Capacity Building & Knowledge Transfer

Specific guidelines for comparisons and CMCs in Electricity and Magnetism

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Bureau International des Poids et Mesures

Outline

- Electricity and Magnetism at a Glance
- Consultative Committee on Electricity and Magnetism (CCEM)
- Comparisons in Electricity and Magnetism
- CMCs in Electricity and Magnetism
- Conclusions

Electricity and Magnetism at a Glance

- Affects daily lives of billions
- Modern measurement instruments use electrical transducers
- Quantum electrical standards allow units to be derived from fundamental constants
- From DC to RF, from very low voltages and fields to high voltage measurements supporting electricity transmission.

T V Ω rad Db F S_{xx} A W H Wb

CCEM Strategic Plan
https://www.bipm.org/utils/en/pdf/CCEM-strategy-document.pdf

Consultative Committee on Electricity and Magnetism (CCEM)

https://www.bipm.org/en/committees/cc/ccem/

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CCEM Meeting in March 2017

SIM TCEM Chair | WGKG Chair | EURAMET TCEM Chair | CCEM President | APMP TCEM Chair | CCEM Secretary | WGSI Chair | GTRF Chair | AFRIMETS TCEM Chair | BIPM Director | WGRMO Chair | WGLF Chair

https://www.bipm.org/en/committees/cc/ccem/

CCEM Guidance Documents on Comparisons

CIPM MRA-D-05: Measurement comparisons in the CIPM MRA. Version 1.6

https://www.bipm.org/utils/common/documents/CIPM-MRA/CIPM-MRA-D-05.pdf

CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons, 2017, 28 pp.

https://www.bipm.org/utils/common/pdf/CC/CCEM/ccem_guidelines.pdf

Registration and progress report form for KCs and SCs

https://www.bipm.org/utils/common/documents/jcrb/registration_and_progress_form.pdf

Publication of a Final Report in Metrologia's Technical Supplement

https://www.bipm.org/utils/common/documents/CIPM-MRA/MET-Technical-Supplement.docx

Types of International Comparisons

Key Comparison - selected by a Consultative Committee to test the principal techniques and methods in the field (CIPM, BIPM or RMO).

Supplementary Comparison - usually carried out by an RMO to meet specific needs not covered by key comparisons (e.g. regional needs)

Pilot Studies - normally undertaken to establish measurement parameters for a "new" field or instrument, or as a training exercise. The results of pilot studies alone are not normally considered sufficient support for calibration and measurement capability (CMC).

CCEM and RMO Key Comparisons

CCEM Key Comparisons

- *Participation is open to laboratories having the **highest technical competence** and experience.*
- *Initiated by CCEM*
- *Balanced representation from RMOs (usually no more than 2-3 labs per RMO to ensure circulation does not exceed 18 months).*
- *Usually one CCEM Key Comparison per key quantity at any one time.*

RMO Key Comparisons

- *Participation is open to **all RMO members** and to other institutes that meet the rules of the regional organization (including institutes invited from outside the region) and **that have technical competence** appropriate to the particular comparison.*
- *A follow-up for CCEM Key Comparison, initiated by the RMO-TCEM*
- *At least two **linking laboratories** to link to the CCEM-KC*

Rationale for CCEM Key Comparisons

- Ensure ongoing consistent realization of the SI
- Quantum standards may eliminate the need for certain key comparisons (Zener voltage standards, 100 Ω resistance)
- Consideration of support for rapidly growing areas (power of harmonics, higher frequencies above 100 GHz, high-voltage measurements)
- WGLF aims to repeat each of the existing key comparisons during the next ten years with modifications
- GT-RF typically does not repeat key comparisons on a regular basis due to finite resources

Suggested pattern for a technical protocol

Section	Paragraph	Principal content
1 Introduction		Background and summary of the comparison; reason for carrying out the comparison
2 Travelling standard(s)	2.1 General requirements	Characteristics of the standard(s)
	2.2 Description of the standard(s)	Type, Sketch, Photos, Technical Data, Designation (make, type, serial number, size, weight, etc.)
	2.3 Quantities to be measured (optional quantities included)	Detailed description of each quantity and relevant parameters; ambient conditions of the measurement
	2.4 Method of computation of the KCRV/Reference value	A statement of how the KCRV/Reference value will be computed or a reference to the prescription that will be used
3 Organisation	3.1 Co-ordinator and members of the support group	Name, organisation and mail address
	3.2 Participants	List of participating institutes with persons responsible, details to be given in Annex A1. For RMO KCs the linking labs should be nominated
	3.3 Time schedule	Detailed circulation time schedule with clearly defined time slots for the participating laboratories (Annex A2); the procedure in case of unexpected delays should be given
	3.4 Transportation	Allowed time and means of transport, ATA carnet, informal note of confirmation for receipt and dispatch etc.
	3.5 Unpacking, handling, packing	In case of several items provide a parts list
	3.6 Failure of the travelling standard	Instructions what to do in this case
	3.7 Financial aspects, insurance	In general: each participant will pay the costs for measurement, transportation and customs formalities
4 Measurement instructions	4.1 Tests before measurements	Inspection and conditioning of the standards
	4.2 Measurement performance	Particular requirements for connecting and measuring, waiting times etc.
	4.3 Method of measurement	Typical methods, description of the methods

