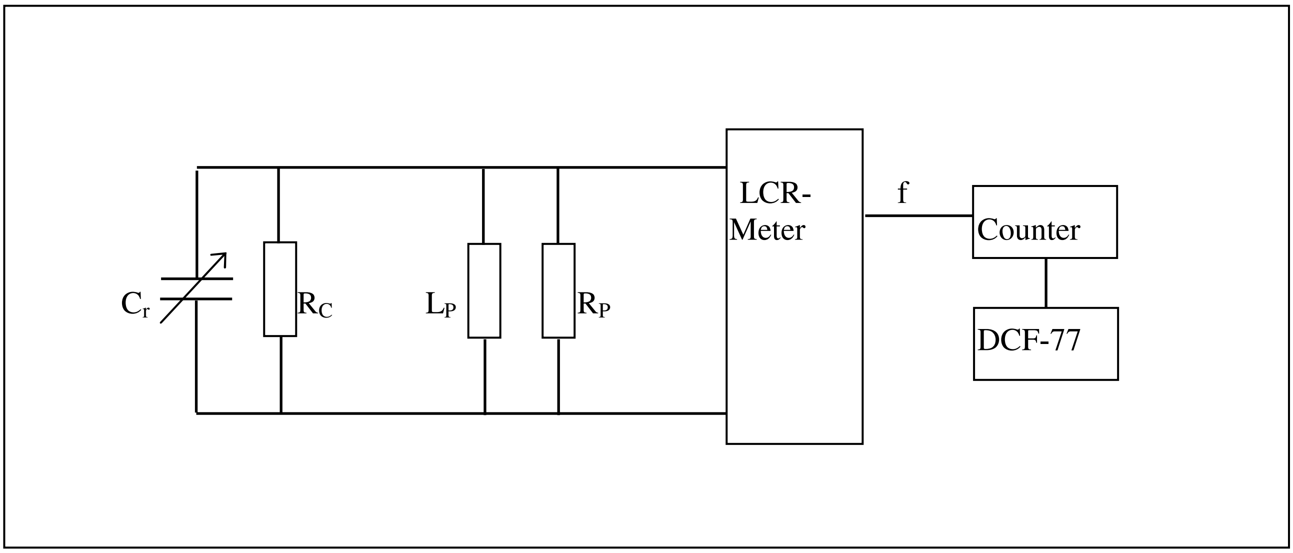


Figure C.2-1. Parallel resonance circuit.

Complete list of equipment:
Quad Tech 7400 LCR-meter
Hewlett Packard 53132 A Counter
DCF-77 Receiver, DK-3060 Instruments
General Radio 1615 A Capacitance Bridge
General Radio 1404-A Standard Capacitor
Danbridge DK4 SV Decade Capacitance Box

C.3 PTB (Germany)

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 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.

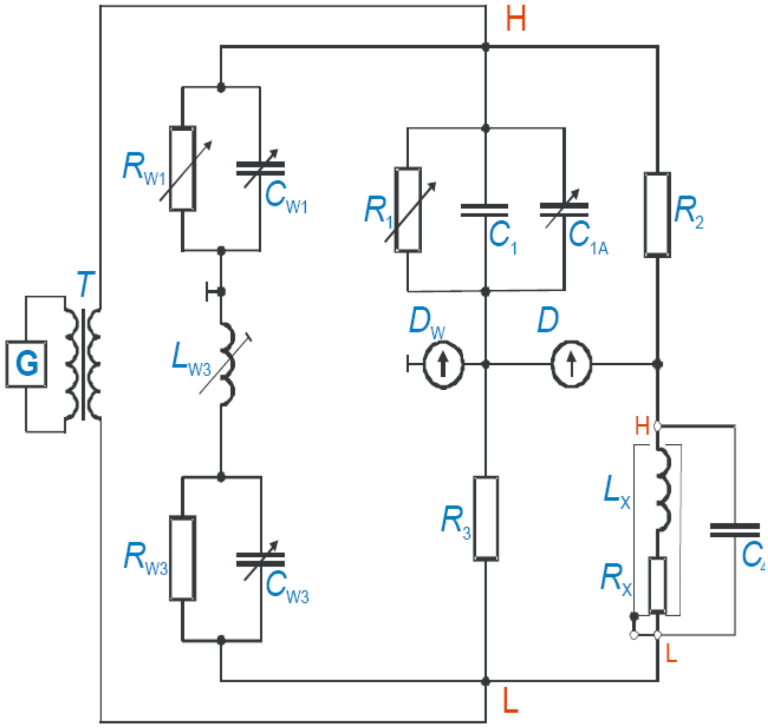


Figure C.3-1. PTB Maxwell-Wien bridge

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 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.

Determination of equivalent series inductance L_S
The INRIM standard was connected with the 4/2 adapter and the PTB standard directly to the bridge without using resistor R_4 (see Fig. 1). Capacitor C_1 is a GR1404 standard of 1 nF. Resistor R_2 is a 10 kΩ Vishay resistor and R_3 is a 10 kΩ Vishay resistor with very low temperature coefficients. This part of the measurement is called main measurement.
In the second part of the measurement (zero-substitution), the standards were replaced by a small air coil (L_{X0}) and the variable resistor R_4 was inserted. The 4/2 adapter was not used. Following this the inductance L_{X0} was measured with an LCR meter.

Instruments for measurement of quantities of secondary importance
f universal counter
I current
$\mathrm{R}_{\mathrm{PT100/NTC}}$ precision multimeter
T_{ext} electronic thermometer with NTC sensor
H_{ext} electronic hygrometer with capacitive sensor

C.4 MKEH (Hungary)

Method of measurement

Comparative measurement, with two-terminal connections.
We used our 10 mH inductance as a reference.
After the measuring Owen-bridge was balanced, we measured the resistance of the balancing arm of the bridge, it is proportinal to the measured inductance (L_x=$R_B C_A R_N$, where $R_B C_A$ is constant), then we make the ratio of the two resistance coming from the measurements of the unknown and the reference inductances.

$L_x = L_s \cdot \frac{R_x}{R_s}$, where

L_x: unknown inductance,
L_s: reference inductance,
R_x: after balancing the bridge the resistance of the balancing arm, when measuring L_x
R_s: after balancing the bridge the resistance of the balancing arm, when measuring L_s

Measurement setup and reference standard

Devices and standard used for measurement:

Name: Inductance measuring assembly
Type: 1660-A
Manufacturer: General Radio Company

Name: Inductance bridge	Audio Oscillator
Type: 1632-A	1311-A
Serial: 1076	2522

Name: Amplifier and null-detector
Type: 1232-A
Serial: 7227

Name: Digital multimeter	Temperature and humidity meter
Type: 8508A	625
Manufacturer: Fluke	Testo
Serial: 854447793	00467260
Name: Standard inductor	Temperature meter
Type: 1482-H	AirTech-4CH
Manufacturer: General Radio Company	Titon Bt.
Serial: 17561	203
Nominal inductance: 10 mH	

C.5 NML (Ireland)

The self-inductance of each traveling standard was measured using a substitution measurement technique. The reference standard was an air-cored 100 mH inductance standard (Sullivan Type R1490 SNo. 751671) placed on a wooden table away from any magnetic disturbances. A digital impedance meter (HP Type 4284A) was used as a transfer standard. The test frequency was 1 kHz and the test current was 1 mA (RMS level).

The standards were connected, in turn, to the impedance meter by means of two 1 metre lengths of coaxial cable, twisted together to minimize stray inductance and fixed to a rigid support so as to maintain a well-defined and stable cable capacitance. A correction for cable impedance was applied. For each inductor, the inductance measured by the impedance meter was that added to the measuring circuit when a short-circuit, placed across the terminals of the measured inductor, was removed. For both the INRIM and PTB standards, the shorting links between the Low terminal and the “Ground” terminal were in place for all measurements.

The impedance meter readings (series inductance and equivalent series resistance) were acquired by a PC. The mean and standard deviation of 100 samples were recorded. During the course of the measurements, the effects on the measurement results of changing the length of the connection cables, the physical location of the standards, and of a small change in the test current were investigated. No deviation in excess of the random day-to-day variations was observed.

C.6 IAI SL (Israel)

Comparison to a 100 mH reference standard through transformer ratio bridge.
The values are given as series inductance with low terminal connected to ground terminal.

Master / standard equipment used

Model	Description	Manufacturer
1482-L	Standard inductor	GENRAD
DT72A	Decade transformer	ESI
1316	Oscillator	GENRAD
1238	Detector	GENRAD
RB-504	Ratio box	NORTH ATLANTIC
1590	Super thermometer	HART SCIENTIFIC

C.7 VSL (The Netherlands)

At NMi-VSL, traceability for inductance measurements is obtained from capacitance. The link between capacitance and inductance is made by a resonance bridge. A schematic diagram of the bridge is given in Figure C.7-1.

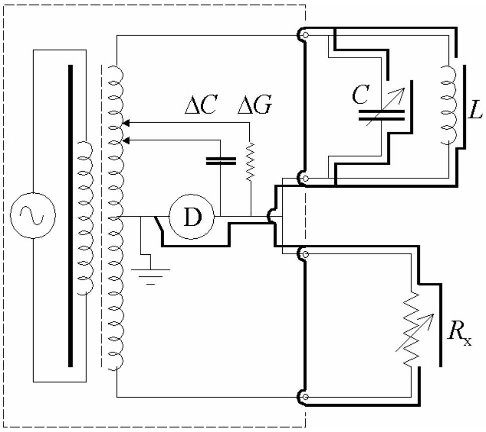


Figure C.7-1. Schematic diagram of the resonance bridge

The resonance bridge in Figure C.7-1 is based on a commercial GR1621 capacitance measurement bridge (enclosed in dashed lines). Inductor *L* is the standard under test. This inductor is connected in parallel with a decade capacitor, *C*. At resonance of the *LC* circuit, the impedance becomes purely real (the imaginary part becomes zero). Therefore the bridge has to be balanced with a resistive impedance R_x. Resistor R_x is a decade resistor. The capacitance ΔC and conductance ΔG are internal, adjustable standards of the GR1621 bridge, that are used for fine adjustment of the bridge balance.

C.8 GUM (Poland)

Method of measurement

The measurements were carried out by comparison of the 100 mH inductance standard with the capacitance standard in the *RLC* comparator model 2100.

Description of the measurement setup

This instrument was developed by Prof. Michael Surdu. This is automatic precision measurement system for mutual comparison of values of primary standards of resistance, capacitance and inductance. It was compared to combined transformer bridge developed by Prof. Andrzej Muciek, that was used in previous EUROMET comparison.

Comparator consists of transformer for equipotentialization VT, autotransformer voltage divider AT, quadrature channel with system of quadrature calibration and common for both autotransformer and quadrature bridges-comparators generator G and vector voltmeter which consists of unbalance signal amplifier UBA, two channels synchronous demodulator VV and microcontroller µC. Comparator operating control and ratios calculation of compared impedances are made by control unit on the base of PC. During measurement, vector voltmeter by the using of commutator C, is connected to two outputs of measurement circuit and measures two output voltages U_1 and U_2. Then the definite variation of arms ratio of autotransformer voltage divider AT is made and output voltage U_{1v} is measured. The equations set, which described these measurements, is calculated by control unit PC. Control unit uses the results of calculation for bridge balancing and for getting of finish measurement result.

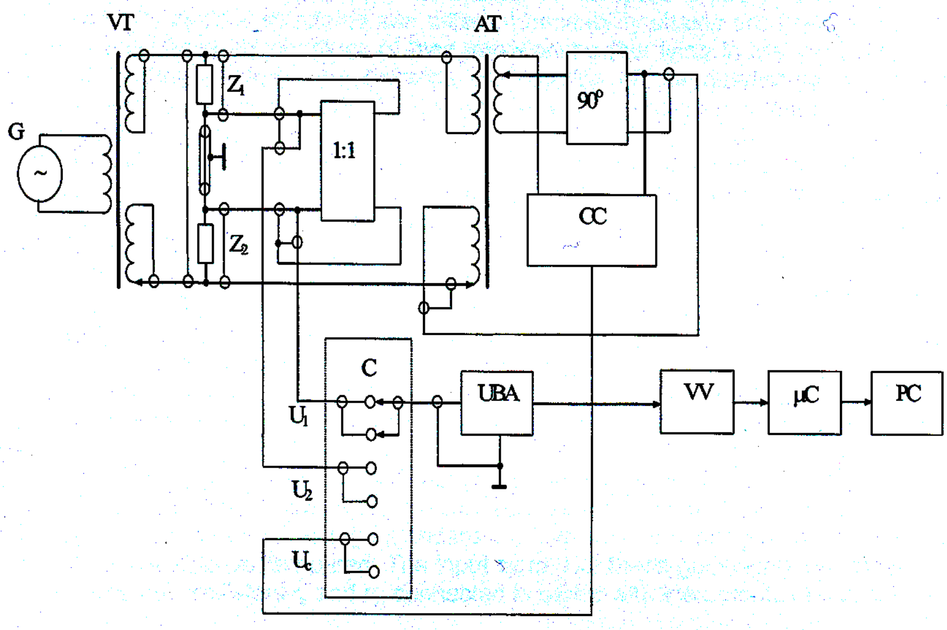


Figure C.8-1. GUM *RLC* comparator bridge

More detailed description: the paper “Bridges for the realization of the units and build-up of the scale for electrical resistance, capacitance and inductance“ - M. Surdu, A, Lameko, I. Karpov, M. Klonz, A. Koffman, J. Kinard, A. Tarlowski, presented during conference CPM 2006 – Torino.

C.9 IPQ (Portugal)

The travelling standards were compared with IPQ's reference standards for Inductance measurement, by a substitution method, using a commercial automatic impedance bridge.

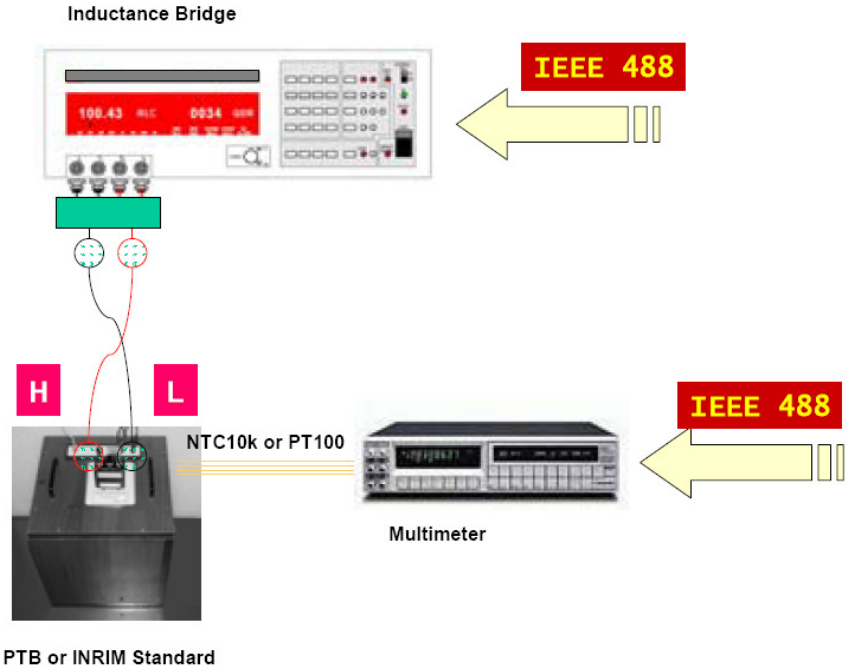


Figure C.9-1. IPQ measurement setup

The IPQ’s primary standards for Inductance measurements consist on a set of four Standard Inductors GR, 1482 type: 1mH, 10 mH, 100 mH and 1 H. Two of them have recent traceability to PTB (10 mH, serial number 9708 and 100 mH, serial number 9712).

After half an hour "warm-up", each standard was measured almost daily, taking 20 measurements at 1 kHz. The measurements were done in an automated way.

The measurements were always performed in a temperature and humidity controlled room ((23 ± 1) °C; (45 ± 10) % RH). This room is not specially shielded against RF interference.

C.10 INM (Romania)

The measurement method used within INM is the substitution comparison. Thus, each of the travelling standards was compared against a INM type (self-built) 100 mH standard inductor under identic measurement conditions.
For the measurement of the pairs (L_s , R_s) of quantities for each inductor, in two terminal connection, a type HP 4284A digital RLC-meter has been used. In order to benefit from the 10^{-5} stability and 10^{-5} resolution of this instrument, a calibration of it against a home made 10 mH standard inductor, which on its turn was calibrated by INRIM in 2006, has been performed directly before and between the different series of 100 mH comparisons.

C.11 SIQ (Slovenia)

Measurement method

The measurements were made by direct substitution method by comparison of inductors with nominally same value. First the laboratory standard inductor was measured (reading *L*re), then the unknown inductor (reading *Lrx*). We take 5 readings of standard inductor and unknown inductor to evaluate type A uncertainty.

Measurement setup

In this comparison method we used LCR meter HP 4284A. Connection between inductor and LCR meter was made by HP 16085B terminal adapter with APC7 to Nf and BNC coaxial cable to BNCf dual banana plug adapter to provided 4/2 adapter on inductor side. Before the measurements SHORT comenstaion was done on the LCR meter with measurement terminals connected together using a shorting link. After compensation measurement parameter (frequency, current…) on LCR meter was set according to Technical protocol.

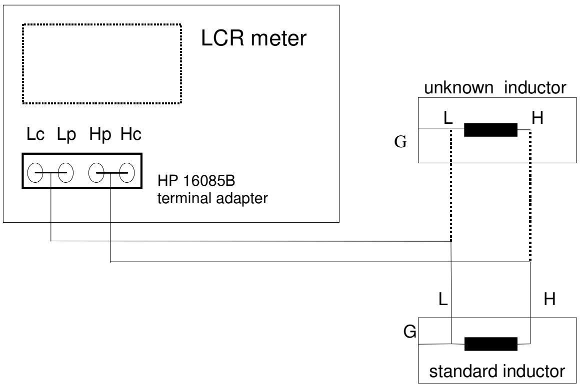


Figure C.11-1. Connection of inductors to LCR meter

C.12 NMISA (South Africa)

The effective inductance of the travelling standard was measured against a GR1482-L inductance standard, serial number 19723 using a QuadTech 1693 RLC Digibridge, serial number 2222610.

1). The QuadTech 1693 low current terminal was connected to the Wavetek 1281 Digital Multimeter low current input. The high current input of the Wavetek 1281 Digital Multimeter and the low potential terminal of the QuadTech 1693 were connected together using a BNC T-connector with one end of the T-connector connected to a BNC to banana connector.

2). The high current and high potential terminals were connected together using a second BNC T-connector and a BNC to banana connector.

3). Thereafter the open and short calibration of the QuadTech 1693 was undertaken.

4). The QuadTech 1693 was then connected across the high and low binding posts of the standard inductor in 2-terminal mode and the QuadTech 1693 inductance reading across the standard inductor recorded.

5). To measure lead inductance, the connecting leads were then removed from the high and low binding posts of the standard inductor and connected across the shorted low and guard binding posts of the standard inductor and the QuadTech 1693 inductance reading across the shorted low and guard binding posts recorded.

6). The effective inductance of the standard inductor was determined by calculating the difference between the measurement result obtained in (4) and (5) using the formula (measured effective inductance = reading across low and high terminals of standard - reading across shorted low and guard terminals of standard).

7). Steps (4) to (6) were repeated in determining the measured effective inductance of the travelling standard.

C.13 METAS (Switzerland)

The standard under test $Z_b=R_s+j\omega L_s$ is calibrated by comparison to the reference standard $Z_t=R_t(1+j\omega\tau)$ using a sampling technique. Two low distortion DACs are used as top source and bottom source. The detector, a 24 bits/200 kHz ADC, is successively connected to the different detector positions through a multiplexer.
The balancing procedure is the following:

- The amplitude ratio and the phase shift of the DACs signals are adjusted to null V_W (Wagner balance).
- Both components of the Kelvin network are adjusted to minimize the effect of the Kelvin switch, Ks, on the Wagner balance V_W (Kelvin Balance).

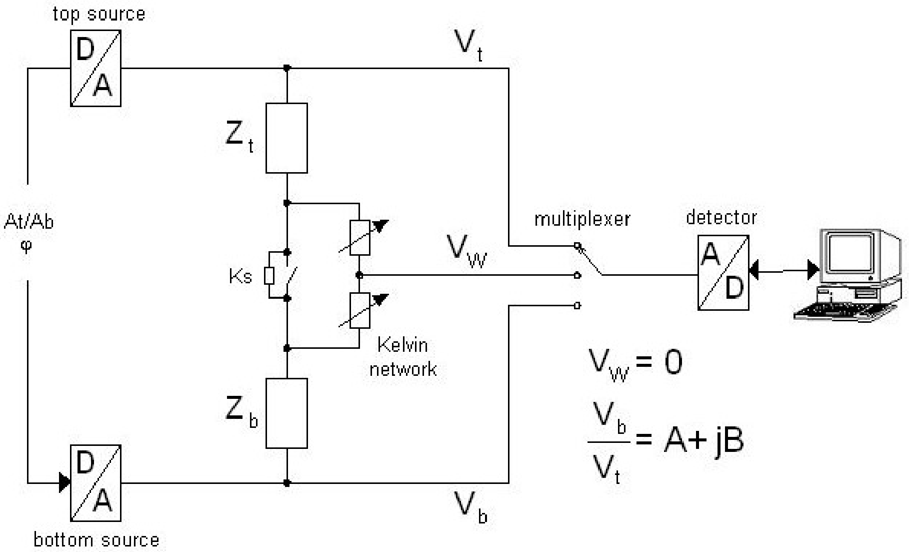


Figure C.13-1. METAS sampling bridge

Under such condition, the voltage ratio V_b / V_t is directly related to the impedance ratio trough:

$$\frac{Z_b}{Z_t}=\frac{R_s+j\cdot\omega\cdot L_s}{R_t\cdot\left(1+j\cdot\omega\cdot\tau\right)}=-\frac{V_b}{V_t}=-\left(A+j\cdot B\right)$$

C.14 UME (Turkey)

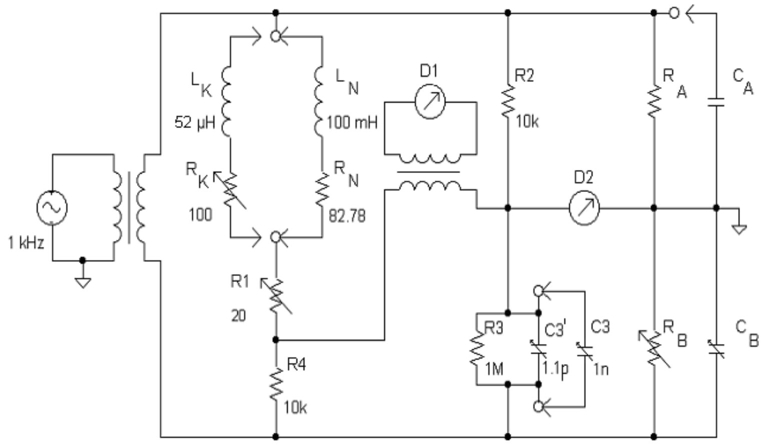


Figure C.14-1. Principal circuit diagram of the Maxwell-Wien Bridge at UME

Two measurements should be performed in Maxwell-Wien measurements in order to determine the value of 100 mH inductance standards. 100 mH inductance standard is connected to the bridge in the first measurement. Then, a known small inductor is measured by using the bridge in order to eliminate the residual effect of the bridge inductance (L_{Bridge}). These two measurements can be expressed with the equations below:

$$L_X = R_2 . R_4 . (C_3 + C_3') + L_{Bridge} \qquad (1)$$

$$L_K = R_2 . R_4 . C' + L_{Bridge} \qquad (2)$$

$$C = C_3 + C_3' \qquad (3)$$

By subtracting equations (1) and (2) and using the equation (3), the equation (4) was obtained. The value of the small inductor standard was measured by using a GR1693 RLC Digibridge and this value was used in the equation (4).

$$L_X = R_2 . R_4 . (C - C') + L_K \qquad (4)$$

C.15 UMTS (Ukraine)

INRIM and PTB inductance standards were measured by precision bridge in C-L transfer mode.
A special quasi-reverberatory transfer method was used, that has been developed in Ukraine. Transfer capacitor with value 200 nF was used. This capacitor was calibrated immediately before inductance standards measurements by Ukrainian National standard of electrical capacitance and tangent of losses DETU 08-06-01.

C.16 NPL (United Kingdom)

Measurement chain and traceability

At NPL the unit of inductance, the henry, is derived from the unit of capacitance, the farad (1), which is traceable to the quantum Hall resistance standard and the consensus value of the von Klitzing constant R_{k-90}. By using a series of DC bridges the value of a 1000 Ω quadrifilar resistor, whose DC and AC values only differ by a few parts in 10^9, is determined. Then using a series of coaxial AC bridges the values of resistors and capacitors are determined culminating in the establishment of our primary 10 pF capacitance standard NBS117 (2,3). To derive inductance from this traceable capacitance scale high Q self-inductors NL500 & NL250 were resonated with a variable capacitor in a parallel tuned circuit, at a measured frequency, so the impedance of the combination is almost purely resistive. Then at the same frequency the conductance and residual capacitance of the combination are measured. The capacitance and shunt conductance of the variable capacitor are also measured. The inductance of each high Q self-inductor is then calculated from these measured values. The inductance comparison bridge (4), shown in figure 1, relates the high Q inductors to our primary inductance standards S/N438 (10 mH), S/N439 (20 mH), S/N440 (50 mH) and S/N907 (400mH) in turn to establish a traceable scale of inductance. These inductors were then used to measure the two travelling inductors.