CCEM WGLF Key Comparisons

Quantity	<1998	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
DC Voltage																							
1.1 Sources	BIPM.K10, K11																						
1.3 Ratios					K8, 8.1																		
DC Resistance																							
2.1.2 1 ohm to 1 Mohm	K1, 1 & 10 k		BIPM.K12 QHR,		K10, 100			K13a/b, 1 / 10 k															
2.1.3 above 1 Mohm			K2, 10 M & 1 G													K2.2012 10 Mohm & 1 Gohm							
DC current to 100 A																							
Impedance																							
4.1 Resistance																							
4.2 Capacitance	K4, 10 pF						BIPM.K14a/b, 10 pF / 100 pF													K4, 10 pF / 100 pF			
4.3 Inductance	K3, 10 mH											K3.1, 10 mH											
AC Voltage																							
5.1.1 AC/DC <0.5V					K11, 10 mV, 100 mV			K11.1 10 / 100 mV															
5.1.2 AC/DC 0.5 to 5V		K6.a, 3 V																				K6.a, 3 V	
5.1.3 AC/DC >5V		K6.b, 500 / 1000 V			K9, 1000 V																	K9, 1000 V	
5.3.1 AC ratio				K7, 1 kHz																			
AC Current																							
									K12, 10 mA / 5A														
AC Power																							
		K5, 50 / 60 Hz																	K5, 50 / 60 Hz				
																			K13, power harmonics				
High voltage & current																							
Other DCLF																							

CCEM GTRF Key Comparison Strategy

Quantity	Number and Type
Power	2 KCs
Power	1 Pilot Study (on-wafer)
S parameters	2 KCs
Noise	2 KCs
Attenuation	2 KCs
Voltage	1 Pilot Study (waveform)
EM Field Strength	1 KC
Antenna Parameters	1 KC

From CCEM Strategy Document

CCEM GTRF Key Comparison Outlook

KC-P-1*	Power, 50 – 75 GHz, waveguide	-	2017	(8 labs × 1.5)+6	Covers power measurements, 50 – 75 GHz
KC-P-2*	Power, 75 – 110 GHz, waveguide	-	2022	(7 labs × 1.5)+6	Covers power measurements, 75 – 110 GHz
PS-P-1*	Pilot Study, On-Wafer Power	-	2015	(5 labs × 2) + 8	
KC-S-1*	S parameters, 2.4 mm, up to 50 GHz	-	2017	(10 labs ×1.5)+8	Covers S parameters to 50 GHz
KC-S-2*	S parameters, 1.85 mm, up to 67 GHz	-	2022	(10 labs ×1.5)+8	Covers S parameters to 67 GHz
KC-Atn-1*	Attenuation, Type N, up to 18 GHz	-	2014	(20 labs × 1)+5	Covers attenuation up to 18 GHz
KC-Atn-2*	Attenuation, 2.4 mm, up to 40 GHz	-	2018	(20 labs × 1)+5	Covers attenuation up to 40 GHz
PS-WF-1*	Pilot Study, Waveform Characterization	-	2016	(5 labs × 2)+8	
KC-N-1*	Noise, 26.5 – 40 GHz, waveguide	-	2014	(6 labs × 1.5)+6	Covers noise-temperature measurements, 26.5 – 40 GHz
KC-N-2*	Noise, 50 – 75 GHz, waveguide	-	2018	(6 labs × 1.5)+6	Covers noise-temperature measurements, 50 - 75 GHz
KC-FS-1*	Field Strength, 30 MHz – 1 GHz	-	2015	(15 labs × 1)+6	Covers Electric Field Strength, 30 MHz – 1 GHz
KC-Ant-1*	Antenna param, Gain 18 – 26.5 GHz	-	2016	(12 labs × 1)+6	Covers antenna Gain, 18 – 26.5 GHz

From CCEM Strategy Document

Supplementary Comparisons

- Initiated by the RMO-TCEM to meet specific needs not covered by the Key Comparisons
  - Extend the physical qualities
  - Extend the ranges
  - Examples from APMP:

APMP.EM- S9	**Comparison of magnetic flux density standards 2010**
Comparison type, Field	Supplementary comparison in Electricity and Magnetism, Magnetism
Status	**Approved and published**
APMP.EM- S12	**Comparison of standards for the calibration of voltage, current and resistance meters 2015 - 2016**
Comparison type, Field	Supplementary comparison in Electricity and Magnetism, DC Voltage and Current
Status	**Report in progress, Draft B**
APMP.EM- S13	**DC magnetic flux density 2012**
Comparison type, Field	Supplementary comparison in Electricity and Magnetism, Magnetism
Status	**Approved and published**

Organizing CCEM and RMO Comparisons, Technical Protocol and Draft A and Draft B Report

- The CCEM Guidelines contain detailed charts (Annexes 1, 2 and 3)

.

CCEM Guidelines | Annex 1

Chart for Organizing CCEM and RMO Comparisons

Abbreviations:
KC Key Comparison
AM Additional Measurements
SC Supplementary Comparison
PC Pilot Comparison

Note: Bilateral comparisons are treated similar to KCs and SCs
The Executive Secretary of the CCEM will automatically be involved in the activities of the WGLF, GT-RF and CCEM

No.	Action	CCEM Comparisons			RMO Comparisons		
		KC	AM	PC	KC	SC	PC
1	Member institutes of the CCEM or an RMO make a proposal for a new comparison	X	X	X	X	X	X
2	Proposals are discussed and agreed upon by WGLF or GT-RF	X	X	X			
3	Proposals are discussed and agreed upon by RMO TCEM				X	X	X
4	Pilot laboratory identified	X	X	X	X	X	X
5	Support group formed (not for bilateral comparisons)	X	X		X	X	
6	Proposals must be approved by CCEM	X	X				
7	Proposals must be approved by the chairperson of WGLF or GT-RF			X	X		
8	Proposals must be approved by the chairperson of the TCEM				X	X	X
9	Pilot laboratory sends an official invitation to the delegates of the CCEM or the contact persons of the RMO	X	X		X	X	
10	Pilot laboratory with the help of the support group prepares declaration form (DF) and technical protocol (TP)	X	X		X	X	
11	Pilot laboratory prepares technical protocol (TP)			X			X
12	DF and TP checked and approved by RMO TCEM chairperson and forwarded to WGLF or GT-RF				X		
13	DF and TP checked and approved by RMO TCEM chairperson and forwarded to the KCDB Manager for registration					X	
14	DF and TP reviewed and approved by chairperson of WGLF or GT-RF on behalf of the CCEM	X	X		X		

CCEM Guidelines | Annex 2

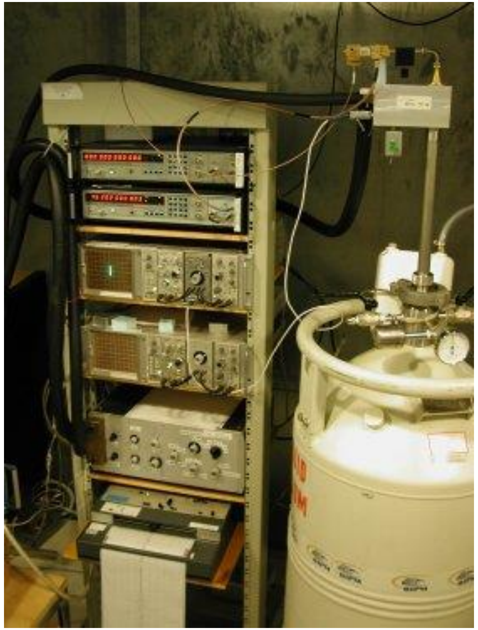
Suggested pattern for a technical protocol

Section	Paragraph	Principal content
1 Introduction		Background and summary of the comparison; reason for carrying out the comparison
2 Travelling standard(s)	2.1 General requirements	Characteristics of the standard(s)
	2.2 Description of the standard(s)	Type, Sketch, Photos, Technical Data, Designation (make, type, serial number, size, weight, etc.)
	2.3 Quantities to be measured (optional quantities included)	Detailed description of each quantity and relevant parameters; ambient conditions of the measurement
	2.4 Method of computation of the KCRV/Reference value	A statement of how the KCRV/Reference value will be computed or a reference to the prescription that will be used
3 Organisation	3.1 Co-ordinator and members of the support group	Name, organisation and mail address
	3.2 Participants	List of participating institutes with persons responsible, details to be given in Annex A1. For RMO KCs the linking labs should be nominated
	3.3 Time schedule	Detailed circulation time schedule with clearly defined time slots for the participating laboratories (Annex A2); the procedure in case of unexpected delays should be given
	3.4 Transportation	Allowed time and means of transport, ATA carnet, informal note of confirmation for receipt and dispatch etc.
	3.5 Unpacking, handling, packing	In case of several items provide a parts list
	3.6 Failure of the travelling standard	Instructions what to do in this case
	3.7 Financial aspects, insurance	In general: each participant will pay the costs for measurement, transportation and customs formalities
4 Measurement instructions	4.1 Tests before measurements	Inspection and conditioning of the standards
	4.2 Measurement performance	Particular requirements for connecting and measuring, waiting times etc.
	4.3 Method of measurement	Typical methods, description of the methods

Technical Protocol

- Travelling Standards (quantities to be measured , computation of reference values)
- Organisation (coordinator and support group, participants, schedule, transportation, handling, financial issues)
- Measurement Instructions (tests before measurements, method of measurement) Uncertainty (main components, scheme to report uncertainty budget)
- Measurement Report
- Contents of the Comparison Report
- Examples of Circulation pattern:
  - single loop(pilot->A->B->... ->N->pilot),
  - multiple loop (pilot->A->B->pilot->C->... ->pilot) and
  - Star configuration (pilot->A->pilot->B... ->pilot)