Inductance comparison bridge

The four-arm bridge shown in Figure 1 equates the ratio of the impedances of the two bridge arms containing the inductors L_1 and L_2 according to the simplified balance equation (1).

$$\frac{L_1}{L_2} = \frac{R_1}{R_2 + R} = \frac{n}{(1-n)} \qquad (1)$$

where $\{L_1, R_1\}$ and $\{L_2, (R_2+R)\}$ are the total values of the series inductance and resistance in the two arms of the bridge. The ratio of the impedances of the two bridge arms containing the inductors is equated, on nulling the detector D, to the ratio n/(1-n) of the inductive voltage divider (IVD), A, where n is its dial reading. The quadrature component of the IVD ratio is negligible. One of the arms of the bridge also includes the decade-switched variable resistance box R whose resistance and residual inductance at various combinations has previously been calibrated.

The effects of capacitive currents within the bridge network are eliminated by completely screening all the bridge components and setting the potential of the screen to that of the output of IVD A by adjusting the output of IVD B to which it is connected.

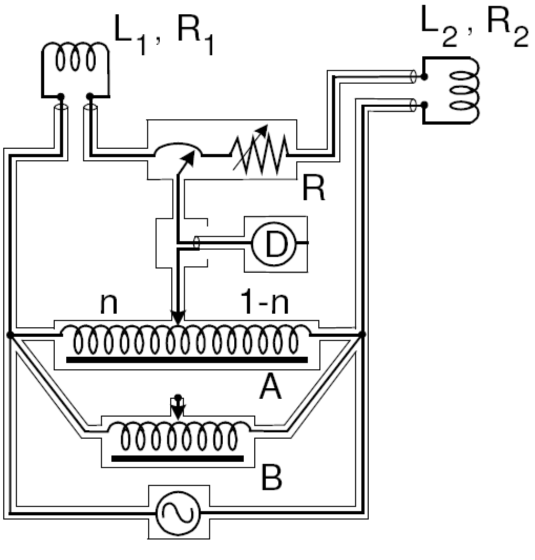
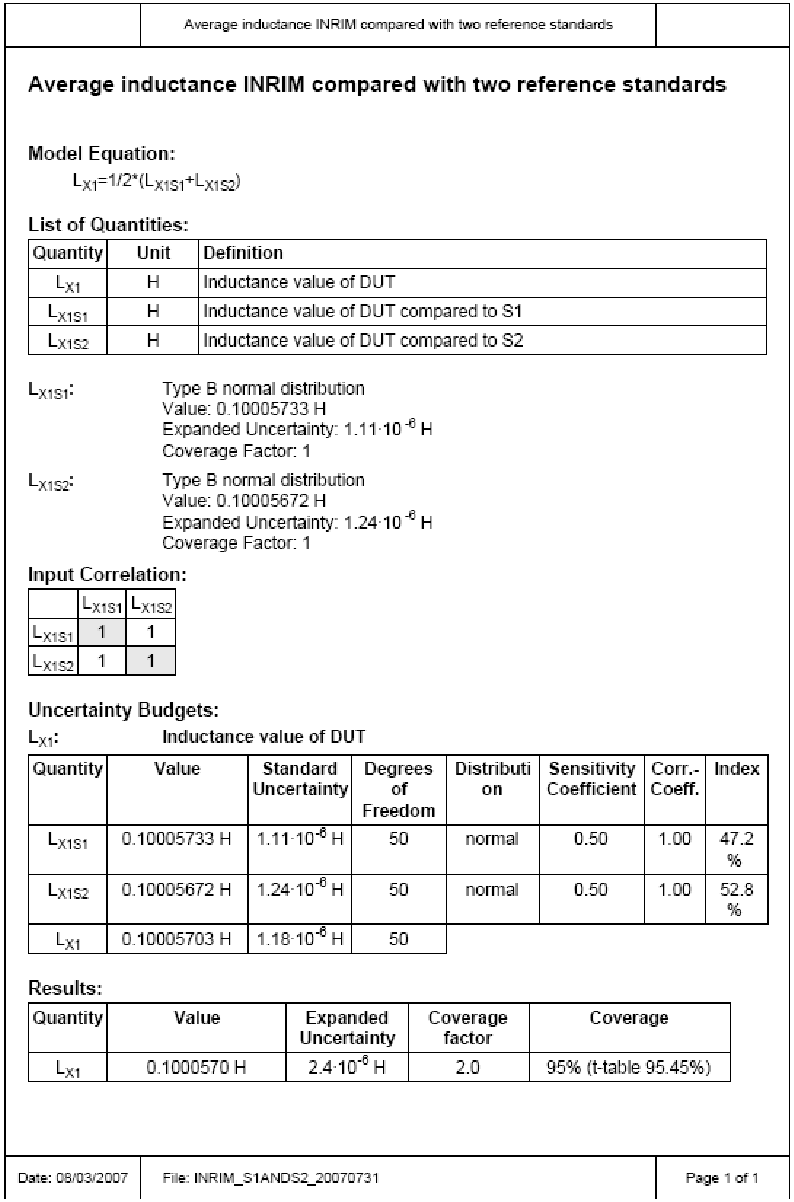


Figure C.16-1. NPL inductance comparison bridge

Annex D. Uncertainty budgets

D.1 Uncertainty budget SMD (Belgium)

The tables are given on the following pages.



Average inductance INRIM compared with two reference standards

Average inductance INRIM compared with two reference standards

Model Equation:

L_{X1}=1/2*(L_{X1S1}+L_{X1S2})

List of Quantities:

Quantity	Unit	Definition
L_{X1}	H	Inductance value of DUT
L_{X1S1}	H	Inductance value of DUT compared to S1
L_{X1S2}	H	Inductance value of DUT compared to S2

L_{X1S1}: Type B normal distribution
Value: 0.10005733 H
Expanded Uncertainty: $1.11\cdot10^{-6}$ H
Coverage Factor: 1

L_{X1S2}: Type B normal distribution
Value: 0.10005672 H
Expanded Uncertainty: $1.24\cdot10^{-6}$ H
Coverage Factor: 1

Input Correlation:

	L_{X1S1}	L_{X1S2}
L_{X1S1}	1	1
L_{X1S2}	1	1

Uncertainty Budgets:

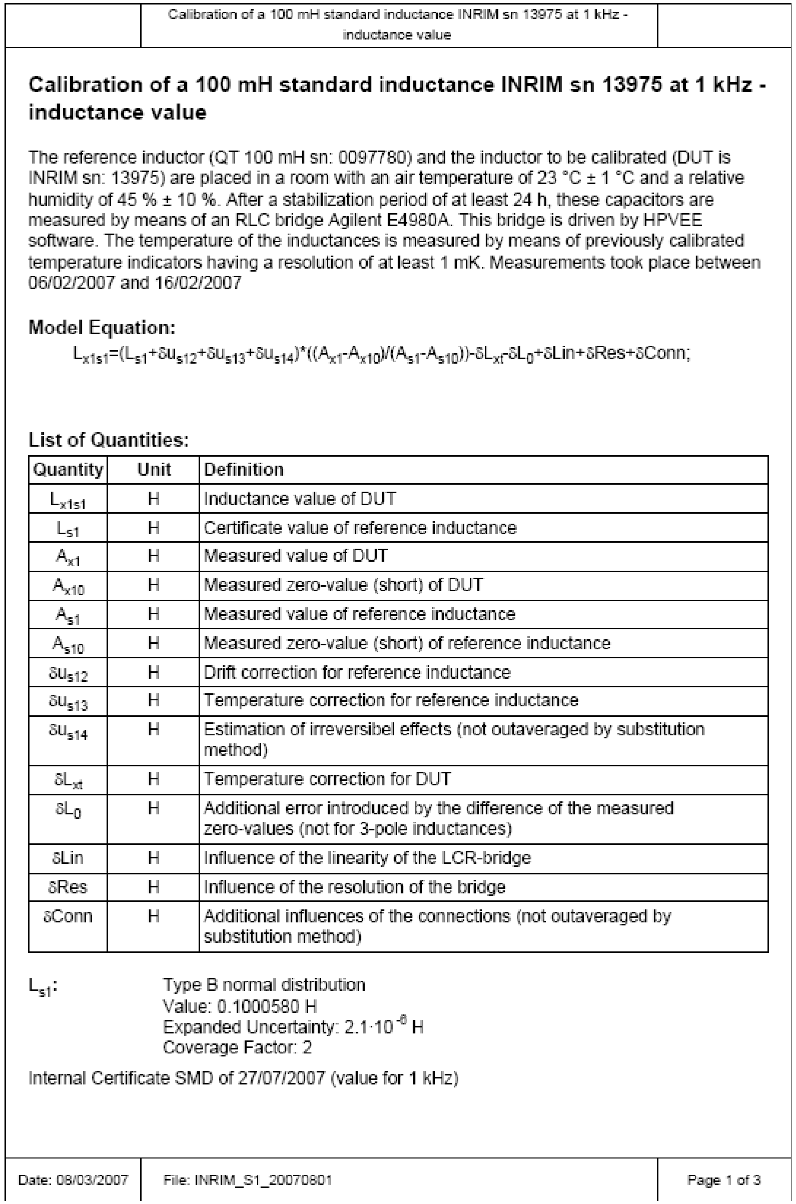
L_{X1}: **Inductance value of DUT**

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Corr.-Coeff.	Index
L_{X1S1}	0.10005733 H	$1.11\cdot10^{-6}$ H	50	normal	0.50	1.00	47.2 %
L_{X1S2}	0.10005672 H	$1.24\cdot10^{-6}$ H	50	normal	0.50	1.00	52.8 %
L_{X1}	0.10005703 H	$1.18\cdot10^{-6}$ H	50				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
L_{X1}	0.1000570 H	$2.4\cdot10^{-6}$ H	2.0	95% (t-table 95.45%)

Date: 08/03/2007 File: INRIM_S1ANDS2_20070731 Page 1 of 1



Calibration of a 100 mH standard inductance INRIM sn 13975 at 1 kHz - inductance value

Calibration of a 100 mH standard inductance INRIM sn 13975 at 1 kHz - inductance value

The reference inductor (QT 100 mH sn: 0097780) and the inductor to be calibrated (DUT is INRIM sn: 13975) are placed in a room with an air temperature of 23 °C ± 1 °C and a relative humidity of 45 % ± 10 %. After a stabilization period of at least 24 h, these capacitors are measured by means of an RLC bridge Agilent E4980A. This bridge is driven by HPVEE software. The temperature of the inductances is measured by means of previously calibrated temperature indicators having a resolution of at least 1 mK. Measurements took place between 06/02/2007 and 16/02/2007

Model Equation:

L_{x1s1}=(L_{s1}+δu_{s12}+δu_{s13}+δu_{s14})*((A_{x1}-A_{x10})/(A_{s1}-A_{s10}))-δL_{xt}-δL_0+δLin+δRes+δConn;

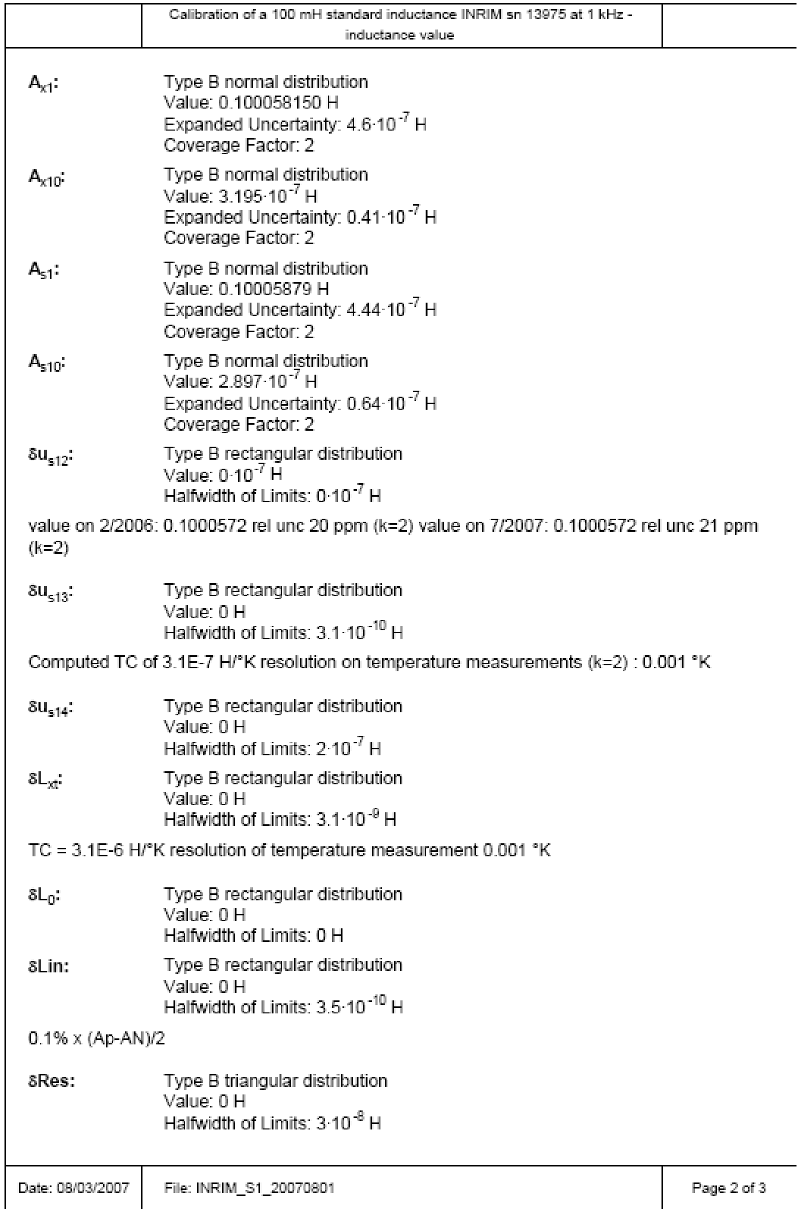
List of Quantities:

Quantity	Unit	Definition
L_{x1s1}	H	Inductance value of DUT
L_{s1}	H	Certificate value of reference inductance
A_{x1}	H	Measured value of DUT
A_{x10}	H	Measured zero-value (short) of DUT
A_{s1}	H	Measured value of reference inductance
A_{s10}	H	Measured zero-value (short) of reference inductance
δu_{s12}	H	Drift correction for reference inductance
δu_{s13}	H	Temperature correction for reference inductance
δu_{s14}	H	Estimation of irreversibel effects (not outaveraged by substitution method)
δL_{xt}	H	Temperature correction for DUT
δL_0	H	Additional error introduced by the difference of the measured zero-values (not for 3-pole inductances)
δLin	H	Influence of the linearity of the LCR-bridge
δRes	H	Influence of the resolution of the bridge
δConn	H	Additional influences of the connections (not outaveraged by substitution method)

L_{s1}: Type B normal distribution
Value: 0.1000580 H
Expanded Uncertainty: $2.1\cdot10^{-6}$ H
Coverage Factor: 2

Internal Certificate SMD of 27/07/2007 (value for 1 kHz)

Date: 08/03/2007 File: INRIM_S1_20070801 Page 1 of 3



A_{x1}: Type B normal distribution
Value: 0.100058150 H
Expanded Uncertainty: $4.6 \cdot 10^{-7}$ H
Coverage Factor: 2

A_{x10}: Type B normal distribution
Value: $3.195 \cdot 10^{-7}$ H
Expanded Uncertainty: $0.41 \cdot 10^{-7}$ H
Coverage Factor: 2

A_{s1}: Type B normal distribution
Value: 0.10005879 H
Expanded Uncertainty: $4.44 \cdot 10^{-7}$ H
Coverage Factor: 2

A_{s10}: Type B normal distribution
Value: $2.897 \cdot 10^{-7}$ H
Expanded Uncertainty: $0.64 \cdot 10^{-7}$ H
Coverage Factor: 2

δu_{s12}: Type B rectangular distribution
Value: $0 \cdot 10^{-7}$ H
Halfwidth of Limits: $0 \cdot 10^{-7}$ H

value on 2/2006: 0.1000572 rel unc 20 ppm (k=2) value on 7/2007: 0.1000572 rel unc 21 ppm (k=2)

δu_{s13}: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: $3.1 \cdot 10^{-10}$ H

Computed TC of 3.1E-7 H/°K resolution on temperature measurements (k=2) : 0.001 °K

δu_{s14}: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: $2 \cdot 10^{-7}$ H

δL_{xt}: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: $3.1 \cdot 10^{-9}$ H

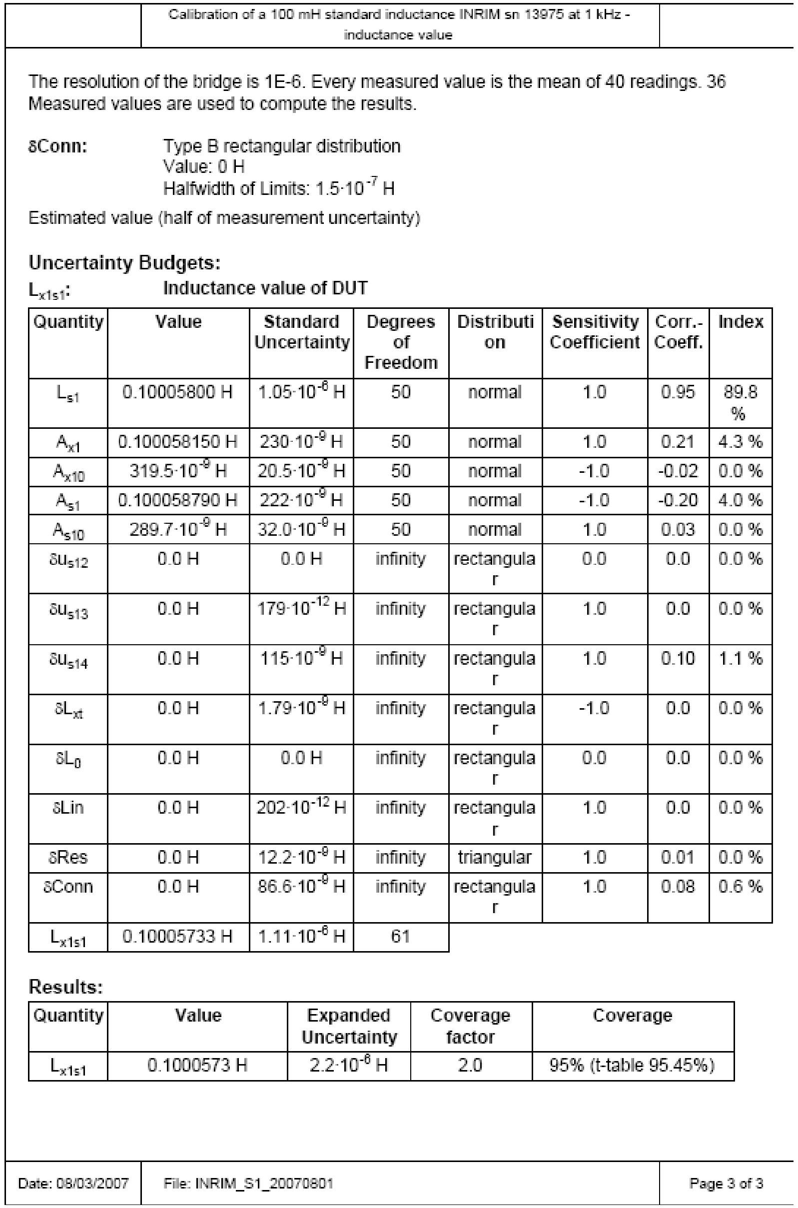
TC = 3.1E-6 H/°K resolution of temperature measurement 0.001 °K

δL_0: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: 0 H

δLin: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: $3.5 \cdot 10^{-10}$ H

0.1% x (Ap-AN)/2

δRes: Type B triangular distribution
Value: 0 H
Halfwidth of Limits: $3 \cdot 10^{-8}$ H



The resolution of the bridge is 1E-6. Every measured value is the mean of 40 readings. 36 Measured values are used to compute the results.

δConn: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: $1.5 \cdot 10^{-7}$ H

Estimated value (half of measurement uncertainty)

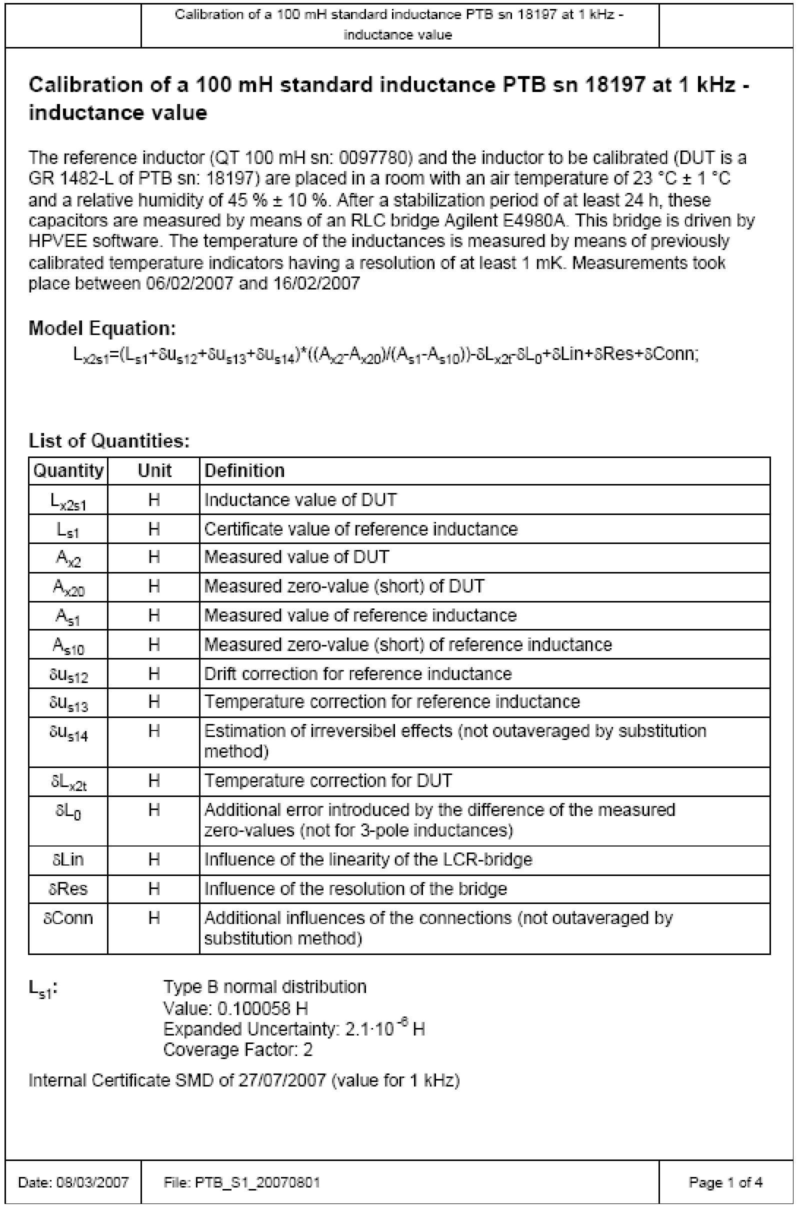
Uncertainty Budgets:

L_{x1s1}: **Inductance value of DUT**

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Corr.-Coeff.	Index
L_{s1}	0.10005800 H	$1.05 \cdot 10^{-6}$ H	50	normal	1.0	0.95	89.8 %
A_{x1}	0.100058150 H	$230 \cdot 10^{-9}$ H	50	normal	1.0	0.21	4.3 %
A_{x10}	$319.5 \cdot 10^{-9}$ H	$20.5 \cdot 10^{-9}$ H	50	normal	-1.0	-0.02	0.0 %
A_{s1}	0.100058790 H	$222 \cdot 10^{-9}$ H	50	normal	-1.0	-0.20	4.0 %
A_{s10}	$289.7 \cdot 10^{-9}$ H	$32.0 \cdot 10^{-9}$ H	50	normal	1.0	0.03	0.0 %
δu_{s12}	0.0 H	0.0 H	infinity	rectangular	0.0	0.0	0.0 %
δu_{s13}	0.0 H	$179 \cdot 10^{-12}$ H	infinity	rectangular	1.0	0.0	0.0 %
δu_{s14}	0.0 H	$115 \cdot 10^{-9}$ H	infinity	rectangular	1.0	0.10	1.1 %
δL_{xt}	0.0 H	$1.79 \cdot 10^{-9}$ H	infinity	rectangular	-1.0	0.0	0.0 %
δL_0	0.0 H	0.0 H	infinity	rectangular	0.0	0.0	0.0 %
δLin	0.0 H	$202 \cdot 10^{-12}$ H	infinity	rectangular	1.0	0.0	0.0 %
δRes	0.0 H	$12.2 \cdot 10^{-9}$ H	infinity	triangular	1.0	0.01	0.0 %
δConn	0.0 H	$86.6 \cdot 10^{-9}$ H	infinity	rectangular	1.0	0.08	0.6 %
L_{x1s1}	0.10005733 H	$1.11 \cdot 10^{-6}$ H	61				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
L_{x1s1}	0.1000573 H	$2.2 \cdot 10^{-6}$ H	2.0	95% (t-table 95.45%)



Calibration of a 100 mH standard inductance PTB sn 18197 at 1 kHz - inductance value

Calibration of a 100 mH standard inductance PTB sn 18197 at 1 kHz - inductance value

The reference inductor (QT 100 mH sn: 0097780) and the inductor to be calibrated (DUT is a GR 1482-L of PTB sn: 18197) are placed in a room with an air temperature of 23 °C ± 1 °C and a relative humidity of 45 % ± 10 %. After a stabilization period of at least 24 h, these capacitors are measured by means of an RLC bridge Agilent E4980A. This bridge is driven by HPVEE software. The temperature of the inductances is measured by means of previously calibrated temperature indicators having a resolution of at least 1 mK. Measurements took place between 06/02/2007 and 16/02/2007

Model Equation:

$$L_{x2s1}=(L_{s1}+\delta u_{s12}+\delta u_{s13}+\delta u_{s14})*((A_{x2}-A_{x20})/(A_{s1}-A_{s10}))-\delta L_{x2t}-\delta L_0+\delta Lin+\delta Res+\delta Conn;$$

List of Quantities:

Quantity	Unit	Definition
L_{x2s1}	H	Inductance value of DUT
L_{s1}	H	Certificate value of reference inductance
A_{x2}	H	Measured value of DUT
A_{x20}	H	Measured zero-value (short) of DUT
A_{s1}	H	Measured value of reference inductance
A_{s10}	H	Measured zero-value (short) of reference inductance
δu_{s12}	H	Drift correction for reference inductance
δu_{s13}	H	Temperature correction for reference inductance
δu_{s14}	H	Estimation of irreversibel effects (not outaveraged by substitution method)
δL_{x2t}	H	Temperature correction for DUT
δL_0	H	Additional error introduced by the difference of the measured zero-values (not for 3-pole inductances)
δLin	H	Influence of the linearity of the LCR-bridge
δRes	H	Influence of the resolution of the bridge
δConn	H	Additional influences of the connections (not outaveraged by substitution method)

L_{s1}: Type B normal distribution
Value: 0.100058 H
Expanded Uncertainty: $2.1\cdot10^{-6}$ H
Coverage Factor: 2

Internal Certificate SMD of 27/07/2007 (value for 1 kHz)

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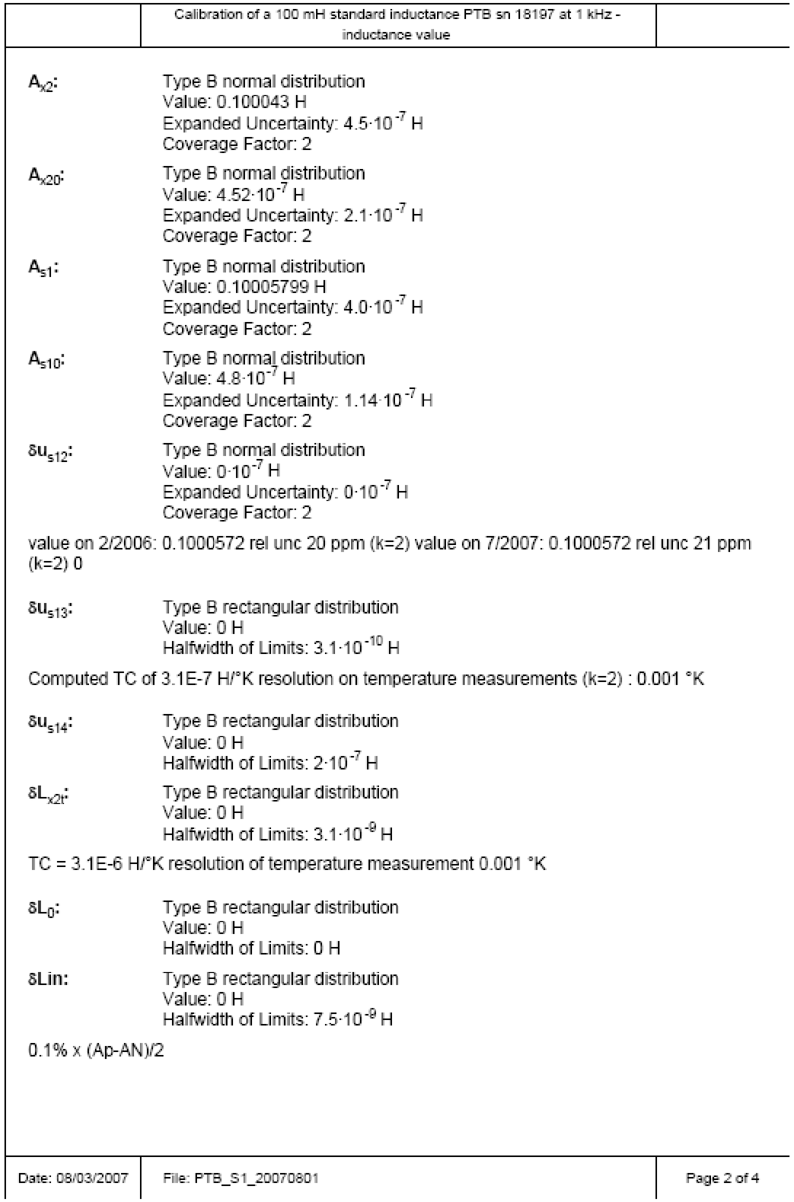

Calibration of a 100 mH standard inductance PTB sn 18197 at 1 kHz - inductance value

A_{x2}: Type B normal distribution
Value: 0.100043 H
Expanded Uncertainty: $4.5\cdot10^{-7}$ H
Coverage Factor: 2

A_{x20}: Type B normal distribution
Value: $4.52\cdot10^{-7}$ H
Expanded Uncertainty: $2.1\cdot10^{-7}$ H
Coverage Factor: 2

A_{s1}: Type B normal distribution
Value: 0.10005799 H
Expanded Uncertainty: $4.0\cdot10^{-7}$ H
Coverage Factor: 2

A_{s10}: Type B normal distribution
Value: $4.8\cdot10^{-7}$ H
Expanded Uncertainty: $1.14\cdot10^{-7}$ H
Coverage Factor: 2

δu_{s12}: Type B normal distribution
Value: $0\cdot10^{-7}$ H
Expanded Uncertainty: $0\cdot10^{-7}$ H
Coverage Factor: 2

value on 2/2006: 0.1000572 rel unc 20 ppm (k=2) value on 7/2007: 0.1000572 rel unc 21 ppm (k=2) 0

δu_{s13}: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: $3.1\cdot10^{-10}$ H

Computed TC of 3.1E-7 H/°K resolution on temperature measurements (k=2) : 0.001 °K

δu_{s14}: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: $2\cdot10^{-7}$ H

δL_{x2t}: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: $3.1\cdot10^{-9}$ H

TC = 3.1E-6 H/°K resolution of temperature measurement 0.001 °K

δL_0: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: 0 H

δLin: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: $7.5\cdot10^{-9}$ H

0.1% x (Ap-AN)/2

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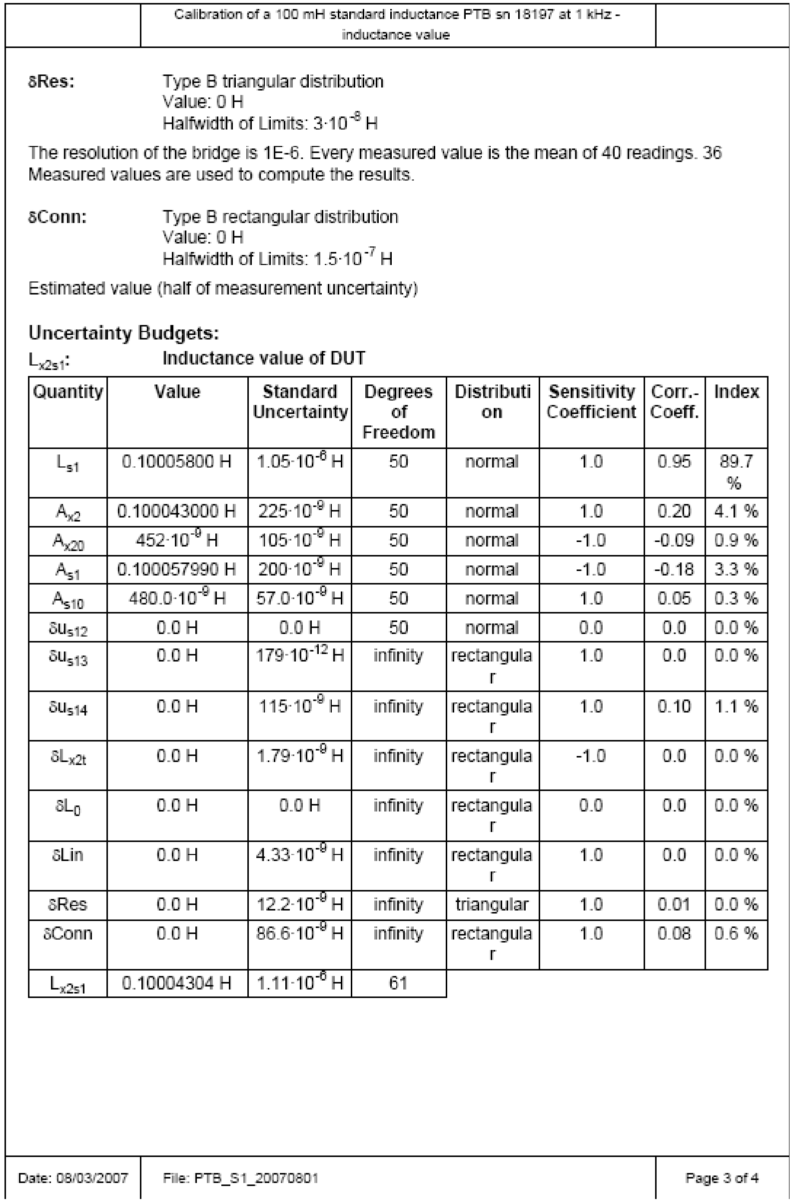


δRes: Type B triangular distribution
Value: 0 H
Halfwidth of Limits: $3 \cdot 10^{-8}$ H

The resolution of the bridge is 1E-6. Every measured value is the mean of 40 readings. 36 Measured values are used to compute the results.

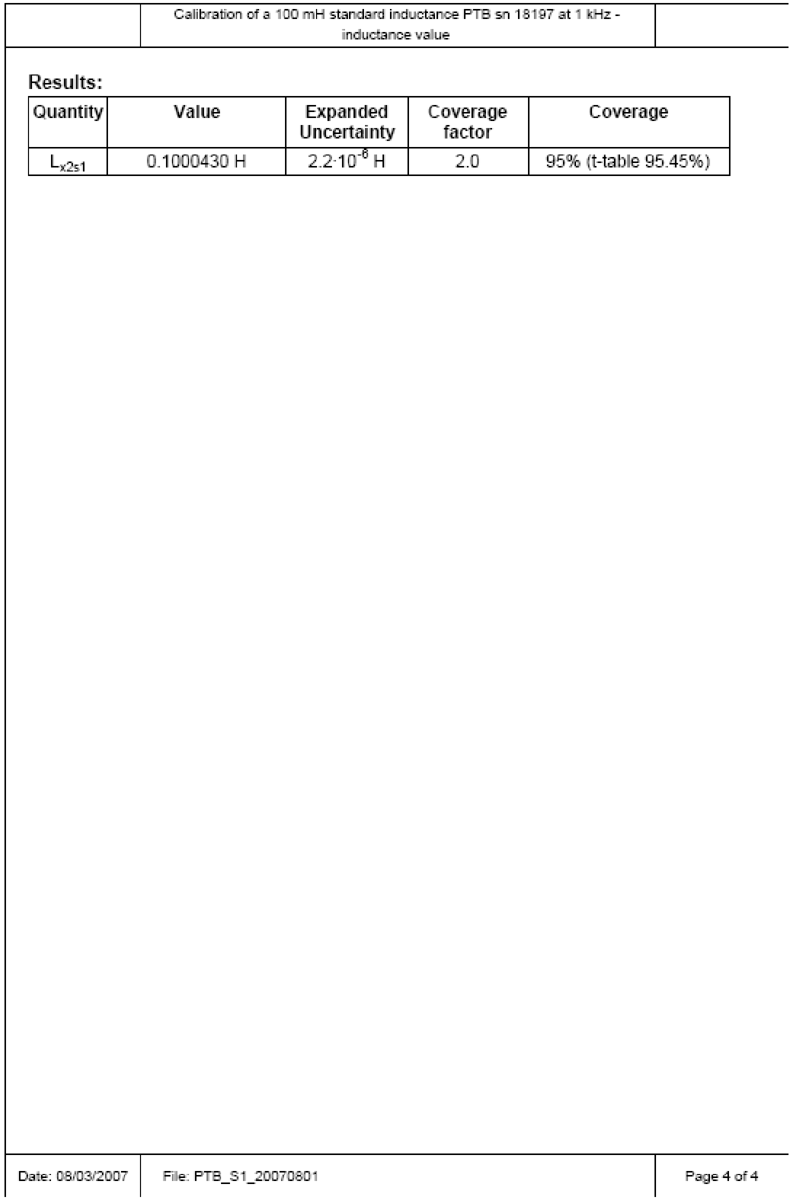
δConn: Type B rectangular distribution
Value: 0 H
Halfwidth of Limits: $1.5 \cdot 10^{-7}$ H

Estimated value (half of measurement uncertainty)

Uncertainty Budgets:

L_{x2s1}: **Inductance value of DUT**

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Corr.-Coeff.	Index
L_{s1}	0.10005800 H	$1.05 \cdot 10^{-6}$ H	50	normal	1.0	0.95	89.7 %
A_{x2}	0.100043000 H	$225 \cdot 10^{-9}$ H	50	normal	1.0	0.20	4.1 %
A_{x20}	$452 \cdot 10^{-9}$ H	$105 \cdot 10^{-9}$ H	50	normal	-1.0	-0.09	0.9 %
A_{s1}	0.100057990 H	$200 \cdot 10^{-9}$ H	50	normal	-1.0	-0.18	3.3 %
A_{s10}	$480.0 \cdot 10^{-9}$ H	$57.0 \cdot 10^{-9}$ H	50	normal	1.0	0.05	0.3 %
δu_{s12}	0.0 H	0.0 H	50	normal	0.0	0.0	0.0 %
δu_{s13}	0.0 H	$179 \cdot 10^{-12}$ H	infinity	rectangular	1.0	0.0	0.0 %
δu_{s14}	0.0 H	$115 \cdot 10^{-9}$ H	infinity	rectangular	1.0	0.10	1.1 %
δL_{x2t}	0.0 H	$1.79 \cdot 10^{-9}$ H	infinity	rectangular	-1.0	0.0	0.0 %
δL_0	0.0 H	0.0 H	infinity	rectangular	0.0	0.0	0.0 %
δLin	0.0 H	$4.33 \cdot 10^{-9}$ H	infinity	rectangular	1.0	0.0	0.0 %
δRes	0.0 H	$12.2 \cdot 10^{-9}$ H	infinity	triangular	1.0	0.01	0.0 %
δConn	0.0 H	$86.6 \cdot 10^{-9}$ H	infinity	rectangular	1.0	0.08	0.6 %
L_{x2s1}	0.10004304 H	$1.11 \cdot 10^{-6}$ H	61				



Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
L_{x2s1}	0.1000430 H	$2.2 \cdot 10^{-6}$ H	2.0	95% (t-table 95.45%)

D.2 Uncertainty budget DANIAmet-NMI (Denmark)

Remarks: The uncertainty budget table below contains the values for the PTB standard, but the only difference between the two travelling standards is the standard deviation of the mean which turned out slightly smaller for the INRIM standard.

Model equation that follows from the measurement set-up:

$$L_s = \frac{C_r + \Delta l_C}{(2\pi f)^2 (C_r + \Delta l_C)^2 + (G_r - G_C)^2} + \Delta_S + \Delta l_L + \Delta_{ext} + \Delta_{TC} + \Delta_{RH}$$

Description of the quantities in the model equation:

Quantity X_i	Description
C_r	Variable capacitor at resonance
Δl_C	Lead inductance between variable capacitor and travelling standard
F	Frequency
G_r	Conductance at resonance
G_C	Conductance of the variable capacitor
Δ_S	Standard deviation of the mean
Δl_L	Lead inductance between LCR-meter and travelling standard
Δ_{ext}	Influence due to external fields
Δ_{TC}	Influence of temperature
Δ_{RH}	Influence of relative humidity

Uncertainty budget table

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
C_r	248,718nF	5pF	Gauss k=2	B	–388200	–0,97 µH	∞
Δl_C		1µH~2,5pF	Uniform	B	–388200	–0,56 µH	∞
f	999,9937Hz	1ppm	Gauss k=2	B	$-1{,}97 \cdot 10^{-4}$	–0,10 µH	∞
G_r	209,501µS	200nS	Uniform	B	–16,814	–1,95 µH	∞
G_C	649nS	50nS	Uniform	B	16,814	0,49 µH	∞
Δ_S		2,9ppm	Gauss k=1	A	1	0,29 µH	6
Δl_L		500nH~5ppm	Uniform	B	1	0,18 µH	∞
Δ_{ext}		10ppm	Uniform	B	1	0,29 µH	∞
Δ_{TC}		0,1°C~3ppm	Uniform	B	1	0,58 µH	∞
Δ_{RH}		5%RH~5ppm	Uniform	B	1	0,29 µH	∞

Combined standard uncertainty	u_c	2,44 µH
Effective degrees of freedom	ν_{eff}	> 10000
Expanded uncertainty ($p \approx 95\%$)	U	4,9 µH

D.3 Uncertainty budget PTB (Germany)

Because of the many measurement periods and two standards we have to give 14 uncertainty budgets. But the differences are only in the numerical parts. So we exemplified the uncertainty budget by means of one standard and one measurement period (PTB standard, period II).

Model equation for bridge configurations

$$
\begin{aligned}
L_{1/2} &= (C_{1H} - C_{1A0})R_2R_3 + L_{X0} + TypB_T \\
&\quad - \omega^2 R_2 R_3 C_1 (k_2 + k_3 - \tau_2\tau_3) \\
&\quad - \omega^2 R_2^2 R_3^2 (C_{4H} C_{1H}{}^2 - C_{40} C_{1A0}^2) \\
&\quad + (C_{4H} - C_{40}) \frac{R_2^2 R_3^2}{R_1^2}
\end{aligned}
$$

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

quantity	**unit**	**Definition**
L_S	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_{X0}	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
$TypB_C$[1]		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
τ_2	s	time constant of resistor R_2

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

Quantities

quantity	type	value	half width, standard uncertainty	degrees of freedom
L_S	result			
C_1	type B normal	$1.00002297\cdot10^{-9}$ F	$200\cdot10^{-18}$ F	50
C_{1A}	interim result			
C_{1A0}	interim result			
C_{1H}	interim result			
C_{40}	type B rectangular	$1.00\cdot10^{-13}$ F	$1\cdot10^{-14}$ F	
C_{4H}	type B rectangular	$2.00\cdot10^{-13}$ F	$1\cdot10^{-14}$ F	
f	type B rectangular	1000 Hz	1 Hz	
k_2	type B rectangular	$1\cdot10^{-16}$ s^2	$1\cdot10^{-16}$ s^2	
k_3	type B rectangular	$1\cdot10^{-16}$ s^2	$1\cdot10^{-16}$ s^2	
L_{X0}	interim result			
R_1	interim result			
R_2	type A combined	10003.7112 Ω	$10.2\cdot10^{-3}$ Ω	1300
R_3	type A combined	10000.1992 Ω	$9.82\cdot10^{-3}$ Ω	1200
$TypB_C$	type B rectangular	0	$1\cdot10^{-4}$	
$TypB_L$	type B rectangular	0	$1\cdot10^{-3}$	
$TypB_{R1}$	type B rectangular	0	$1\cdot10^{-3}$	
$TypB_T$	type B rectangular	0 H	$3\cdot10^{-9}$ H	
ω	interim result			
π	constant	3.141592653589		
τ_2	type B rectangular	$6\cdot10^{-10}$ s	$3.5\cdot10^{-9}$ s	
τ_3	type B rectangular	$6\cdot10^{-10}$ s	$3.5\cdot10^{-9}$ s	

Measurements

Observation No.	c_{1A} **in F**	c_{1A0} **in F**	l_{X0} **in H**	r_1 **in Ω**
1	$1.00204\cdot10^{-12}$	$1.04268\cdot10^{-12}$	$3.79\cdot10^{-6}$	1191182.0
2	$1.00560\cdot10^{-12}$	$1.04592\cdot10^{-12}$	$3.78\cdot10^{-6}$	1191201.0
3	$1.00631\cdot10^{-12}$	$1.04669\cdot10^{-12}$	$3.79\cdot10^{-6}$	1191190.0
4	$1.00384\cdot10^{-12}$	$1.04453\cdot10^{-12}$	$3.82\cdot10^{-6}$	1191192.0
5	$1.00364\cdot10^{-12}$	$1.04359\cdot10^{-12}$	$3.81\cdot10^{-6}$	1191173.0
6	$1.00526\cdot10^{-12}$	$1.04252\cdot10^{-12}$	$3.88\cdot10^{-6}$	1191190.0
Arithmetic mean	$1.00445\cdot10^{-12}$	$1.04432\cdot10^{-12}$	$3.812\cdot10^{-6}$	$1.191188\cdot10^{6}$ Ω
Standard uncertainty	$640\cdot10^{-18}$ F	$700\cdot10^{-18}$ F	$14.9\cdot10^{-9}$ H	3.89 Ω
degrees of freedom	5	5	5	5

Correlation coefficients

r(τ_2,τ_3)	0.5
r(c_{1A},c_{1A0})	0.67
r(c_{1A},l_{XO})	0.11
r(c_{1A},r_1)	0.60
r(c_{1A0},l_{XO})	-0.60
r(c_{1A0},r_1)	0.53
r(l_{XO},r_1)	-0.07
r(R_2,R_3)	0.5
r(C_{40},C_{4H})	1

Uncertainty budget

Quantity	value	standard uncertainty	degrees of freedom	sensitivity coefficient	uncertainty contribution	index
C_1	$1.000022970\cdot10^{-9}$ F	$200\cdot10^{-18}$ F	50	$100\cdot10^{6}$	$20\cdot10^{-9}$ H	1.1 %
C_{1A}	$1.004448\cdot10^{-12}$ F	$642\cdot10^{-18}$ F	5			
c_{1A}	$1.004448\cdot10^{-12}$ F	$640\cdot10^{-18}$ F	5	$100\cdot10^{6}$	$64\cdot10^{-9}$ H	3.4 %
C_{1A0}	$1.044322\cdot10^{-15}$ F	$702\cdot10^{-18}$ F	5			
c_{1A0}	$1.044322\cdot10^{-15}$ F	$700\cdot10^{-18}$ F	5	$-100\cdot10^{6}$	$-70\cdot10^{-9}$ H	7.2 %
C_{1H}	$1.001027418\cdot10^{-9}$ F	$673\cdot10^{-18}$ F	6			
C_{40}	$100.00\cdot10^{-15}$ F	$5.77\cdot10^{-15}$ F	∞	-7100	$-41\cdot10^{-12}$ H	0.0 %
C_{4H}	$200.00\cdot10^{-15}$ F	$5.77\cdot10^{-15}$ F	∞	$-390\cdot10^{3}$	$-2.20\cdot10^{-9}$ H	0.0 %
f	1000.00 Hz	0.577 Hz	∞	$-160\cdot10^{-12}$	$-91\cdot10^{-12}$ H	0.0 %
k_2	$100.0\cdot10^{-18}$ s^2	$57.7\cdot10^{-18}$ s^2	∞	$3.9\cdot10^{6}$	$230\cdot10^{-12}$ H	0.0 %
k_3	$100.0\cdot10^{-18}$ s^2	$57.7\cdot10^{-18}$ s^2	∞	$3.9\cdot10^{6}$	$230\cdot10^{-12}$ H	0.0 %
L_{X0}	$3.8117\cdot10^{-6}$ H	$15.1\cdot10^{-9}$ H	5			
l_{X0}	$3.8117\cdot10^{-6}$ H	$14.9\cdot10^{-9}$ H	5	1.0	$15\cdot10^{-9}$ H	2.7 %
R_1	$1.191188\cdot10^{6}$ Ω	688 Ω	∞			
r_1	$1.19118800\cdot10^{6}$ Ω	3.89 Ω	5	$-1.2\cdot10^{-15}$	$-4.6\cdot10^{-15}$ H	0.0 %
R_2	10003.7112 Ω	$10.2\cdot10^{-3}$ Ω	1300	$10\cdot10^{-6}$	$100\cdot10^{-9}$ H	43.7 %
R_3	10000.19915 Ω	$9.82\cdot10^{-3}$ Ω	1200	$10\cdot10^{-6}$	$98\cdot10^{-9}$ H	41.8 %
$TypB_C$	0.0	$57.7\cdot10^{-6}$	∞	$-4.0\cdot10^{-6}$	$-230\cdot10^{-12}$ H	0.0 %
$TypB_L$	0.0	$577\cdot10^{-3}$	∞	$3.8\cdot10^{-6}$	$2.2\cdot10^{-9}$ H	0.0 %
$TypB_{R1}$	0.0	$577\cdot10^{-6}$	∞	$-1.4\cdot10^{-9}$	$-810\cdot10^{-15}$ H	0.0 %
$TypB_T$	0.0 H	$1.73\cdot10^{-9}$ H	∞	1.0	$1.7\cdot10^{-9}$ H	0.0 %
ω	6283.19 s^{-1}	3.63 s^{-1}	∞			
π	3.1415926535898					
τ_2	$600\cdot10^{-12}$ s	$2.02\cdot10^{-9}$ s	∞	$-2.4\cdot10^{-3}$	$-4.8\cdot10^{-12}$ H	0.0 %
τ_3	$600\cdot10^{-12}$ s	$2.02\cdot10^{-9}$ s	∞	$-2.4\cdot10^{-3}$	$-4.8\cdot10^{-12}$ H	0.0 %
L_S	0.100041147 H	$187\cdot10^{-9}$ H	480			

Result

quantity	estimator	combined standard uncertainty	relative expanded uncertainty	coverage factor	coverage
L_S	0.10004115 H	$187\cdot10^{-9}$ H	$3.7\cdot10^{-6}$	2.0	t-table 95%

D.4 Uncertainty budget MKEH (Hungary)

Model equation that follows from the measurement set-up:

$$L_x = \left(L_s + \delta L_D + \delta L_R + \delta L_u + \delta L_C + \delta L_{TS}\right) \cdot \frac{\left(R_X + \delta R_{iX}\right)}{\left(R_S - \delta R_{iS}\right)}$$, where