Travelling Standards



Quantum Standards

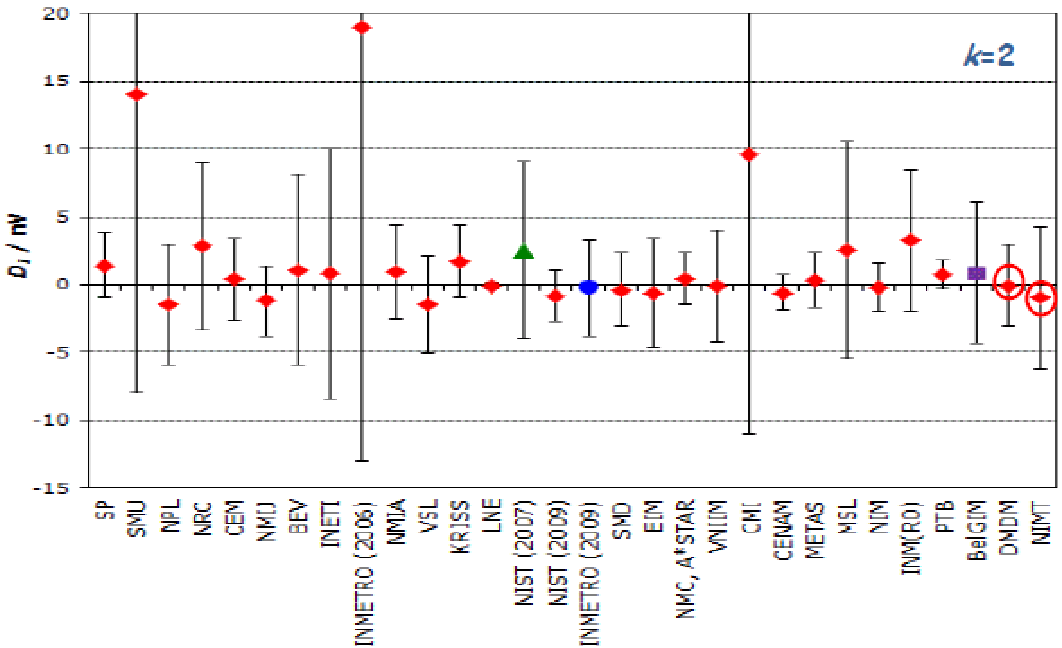
Physical Artefacts

Electronic Measuring Instruments

Varying complexity and stability

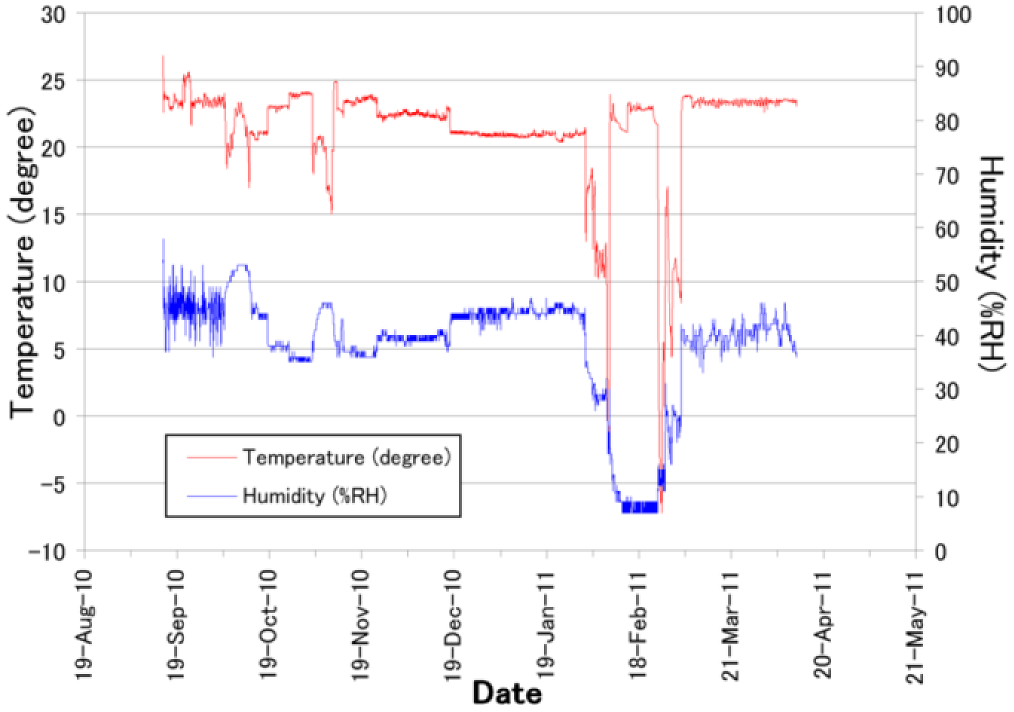
Stability of Travelling Standards – Quantum Voltage Standards

BIPM.EM-K10.b: on-site Josephson comparison (10 V)



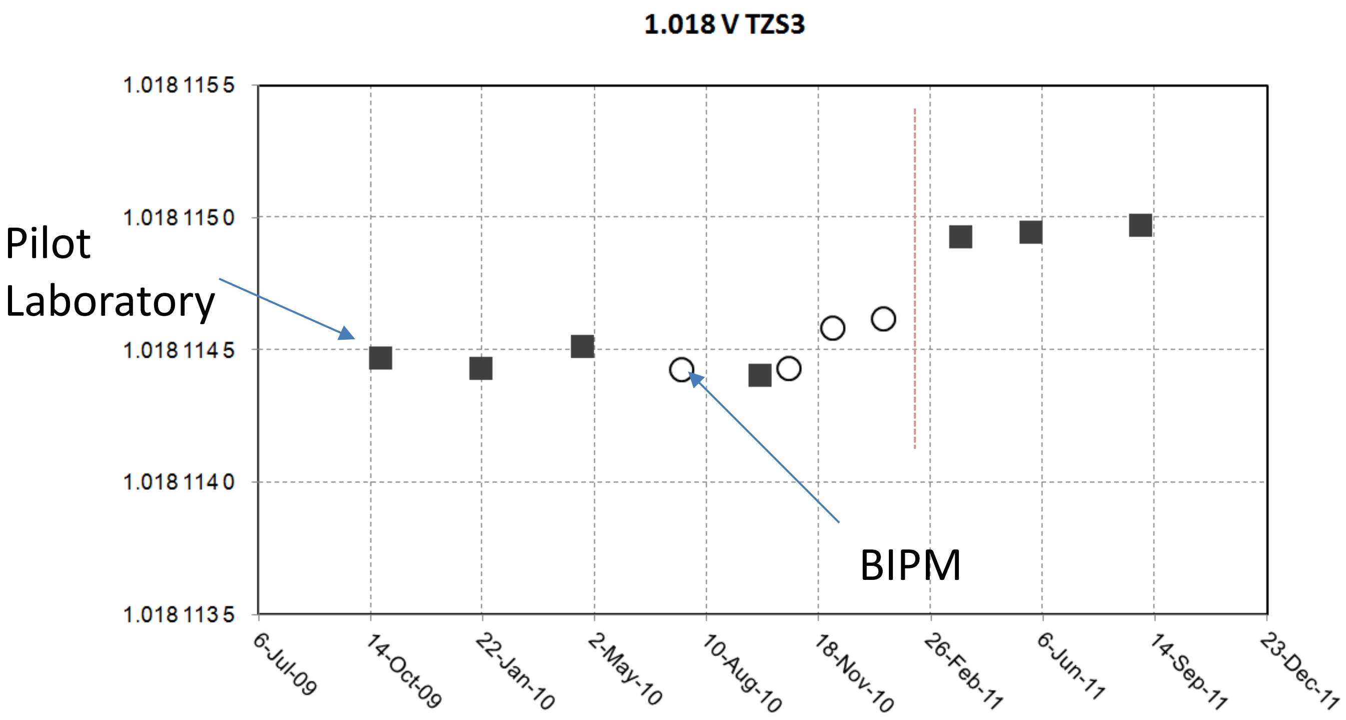
Stability of Travelling Standards - APMP.EM.BIPM-K11.3

Travelling Standard
(Battery-operated)

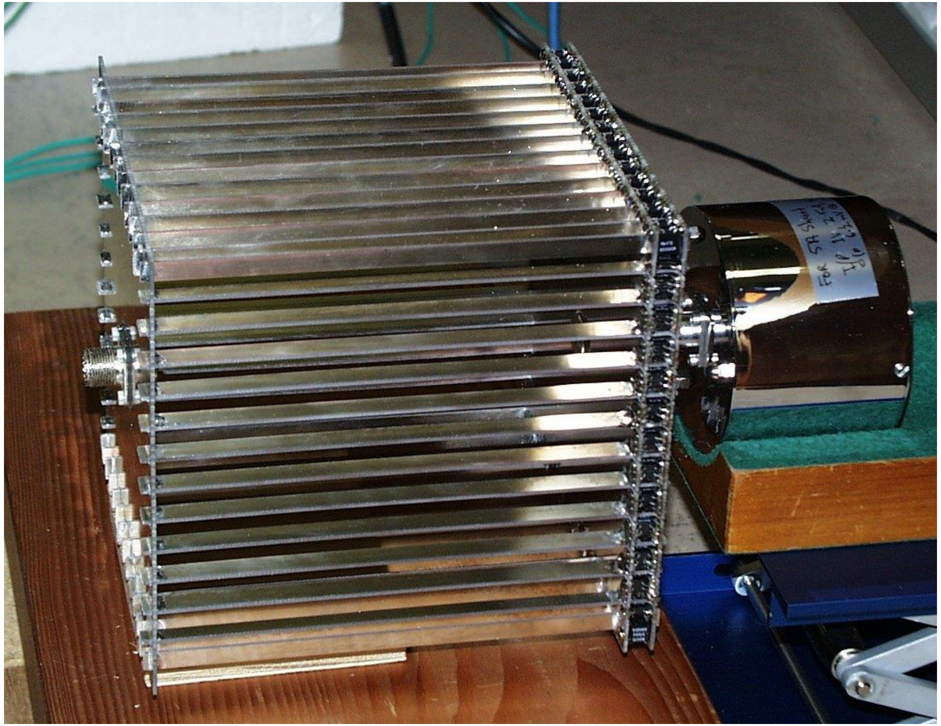


Temperature and Humidify during Circulation

Stability of Travelling Standards - APMP.EM.BIPM-K11.3



Example of Circulation Problem – CCEM-K12



Travelling Standard (NMIA)
0.2 Ω Current Shunt + Single-Junction TVC

Example of Calculating Comparison Results - APMP.EM-K6a

Travelling Standard

Holt Model 11 Single-Junction Thermal Voltage Converter, Part Number 90081C, with the following nominal parameters:

Rated Input Voltage:	4V
Heater Resistance:	400 Ω
Thermocouple Resistance:	7 Ω
Output Voltage:	7 mV

The Thermal Converter was supplied with a GR Type 874 adapter plate Part Number 84980 and two Tee-pieces, a GR Type 874 and an N-male with an N-to-GR Type 874 adapter.