L_x	unknown inductance,
L_s	reference inductance,
δL_D	uncertainty from the long term stability of the reference inductance,
δL_U	uncertainty from the unbalance of the bridge,
δL_R	uncertainty from the repeatability of the bridge,
δL_C	uncertainty from the inductivity of the connection to the bridge
δL_{TS}	temperature correction of the reference inductance,
R_x	the resistance of the balancing arm after balancing the bridge, when measuring L_x
R_s	the resistance of the balancing arm after balancing the bridge, when measuring L_s
δR_{ix}	uncertainty of the resistance measurements of the balancing arm of the bridge, when measuring L_x
δR_{is}	uncertainty of the resistance measurements of the balancing arm of the bridge, when measuring L_s
r	R_x/R_s , ratio of the resistance of the balancing arms when measuring L_x and L_s.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Proba-bility distri-bution	Method of evalua-tion	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
L_s	10.00117 mH	0.0001 mH	normal	B	10	0.001 mH	12
δL_D	0	0.0005 mH	rectangular			0.005 mH	inf.
δL_R	0	0.0001 mH	normal			0.001 mH	9
δL_U	0	0.0002 mH	rectangular			0.002 mH	20
δL_C	0	0.00006 mH	rectangular			0.0006 mH	19
δL_{TS}	0	0.25 K	normal		$5 \cdot 10^{-5}$ mH/K	0.0001 mH	inf.
r_{INRIM}	10.0167	0.00008	normal		100 mH	0.008 mH	8
r_{PTB}	10.0176	0.00008	normal		100 mH	0.008 mH	

Combined standard uncertainty	u_c	0,0098 mH
Effective degrees of freedom	ν_{eff}	17
Expanded uncertainty ($p \approx 95\%$)	U	0,0207 mH

D.5 Uncertainty budget NML (Ireland)

Model equation that follows from the measurement set-up:

$$L_X = r_X \cdot L_S^{CAL} \cdot [1 + \delta_t + \alpha \cdot (T - T_{CAL}) + \delta_H + \delta_I + \delta_{LIN} + \delta_Q)] + (\delta_Z - \delta_Z')$$

Description of the quantities in the model equation:

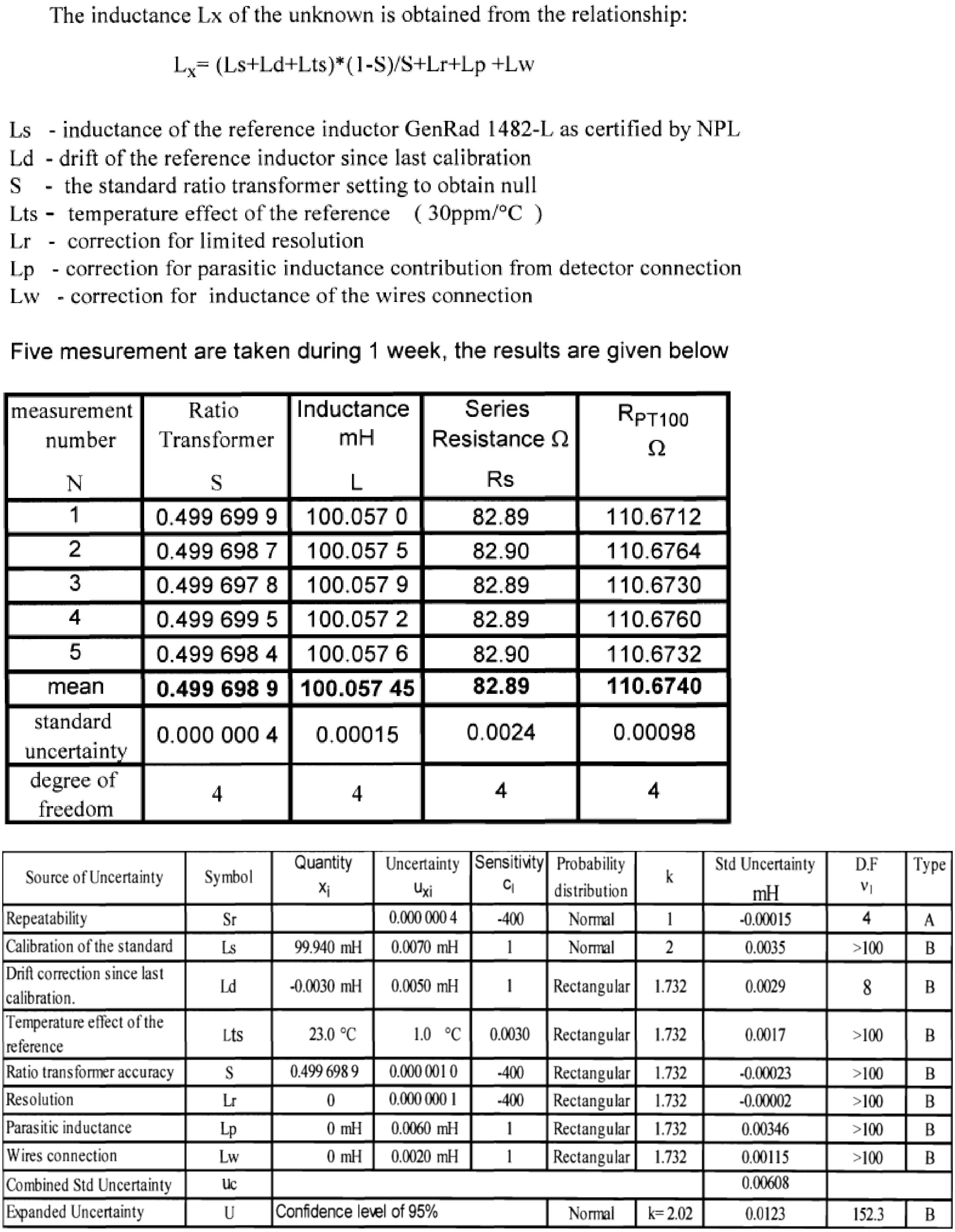
Quantity X_i	Description
r_X	Ratio of impedance meter readings
L_S^{CAL}	Certified value of NML 100 mH reference standard
δ_t	Correction for temporal drift of NML ref. standard
α	Temperature coefficient of NML reference standard
T	Measuring temperature
T_{CAL}	Calibration temperature of NML Reference standard
δ_H	Correction for humidity effects on NML reference standard
δ_I	Correction for effect of measuring current on NML reference standard
δ_{LIN}	Correction for non-linearity of the impedance meter
δ_Q	Correction for the effect on in-phase components on reading of impedance meter
δ_Z, δ'_Z	Corrections due to uncompensated stray impedances

Uncertainty budget table

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
r_X	1.000 050	0.000 008	Norm	A	100 mH	0.000 8 mH	10
L_S^{CAL}	100.002 mH	0.003 5 mH	Norm	B	1	0.003 5 mH	$>10^4$
δ_t	0.000 000	0.000 082	Triangular	B	100 mH	0.008 2 mH	$>10^4$
α	0.000 008 K^{-1}	0.000 005 K^{-1}	Uniform	B	300 mHK	0.001 5 mH	$>10^4$
$(T-T_{CAL})$	3 K	0.1 K	Uniform	B	0.000 8 mHK^{-1}	0.000 1 mH	$>10^4$
δ_H	0.000 000	0.000 014	Uniform	B	100 mH	0.001 4 mH	$>10^4$
δ_I	0.000 000	0.000 014	Uniform	B	100 mH	0.001 4 mH	$>10^4$
δ_{LIN}	0.000 000	0.000 050	Uniform	B	100 mH	0.005 0 mH	$>10^4$
δ_Q	0.000 000	0.000 020	Uniform	B	100 mH	0.002 0 mH	$>10^4$
$\delta_Z - \delta'_Z$	0.000 000	0.000 050	Uniform	B	100 mH	0.005 0 mH	$>10^4$

Combined standard uncertainty	u_c	0.011 7 mH
Effective degrees of freedom	ν_{eff}	$>10^4$
Expanded uncertainty ($p \approx 95\%$)	U	0.023 mH

D.6 Uncertainty budget IAI SL (Israel)



The inductance Lx of the unknown is obtained from the relationship:

$$L_x = (Ls+Ld+Lts)*(1-S)/S+Lr+Lp+Lw$$

Ls - inductance of the reference inductor GenRad 1482-L as certified by NPL
Ld - drift of the reference inductor since last calibration
S - the standard ratio transformer setting to obtain null
Lts - temperature effect of the reference (30ppm/°C)
Lr - correction for limited resolution
Lp - correction for parasitic inductance contribution from detector connection
Lw - correction for inductance of the wires connection

Five mesurement are taken during 1 week, the results are given below

measurement number N	Ratio Transformer S	Inductance mH L	Series Resistance Ω Rs	R_{PT100} Ω
1	0.499 699 9	100.057 0	82.89	110.6712
2	0.499 698 7	100.057 5	82.90	110.6764
3	0.499 697 8	100.057 9	82.89	110.6730
4	0.499 699 5	100.057 2	82.89	110.6760
5	0.499 698 4	100.057 6	82.90	110.6732
mean	**0.499 698 9**	**100.057 45**	**82.89**	**110.6740**
standard uncertainty	0.000 000 4	0.00015	0.0024	0.00098
degree of freedom	4	4	4	4

Source of Uncertainty	Symbol	Quantity x_i	Uncertainty u_{xi}	Sensitivity c_i	Probability distribution	k	Std Uncertainty mH	D.F ν_i	Type
Repeatability	Sr		0.000 000 4	-400	Normal	1	-0.00015	4	A
Calibration of the standard	Ls	99.940 mH	0.0070 mH	1	Normal	2	0.0035	>100	B
Drift correction since last calibration.	Ld	-0.0030 mH	0.0050 mH	1	Rectangular	1.732	0.0029	8	B
Temperature effect of the reference	Lts	23.0 °C	1.0 °C	0.0030	Rectangular	1.732	0.0017	>100	B
Ratio transformer accuracy	S	0.499 698 9	0.000 001 0	-400	Rectangular	1.732	-0.00023	>100	B
Resolution	Lr	0	0.000 000 1	-400	Rectangular	1.732	-0.00002	>100	B
Parasitic inductance	Lp	0 mH	0.0060 mH	1	Rectangular	1.732	0.00346	>100	B
Wires connection	Lw	0 mH	0.0020 mH	1	Rectangular	1.732	0.00115	>100	B
Combined Std Uncertainty	uc						0.00608		
Expanded Uncertainty	U	Confidence level of 95%			Normal	k= 2.02	0.0123	152.3	B

D.7 Uncertainty budget VSL (The Netherlands)

In the resonance bridge, the inductance standard (and its connecting cables) is treated as a parallel circuit of an ideal inductor L_p and an ideal conductance $G_p = 1/R_p$. The balance equations of the bridge are given by:

$$\frac{1}{R_p} = \frac{1}{R_x} - \Delta G - G_C$$

$$L_p = \frac{1}{\omega^2 C_p}$$

Where C_p is defined as:

$$C_p = C + \Delta C + C_l - C_x$$

G_c is the parasitic conductance of the capacitor, C.
C_x is the parasitic capacitance of the resistor, R_x.
C_l is the parasitic capacitance introduced by the connectors that are used to connect the inductance standard (0 fF ± 20 fF).

Self-inductance standards are commonly characterized in terms of a series inductance, L_s and a series resistances, R_s. The values of L_p and G_p can be transformed in values of L_s and R_s.

The quality factor Q is defined as:

$$Q = \omega R_p C_p$$

where $\omega = 2\pi f$, where f is the resonance frequency.
L_s and R_s are now found from:

$$L_s = \frac{L_p}{1 + \frac{1}{Q^2}} - l_w$$

$$R_s = \frac{R_p}{1 + Q^2} - r_w$$

where l_w and r_w are respectively the series inductance and series resistance of the connecting leads to the standard inductor.

Using the equations above, the uncertainty contributions of each of the parameters can be found.

Note: The measurements were performed at 997 Hz and 1003 Hz in order to avoid interference from the 50 Hz line power. All results were corrected to the nominal frequency of 1000 Hz, assuming that L_s is proportional with f^2.

Description of the quantities in the model equation:

Quantity X_i	Description
L_s	Series inductance of the standard under test (DUT)
R_s	Series resistance of the DUT
l_w	Series inductance of the cable connecting the DUT to the bridge
r_w	Series resistance of the cable connecting the DUT to the bridge
Q	Quality factor of the DUT, at the measurement frequency f
L_p	Equivalent parallel inductance of the DUT including the connecting cable, at frequency f.
R_p	Equivalent parallel resistance of the DUT including the connecting cable ($R_p = 1 / G_p$)
C_p	Equivalent negative parallel capacitance of the DUT incl. the cable at frequency f.
C	Value of the decade capacitor in the resonance bridge
ΔC	Capacitance setting on the GR1621 at bridge balance (fine adjustment in addition to the decade capacitor)
C_l	Parasitic capacitance introduced by the connectors that are used to connect the DUT to the cable
C_x	Parasitic capacitance of the decade resistor in the resonance bridge
R_x	($R_x = 1 / G_x$) Parallel resistance of the decade resistor in the resonance bridge
ΔG	Conductance setting on the GR1621 at bridge balance (fine adjustment in addition to the decade resistor)
G_c	Parasitic conductance of the decade capacitor
f	Measurement frequency ($\omega = 2\pi f$, where ω is the radial frequency)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
C	2.47E-07 F	2.47E-12 F	normal	B	-3.90E+05 H/F	-9.66E-07 H	30
ΔC	9.06E-11 F	2.89E-14 F	rectangular	B	-3.90E+05 H/F	-1.13E-08 H	20
C_x	-1.43E-11 F	1.15E-13 F	rectangular	B	-3.90E+05 H/F	-4.51E-08 H	20
C_l	0.00E+00 F	1.15E-14 F	rectangular	B	-3.90E+05 H/F	-4.51E-09 H	20
R_x	4799.415 Ω						
G_x	2.084E-04 S	1.20E-09 S	rectangular	B	-1.68E+01 H/S	-2.02E-08 H	20
ΔG	1.50E-09 S	2.89E-08 S	rectangular	B	-1.68E+01 H/S	-4.85E-07 H	20
G_c	6.44E-07 S	2.89E-08 S	rectangular	B	-1.68E+01 H/S	-4.85E-07 H	20
f	1003.0 Hz						
ω	6301.953 rad/s	6.30E-03 rad/s	normal	B	-3.12E-05 Hs/rad	-1.97E-07 H	100
dL/df	4.00E-08 H/Hz	2.89E-08 H/Hz	rectangular	B	2.99 Hz	8.62E-08 H	20
l_w	1.62E-06 H	1.73E-07 H	rectangular	B	1	1.73E-07 H	10
r_w	1.28E-01 Ω	1.15E-02 Ω	rectangular	B			
std	0 H	3.00E-06 H/H	normal	A	1.00E-01 H	3.00E-07 H	5
			Combined standard uncertainty		u_c	1.25E-06 H	
			Effective degrees of freedom		ν_{eff}	68	
			Expanded uncertainty (p = 95%)		U	26 µH/H	
C_p	2.47E-07 F						
G_p	2.08E-04 S						
L_p	0.1018213 H						
Q	7.5026678						
L_s	0.1000424 H						
R_s	83.905635 Ω						

D.8 Uncertainty budget GUM (Poland)

Model equation that follows from the measurement set-up:

$$L_s = L_C + \delta L_K + \delta L_d + \delta L_{CW} + \delta L_{TX}$$

Description of the quantities in the model equation:

Quantity X_i	Description
L_C	inductance value obtained from C-L comparison
δL_K	correction due to comparison error
δL_d	correction due to comparator resolution
δL_{CW}	correction due to reference standard uncertainty
δL_{TX}	correction due to temperature influence travelling standard

Uncertainty budget table (sn. 18197)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
L_C	100,0409 mH	0,6*10e-4 mH	normal	A	1	0,6*10e-4 mH	200
δL_K	0	5,8*10e-4 mH	rectang.	B	1	5,8*10e-4 mH	∝
δL_d	0	2,9*10e-7 mH	rectang.	B	1	2,9*10e-7 mH	∝
δL_{CW}	0	4,3*10e-4 nF	normal	B	-3,95 mH/nF	-1,7*10e-3 mH	∝
δL_{TX}	0	5,8*10e-5 mH	rectang.	B	1	5,8*10e-5 mH	∝
L_s	100,0409 mH						

Combined standard uncertainty	u_c	0,0018 mH
Effective degrees of freedom	ν_{eff}	>200, assumed k=2
Expanded uncertainty ($p \approx 95\%$)	U	0,0036 mH

Uncertainty budget table (sn. 13975)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
L_C	100,0555 mH	0,6*10e-4 mH	normal	A	1	0,6*10e-4 mH	200
δL_K	0	5,8*10e-4 mH	rectang.	B	1	5,8*10e-4 mH	∝
δL_d	0	2,9*10e-7 mH	rectang.	B	1	2,9*10e-7 mH	∝
δL_{CW}	0	4,3*10e-4 nF	normal	B	-3,95 mH/nF	-1,7*10e-3 mH	∝
δL_{TX}	0	5,8*10e-5 mH	rectang.	B	1	5,8*10e-5 mH	∝
L_s	100,0555 mH						

Combined standard uncertainty	u_c	0,0018 mH
Effective degrees of freedom	ν_{eff}	>200, assumed k=2
Expanded uncertainty ($p \approx 95\%$)	U	0,0036 mH

Model equation that follows from the measurement set-up for reference standard C_W:

$$C_W = C_{CA+1413} + \delta B_{AH} + \delta B_{AHd} + \delta C_{TCA} + \delta C_{T1413}$$

Quantity X_i	Description
$C_{CA+1413}$	capacitance value obtained from AH bridge
δB_{AH}	correction due to AH bridge error
δB_{AHd}	correction due to AH bridge resolution
δC_{TCA}	correction due to temperature influence thermostated C_{CA}
δC_{T1413}	correction due to temperature influence C_{1413}

Uncertainty budget table (C_W)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
$C_{CA+1413}$	25333 pF	0,003 pF	normal	A	1	0,003 pF	50
δB_{AH}	0	0,425 pF	rectang.	B	1	0,425 pF	∝
δB_{AHd}	0	0,003 pF	normal	B	1	0,003 pF	∝
δC_{TCA}	0	0,043 pF	rectang.	B	1	0,043 pF	∝
δC_{T1413}	0	0,0038 pF	rectang.	B	1	0,0038 pF	∝
C_W						0,427 pF	

Combined standard uncertainty	u_c	0,43 pF
Effective degrees of freedom	ν_{eff}	>200, assumed k=2
Expanded uncertainty ($p \approx 95\%$)	U	0,86 pF

D.9 Uncertainty budget IPQ (Portugal)

The measurements were carried out at IPQ's lowest uncertainty level. IPQ's uncertainties (in µH/H) at 100 mH are shown in the table below. IPQ does not have recognized CMC’s for Inductance yet.
For the uncertainty budget, the ISO Guide to the Expression of Uncertainty in Measurement has been followed.

Uncertainty (µH/H)						
Uncertainty Components		Probability distribution/ Method of evaluation	Uncertainty contribution $u(x_i)$	Sensitivity coefficient c_i	Quadratic components $[c_i \cdot u(x_i)]^2$	Degrees of freedom ν_i
20 Measurements	Experimental standard deviation	normal/A	0.80	1	0.64	$n - 1 = 19$
Bridge & Connections	Overall range	rectangular/A	4.10	1	16.81	∞
Reference standard	Traceability	rectangular/B	20.00	1	412.09	∞
	Drift	normal/A	0.30	1		∞
Other influences		rectangular/B	2.00	1	4.00	∞
Combined standard uncertainty uc(y) =			20.77		[ν_{eff}]=	∞
Coverage factor k =			2			
Expanded uncertainty (at 95%) U =			42			

D.10 Uncertainty budget INM (Romania)

Remarks:

1) Self-inductance L_S measured in two - terminal connection of the travelling standard.

2) Measurement method applied: substitution against a 100 mH reference standard inductor

3) SI traceability of the 100 mH inductor used as reference standard within the measurements is provided by PTB

4) In the model equation, L_x stands for the unknown self - inductance of the inductor being measured, while the index "e" refers to the reference standard

Model equation that follows from the measurement set-up:

$$L_x = (L_e + \Delta L_{eI} + \delta L_{drift} + \Delta L_{eT}) \cdot K_c \cdot K - \delta L_{xT}$$

Description of the parameters in the equation:

Param.	Description
L_e	Inductance of the reference standard inductor
ΔL_{eI}	Variation of the self-inductance of the reference standard due to the intensity of the measurement current
δL_{drift}	Variation of the self-inductance of the reference standard from the last calibration
ΔL_{eT}	Variation of the self-inductance of the reference standard due to temperature changes
K_c	Correction factor due to some systematic effects within the measurement setup (finite resolution of the RLC-meter, parasitic coupling, variation of the inductance of the measurement cables)
$K = L_{ix}/L_{ie}$	Ratio between the self-inductances of the measured inductor and the reference inductor, displayed by the RLC-meter
δL_{xT}	Variation of the self-inductance of the measured inductor due to temperature changes

Uncertainty budget table for the measurement of the PTB sn 18197 inductor

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_\mathrm{i})$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_\mathrm{i} \cdot u(x_\mathrm{i})$	Degrees of freedom ν_i
L_e	99.996 mH	0.002000 mH	normal	B	1	0.002000 mH	inf
□L_{eI}	0.00054 mH	0.000002 mH	rectangular	B	1	0.000002 mH	inf
δL_{drift}	0.00250 mH	0.003200 mH	rectangular	B	1	0.003200 mH	inf
□L_{eT}	0.00014 mH	0.000040 mH	rectangular	B	1	0.000040 mH	inf
δL_{xT}	0.00000 mH	0.000000 mH	rectangular	B	-1	0.000000 mH	inf
K_c	1.00000	0.000013	triangular	B	100 mH	0.001266 mH	inf
$K = L_{ix}/L_{ie}$	1.000549	0.000001	normal	A	100 mH	0.000149 mH	29
L_x	100.0540 mH						

Combined standard uncertainty	u_c	0.0040 mH
Effective degrees of freedom	ν_eff	9.30695E+11
Expanded uncertainty ($p \approx 95\%$)	U	0.0080 mH

Uncertainty budget table for the measurement of the INRIM sn 13975 inductor

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_\mathrm{i})$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_\mathrm{i} \cdot u(x_\mathrm{i})$	Degrees of freedom ν_i
L_e	99.996 mH	0.002000 mH	normal	B	1	0.002000 mH	inf
ΔL_{eI}	0.00054 mH	0.000002 mH	rectangular	B	1	0.000002 mH	inf
δL_{drift}	0.00250 mH	0.003200 mH	rectangular	B	1	0.003200 mH	inf
ΔL_{eT}	0.00014 mH	0.000040 mH	rectangular	B	1	0.000040 mH	inf
δL_{xT}	0.00000 mH	0.000000 mH	rectangular	B	-1	0.000000 mH	inf
K_c	1.00000	0.000005	triangular	B	100 mH	0.000490 mH	inf
$K = L_{ix}/L_{ie}$	1.000645	0.000001	normal	A	100 mH	0.000090 mH	29
L_x	100.0637 mH						

Combined standard uncertainty	u_c	0.0038 mH
Effective degrees of freedom	ν_eff	6.42283E+12
Expanded uncertainty ($p \approx 95\%$)	U	0.0076 mH

D.11 Uncertainty budget SIQ (Slovenia)

Inductance L_S is derived from the following equation:

$$L_s = (L_e + dL_d) \bullet \left(\frac{L_{rx} + dL_{r\_LCR}}{L_{re} + dL_{r\_LCR}} \right) + dL_{TA\_LCR}$$

Description of the quantities in the model equation:

Quantity X_i	Description
L_e	Inductance of standard inductor
dL_d	Drift of standard inductor from its last calibration
L_{rx}	Inductance reading from LCR meter of unknown inductor
L_{re}	Inductance reading from LCR meter of standard inductor
dL_{r_LCR}	Correction factor due to LCR indicator resolution
dL_{TA_LCR}	Correction factor due to LCR meter transfer accuracy

Contributions to standard uncertainty

Inductance of standard inductor (L_e)

The value of inductance is taken from last calibration certificate of reference standard inductor. The uncertainty for this value is also taken from calibration certificate as expanded associated uncertainty with normal probability distribution and coverage factor k=2.

Drift of standard inductor from its last calibration (dL_d)

Drift is assumed on the basis analysis of difference between the calibrated values of standard inductor from all previous certificates. Its value is estimated to be 0H with associated uncertainty at rectangular distribution witch calculated from linear fit multiplied by factor of expected changes of standard inductor in 2 year.

Inductance reading from LCR meter of unknown inductor (L_{rx})

Inductance reading is obtained by calculated mean value of the LCR display readings noted during calibration. This quantity has a standard uncertainty calculated as standard deviation of the mean of all the readings that have been used for calculation of the mean. This uncertainty contribution is assumed to have normal probability distribution.

Inductance reading from LCR meter of standard inductor (L_{re})

Inductance reading is obtained by calculated mean value of the LCR display readings noted during calibration. This quantity has a standard uncertainty calculated as standard deviation of the mean of all the readings that have been used for calculation of the mean. This uncertainty contribution is assumed to have normal probability distribution.