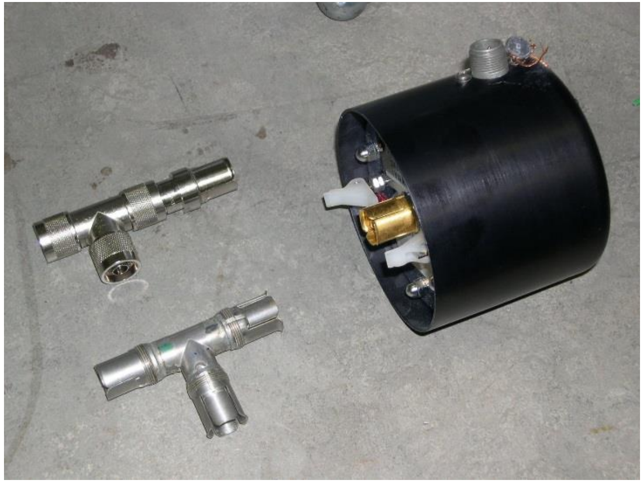


Figure 1. The Travelling Standard

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Influence of Input Connector and Tee Adaptor

It is known that the ac-dc difference of a TVC depends greatly on its input connector and the tee-adaptor used to connect it to the reference TVC. However, it is important to enable comparison of NMIs that use either type of connector in their reference TVC. For this purpose, the travelling standard was circulated with two tee-adaptors, one being Type 874 and the other Type N-male with an additional N-female to Type 874 adaptor at the travelling standard end. Prior to the start of the comparison, NML conducted a study of the differences that arise from the use of the travelling standard with the two circulated adaptors. These differences are presented in Table 1.

Table 1

Correction δ_{874} - δ_{N+874} in μV/V					
1 kHz	**20 kHz**	**50 kHz**	**100 kHz**	**500 kHz**	**1 MHz**
0	**-0.3**	**-0.7**	**-1.5**	**-4**	**-6.2**

Reported Results

Table 2

Laboratory	Nominal Measurement Period	Measured Ac-dc Difference δ_{LAB} and Expanded Uncertainty (95%) U_{LAB} in μV/V											
		1 kHz		20 kHz		50 kHz		100 kHz		500 kHz		1 MHz	
		δ	U	δ	U	δ	U	δ	U	δ	U	δ	U
NML		**-5.0**	0.8	**-2.5**	1.9	**1.0**	4.0	**4.6**	5.0	**24.1**	12.0	**34.0**	18.0
SIRIM	15/11/2000-31/12/2000	**-5.5**	5.0	**-3.7**	7.0	**2.2**	6.0	**2.0**	8.0	**26.2**	17.0	**40.5**	27.0
SCL	1/1/2001-15/2/2001	**-10.0**	9.0	**-6.0**	9.0	**-7.0**	10.0	**-1.0**	15.0	**11.0**	33.0	**16.0**	78.0
SPRING	15/2/2001-31/3/2001	**-5.1**	5.2	**-3.4**	5.2	**-0.4**	5.6	**1.1**	5.6	**7.0**	11.2	**16.8**	32.0
NML	1/4/2001-15/5/2001	**-5.0**	0.8	**-1.5**	1.9			**4.2**	5.0	**24.0**	12.0	**34.5**	18.0
NPLI	15/5/2001-30/6/2001	**-8.4**	4.4	**4.4**	4.6	**-3.5**	5.6	**-1.1**	6.4	**11.2**	22.8	**9.5**	26.0
PTB	1/7/2001-15/8/2001	**-5.3**	0.8	**-2.8**	0.8	**-0.6**	1.4	**1.1**	2.8	**5.4**	11.0	**8.9**	25.0
ITRI	15/8/2001-30/9/2001	**-5.5**	2.0	**-3.0**	2.4	**-0.2**	2.7	**1.7**	6.7	**16.0**	16.0	**28.0**	29.0
MSL	1/10/2001-15/11/2001	**-4.4**	6.2	**-1.3**	8.4	**0.7**	12.7	**5.2**	16.3	**28.3**	33.0	**27.4**	53.4
NML	15/11/2001-31/12/2001	**-4.8**	0.8	**-2.2**	1.9	**1.1**	4.0	**4.4**	5.0	**22.1**	12.0	**29.7**	18.0
NMIJ	1/1/2002 - 15/2/2002	**-5.3**	1.1	**-3.1**	1.1	**0.1**	1.3	**4.2**	1.9	**22.9**	7.1	**27.7**	20.2
NIMT	15/2/2002 - 31/3/2002	**-4.7**	5.0	**-4.0**	6.0	**-1.2**	7.0	**3.0**	11.0	**29.9**	20.0	**49.7**	28.0
KRISS	1/4/2002 - 15/5/2002	**-6.6**	2.9	**-3.1**	2.9	**-0.7**	3.3	**2.1**	3.4	**12.5**	11.9	**16.1**	23.3
NML	15/5/2002-15/8/2002	**-4.9**	0.8	**-2.3**	1.9	**1.1**	4.0	**4.5**	5.0	**22.4**	12.0	**30.5**	18.0
VMI	15/8/2002-30/9/2002	**-4.7**	4.4	**-1.7**	6.5	**0.7**	14.1	**3.5**	16.3			**22.8**	65.0
KIM-LIPI	1/10/2002-30/11/2002	**-4.8**	5.0	**-2.9**	6.0	**0.0**	14.0	**3.1**	21.0	**17.5**	44.0	**20.8**	73.0
NML-CSIR	1/12/2002-15/1/2003	**-3.9**	3.0	**-2.4**	3.0	**-0.1**	4.0	**1.6**	4.0	**6.1**	11.0	**7.8**	31.0
NML	15/1/2003-28/2/2003	**-5.0**	0.8	**-2.4**	1.9	**0.9**	4.0	**4.1**	5.0	**22.9**	12.0	**32.1**	18.0
ITDI	1/3/2003-15/4/2003	**-1.6**	8.8	**-3.0**	6.6	**1.3**	13.0	**3.5**	14.0	**120.0**	25.0	**138.8**	41.0
NML	1/6/2003-15/7/2003	**-5.1**	0.8	**-2.5**	1.9	**1.1**	4.0	**4.6**	5.0	**22.9**	12.0	**35.2**	18.0
NML Mean		**-5.0**	0.8	**-2.2**	1.9	**1.0**	4.0	**4.4**	5.0	**23.1**	12.0	**32.7**	18.0
Ref Value		**-5.2**	0.5	**-2.8**	0.6	**-0.1**	0.9	**3.3**	1.5	**18.8**	5.3	**25.6**	11.8