Correction factor due to LCR indicator resolution (dL_{r_LCR})

The quantity corresponding to the least significant digit if the LCR display equals the finite resolution of the display. The correction is estimated to be 0 H with associated uncertainty ±half the resolution (half the magnitude of the least significant digit) with rectangular distribution. If the LCR has analogue display the resolution is estimated according to the ability to read the value from the display but it must not be less than one third of the value between two minor lines on the display.

$$u\_r = \frac{DUT\_resolution}{2}$$

Correction factor due to LCR meter transfer accuracy (dL_{TA_LCR})

This correction is assumed to be 0 H. Uncertainty is obtained from reference LCR meter accuracy specification. This uncertainty contribution is assumed to have rectangular probability distribution. Transfer accuracy *Ae* includes basic accuracy, impedance proportional factor, cable length factor, stability, temperature coefficient, linearity, and repeatability.

$$u\_TAaac = \frac{Lse * Ae(\%)}{100}$$

Uncertainty budget table

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
Le	100,018 mH	0,003500 mH	normal	B	1	0,003500 mH	1E+99
dLd	0,0 mH	-0,000008 mH	rectangular	A	1	-0,000008 mH	4E+00
$dLrx$	100,108 mH	0,000548 mH	normal	A	1	0,000548 mH	4E+00
$dLre$	100,066 mH	0,000548 mH	normal	A	1	0,000548 mH	1E+99
dL_{r_LCR}	0,0 mH	0,000003 mH	rectangular	A	-1	-0,000003 mH	1E+99
dL_{TA_LCR}	0,0 mH	0,029464 mH	rectangular	A	-1	-0,029464 mH	1E+99

Combined standard uncertainty	u_c	0,030 mH
Effective degrees of freedom	ν_{eff}	3E+09
Expanded uncertainty ($p \approx 95\%$)	U	0,060 mH

D.12 Uncertainty budget NMISA (South Africa)

Remarks: Uncertainty budget for the 100 mH @ 1 kHz measurements using the substitution method

Model equation that follows from the measurement set-up:

$$L_x = \frac{L_{x(\mathrm{Re}ad)}}{L_{s(\mathrm{Re}ad)}} * (L_{s(Cert)} + L_{s(Dr)} + L_{s(Tc)})$$

Description of the quantities in the model equation:

Quantity X_i	Description
$L_{x(\mathrm{Re}ad)}$	1693 RLC Digibridge reading of 100 mH travelling standard
$L_{s(\mathrm{Re}ad)}$	1693 RLC Digibridge reading of 100 mH laboratory standard
$L_{s(Cert)}$	100 mH reference inductor certified value
$L_{s(Dr)}$	Drift of 100 mH reference inductor since last calibration
$L_{s(Tc)}$	Correction due to temperature coefficient of 100 mH reference inductor
s	Standard deviation of reported mean

Uncertainty budget table

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_\mathrm{i})$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_\mathrm{i} \cdot u(x_\mathrm{i})$	Degrees of freedom ν_i
$L_{s(Cert)}$	7 µH	3,5 µH	Normal	B	1	3,5 µH	∞
$L_{s(Dr)}$	1,62 µH	0,94 µH	Rectangular	B	1	0,94 µH	∞
$L_{s(Tc)}$	3,3 µH	1,91 µH	Rectangular	B	1	1,91 µH	∞
s	2,07 µH	2,07 µH	Normal	A	1	2,07 µH	34

Combined standard uncertainty	u_c	4,59 µH
Effective degrees of freedom	ν_eff	730
Expanded uncertainty ($p \approx 95\%$)	U	9 µH

D.13 Uncertainty budget METAS (Switzerland)

sn. 13975

Model equation that follows from the measurement setup:

$$L_s = -R_t\left(\frac{B_m - \varepsilon_B}{\omega} + \left(A_m - \varepsilon_A\right)\cdot\tau\right) + \varepsilon_{Zin} + \varepsilon_{Kelvin} - L_{short}$$

Description of the quantities in the model equation:

Quantity X_i	Description
R_t	resistance value of the reference resistor at 1 kHz (traceable to R_{K-90})
τ	time constant of the reference resistor
ω	angular frequency of the applied signal
A_m	real part of the measured complex ratio of voltages
B_m	imaginary part of the measured complex ratio of voltages
ε_A	error on the measured value of A due to the non linearity of the input stage of the detector
ε_B	error on the measured value of B due to the non linearity of the input stage of the detector
ε_{Zin}	error on Ls due to the finite impedance of the input stage of the detetcor
ε_{Kelvin}	error on Ls due to the finite resolution of the Kelvin Balance
L_{short}	residual inductance of a short

Uncertainty budget table:

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
R_t	667.0335	0.0019	Normal	A&B	1.50E-04	0.28	50
τ	0.74	4.00	Normal	A&B	8.29E-08	0.33	50
ω	6283.146	0.006	Normal	A&B	1.59E-05	0.10	50
A_m	-0.12426661	0.00000040	Normal	A	4.94E-07	0.00	137
B_m	-0.94255573	0.00000111	Normal	A	1.06E-01	0.12	137
ε_A	0	0.00000321	Box	B	4.94E-07	0.00	5
ε_B	0	0.00000756	Box	B	1.06E-01	0.46	5
ε_{Zin}	0	3.72E-07	Box	B	1	0.21	5
ε_{Kelvin}	0	5.63E-08	Box	B	1	0.03	5
L_{short}	0	3.00E-07	Normal	A&B	1	0.30	5

Combined standard uncertainty	u_c	0.75 µH
Effective degree of freedom	ν_i	28
Expanded uncertainty (p=95%)	U	**1.54 µH**
Series Inductance	L_s	**100.063 99 mH**

Model equation that follows from the measurement setup:

$$R_s = -R_t \left\{ \left(A_m - \varepsilon_A \right) - \omega \cdot \left(B_m - \varepsilon_B \right) \cdot \tau \right\} + \varepsilon'_{Zin} + \varepsilon'_{Kelvin} - R_{short}$$

Uncertainty budget table:

Quantity	Estimate	Standard uncertainty	Probability distribution	Method of evaluation	Sensitivity coefficient	Uncertainty contribution	Degrees of freedom
X_i	x_i	$u(x_i)$		(A, B)	c_i	$c_i * u(x_i)$	ν_i
R_t	667.0335	0.0019	Normal	A&B	1.24E-01	0.0002	50
τ	0.74	4.00	Normal	A&B	3.95E-03	0.0158	50
ω	6283.15	0.006	Normal	A&B	4.65E-07	0.0000	50
A	-0.12426661	0.00000040	Normal	A	6.67E+02	0.0003	137
B	-0.94255573	0.00000111	Normal	A	3.10E-03	0.0000	137
ε_A	0	0.00000321	Box	B	6.67E+02	0.0012	5
ε_B	0	0.00000756	Box	B	3.10E-03	0.0000	5
ε'_{Zin}	0	0.00100	Box	B	1	0.0006	5
ε'_{Kelvin}	0	0.00046	Box	B	1	0.0003	5
R_{short}	0	0.050	Normal	A&B	1	0.0500	5

Combined standard uncertainty	u_c	0.052 Ω
Effective degree of freedom	ν_i	6
Expanded uncertainty (p=95%)	U	**0.128 Ω**
Series Resistance	R_s	**82.887 Ω**

(METAS continued)

sn. 18197

Model equation that follows from the measurement setup:

$$L_s = -R_t\left(\frac{B_m - \varepsilon_B}{\omega} + \left(A_m - \varepsilon_A\right)\cdot\tau\right) + \varepsilon_{Zin} + \varepsilon_{Kelvin} - L_{short}$$

Description of the quantities in the model equation:

Quantity X_i	Description
R_t	resistance value of the reference resistor at 1 kHz (traceable to $R_{K\text{-}90}$)
τ	time constant of the reference resistor
ω	angular frequency of the applied signal
A_m	real part of the measured complex ratio of voltages
B_m	imaginary part of the measured complex ratio of voltages
ε_A	error on the measured value of A due to the non linearity of the input stage of the detector
ε_B	error on the measured value of B due to the non linearity of the input stage of the detector
ε_{Zin}	error on Ls due to the finite impedance of the input stage of the detetcor
ε_{Kelvin}	error on Ls due to the finite resolution of the Kelvin Balance
L_{short}	residual inductance of a short

Uncertainty budget table:

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i{*}u(x_i)$	Degrees of freedom ν_i
R_t	667.0335	0.0019	Normal	A&B	1.50E-04	0.28	50
τ	0.74	4.00	Normal	A&B	8.40E-08	0.34	50
ω	6283.146	0.006	Normal	A&B	1.59E-05	0.10	50
A_m	-0.12587651	0.00000024	Normal	A	4.94E-07	0.00	319
B_m	-0.94234927	0.00000072	Normal	A	1.06E-01	0.08	319
ε_A	0	0.00000345	Box	B	4.94E-07	0.00	5
ε_B	0	0.00000745	Box	B	1.06E-01	0.46	5
ε_{Zin}	0	3.72E-07	Box	B	1	0.21	5
ε_{Kelvin}	0	5.62E-08	Box	B	1	0.03	5
L_{short}	0	3.00E-07	Normal	A&B	1	0.30	5

Combined standard uncertainty	u_c	0.74 µH
Effective degree of freedom	ν_i	28
Expanded uncertainty (p=95%)	U	**1.53 µH**
Series Inductance	L_s	**100.042 07 mH**

Model equation that follows from the measurement setup:

$$R_s = -R_t \left\{ \left(A_m - \varepsilon_A \right) - \omega \cdot \left(B_m - \varepsilon_B \right) \cdot \tau \right\} + \varepsilon'_{Zin} + \varepsilon'_{Kelvin} - R_{short}$$

Uncertainty budget table:

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i * u(x_i)$	Degrees of freedom ν_i
R_t	667.0335	0.0019	Normal	A&B	1.26E-01	0.0002	50
τ	0.74	4.00	Normal	A&B	3.95E-03	0.0158	50
ω	6283.15	0.006	Normal	A&B	4.65E-07	0.0000	50
A	-0.12587651	0.00000024	Normal	A	6.67E+02	0.0002	319
B	-0.94234927	0.00000072	Normal	A	3.10E-03	0.0000	319
ε_A	0	0.00000345	Box	B	6.67E+02	0.0013	5
ε_B	0	0.00000745	Box	B	3.10E-03	0.0000	5
ε'_{Zin}	0	0.0010	Box	B	1	0.0006	5
ε'_{Kelvin}	0	0.0005	Box	B	1	0.0003	5
R_{short}	0	0.050	Normal	A&B	1	0.0500	5

Combined standard uncertainty	u_c	0.052 Ω
Effective degree of freedom	ν_i	6
Expanded uncertainty (p=95%)	**U**	**0.128 Ω**
Series Resistance	**R_s**	**83.961 Ω**

D.14 Uncertainty budget UME (Turkey)

The inductance value of L_X is obtained from the equation of

$$L_x = (R_2 + \delta R_{2drf}) \cdot (R_4 + \delta R_{4drf}) \cdot (C - C' + \delta C - \delta C') + L_K + \delta L_K + \delta L_{STB} + \delta L_S$$

Where:

L_X – The inductance value of the travelling standard
R_2 – The calibrated value of R_2
δR_2 – Correction due to the drift of R_2
R_4 – The calibrated value of R_4
δR_4 – Correction due to the drift of R_4
C – The value of the variable capacitance *(C_3+C_3')* in the main measurements
δC – Correction due to the stability of C
C' – The value of the variable capacitance in small value inductance measurements
$\delta C'$ – Correction due to the stability of C'
L_K – The value of the small inductor standard
δL_K – Correction due to the stability of L_K
δL_{STB} – Correction due to the stability of the bridge inductance
δL_S – Correction due to the total systematic errors of the bridge

Uncertainty components of the budget for the inductance standard sn. 18197

	Value	Standard Uncertainty	Degrees of Freedom	Divisor	Sensitivity Coefficient	Uncertainty Contribution
C	1000,267 pF	0,006 pF	15	1,732	$10^8\ \Omega^2$	$3,47.10^{-7}$ H
δC	0 pF	0,0005 pF	19	1,732	$10^8\ \Omega^2$	$2,89.10^{-8}$ H
C'	0,344 pF	$0,172.10^{-3}$ pF	15	1,732	$10^8\ \Omega^2$	$9,93.10^{-9}$ H
$\delta C'$	0 pF	$0,034.\ 10^{-3}$ pF	19	1,732	$10^8\ \Omega^2$	$2,05.10^{-9}$ H
R_2	9999,738 Ω	0,05 Ω	∞	2	$10^{-5}\ \Omega.F$	$2,5.10^{-7}$ H
δR_{2Drf}	0 Ω	0,01 Ω	∞	1,732	$10^{-5}\ \Omega.F$	$5,8.10^{-8}$ H
R_4	10000,046 Ω	0,05 Ω	∞	2	$10^{-5}\ \Omega.F$	$2,5.10^{-7}$ H
δR_{4Drf}	0 Ω	0,01 Ω	∞	1,732	$10^{-5}\ \Omega.F$	$5,8.10^{-8}$ H
L_K	52,4 µH	0,4 µH	15	2	1	2.10^{-7} H
δL_K	0 H	0,1 µH	19	1,732	1	$5,77.10^{-8}$ H
δL_{STB}	0 H	50.10^{-9} H	15	1,732	1	$2,89.10^{-8}$ H
δL_S	0 H	1.10^{-6} H	∞	1,732	1	$5,77.10^{-7}$ H
Standard Deviation of the Measurements	0 H	$0,11.10^{-6}$ H	15	1	1	$1,1.10^{-7}$ H
Standard uncertainty (RSS)					$7,94.10^{-7}$H	
Expanded Uncertainty (k=2, Veff >100)					**16.10^{-7} H**	

Uncertainty components of the budget for the inductance standard sn. 13975

	Value	Standard Uncertainty	Degrees of Freedom	Divisor	Sensitivity Coefficient	Uncertainty Contribution
C	1000,410 pF	0,006 pF	16	1,732	$10^8\ \Omega^2$	$3,47.10^{-7}$ H
δC	0 pF	0,0005 pF	19	1,732	$10^8\ \Omega^2$	$2,89.10^{-8}$ H
C’	0,344 pF	$0,172.10^{-3}$ pF	16	1,732	$10^8\ \Omega^2$	$9,93.10^{-9}$ H
δC’	0 pF	$0,034.\ 10^{-3}$ pF	19	1,732	$10^8\ \Omega^2$	$2,05.10^{-9}$ H
R_2	9999,738 Ω	0,05 Ω	∞	2	10^{-5} Ω.F	$2,5.10^{-7}$ H
δR_{2Drf}	0 Ω	0,01 Ω	∞	1,732	10^{-5} Ω.F	$5,8.10^{-8}$ H
R_4	10000,046 Ω	0,05 Ω	∞	2	10^{-5} Ω.F	$2,5.10^{-7}$ H
δR_{4Drf}	0 Ω	0,01 Ω	∞	1,732	10^{-5} Ω.F	$5,8.10^{-8}$ H
L_K	52,4 µH	0,4 µH	16	2	1	2.10^{-7} H
δL_K	0 H	0,1 µH	19	1,732	1	$5,77.10^{-8}$ H
δL_{STB}	0 H	50.10^{-9} H	16	1,732	1	$2,89.10^{-8}$ H
δL_S	0 H	1.10^{-6} H	∞	1,732	1	$5,77.10^{-7}$ H
Standard Deviation of the Measurements	0 H	$0,09.10^{-6}$ H	16	1	1	$0,9.10^{-7}$ H
Standard uncertainty (RSS)					$7,94.10^{-7}$H	
Expanded Uncertainty (k=2, Veff >100)					**16.10^{-7} H**	

D.15 Uncertainty budget UMTS (Ukraine)

Model equation that follows from the measurement set-up:

$$L_S = K_{CL} \cdot \frac{1}{(2\pi f)^2 \cdot C_{200nF}}$$

Description of the quantities in the model equation:

Quantity X_i	Description
C_{200nF}	Transfer capacitance (200 nF) that is used for capacitance to inductance transfer
K_{CL}	Capacitance to inductance transfer coefficient of the bridge
f	Frequency of sinusoidal signal applied to the inductance standard

Note: There are no correlated input estimates

Uncertainty budget components for INRIM inductance standard sn. 13975:

Source of uncertainty	Relative standard uncertainty *	Type
Uncertainty of 100 pF capacitors bank (AH11A, 3 units)	0.5×10^{-6}	B
Calibration uncertainty of 200 nF transfer capacitor against 100 pF capacitors bank	8.0×10^{-6}	B
Uncertainty of 200 nF transfer capacitor due to temperature variations while conducting C-L transfer procedure	0.7×10^{-6}	B
Standard deviation of 200 nF transfer capacitor calibration	0.2×10^{-6}	A
Uncertainty of bridge in C-L transfer mode (while measuring 100 mH against 200 nF transfer capacitor)	6.0×10^{-6}	B
Frequency measurements uncertainty	0.1×10^{-6}	A
Uncertainty due to INRIM inductance standard thermostat on-off cycle	1.4×10^{-6}	A
Repeatability (for INRIM inductance standard measurements)	1.3×10^{-6}	A

* Uncertainties that relates to calibration uncertainty of 200 nF transfer capacitor are highlighted in gray

Uncertainty budget table for INRIM inductance standard sn. 13975:

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ *	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
C_{200nF}	199.99420 nF	1.00×10^{-4} nF	rectangular	B	500273 H/F	0.050 µH	∞
		1.60×10^{-3} nF	normal	B	500273 H/F	0.800 µH	∞
		1.40×10^{-4} nF	normal	B	500273 H/F	0.070 µH	∞
		4.00×10^{-5} nF	normal	A	500273 H/F	0.020 µH	9
K_{CL}	0.78991482	4.74×10^{-6}	normal	B	0.12666 H	0.600 µH	∞
f	999.97520 Hz	1.00×10^{-4} Hz	normal	A	0.00020 H/Hz	0.020 µH	9
L_{S_therm}	100.051744 mH	1.40×10^{-4} mH	rectangular	A	1	0.140 µH	12
L_{S_repeat}	100.051744 mH	1.30×10^{-4} mH	normal	A	1	0.130 µH	8

Combined standard uncertainty	u_c	1.02 µH
Effective degrees of freedom	ν_{eff}	15976
Expanded uncertainty ($p \approx 95\%$)	U	2.00 µH

* Uncertainties that relates to calibration uncertainty of 200 nF transfer capacitor are highlighted in gray

(Ukrmetrteststandard continued)

Uncertainty budget components for PTB inductance standard sn. 18197:

Source of uncertainty	Relative standard uncertainty *	Type
Uncertainty of 100 pF capacitors bank (AH11A, 3 units)	0.5×10^{-6}	B
Calibration uncertainty of 200 nF transfer capacitor against 100 pF capacitors bank	8.0×10^{-6}	B
Uncertainty of 200 nF transfer capacitor due to temperature variations while conducting C-L transfer procedure	0.7×10^{-6}	B
Standard deviation of 200 nF transfer capacitor calibration	0.2×10^{-6}	A
Uncertainty of bridge in C-L transfer mode (while measuring 100 mH against 200 nF transfer capacitor)	6.0×10^{-6}	B
Frequency measurements uncertainty	0.1×10^{-6}	A
Uncertainty due to PTB inductance standard thermostat on-off cycle	1.0×10^{-6}	A
Repeatability (for PTB inductance standard measurements)	1.6×10^{-6}	A

* Uncertainties that relates to calibration uncertainty of 200 nF transfer capacitor are highlighted in gray

Uncertainty budget table for PTB inductance standard sn. 18197:

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ *	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
C_{200nF}	199.99420 nF	1.00×10^{-4} nF	rectangular	B	500273 H/F	0.050 µH	∞
		1.60×10^{-3} nF	normal	B	500273 H/F	0.800 µH	∞
		1.40×10^{-4} nF	normal	B	500273 H/F	0.070 µH	∞
		4.00×10^{-5} nF	normal	A	500273 H/F	0.020 µH	9
K_{CL}	0.78979903	4.74×10^{-6}	normal	B	0.12666 H	0.600 µH	∞
f	999.97520 Hz	1.00×10^{-4} Hz	normal	A	0.00020 H/Hz	0.020 µH	9
L_{S_therm}	100.037078 mH	1.00×10^{-4} mH	rectangular	A	1	0.100 µH	12
L_{S_repeat}	100.037078 mH	1.60×10^{-4} mH	normal	A	1	0.160 µH	8

Combined standard uncertainty	u_c	1.02 µH
Effective degrees of freedom	ν_{eff}	11988
Expanded uncertainty ($p \approx 95\%$)	U	2.00 µH

* Uncertainties that relates to calibration uncertainty of 200 nF transfer capacitor are highlighted in gray

D.16 Uncertainty budget NPL (United Kingdom)

Model equation that follows from the measurement set-up:

$$L_S = L_2\left[\frac{R_S}{R+R_2}\right] = L_2\left[\frac{n}{1-n}\right]$$

Description of the quantities in the model equation:

Quantity X_i	Description
C	QHR measurement to establish value of Primary 10 pF capacitor (NBS117)
H	Henry from Farad measurement of to establish NL250 inductor
L_2	Measurement of NPL 400 mH standard inductor (ES907)
BR	Inductance measurement bridge resolution
MR	Measurement repeatability of travelling standard inductor

Uncertainty budget table

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ ppm	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$ ppm	Degrees of freedom ν_i
C	9.999 667 pF	0.034	Normal	B	1.0	0.034	∞
H	251.976 5 mH	10.0	Normal	B	1.0	10.0	∞
L_2	400.058 6 mH	18.0	Normal	B	1.0	18.0	∞
BR	N/A	4.0	Rectangular	B	1.0	2.312	∞
MR	N/A	2.0	Normal	A	1.0	2.0	8

Combined standard uncertainty	u_c	21 ppm
Effective degrees of freedom	ν_{eff}	325
Expanded uncertainty ($p \approx 95\%$)	U	42 ppm

Annex E. Additional measurement data

In Table E-1 and Table E-2 the results are reported of the measured series resistance R_s for both travelling standards, together with the corresponding uncertainties $U(R_s)$.
In the same tables, the measurement frequency, f, and the current, I, through the inductor have also been reported with their corresponding uncertainties $U(f)$ and $U(I)$.
All uncertainty values are expanded uncertainties ($k = 2$) covering a probability interval of approximately 95 %.

Note 1: "x" means that this information was not reported.

Note 2: Some uncertainty values have been rounded and as a result of this, an uncertainty of "0" appears in the table. "0" uncertainty then means that the uncertainty claimed by the laboratory is less than 0.5 of the least significant digit indicated in the table.

Table E-1. Additional measurement data for travelling standard sn. 13975

Laboratory	Series resistance	Resistance Unc.	Frequency	Frequency Uncertainty	Current	Current Uncertainty
	R_s	$U(R_s)$	f	$U(f)$	I	$U(I)$
	Ω	Ω	Hz	Hz	mA	mA
PTB1	x	x	1000.500	0.600	0.9500	0.1000
NPL	82.832	0.010	1000.000	0.000	1.0000	0.0010
PTB2	x	x	1000.500	0.600	0.9500	0.1000
UMTS	82.951	0.020	999.975	0.000	0.3200	0.0100
PTB3	x	x	1000.500	0.600	0.9500	0.1000
IPQ	82.904	0.042	1000.000	0.005	1.0000	x
SMD	82.920	0.040	1000.000	0.100	1.0000	0.0200
DANIAmet-NMI	82.965	0.090	999.994	0.001	0.9640	0.0010
VSL	82.859	0.050	1000.000	0.002	1.0000	0.0500
PTB4	x	x	1000.500	0.600	0.9500	0.1000
GUM	82.910	0.025	1000.000	0.020	0.3000	x
MKEH	75.600	1.500	992.500	0.010	1.0740	0.0001
INM	82.902	0.008	1000.000	11.500	0.9910	0.0430
PTB5	x	x	1000.500	0.600	0.9500	0.1000
METAS	82.890	0.130	999.994	0.001	1.0000	0.0500
UME	82.910	0.010	1000.000	0.050	1.0000	0.0500
NML	83.030	0.200	1000.000	0.200	1.0000	0.0300
PTB6	82.930	0.250	1000.500	0.600	0.9500	0.1000
NMI SA	82.785	0.005	999.865	0.004	1.0028	0.0008
IAI SL	82.890	0.050	1000.000	0.020	1.0000	0.1000
PTB7	x	x	1000.500	0.600	0.9500	0.1000
SIQ	82.982	0.042	1000.008	0.000	0.9976	0.0003
PTB8	x	x	1000.500	0.600	0.9500	0.1000

Table E-2. Additional measurement data for travelling standard sn. 18197

Laboratory	Series resistance	Resistance Unc.	Frequency	Frequency Uncertainty	Current	Current Uncertainty
	R_s	$U(R_s)$	f	$U(f)$	I	$U(I)$
	Ω	Ω	Hz	Hz	mA	mA
PTB1	x	x	1000.500	0.600	0.9500	0.1000
NPL	83.889	0.010	1000.000	0.000	1.0000	0.0010
PTB2	x	x	1000.500	0.600	0.9500	0.1000
UMTS	83.994	0.015	999.975	0.000	0.3200	0.0100
PTB3	x	x	1000.500	0.600	0.9500	0.1000
IPQ	83.955	0.042	1000.000	0.005	1.0000	x
SMD	84.010	0.060	1000.000	0.100	0.9960	0.0050
DANIAmet-NMI	84.019	0.090	999.994	0.001	0.9640	0.0010
VSL	83.901	0.050	1000.000	0.002	1.0000	0.0500
PTB4	x	x	1000.500	0.600	0.9500	0.1000
GUM	83.960	0.025	1000.000	0.020	0.3000	x
MKEH	76.800	1.500	992.500	0.010	1.0740	0.0001
INM	83.958	0.025	1000.000	11.500	0.9910	0.0430
PTB5	x	x	1000.500	0.600	0.9500	0.1000
METAS	83.960	0.130	999.994	0.001	1.0000	0.0500
UME	83.960	0.010	1000.000	0.050	1.0000	0.0500
NML	84.080	0.200	1000.000	0.200	1.0000	0.0300
PTB6	83.970	0.025	1000.500	0.600	0.9500	0.1000

In Table E-3 and Table E-4 the measurements from the inductors' internal temperature sensors are reported, together with the ambient temperature and relative humidity.