APMP Reference Value

The reference values for the APMP.EM-K6a comparison have been based on the results obtained by three participants, chosen on the basis of having an **independent realisation of primary standards** for ac-dc difference and the **lowest values of reported uncertainties**: NML [2], PTB [3,4] and NMIJ [5]. For each frequency, the APMP.EM-K6a reference value $\delta_{REF\text{-}APMP}$ and its standard uncertainty $u_{REF\text{-}APMP}$ have been calculated from the results of these three laboratories as a weighted mean [6] given by

$$\delta_{REF-APMP} / u^2{}_{REF-APMP} = \sum \delta_{LAB_i} / u^2{}_{LAB_i}$$

where

$$1/u^2{}_{REF-APMP} = \sum 1/u^2{}_{LAB_i}$$

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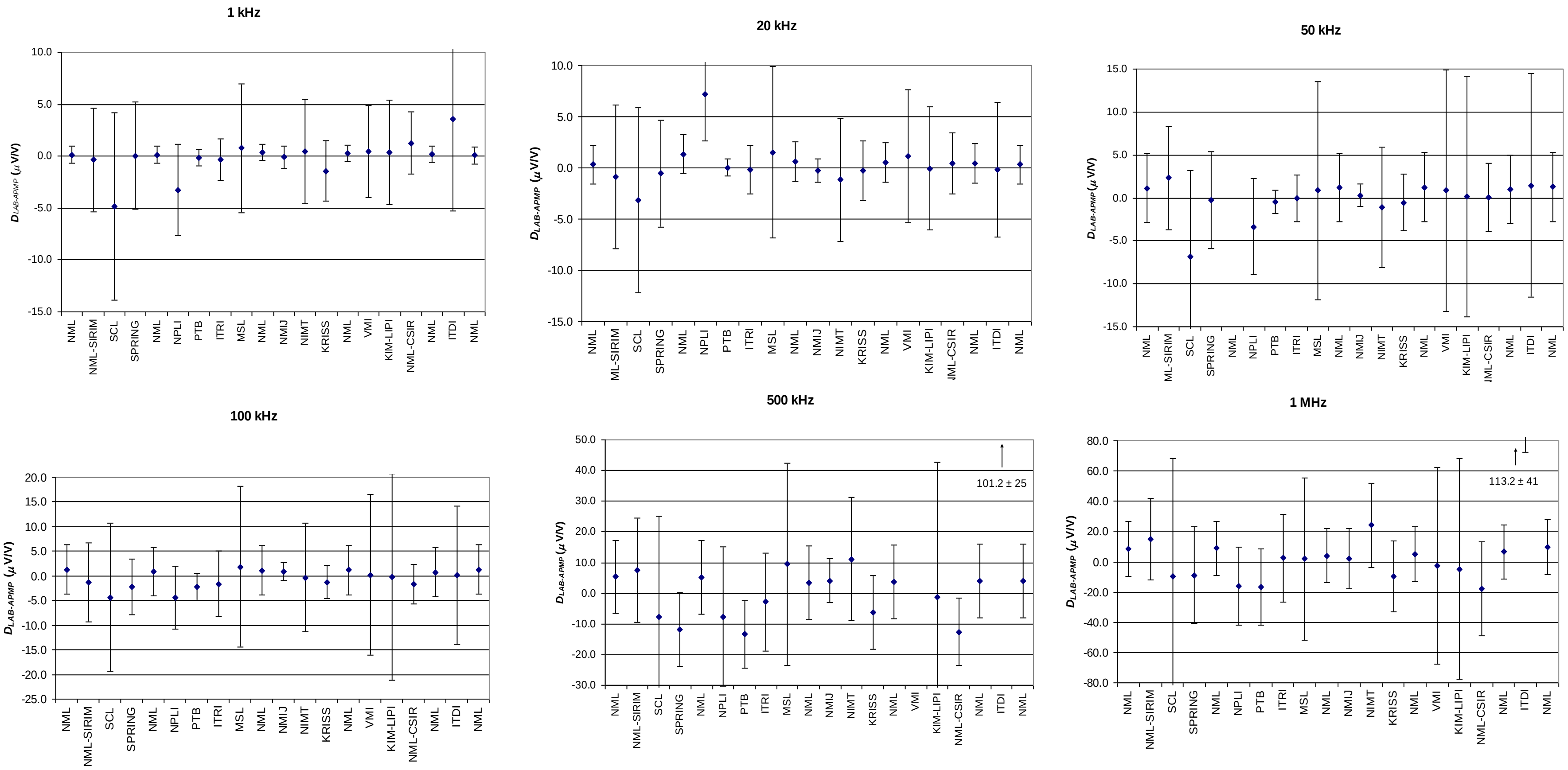
Table 3