Table E-3. Internal temperature and ambient conditions for travelling standard sn. 13975

Laboratory	Thermistor resistance	Thermistor resistance Unc.	Ambient temperature	Temperature Unc.	Relative humidity	Relative humidity Unc.
	R_{PT100}	$U(R_{PT100})$	T	$U(T)$	RH	$U(RH)$
	Ω	Ω	°C	°C	%	%
PTB1	110.768	0.010	23.15	0.20	45.5	3.0
NPL	110.686	0.000	20.00	1.00	50.0	10.0
PTB2	110.773	0.010	23.09	0.20	38.3	3.0
UMTS	110.673	0.001	22.90	0.20	41.0	3.0
PTB3	110.761	0.010	23.13	0.20	30.9	3.0
IPQ	110.669	0.000	23.00	1.00	50.0	5.0
SMD	110.671	0.003	23.35	0.25	36.8	1.1
DANIAmet-NMI	110.672	0.003	23.00	0.50	45.0	5.0
VSL	110.652	0.022	23.00	0.50	49.0	10.0
PTB4	110.766	0.010	23.01	0.20	38.1	3.0
GUM	110.676	0.007	23.00	1.00	45.0	10.0
MKEH	110.804	0.010	22.51	0.05	55.5	2.0
INM	110.679	0.014	22.50	0.02	36.0	2.5
PTB5	110.768	0.010	23.08	0.20	52.8	3.0
METAS	110.673	0.005	23.00	0.50	43.0	10.0
UME	110.675	0.004	23.00	0.50	45.0	10.0
NML	110.672	0.004	23.55	0.20	44.0	4.0
PTB6	110.767	0.010	23.04	0.20	35.8	3.0
NMI SA	110.670	0.020	24.10	0.60	0.0	0.0
IAI SL	110.674	0.005	23.00	1.00	40.0	10.0
PTB7	110.772	0.010	22.98	0.20	30.4	3.0
SIQ	100.761	0.002	23.50	1.00	49.1	10.0
PTB8	110.762	0.010	23.03	0.20	48.9	3.0

Table E-4. Internal temperature and ambient conditions for travelling standard sn. 18197

Laboratory	Thermistor resistance	Thermistor resistance Unc.	Ambient temperature	Temperature Unc.	Relative humidity	Relative humidity Unc.
	R_{NTC}	$U(R_{\mathrm{NTC}})$	T	$U(T)$	RH	$U(RH)$
	Ω	Ω	°C	°C	%	%
PTB1	9482.50	1.24	23.19	0.20	44.5	3.0
NPL	9470.36	0.10	20.00	1.00	50.0	10.0
PTB2	9480.30	1.24	23.12	0.20	38.3	3.0
UMTS	9471.10	0.80	22.90	0.20	41.0	3.0
PTB3	9480.30	1.24	23.17	0.20	29.9	3.0
IPQ	9486.82	1.17	23.00	1.00	50.0	5.0
SMD	9476.00	11.00	23.35	0.25	36.8	1.1
DANIAmet-NMI	9470.20	0.20	23.00	0.50	45.0	5.0
VSL	9488.70	1.90	23.00	0.50	49.0	10.0
PTB4	9485.60	1.24	23.03	0.20	38.1	3.0
GUM	9479.00	3.00	23.00	1.00	45.0	10.0
MKEH	9467.80	0.90	22.65	0.05	59.5	2.0
INM	9474.69	1.87	22.50	0.02	38.0	2.5
PTB5	9483.20	1.24	23.15	0.20	53.0	3.0
METAS	9472.80	0.40	23.00	0.50	43.0	10.0
UME	9467.00	2.00	23.00	0.50	45.0	10.0
NML	9480.60	2.00	23.54	0.20	44.0	4.0
PTB6	9481.50	1.24	23.13	0.20	35.8	3.0

Annex F. Corrective actions

F.1 METAS

An analysis of the preliminary results of the comparison clearly shows that the METAS measurements of the INRIM (sn 13975) standard deviates from the RV (Reference Value) by many times the standard deviation while the measurements of the PTB (sn 18197) standard are in good agreement with the RV.

Extensive investigations of the measuring system used at METAS during the comparison showed an inappropriate ground connection and current equalization. This inappropriate bridge design resulted in a systematic error when the measured standard is not floating with respect to the power line ground. This effect explains the large deviation observed on the measurement of the INRIM standard which was not floating from ground due to the 12 V DC supply of the thermostat.

With the PTB inductor, the thermostat was powered from batteries making the standard floating during the measurement. Therefore no leakage current did flow and the bridge was working properly in this case.

To settle this problem, INRIM kindly accepted to send its standard back to METAS for additional investigations. New measurements have been carried out in October 2009 whose results are shown in Figure F-1.

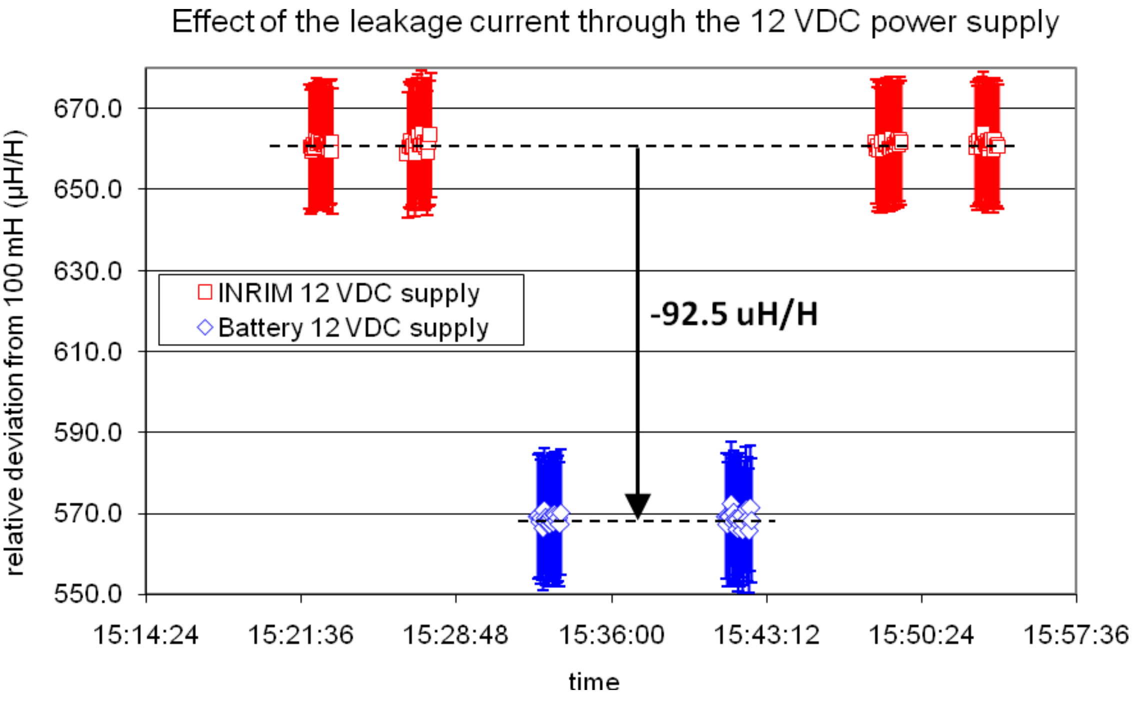


Figure F-1: Relative deviation from 100 mH obtained during the measurements carried out on the INRIM standard on October 29, 2009. Square: original bridge configuration with the INRIM 12 V DC source. Diamonds: original bridge configuration using 12 V DC batteries. The uncertainty bars correspond to the expanded uncertainty given in the comparison.

For these additional measurements, the bridge has been setup into a configuration similar to the system used during the comparison i.e. with an inappropriate ground connection. The thermostat of the standard was powered either form the INRIM 12 V DC source (squares) or from 12 V DC batteries (diamonds). A systematic shift of about 92.5 uH/H is clearly visible between the two configurations.

These new results are obtained two years after the comparison campaign. It is therefore meaningless to compare the new value to the reference value of the comparison. However, the difference of the results obtained using either the INRIM 12 V DC source or the 12 V DC batteries is a good estimation of the systematic error done during the comparison. Therefore, the reported value by METAS for the measurement of the INRIM (sn 13975) standard should be corrected by a factor of -92.5 uH/H with an expanded (k=2) uncertainty of 21.8 uH/H.

Finally, the corrected results for the **INRIM (sn 13975)** standard is:

Ls = (100.05474 ± 0.00267) mH

The effect of the leakage current on the resistive part of the inductance is well below the measuring uncertainty and no correction has to be applied.

CH-3003 Bern-Wabern, 3 November 2009

For the Measurements:	Section Electricity
Frédéric Overney	Dr Beat Jeckelmann, Head of Section

Using the value given above and applying corrections for the drift of the standard, we find:

$L_{\mathrm{s\_corr}}$ = 100.054 77 mH and $U(L_{\mathrm{s\_corr}})$ = 0.002 70 mH.

This corrected result is shown in Figure F-2, indicated by "METAS 2".

Recomputing the degrees of equivalence with the reference values with the corrected results for sn. 13975, we find:

$D_{\mathrm{METAS\ 2}}$ = -0.00016 mH $U(D_{\mathrm{METAS\ 2}})$ = 0.00227 mH E_n = -0.1

The degree of equivalence with respect to the reference value of EUROMET.EM-S20 is:

$D_{\mathrm{EM20,METAS2}}$ = -0.000 30 mH $U(D_{\mathrm{EM20,METAS2}})$ = 0.002 37 mH.

This corrected degree of equivalence is shown in Figure F-3.

F.2 UMTS

Ukrmetrteststandard (Ukraine)
Oleh Velychko
Comments, December 2010

As we found out, our results differ from the mean value of the traveling standards by about 40 ppm while our expanded uncertainty was estimated at the level of 20 ppm.
To find out the reason, we checked our measurement layout. Ukrmetrteststandard (UMTS) carried out the measurements in November 2006. At that time, Ukraine's National standard of Inductance was in the development stage (it was fully completed at 2009) and measurements were carried out on a prototype of this National standard.
We further analyzed the UMTS uncertainty and want to expand the uncertainty of the bridge in C-L transfer mode (while measuring 100 mH against 200 nF transfer capacitor) to 2.3 µH (old value 0.6 µH) and our expanded uncertainty for both traveling standards enlarges to 4.9 µH. The revised uncertainty table is given on the following pages.
The results with the corrected uncertainties are shown in Figure F-2, indicated by "UMTS 2".
Recomputing the degree of equivalence with the reference value, we find:

$D_{\mathrm{UMTS\,2}} = -0.004\,52$ mH $\quad U(D_{\mathrm{UMTS\,2}}) = 0.004\,96$ mH $\quad E_{\mathrm{n}} = -0.9$

The degree of equivalence with respect to the reference value of EUROMET.EM-S20 is:

$D_{\mathrm{EM20,UMTS2}} = -0.004\,66$ mH $\quad U(D_{\mathrm{EM20,UMTS2}}) = 0.005\,01$ mH.

This corrected degree of equivalence is shown in Figure F-3.

In October 2006 the traveling standards experienced a severe shock during the transport from NPL to PTB. From the measurements PTB1 and PTB2, it is expected that in both standards the inductance value jumped by about -1.0 µH. At the time of the UMTS measurements, the standards had not yet completely recovered from this jump. Therefore, this behaviour of the standards affected the UMTS results in this comparison.

Considering the fact the effect of the jump in the value of the travelling standards is difficult to estimate, and the fact that the UMTS measurement set-up was still in the development stage at the time of the comparison, UMTS has decided that it would be best to participate in a new (bilateral) comparison as soon as possible.

Revised Uncertainty budget Ukrmetrteststandard (Ukraine)

Model equation that follows from the measurement set-up:

$$L_S = K_{CL} \cdot \frac{1}{(2\pi f)^2 \cdot C_{200nF}}$$

Description of the quantities in the model equation:

Quantity X_i	Description
C_{200nF}	Transfer capacitance (200 nF) that is used for capacitance to inductance transfer
K_{CL}	Capacitance to inductance transfer coefficient of the bridge
f	Frequency of sinusoidal signal applied to the inductance standard

Note: There are no correlated input estimates

Uncertainty budget components for INRIM inductance standard sn. 13975:

Source of uncertainty	Relative standard uncertainty *	Type
Uncertainty of 100 pF capacitors bank (AH11A, 3 units)	0.5×10^{-6}	B
Calibration uncertainty of 200 nF transfer capacitor against 100 pF capacitors bank	8.0×10^{-6}	B
Uncertainty of 200 nF transfer capacitor due to temperature variations while conducting C-L transfer procedure	0.7×10^{-6}	B
Standard deviation of 200 nF transfer capacitor calibration	0.2×10^{-6}	A
Uncertainty of bridge in C-L transfer mode (while measuring 100 mH against 200 nF transfer capacitor)	23.0×10^{-6}	B
Frequency measurements uncertainty	0.1×10^{-6}	A
Uncertainty due to INRIM inductance standard thermostat on-off cycle	1.4×10^{-6}	A
Repeatability (for INRIM inductance standard measurements)	1.3×10^{-6}	A

* Uncertainties that relates to calibration uncertainty of 200 nF transfer capacitor are highlighted in gray

Uncertainty budget table for INRIM inductance standard sn. 13975:

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ *	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
C_{200nF}	199.99420 nF	1.00×10^{-4} nF	rectangular	B	500273 H/F	0.050 µH	∞
		1.60×10^{-3} nF	normal	B	500273 H/F	0.800 µH	∞
		1.40×10^{-4} nF	normal	B	500273 H/F	0.070 µH	∞
		4.00×10^{-5} nF	normal	A	500273 H/F	0.020 µH	9
K_{CL}	0.78991482	1.816×10^{-5}	normal	B	0.12666 H	2.300 µH	∞
f	999.97520 Hz	1.00×10^{-4} Hz	normal	A	0.00020 H/Hz	0.020 µH	9
L_{S_therm}	100.051744 mH	1.40×10^{-4} mH	rectangular	A	1	0.140 µH	12
L_{S_repeat}	100.051744 mH	1.30×10^{-4} mH	normal	A	1	0.130 µH	8

Combined standard uncertainty	u_c	2.44 µH
Effective degrees of freedom	ν_{eff}	> 500 000
Expanded uncertainty ($p \approx 95\%$)	U	4.90 µH

* Uncertainties that relates to calibration uncertainty of 200 nF transfer capacitor are highlighted in gray

(Ukrmetrteststandard continued)

Uncertainty budget components for PTB inductance standard sn. 18197:

Source of uncertainty	Relative standard uncertainty *	Type
Uncertainty of 100 pF capacitors bank (AH11A, 3 units)	0.5×10^{-6}	B
Calibration uncertainty of 200 nF transfer capacitor against 100 pF capacitors bank	8.0×10^{-6}	B
Uncertainty of 200 nF transfer capacitor due to temperature variations while conducting C-L transfer procedure	0.7×10^{-6}	B
Standard deviation of 200 nF transfer capacitor calibration	0.2×10^{-6}	A
Uncertainty of bridge in C-L transfer mode (while measuring 100 mH against 200 nF transfer capacitor)	23.0×10^{-6}	B
Frequency measurements uncertainty	0.1×10^{-6}	A
Uncertainty due to PTB inductance standard thermostat on-off cycle	1.0×10^{-6}	A
Repeatability (for PTB inductance standard measurements)	1.6×10^{-6}	A

* Uncertainties that relates to calibration uncertainty of 200 nF transfer capacitor are highlighted in gray

Uncertainty budget table for PTB inductance standard sn. 18197:

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ *	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
C_{200nF}	199.99420 nF	1.00×10^{-4} nF	rectangular	B	500273 H/F	0.050 μH	∞
		1.60×10^{-3} nF	normal	B	500273 H/F	0.800 μH	∞
		1.40×10^{-4} nF	normal	B	500273 H/F	0.070 μH	∞
		4.00×10^{-5} nF	normal	A	500273 H/F	0.020 μH	9
K_{CL}	0.78979903	1.816×10^{-5}	normal	B	0.12666 H	2.300 μH	∞
f	999.97520 Hz	1.00×10^{-4} Hz	normal	A	0.00020 H/Hz	0.020 μH	9
L_{S_therm}	100.037078 mH	1.00×10^{-4} mH	rectangular	A	1	0.100 μH	12
L_{S_repeat}	100.037078 mH	1.60×10^{-4} mH	normal	A	1	0.160 μH	8

Combined standard uncertainty	u_c	2.44 μH
Effective degrees of freedom	ν_{eff}	> 500 000
Expanded uncertainty ($p \approx 95\%$)	U	4.90 μH

* Uncertainties that relates to calibration uncertainty of 200 nF transfer capacitor are highlighted in gray

F.3 DANIAmet-NMI

DANIAmet-NMI-Trescal (Denmark)
Torsten Lippert
Comment, December 2010

Since our measurement results are roughly 150 ppm too high we have made some investigations of the set-up which was used for this intercomparison. First we would like to point out that this is an experimental set-up not usually used, and that our CMC value for this measurement is 300 ppm. During the intercomparison the set-up was tested against our reference inductor (Tinsley BG 8/2 100 mH), which is calibrated by another NMI (which has done very well in this intercomparison), and we were able to reproduce its calibrated value within 10 ppm with a standard deviation of 5 ppm. However, subsequent recalibration of this reference inductor showed a shift or drift to a lower value of around 75 ppm. Such a shift/drift has not been observed earlier. Since the intercomparison we have got a GR 1482-L (100 mH) at our disposal, traceable to another NMI. In order to investigate the origin of the rather large deviation of roughly 150 ppm, we have made a series of measurements with the GR 1482-L and the Tinsley BG 8/2 standard. The Tinsley BG 8/2 inductor consists only of a number of windings, no shielding and no core (air), so it is quite sensitive to external fields. Although we have a wooden table for inductance measurements, the measurements using this set-up showed a considerable sensitivity to the proximity to other equipment as well as the orientation of the inductor, resulting in variations of approximately ±100 ppm. The measurements with our GR 1482-L showed a much better repeatability and we were able to reproduce its calibrated value within 20 ppm. In the intercomparison exactly the same equipment, cables etc. was used for the Tinsley BG 8/2 and the travelling standards, and all test measurements with the Tinsley BG 8/2 were carried out with the Tinsley BG 8/2 in the same position. Although we have not been able to pinpoint the origin of our poor results, we believe that a combination of the subsequently observed shift/drift of our reference inductor, Tinsley BG 8/2, and its large sensitivity to external fields is the major contributor to our deviation. Certainly the experience gained suggests that the good agreement between our measurement and the calibrated value of the Tinsley bG 8/2 observed during the intercomparison (10 ppm mentioned above) might have been accidental, thus leading to a false sense of security. Naturally this set-up is not used for calibration work as further testing is required, and we have also announced our interest to participate in another intercomparison, 100 mH, 1 kHz, piloted by another NMI.

F.4 Degrees of equivalence after corrective actions

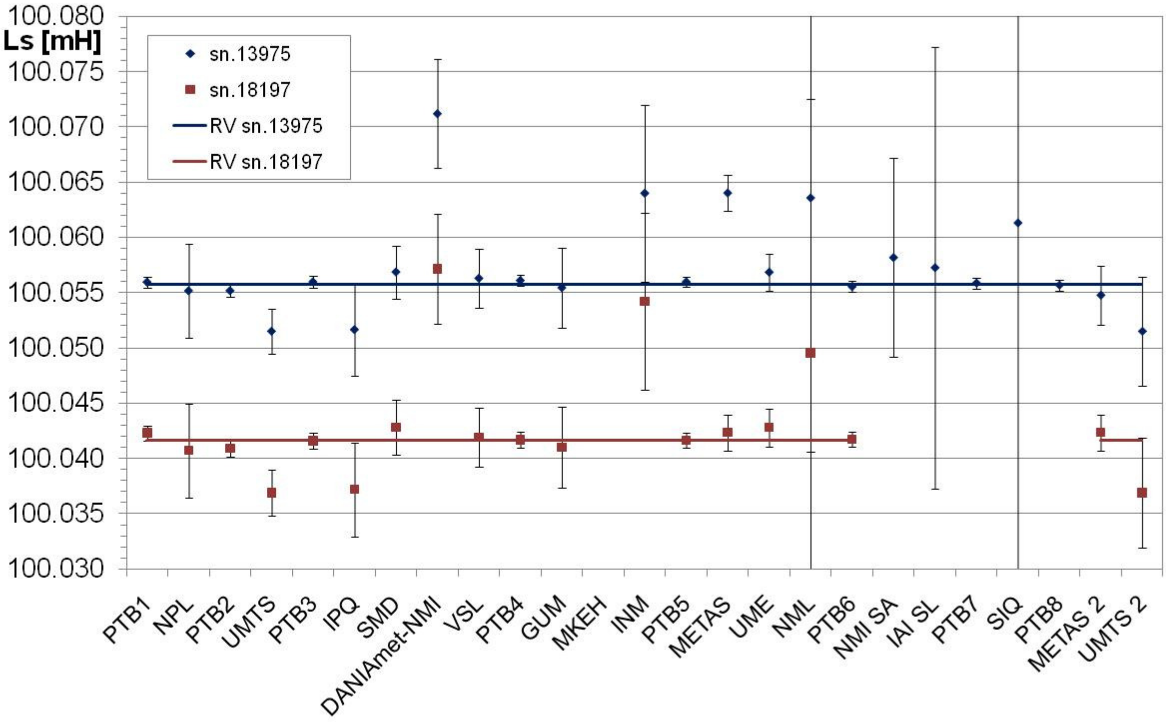


Figure F-2. Measurement results after drift corrections, with the corrected result of METAS and UMTS, indicated by "METAS 2" and "UMTS 2".

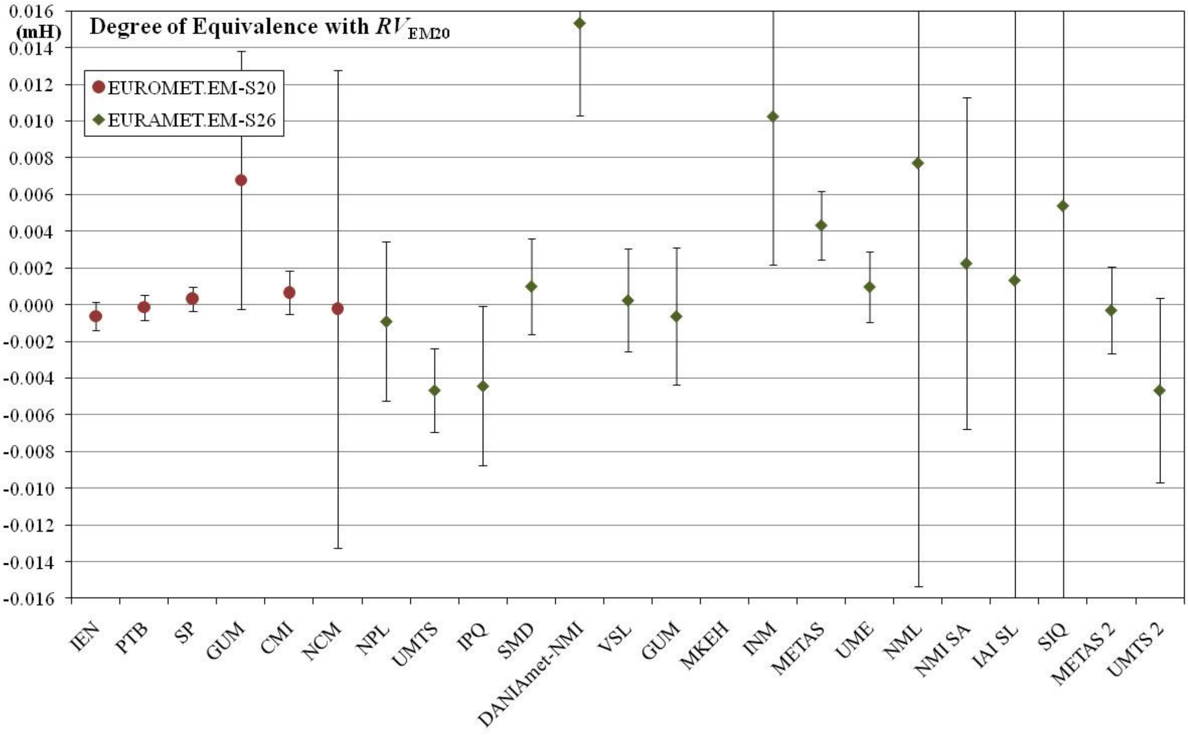


Figure F-3. Degrees of equivalence after the corrective actions from METAS and UMTS, indicated by "METAS 2" and "UMTS 2".

Annex G. Comparison protocol

NMi VSL	INM	PTB	INRIM
Netherlands	Romania	Germany	Italy

EUROMET project 816

Supplementary Comparison

Inductance measurements of 100 mH at 1 kHz

Technical protocol

E. Dierikx NMi VSL
A. Nestor INM
J. Melcher PTB
L. Callegaro INRIM

Version: 21 September 2006

NMi Van Swinden Laboratorium
P.O. Box 654
NL-2600 AR, Delft
The Netherlands

Table of contents

1 Introduction

Within the EUROMET region, a supplementary comparison is organized in the field of inductance measurements of 100 mH at 1 kHz. This comparison will be a follow-up comparison of the EUROMET.EM-S20 comparison that was organized by Istituto Elettrotecnico Nazionale Galileo Ferraris (IEN currently known as INRIM), Italy, between 2002 and 2003. The EUROMET.EM-S20 comparison originally started as a pilot comparison to study the stability of the travelling standard. After the measurements had been completed, it was decided to convert this pilot comparison into a supplementary comparison. Since not all EUROMET members had a chance to participate in the S20 comparison, there was a need for a follow-up comparison. INRIM kindly agreed that the same travelling standard could be used in the follow-up comparison. However, the value of the standard has been slightly modified.

A second 100 mH travelling standard will be kindly provided by the Physikalisch-Technische Bundesanstalt (PTB), Germany.

In this comparison we will compare measurements of self-inductance at the lowest level of uncertainty. The aim will be to achieve an agreement within 0.005 % for two terminal measurements.

2 Travelling standards

2.1 Description of the INRIM inductance standard

The travelling standard provided by INRIM (Figure 1) is a modified GR1482-L 100 mH inductance standard. The standard is enclosed in a temperature controlled wooden box.

Figure 17 The travelling standard provided by INRIM

The standard is designed as a 4 terminal pair (4TP) impedance and is therefore equipped with 4 coaxial MUSA BPO connectors (Figure 2 and Figure 3). The connectors are indicated with IH and IL for the *current high* and *current low* respectively, and VH and VL for the *potential high* and *potential low* respectively.

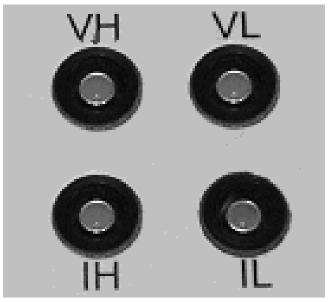


Figure 18 4TP BPO connectors on the travelling standard.

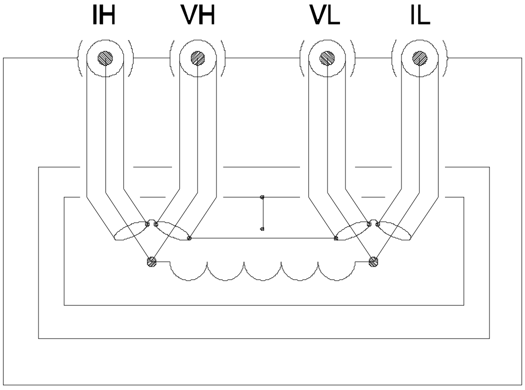


Figure 19 Schematic diagram of the internal 4TP connection of the travelling standard.

There are two banana sockets on the standard indicated with +12V (red) and 0V (black) (Figure 4). This is the 12 V power supply input for the thermostated enclosure. The internal temperature of the enclosure is measured by PT100 resistance thermometer that can be accessed through the LEMO connector indicated with PT100 (Figure 5).

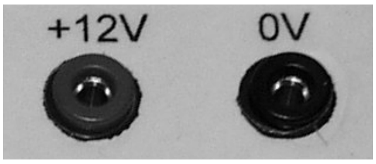


Figure 20 Banana socket for 12 V DC input of thermostated enclosure.

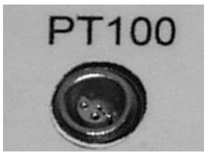


Figure 21 LEMO socket for measurement of the internal temperature: R_{PT100}.

2.2 Accessories with the INRIM inductance standard

In the transport case with the INRIM inductance standard, several accessories are provided. All 2-terminal (2T) measurements must be performed using the provided 4/2 adapter (Figure 6 and Figure 7). This adapter should be placed directly on the IH and IL BPO connectors of the standard. During the 2T measurement, the shorting bar (shown in Figure 6) must always be connected between the low, L, and ground, G, banana terminals of the adapter.

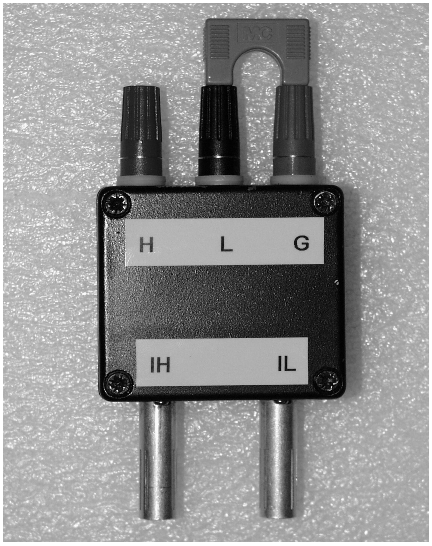


Figure 22 4/2 adapter with shorting bar

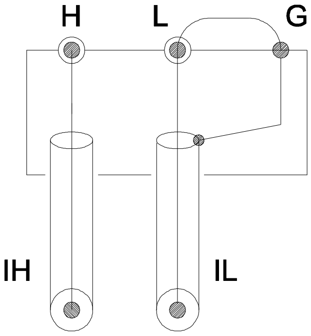


Figure 23 Schematic diagram of the 4/2 adapter

In order to power the thermostated enclosure, a 12 V dc power supply is provided (Figure 8). It requires 220 V / 240 V ac, 50 Hz line power at the input.

Figure 24 Power supply 12 V dc

Four BPO dust caps are provided to cover the connectors of the inductor when they are not used.

A 4-wire shielded R_{PT100} cable with LEMO-connector is provided to measure the resistance of the internal thermometer. The connections should be made as follows:

Red = high-current terminal, IH;
Black = low-current terminal, IL;
Yellow = high-voltage terminal,VH;
Green = low-voltage terminal,VL;

2.3 Description of the PTB inductance standard

The thermostatically controlled inductance standard (Figure 9) consists of a commercial inductance standard GR1482-L. It is built in a thermostat with an electronic controller. This construction guarantees a constant operating temperature. The standard has three terminals (high, low, ground) with a removable ground strap to connect the low-terminal with ground (Figure 10).

There are two LEMO connectors.

- The two-terminal one (Figure 11) is the connection of the 24 V dc power supply. The thermostat is supplied by a 24 V DC-uninterruptible power system (UPS). Between the measurements the UPS must be connected to the line.
- The internal temperature of the standard is measured by a 10 kΩ NTC resistor that can be accessed through the four-terminal LEMO connector (Figure 12).

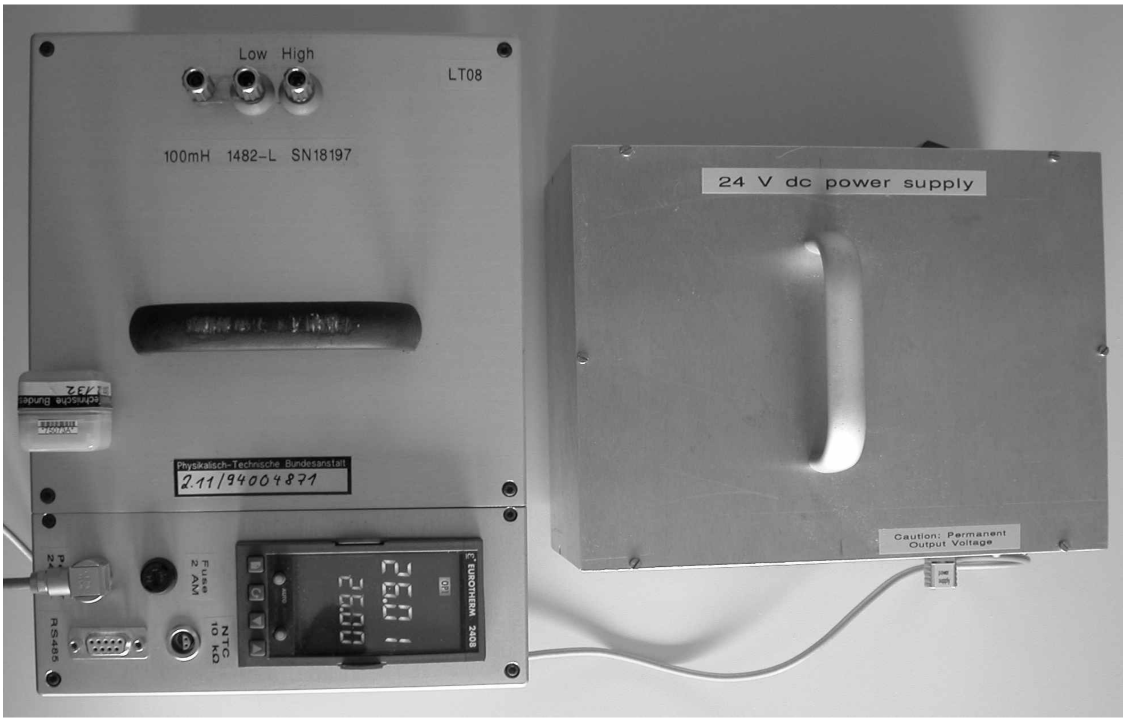


Figure 9 The travelling standard provided by PTB and the UPS

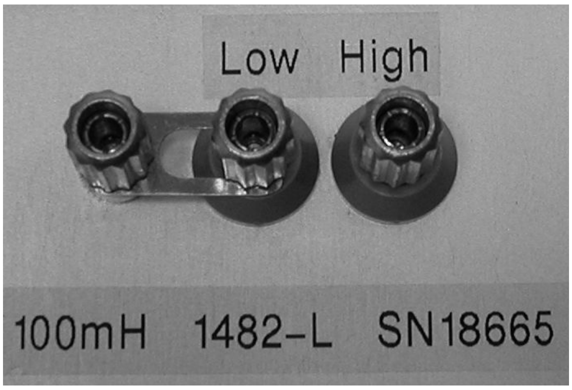


Figure 10 Terminals of the PTB standard: Jack-top binding posts on ¾-in. spacing with removable ground strap

Figure 11 2-terminal LEMO socket for the 24 V DC power supply of the thermostat.

Figure 12 4-terminal LEMO socket for measurement of the internal temperature R_{NTC} of the thermostat.

The electronic heating controller works automatically. It has a protection against wrong operation.

2.4 Accessories with the PTB inductance standard

The transport case of the PTB standard contains several accessories:

- Two 12V lead-acid batteries (non-spillable) for the transport without external power supply
- Cable set with fuse (2 A) and temperature switch (placed on the standard) to connect the transport batteries with the standard
- 24 V DC-uninterruptible power system (UPS) for measurement,
- cable set for the UPS and a line adapter for different socket-outlets with earthing contact,

- DC/DC converter 12 V / 24 V to supply the standard in a car
- cable set for the DC/DC converter
- 1 data logger to control the ambient temperature and humidity on transport,
- infrared adapter to connect the data logger to the computer,
- CD with software to read out the data loggers,
- 4-wire shielded cable with LEMO-connector to measure the resistance of the internal thermometer (NTC-resistor).
  Red = high-current terminal, IH; Blue = low-current terminal, IL;
  White = high-voltage terminal,VH; Black = low-voltage terminal,VL;

2.5 Quantities to be measured

The impedance of the travelling standard between the high and low connector can be modelled as a series connection of an ideal inductor L_s and an ideal resistor R_s. The complex impedance, Z, is given by $Z = R_s + j\omega L_s$, with $\omega = 2\pi f$ and f is the frequency.
The measurand in this comparison is the self-inductance L_s, expressed in the unit of henry (H). The value of L_s should be determined with a sinusoidal excitation current with an effective value of 1 mA and a frequency, f, of 1 kHz.
The mandatory measurement in this comparison is to determine the value of L_s by means of a two-terminal connection of the travelling standard: the standard is connected between the high and low terminal and the case of the standard is connected to the low terminal.

2.6 Method of computation of the reference value

The reference value of this comparison will be determined from the results of participants with an independent realization of the unit of inductance (Henry). Participants of whom the results show a strong deviation from the other participants will not be included in the reference value. If all reported uncertainties are of the same order of magnitude, the reference value will be computed as the mathematical mean of the independent results. If there are significant differences in the reported uncertainties, a weighted mean may be preferred.
This comparison will be linked to the EUROMET.EM-S20 comparison through the independent laboratories that participated in both comparisons.

3 Organisation

3.1 Co-ordinators and members of the support group

The comparison is organized as a co-operative effort between the following laboratories:

- Institutul National de Metrologie (INM), Romania.
  Contact person: Mrs. Anca Nestor
  E-mail: anca.nestor@inm.ro
  Tel.: +4021 334 48 30; +4021 334 50 60 ext. 170
- Physikalisch Technische Bundesanstalt (PTB) Germany
  Contact person: Dr. Jürgen Melcher / Axel Kölling
  E-mail: Juergen.Melcher@ptb.de / Axel.Koelling@ptb.de
  Tel.: + 49 531 592 2100
- Nederlands Meetinstituut Van Swinden Laboratorium (NMi VSL), The Netherlands
  Contact person: Erik Dierikx
  E-mail: edierikx@nmi.nl
  Tel.: +31 15 269 16 88
- Istituto Nazionale di Ricerca Metrologica (INRIM), Italy
  Contact person: Luca Callegaro
  E-mail: lcallega@inrim.it
  Tel.: +39 011 391 94 35

INM: is responsible for the schedule and keeps track of the travelling standards.
PTB: performs the pilot measurements on the travelling standards to determine their behaviour during the comparison and prepares the PTB inductance standard.
NMi VSL: prepares the technical protocol, collects the results, performs the data analysis and prepares the draft/final reports.
INRIM: associate organizer: responsible for the preparation of the INRIM inductance standard, contributions to technical protocol.

All general questions concerning this comparison may be directed to Erik Dierikx.
The support group of this comparison consists of the same persons that are included in the organizing group mentioned above.

3.2 Participants

There is a total number of 15 participants in this comparison.
The complete list of participants with there contact details is given in Annex 1.

3.3 Time schedule

After PTB has performed the initial characterization of the travelling standard, the comparison will start on 28 September 2006. Each participant will be allowed three or four weeks for performing the measurements and shipment of the standard to the next participant. If unforeseen circumstances prevent a laboratory from carrying out its measurements within the agreed time period, it has to send the travelling standard without delay to the laboratory next in line. INM has to be informed about this incident immediately. A new date at a later time shall be fixed to allow the laboratory to carry out its measurements.
The circulation scheme is given in Annex 2.

3.4 Transportation

The standards have to be protected against excessive mechanical shocks. The maximum permissable acceleration is 25 g. **The PTB standard has to be transported in thermostated**

condition. Without external power supply the internal batteries allows a maximum operating time of 72 hours. The ambient temperature has to be between 10 °C to 30 °C. The ambient parameters temperature, humidity will be recorded during transportation with a data logger. The travelling standards and their accessories will be sent to you in two transport cases that are suitable for shipment as freight. There are sensors for tilt and shocks on the surface of the cases to watch rough handling. Unless the transport cases are damaged, it will be requested to use the same cases for transport of the standards to the next participant. The dimensions of the case for the INRIM inductance standard are 610 mm height, 590 mm depth, 790 mm width: the approximate weight being 32 kg (standard and accessories included). The dimensions of the case for the PTB inductance standard are 610 mm height, 590 mm depth, 790 mm width: the approximate weight being 66 kg (standard and accessories included). The transportation of the standards to the next participant may be arranged preferably hand carried by car or by a shipping agent, courier or parcel delivery service of your choice, provided the margins for acceleration, ambient temperature, and humidity are kept.

3.5 Unpacking, handling, packing

Upon arrival, the transport cases and their contents must be checked for visible damage. In case the cases or the standards are damaged, this should be reported to the person who delivers the package. If you notice any damage, it is recommended to take pictures of it.
After unpacking the standard, it is important to read out the data from the data loggers. You have to install the software on your computer and connect the infrared-adapter following the instructions included in the annex 7. If the margins were exceeded, the pilot laboratory has to decide how to carry on. In case of severe violations of the margins, the standards may have to be sent to PTB. This would require to modify the whole remaining schedule.
After inspection of the packages and reading the data loggers, the pilot laboratory (in this case Mrs. Anca Nestor at INM) and the participant that sent the packages to you should be informed about the arrival of the packages at your laboratory and about the status of the packages. Use the form as given in Annex 5.
After unpacking the standards, it is important that the thermostated enclosure of the standards are energized for at least 24 hours before the measurements are started. The enclosures can be energized by the power supplies that are provided with the standards. The transport batteries of the PTB standard must be charged by a standard charger for lead-acid batteries. The batteries must be fully charged, at maximum capacity, before shipment.
After completing the measurements, the standards should be carefully repacked in their transport cases. Before shipment, both the pilot laboratory (in this case Mrs. Anca Nestor at INM) and the receiving laboratory should be informed by e-mail or fax that the packages are about to be shipped. The form given in Annex 6 must be sent to INM.

3.6 Failure of a travelling standard

In the event of a failure of a travelling standard, the pilot laboratory (Mrs. Anca Nestor, INM) should be informed at once. Please report any details about the nature of the failure and wait for further instructions.

3.7 Financial aspects, insurance

Each participant laboratory is responsible for its own costs for the measurement, transportation and any custom charges, as well as any damage that may occur during transport of the standard to the next participant.
It is therefore strongly recommended that you properly insure the standard during the stay in your laboratory and during transport to the next participant. The standards should be insured for an amount of € 20000,-.

4 Measurement instructions

4.1 Before the measurements

The standards must be positioned with the connectors facing upwards.
Before and during the measurement, the thermostatic enclosures of the standards must be energized.

4.1.1 INRIM inductance standard

A +12.0 V, 500 mA dc low-noise power supply has to be connected to the banana sockets (+ red, - black). The 12 V supply provided with the travelling standard is suited for this purpose but its employment is not mandatory.
At power-up, the thermostat green LED lights, indicating thermostat ON cycle. After some hours, the lamp goes off, then on again, with an approximate period of 30 minutes.
The standard reaches its operating temperature, around 28 °C, in 24 hours. Tentative measurements on the standard can be carried out before this period, but cannot be considered reliable for the comparison. DO NOT consider the reaching of a plateau for R_{PT100} the signal of a temperature stabilization of the standard. If the thermostat power supply is disconnected for any reason, the user must wait again 24 hours before measurement.

4.1.2 PTB inductance standard

The PTB inductance standard must be supplied all the time. During the stay in the laboratory the UPS with the accessory cable (see capture 2.3) must be used for supply. Please notice the inscription on the LEMO connectors of the accessory cable. The right direction is important for protection against noise. Before and after each measurement the UPS has to connect to the line and turn on (indicated through the green LED). These guarantees always loaded batteries inside the UPS. Only for the measurement the UPS mains cable must disconnect from line. Then, the standard will be supplied automatically by the UPS batteries.
For accurate function of the thermostat controller (operating temperature 26 °C) the ambient temperature must be below 24 °C.

4.2 Measurement performance

As mentioned above, the thermostatic enclosure of the standards must be energized during the measurements.

4.2.1 INRIM inductance standard

For the two terminal measurements, the 4/2 adapter that is provided with the standard must be used. This adapter must be connected on the IL and IH BPO connectors of the standard and should be considered as an integral part of the standard. The VL and VH BPO connectors should be protected by dust caps included with the standard.
During the two terminal measurements, the ground, G, terminal and the low, L, terminal of the 4/2 adapter should always be connected together by the shorting bar that is included in the package. Do not use any other shorting bars, and do not report any results of measurements with the shorting bar removed.
Participants are requested to record all relevant parameters during the measurements. This includes for example: excitation current, frequency, internal temperature (R_{PT100}), ambient temperature and relative humidity. (Note: to avoid self-heating of the PT100, it is recommended to use a measuring current of less than 3 mA.)

4.2.2 PTB inductance standard

During the measurements the ground- and low-terminal must always be connected together by the ground strap.

Participants are requested to record all relevant parameters during the measurements. This includes with minimum the parameters who must state in the “Summery of results” (see annex 4): inductance value, series resistance, frequency, current, internal temperature (R_{NTC}), ambient temperature and relative humidity.

4.3 Method of measurement

This protocol does not prescribe a specific method of measurement or measurement set-up, as long as the following requirements are met:

- The excitation signal should be sinusoidal; the total harmonic distortion and noise should be less than 0.01 %.
- The effective value of the excitation signal should be 1 mA.
- The frequency should be (1.00 ± 0.01) kHz. (Note: the inductance standard exhibits a significant frequency dependence, so the measurement frequency should be reported with sufficient accuracy in order to make appropriate corrections.
- The ambient temperature should be (23.0 ± 1.0) °C.
- The relative humidity should be (45 ± 10) %.

5 Uncertainty of measurement

The uncertainty in the measurements should be determined in accordance with the Guide to the expression of Uncertainty in Measurement (*GUM*, ISO, 1995). A model equation has to be given that describes how the inductance value was calculated from all quantities that are involved in the measurement. For each of these quantities a description and/or the source of uncertainty should be given as well as a typical value and its estimated uncertainty. For each of the quantities, the contribution to the combined standard uncertainty is determined by (if necessary) converting the uncertainty to a standard uncertainty and applying the appropriate sensitivity coefficients. The combined standard uncertainty in the measurement is given by the root sum square of the individual contributions. All quantities, estimated values, uncertainty values, sensitivity coefficients, degrees of freedom should be reported in an uncertainty budget table as shown in annex 3.

Estimated covariances and/or estimated correlation coefficients associated with all input estimates that are correlated, and the method used to obtain them have to be stated. If there are no correlated input estimates an appropriate statement is necessary.

The effective degrees of freedom should be estimated and reported in order to determine the expanded uncertainty that corresponds to a level of confidence of approximately 95 %.

The extend of the uncertainty budget should be such that it includes all contributions to and including the determination of the inductance value at the highest level of accuracy in your laboratory that is relevant for this measurement. (So, for example: if the travelling inductor of 100 mH was measured against a 10 mH reference in an inductance ratio bridge, and the 10 mH was determined in your laboratory with a Maxwell-Wien bridge, then your uncertainty budget should contain both the measurement with the ratio bridge as well as the measurement with the Maxwell-Wien bridge. You may however decide to split the uncertainty budget into two separate tables.)

6 Measurement report

Each participating laboratory should report its results within six weeks after the standard has been shipped to the next participant. The measurement reports should be sent to Erik Dierikx, NMi VSL.

The report should contain at least:

- a description of the method of measurement;
- a description of the measurement setup and the reference standard;
- a statement about the traceability of your measurement (If your laboratory doesn't have an independent realisation of inductance, from which other laboratory do you obtain your traceability?);
- the ambient conditions of the measurement: the temperature and the humidity with limits of variation;
- the values of other influence quantities:
    - the internal temperature of the standard given as the resistance of the PT100 resistance thermometer;
    - the amplitude and frequency of the measuring signal and its uncertainty;
    - the effective series resistance of the inductor;
- the result of the measurements: the series inductance;
- the associated standard uncertainties, the effective degrees of freedom and the expanded uncertainties;
- a detailed uncertainty budget, which will be included in the final report,
- the read out data file of the transport data logger (see annex 7, capture 3.1).

The participants are also asked to report a summary of the measuring results, as shown in Annex 4. The report and the summary should preferably be sent by e-mail.

The pilot laboratory will inform a participating laboratory if there is a large deviation between the results of the laboratory and the preliminary reference values. No other information on the results will be communicated before the completion of the circulation.

7 Report of the comparison

The draft and final versions of the comparison report will be prepared by NMi VSL. The support group will decide how the reference value should be determined from the reported data. The draft A report will be distributed to the participants within 6 months after the last measurement results have been reported. The draft A report is confidential to the participants and the support group. Comments on the draft A report should be sent to the pilot laboratory within 2 month after distribution of this report. The comments will be taken into account in the draft B report. The draft B report will be distributed within about 12 months after the measurements have been completed. While NMi VSL prepares the draft B report, the support group will be asked to check the calculations of the results. The participants and support group will be allowed 2 months to report their comment on the draft B report. The final report will then be completed within about 1 month after receiving the comments on the draft B report.

Annex 1 Detailed list of participants

No	Name	Institute	Acronym	Postal address	Delivery address	Country	Telephone	Telefax	e-mail
1	Jacques Nicolas and Hugo Verbeeck	Federal Public Service Economy-Metrology Division-Calibration Service	SMD (Service de la Métrologie - Metrologische Dienst)	Boulevard du Roi Albert II, 16, BE 1000 Brussels	Boulevard du Roi Albert II, 16, BE 1000 Brussels	Belgium	+32 2 277 63 23; +32 2 277 60 84	+32 2 277 54 05	Jacques.Nicolas@mineco.fgov.be; Hugo.Verbeeck@mineco.fgov.be
2	Torsten Lippert	Arepa Test & Kalibrering A/S	DANIAmet-DPLE	Mads Clausens Vej 12, 8600 Silkeborg	Mads Clausens Vej 12, 8600 Silkeborg	Denmark	+45 87 20 69 69	+45 86 81 26 54	torsten.lippert@trescal.com
3	Jürgen Melcher and Axel Kölling	Physikalisch-Technische Bundesanstalt	PTB	Physikalisch-Technische Bundesanstalt Department 2.1 Direct Current and Low Frequency Bundesallee 100 38116 Braunschweig	Physikalisch-Technische Bundesanstalt Department 2.1 Direct Current and Low Frequency Bundesallee 100 38116 Braunschweig	Germany	+40 531 592 2100	+40 531 592 2105	Juergen.Melcher@ptb.de Axel.Koelling@ptb.de
4	György Hegyi	Országos Mérésügyi Hivatal	OMH	Országos Mérésügyi Hivatal H - 1535 Budapest, Pf.919 Hungary	Országos Mérésügyi Hivatal H - 1124 Budapest, Németvölgyi út. 37-39, Hungary	Hungary	+36 1 458 5880	+36 1 458 5949	m.telepy@omh.hu

No	Name	Institute	Acronym	Postal address	Delivery address	Country	Telephone	Telefax	e-mail
5	Oliver Power	National Metrology Laboratory (Ireland)	NML	Enterprise Ireland Campus Glasnevin Dublin 9 Ireland	National Metrology Laboratory (Ireland) Goods Inwards Section Car Park Number 3 Enterprise Ireland Campus Glasnevin Dublin 9	Ireland	+353 1 808 2252	+ 353 1 808 2026	oliver.power@enterprise-ireland.com
6	Chaikin Itzchak / Sasson Shilo	I.A.I. Standards Laboratories	IAI SL	Dept. 4238 Israel Aircraft Industries ,Ben Gurion Airport 70100	Dept. 4238 Israel Aircraft Industries ,Ben Gurion Airport 70101	Israel	972-3-9353359	972-3-9354104	ichaikin@iai.co.il
7	Erik Dierikx	Nederlands Meetinstituut Van Swinden Laboratorium	NMi VSL	PO Box 654, NL - 2600 AR, DELFT, The NETHERLANDS	Thijsseweg 11, NL - 2629 JA, DELFT, The NETHERLANDS	The Netherlands	+31 (0) 15 269 1688	+31 (0) 15 261 2971	edierikx@nmi.nl
8	Robert Rzepakowski	Central Office of Measures Electricity Department Inductance & Capacitance Standards Laboratory	GUM	Glówny Urząd Miar, Zaklad Metrologii Elektrycznej 00 - 950 Warszawa, P - 10 Poland	Glówny Urząd Miar, Zaklad Metrologii Elektrycznej, ul. Elektoralna 2, 00 - 139 Warszawa, P - 10 Poland	Poland	+48 22 581 9353	+48 22 581 9499	electricity@gum.gov.pl
9	Rui de Mello Freitas	Instituto Nacional de Engenharia, Tecnologia e Inovação, I.P.	INETI	Estrada do Paço do Lumiar, 1649-038 LISBOA Portugal	INETI - LME (Edificio D) Estrada do Paço do Lumiar, 1649-038 LISBOA Portugal	Portugal	+35 1 210 924 680	+35 1 217 143 997	Rui.Freitas@ineti.pt

No	Name	Institute	Acronym	Postal address	Delivery address	Country	Telephone	Telefax	e-mail
10	Anca Nestor	Institutul National de Metrologie	INM	Institutul National de Metrologie Sos. Vitan - Bârzeşti, nr. 11, RO-042122 Bucureşti, ROMANIA	Institutul National de Metrologie Sos. Vitan - Bârzeşti, nr. 11, RO-042122 Bucureşti, ROMANIA	Romania	+40 21 334 48 30 ext. 170; +40 21 334 50 60 ext 170	+40 21 334 55 33; +40 21 334 53 45	anca.nestor@inm.ro
11	Alexander Matlejoane	National Metrology Institute of South Africa	NMISA	Private Bag X34, Lynnwood Ridge, 0040 SOUTH AFRICA	CSIR Scientia Campus Building 5, Room 222 Meiring Naude Ave. Brummeria, Pretoria	South Africa	+27 12 841 4343	+27 12 841 2131	amatlejoane@nmisa.org
12	Frédéric Overney	Swiss Federal Office of Metrology	METAS	Lindenweg 50 CH-3003 Bern-Wabern	Lindenweg 50 CH-3084 Wabern	Switzerland	+41 31 32 33 296	+41 31 32 33 210	frederic.overney@metas.ch
13	Gülay Gülmez	Ulusal Metroloji Enstitütsü	UME	TUBITAK-UME Anibal Cad. PK 54 41470, Gebze-Kocaceli - Turkey	TUBITAK-UME Anibal Cad. PK 54 41470, Gebze-Kocaceli	Turkey	+90 262 679 5000 ext 4150	+902 626 795 001	gulay.gulmez@ume.tubitak.gov.tr
14	Janet Belliss	National Physical Laboratory	NPL	National Physical Laboratory, Hampton Road, Teddington Middlesex TW11 0LW, UK	Division for Enabling Metrology, National Physical Laboratory, Hampton Road, Teddington Middlesex TW11 0LW, UK	United Kingdom	+44 (0) 208 943 6294	+44(0) 208 943 6341	janet.belliss@npl.co.uk

No	Name	Institute	Acronym	Postal address	Delivery address	Country	Telephone	Telefax	e-mail
15	Oleh Velychko	State Enterprise "Ukrmetrtest-standard"	Ukrmetrtest-standard	4, Metrologichna Str. Kyiv-143, 03143	4, Metrologichna Str. Kyiv-143, 03144	Ukraine	+380 445 260 335	+380 445 260 335	velychko@ukrcsm.kiev.ua

Annex 2 Schedule of the measurements

First loop (2006)

No.	Institute	Country	Measurements		Time for stabilisation, measurement and transport		
			Start date	End date	Stabilisation	Measurement	Transport
0	PTB	Germany	char. of standards	24 September			3 days
1	NPL	United Kingdom	2 October 2006	16 October 2006	up to 4 days	two weeks	3 days
2	PTB	Germany	23 October 2006	29 October 2006	up to 4 days	two weeks	3 days
3	Ukrmetrteststandard	Ukraine	6 November 2006	19 November 2006	up to 4 days	two weeks	3 days
4	PTB	Germany	27 November 2006	20 December 2006	up to 4 days		

Second loop (2007)

No.	Institute	Country	Measurements		Time for stabilisation, measurement and transport		
			Start date	End date	Stabilisation	Measurement	Transport
0	PTB	Germany	char. of standards	07 January 2007			3 days
1	INETI	Portugal	15 January 2006	28 January 2007	up to 4 days	two weeks	3 days
2	SMD	Belgium	5 February 2007	18 February 2007	up to 4 days	two weeks	3 days
3	DANIAmet-DPLE	Denmark	26 February 2007	11 March 2007	up to 4 days	two weeks	3 days
4	NMi	Netherlands	19 March 2007	1 April 2007	up to 4 days	two weeks	3 days
5	PTB	Germany	16 April 2007	29 April 2007	up to 4 days	two weeks	3 days
6	GUM	Poland	7 May 2007	20 May 2007	up to 4 days	two weeks	3 days
7	OMH	Hungary	28 May 2007	10 June 2007	up to 4 days	two weeks	3 days
8	INM	Romania	18 June 2007	1 July 2007	up to 4 days	two weeks	3 days

Third loop (2007)

No.	Institute	Country	Measurements		Time for stabilisation, measurement and transport		
			Start date	End date	Stabilisation	Measurement	Transport
0	PTB	Germany	16 July 2007	29 July 2007		two weeks	up to 1 week
1	METAS	Switzerland	6 August 2007	19 August 2007	up to 4 days	two weeks	3 days
2	UME	Turkey	27 August 2007	9 September 2007	up to 4 days	two weeks	3 days
3	NML	Irland	17 September 2007	30 September 2007	up to 4 days	two weeks	3 days
4	PTB	Germany	8 October 2007	21 October 2007	up to 4 days	two weeks	3 days
5	NMI SA	South-Africa	29 October 2007	11 November 2007	up to 1 week	two weeks	up to 1 week
6	IAI SL	Israel	26 November 2007	9 December 2007	up to 1 week	two weeks	up to 1 week
7	PTB	Germany	17 December 2007	Dec. 2007/Jan. 2008	up to 1 week		

Annex 3 Typical scheme for an uncertainty budget

Supplementary comparison EUROMET.EM-S26
Inductance measurements of 100 mH at 1 kHz.
In addition to your measurement report, please send this information by e-mail to NMi VSL (EDierikx@nmi.nl).
Acronym of institute: ..... Country: .....
Average date of measurements:
Remarks:

Model equation that follows from the measurement setup:

$L_s = \dots$

Description of the quantities in the model equation:

Quantity X_i	Description

Uncertainty budget table

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
...							
...							
...							

Combined standard uncertainty	u_c	
Effective degrees of freedom	ν_{eff}	
Expanded uncertainty ($p \approx 95\%$)	U	

Annex 4 Summary of results

Supplementary comparison EUROMET.EM-S26
Inductance measurements of 100 mH at 1 kHz.
In addition to your measurement report, please send this information by e-mail to NMi VSL (EDierikx@nmi.nl).
Acronym of institute: ..... Country: .....
Average date of measurements:
Remarks:

Measurement result:

Connection	Inductance value L_s INRIM, sn. 13975 (mH)	Inductance value L_s PTB, sn. 18197 (mH)
2-terminal		

Uncertainty:

Connection	Expanded Uncertainty $U(L_s)$ INRIM, sn. 13975 (µH)	Expanded Uncertainty $U(L_s)$ PTB, sn. 18197 (µH)
2-terminal		

Additional parameters:

	INRIM	sn. 13975	PTB	sn. 18197
	Value	Exp. Unc.	Value	Exp. Unc.
2-terminal				
Series Resistance, R_s, (Ω)				
Frequency, f, (Hz)				
Current, I, (rms mA)				
R_{PT100} or R_{NTC} (Ω)				
Ambient temperature (°C)				
Relative humidity (%)				

Annex 5 Confirmation note of receipt

Supplementary comparison EUROMET.EM-S26
Inductance measurements of 100 mH at 1 kHz.
When you receive the travelling standards, please check the packages and their contents and read out the data logger. Send this information by e-mail to INM (Anca.Nestor@inm.ro).
Acronym of institute: ..... Country: .....
The packages were received on: ... (date)...

The package of the INRIM inductance standard contains the following items	yes / no
Transport case	
Inductance standard sn. 13975 (INRIM)	
Power supply 12 V	
4/2 adapter	
Shorting bar	
4x BPO dust cap	
R_{PT100} cable	
Technical protocol of EUROMET.EM-S??	
...	

The package of the PTB inductance standard contains the following items:	yes / no
Transport case	
Inductance standard sn. 18197 (PTB)	
24 V DC-uninterruptible power system (UPS)	
Cable set for UPS and line adapter	
DC/DC converter 12 V / 24 V	
cable set for DC/DC converter	
data logger for ambient parameters	
infrared-adapter for data loggers	
CD with software for data logger	
two 12 V lead-acid batteries	
cable set to connect transport batteries with the standard	
R_{NTC} cable	

Data loggers:

Maximum temperature		° C
Minimum temperature		° C
Maximum humidity		% rh
Minimum humidity		% rh

If the package or its contents shows any visible damage, please describe it here.
(If possible, include a picture):
...
...
....
(Name) (Date)

Annex 6 Confirmation note of dispatch

Supplementary comparison EUROMET.EM-S26
Inductance measurements of 100 mH at 1 kHz.
Before shipment of the travelling standards to the next participant, please check the packages and their contents and send this information by e-mail to INM (Anca.Nestor@inm.ro).
Acronym of institute: ..... Country: .....
The packages will be sent to: ...(acronym of next participant)... on: ... (date)...
I have checked the packages and they contain the following items:

The package of the INRIM inductance standard contains the following items	yes / no
Transport case	
Inductance standard sn. 13975 (INRIM)	
Power supply 12 V	
4/2 adapter	
Shorting bar	
4x BPO dust cap	
R_{PT100} cable	
Technical protocol of EUROMET.EM-S??	
...	

The package of the PTB inductance standard contains the following items:	yes / no
Transport case	
Inductance standard sn. 18197 (PTB)	
24 V DC-uninterruptible power system (UPS)	
Cable set for UPS and line adapter	
DC/DC converter 12 V / 24 V	
cable set for DC/DC converter	
data logger for ambient parameters	
infrared-adapter for data loggers	
CD with software for data logger	
two 12 V lead-acid batteries	
cable set to connect transport batteries with the standard	
R_{NTC} cable	

Remarks:
...
...
...

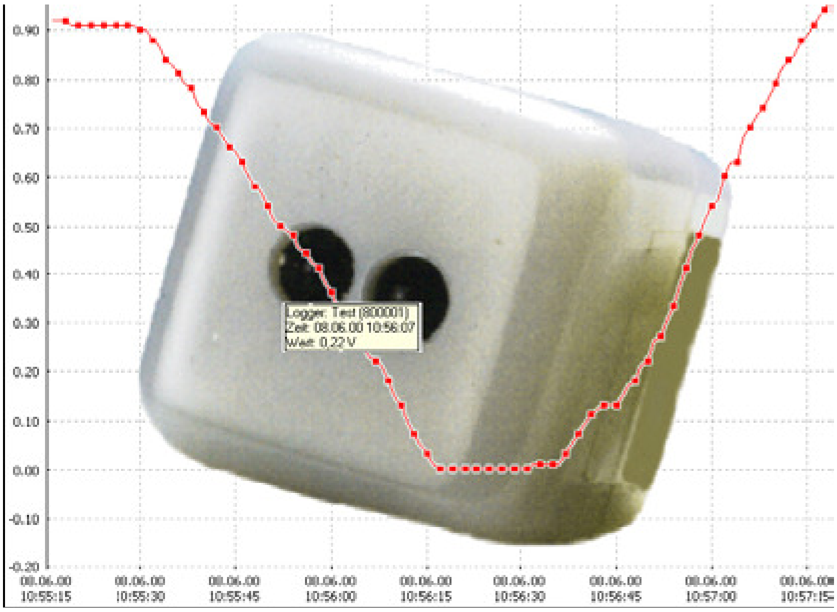
....
(Name) (Date)

Annex 7 Data logger software instructions

MINIATURE DATA LOGGER FAMILY

MINIDAN

VERSION 3.04



Extract from
USER MANUAL

By permission of

ESYS®

Physikalisch-Technische Bundesanstalt, Germany

1. Getting Started

Preparing your PC

At first, start Windows on your PC. Furthermore, check if your computer is using the correct time and date. This fact is crucial, because these settings will become the time base of your data logger.

Installing the PC-Software

Please insert the provided CD into your PC´s CD-ROM drive. The installation routine of the data logger software may be started by choosing the Windows start bar. Browse to "*Run*", type "d:\setup.exe" (where d:\ is the designation of your CD-ROM drive), click OK and follow the online-screen instructions. After confirmation of the destination directory (e. g. c:\logger) the installation will be completed.
As a result of a successful installation, the program group *Logger* with the program icon *Logger* is listed as an entry in the program bar of Windows. The software can be executed by double clicking the Icon (with the left-hand mouse key) or may be selected in Start/Programs.

Minidan

Note:
Before installing new logger-software please delete older versions from your PC.

Communication Set-Up

Communication between the data logger and the PC is provided by the wireless Infrared Interface (IrDA).

Infrared interface

This interface type eliminates the need for any wire-based-connections. An IrDA connection can be realised by connecting the IrDA-adapter *iRMATE 210* to the serial port of the PC. However, state of the art laptop computers have an IrDA interface already build in.
For establishing the data communication, the IrDA-adapter of the PC or notebook (2 diodes) is positioned as close as possible (10cm...1m distance) in front of the infrared interface of the data logger.

For error-free communication, make sure that the ***Infrared*** value is set in the menu ***Setup*** in the field ***Communication*** (default).

Communication

COM 2 | Infrared | This serial port is used to communicate with data logger.

Please note:

- For using the data logger software the automatic IrDA support under Windows must be disabled!
- Some older IrDA-Interfaces on notebooks or PC-adapters do not allow large distances because of their low sensibility. The data logger is not the cause for this difficulty. A different IrDA-adapter or a shorter distance will fix the problem.

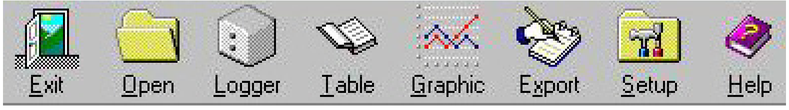
2. Preparing, Starting and Turning-off the Data Logger

2.1 Data Logger Software and PC-Data Logger Communication

Executing the Data Logger Software under Windows is done by double-clicking the left hand mouse key onto the *Logger*-icon or by selecting the Logger software from the entry Start/Program. The main Window of the Data Logger Software appears with the menu-buttons

- Exit Quits the PC data logger program
- Open Loads already stored measurement data files *(*.cu2)*
- Logger Search, read out, configure, start, switch off the data logger and display current values
- Table Alpha-numeric display of measurement values in table format
- Graphic Graphic display of measurement values
- Export Export of activated measurement values (*.xls)
- Setup Basic settings of parameters, software version-information

- Help Online-help to use the data logger software



In most of the cases by pressing the button ***Logger*** a connection to the data logger will be necessary. To establish this connection automatically, at least one logger has to be placed in front of the IrDA-interface and the correct serial port has to be selected.

Selection of the Serial Interface Port

Selecting the serial port, which is connected to the IrDA Interface is done by clicking the button ***Setup*** and choosing the appropriate port in the field ***Communication***. In case this selected port is mistakenly occupied by another device (e.g. mouse) the software will recognise and report this error immediately.

Communication

COM 2 | Infrared | This serial port is used to communicate with data logger.

A correctly selected port is automatically stored at the program exit and shown in the field ***Communication*** at the next start of this software.

2.2 Selection of the Data Logger

Activating the Button *Logger* in the main window, the logger-window is shown:

● Search for: 1 Logger

○ Search for: Logger ID

The logger identification is either automatically done by selecting one or more data loggers found or by manual input of the required logger ID-number.

Prefer Manual selection of a Required Data Logger

Activating the field ***Search for [ ] Logger ID*** and selecting or editing the ID-number **75073A** of the *CLIMA* data logger in the field ***Logger ID***.

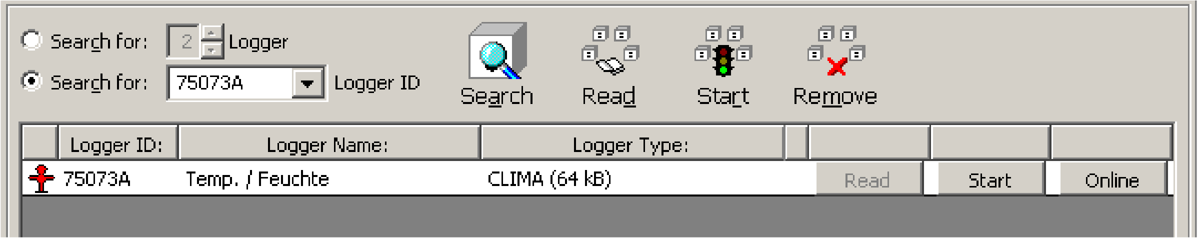
The used data logger ID-numbers are registered by the software automatically.

Please note:

The time needed to establish a connection with a data logger can last up to 20 seconds. This time can even increase (up to 4.5 min) during the establishing of a connection to a switched-off data logger.

If the communication or data transfer is disturbed, error messages will be displayed indicating the problem. At any time it is possible to re-establish the connection.

The contacted loggers are listed by the status (*found/selected/switched off*), ID-number, logger name and type, memory capacity and the current level of memory extent of utilization. If the pointer of mouse is led on the symbols, the describing information is indicated.



○ Search for: 2 Logger

● Search for: 75073A Logger ID

	Logger ID:	Logger Name:	Logger Type:				
	75073A	Temp. / Feuchte	CLIMA (64 kB)		Read	Start	Online

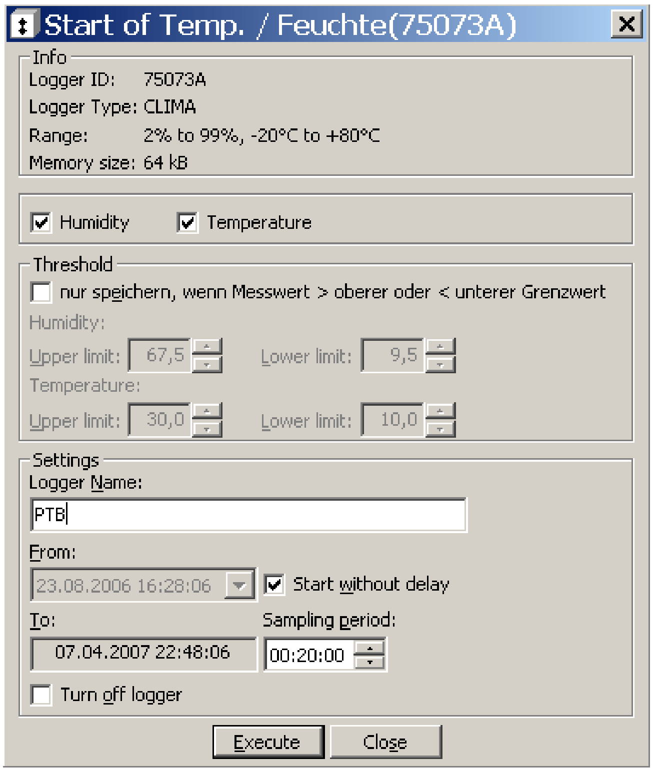
2.3 Preparing the Data Logger for Measuring Program

To configure the data logger *CLIMA* for a new measuring sequence press the button ***Start*** in the corres-ponding row of the logger. After successfully connecting to the data logger a window opens. It contains general data to the specific logger such as logger-ID, logger-type (CLIMA), measuring range and memory capacity. All parameters necessary for the measuring sequence are editable:

Field Settings: Logger-Name

Editing the acronym of the institute in the field ***Logger-Name***. This name will be assigned to the measured values.

The other fields editing like the picture beside



Start of Temp. / Feuchte(75073A)

Info

Logger ID: 75073A

Logger Type: CLIMA

Range: 2% to 99%, -20°C to +80°C

Memory size: 64 kB

☑ Humidity ☑ Temperature

Threshold

☐ nur speichern, wenn Messwert > oberer oder < unterer Grenzwert

Humidity:

Upper limit: 67,5 Lower limit: 9,5

Temperature:

Upper limit: 30,0 Lower limit: 10,0

Settings

Logger Name: PTB

From: 23.08.2006 16:28:06 ☑ Start without delay

To: 07.04.2007 22:48:06 Sampling period: 00:20:00

☐ Turn off logger

2.4 Start of the Measuring Sequence

The logger is started by clicking the button ***Execute*** in the logger-start window. The program performs a check of the entered parameters, attempts to connect to the data logger and to start it. In case of success, a message will be displayed.

Please note:

- Each reading terminates a current measuring program. If the measuring program is to be continued, the logger is to be started again.
- The time needed to establish a connection to a data logger could last up to 20 seconds. This time can even increase (up to 4.5 min) while making a connection to a switched-off data logger.
- All inputs of date and time refer to the current date and time of the PC used. Starting the logger, the PC time is used as base for the data logger. Therefore, it is very important to have a correctly set PC time.

2.5 Switching off the Data Logger

After data reading (see capture 3.1) please switch off the device using the data logger software during the stay in institute. To do that, please activate in the start window of the logger the box *Switch off* with ✓ (click) and also click the button ***Execute***. This draws the data logger into a mode with minimal power consumption. Before the transport will be started reinitialise the date logger again, but the first attempt to contact the device can last up to 4.5 minutes.

3. Reading and Displaying Measured Values

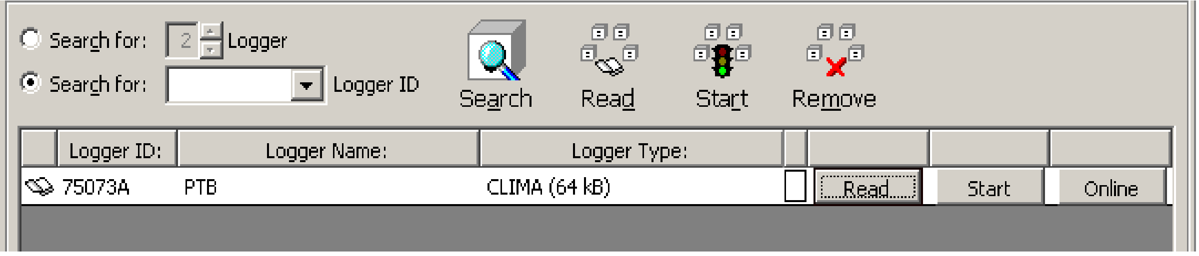
3.1 Data Reading

To read out data of the logger press the button ***Read*** in the logger-row (see capture 2.2). After successfully connecting to the data logger, the read-out of the data starts. If there are problems, appropriate messages will be displayed.

Please note:

- It is possible to read data from the logger several times. Only a new start of the logger deletes the stored data. Each data reading process will end the current logging cycle. To continue the measuring sequence after reading, the logger has to be started again.
- The time needed to establish a connection to a data logger could last up to 20 seconds. This time can even increase (up to 4.5 min) while making a connection to a switched-off data logger.

If the data transfer was successful, in the logger-row an opened book is symbolized:



○ Search for: 2 Logger

● Search for: Logger ID

	Logger ID:	Logger Name:	Logger Type:				
	75073A	PTB	CLIMA (64 kB)	☐	Read	Start	Online

After the successful transfer the data will be stored automatically in software custom format as *.cu2 file with the current folder as destination (e.g. C:\Program Files\Logger Cub). It is possible to change the current path and folder by activating the button***Browse*** in the ***Setup*** menu field ***Folder***.

File-storage space

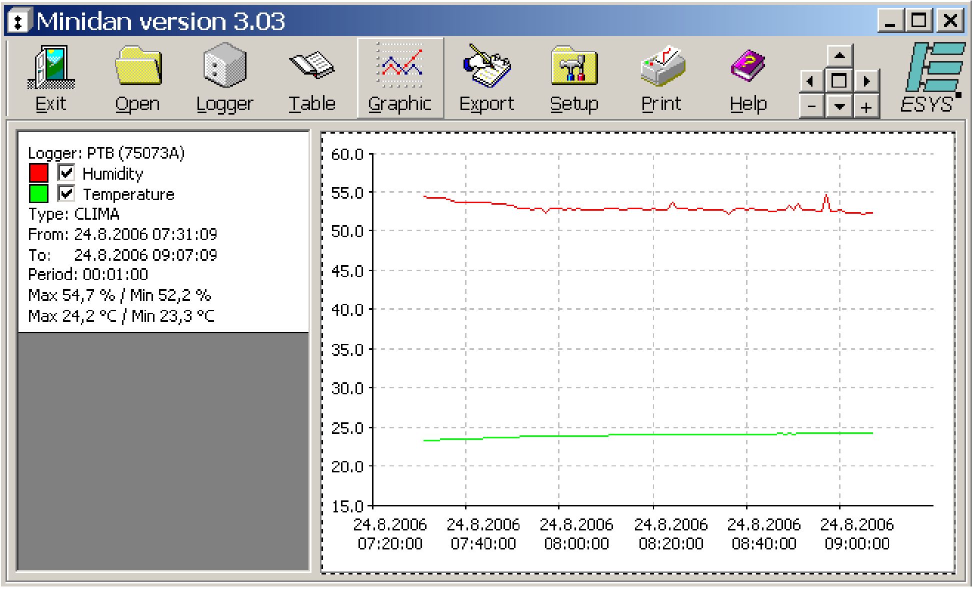
Current folder: C:\PROGRAM FILES\LOGGER\MINIDAN\CUB

This is the current path for "*.cu2"-files. To modify it, click on button "Browse..."

3.2 Displaying Measurement Values

Graphical Display

The contents of the *.cu2 - files can be displayed by pressing the button ***Graphics*** on the main bar. The currently available values are visualised graphically.



Logger: PTB (75073A)
🟥 ☑ Humidity
🟩 ☑ Temperature
Type: CLIMA
From: 24.8.2006 07:31:09
To: 24.8.2006 09:07:09
Period: 00:01:00
Max 54,7 % / Min 52,2 %
Max 24,2 °C / Min 23,3 °C

A graphical display is only possible, if the box is activated with ✓ beside the colour square (default). Clicking in this box with the mouse cursor you are able to de/activate this representation. This may be useful to show different measurements within the same diagram.

Further information about the measurement, such as Logger-ID, -type, begin and end of the measure-ments, sampling period, maximum and minimum values are shown by the graphics left.

Tabular Representation of the Measured Values

The individual measured values can also be indicated in tabular form by pressing the button *Table* in the upper menu bar. The current measured values will be displayed. The tabular representation of the measured values takes place, if the small box next to the coloured square is activated by ✓ mouse-click (default: deactivated). These last two activities are necessary, in order to represent and to compare different measurements in tables next to each other.

3.7 Exit Program

To quit the data logger software, click the ***Exit*** button in the main menu bar.

Conclusion

For more details please read the original USER MANUAL on CD.