Laboratory	Deviation from APMP Reference Value $D_{LAB\text{-}APMP}$ and Expanded Uncertainty (95%) U_{LAB} in μV/V at Frequencies											
	1 kHz		20 kHz		50 kHz		100 kHz		500 kHz		1 MHz	
	δ	U	δ	U	δ	U	δ	U	δ	U	δ	U
NML	**0.1**	0.8	**0.3**	1.9	**1.1**	4.0	**1.3**	5.0	**5.3**	12.0	**8.4**	18.0
NML-SIRIM	**-0.3**	5.0	**-0.9**	7.0	**2.3**	6.0	**-1.3**	8.0	**7.4**	17.0	**14.9**	27.0
SCL	**-4.8**	9.0	**-3.2**	9.0	**-6.9**	10.0	**-4.3**	15.0	**-7.8**	33.0	**-9.6**	78.0
SPRING	**0.1**	5.2	**-0.6**	5.2	**-0.3**	5.6	**-2.2**	5.6	**-11.8**	12.0	**-8.8**	32.0
NML	**0.1**	0.8	**1.3**	1.9			**0.9**	5.0	**5.2**	12.0	**8.9**	18.0
NPLI	**-3.2**	4.4	**7.2**	4.6	**-3.4**	5.6	**-4.4**	6.4	**-7.6**	22.8	**-16.1**	26.0
PTB	**-0.1**	0.8	**0.0**	0.8	**-0.5**	1.4	**-2.2**	2.8	**-13.4**	11.0	**-16.7**	25.0
ITRI	**-0.3**	2.0	**-0.2**	2.4	**-0.1**	2.7	**-1.6**	6.7	**-2.8**	16.0	**2.4**	29.0
MSL	**0.8**	6.2	**1.5**	8.4	**0.8**	12.7	**1.9**	16.3	**9.5**	33.0	**1.8**	53.4
NML	**0.3**	0.8	**0.6**	1.9	**1.2**	4.0	**1.1**	5.0	**3.3**	12.0	**4.1**	18.0
NMIJ	**-0.1**	1.1	**-0.3**	1.1	**0.3**	1.3	**0.9**	1.9	**4.1**	7.1	**2.0**	20.2
NIMT	**0.5**	5.0	**-1.2**	6.0	**-1.1**	7.0	**-0.3**	11.0	**11.1**	20.0	**24.1**	28.0
KRISS	**-1.4**	2.9	**-0.3**	2.9	**-0.6**	3.3	**-1.2**	3.4	**-6.3**	11.9	**-9.5**	23.3
NML	**0.3**	0.8	**0.5**	1.9	**1.2**	4.0	**1.2**	5.0	**3.7**	12.0	**4.9**	18.0
VMI	**0.5**	4.4	**1.1**	6.5	**0.8**	14.1	**0.2**	16.3			**-2.8**	65.0
KIM-LIPI	**0.4**	5.0	**-0.1**	6.0	**0.1**	14.0	**-0.2**	21.0	**-1.3**	44.0	**-4.8**	73.0
NML-CSIR	**1.3**	3.0	**0.4**	3.0	**0.0**	4.0	**-1.7**	4.0	**-12.7**	11.0	**-17.8**	31.0
NML	**0.2**	0.8	**0.4**	1.9	**1.0**	4.0	**0.7**	5.0	**4.1**	12.0	**6.5**	18.0
ITDI	**3.6**	8.8	**-0.2**	6.6	**1.4**	13.0	**0.2**	14.0	**101.2**	25.0	**113.2**	41.0
NML	**0.1**	0.8	**0.3**	1.9	**1.3**	4.0	**1.3**	5.0	**4.1**	12.0	**9.6**	18.0
NML Mean	**0.2**	0.8	**0.6**	1.9	**1.2**	4.0	**1.1**	5.0	**4.3**	12.0	**7.0**	18.0



Bureau International des Poids et Mesures

Figure 2. Deviation from APMP reference value $D_{LAB\text{-}APMP}$ and expanded uncertainty at 95% confidence level U_{LAB} in μV/V

Linking with CCEM-K6a

At the compulsory frequencies of 1 kHz, 20 kHz, 100 kHz and 1 MHz, the results of APMP.EM-K6a can be linked to CCEM-K6a through two of the three above laboratories, NML and PTB, that took part in both comparisons.

Using their results, the difference between the APMP.EM-K6a reference value $\delta_{REF\text{-}APMP}$ and the CCEM-K6a reference value $\delta_{REF\text{-}CCEM}$ can be expressed as follows:

$$\delta_{REF-APMP} - \delta_{REF-CCEM} = \frac{\sum \frac{D_{LAB-CCEM}}{u^2_{LAB-CCEM}}}{\sum \frac{1}{u^2_{LAB-CCEM}}} - \frac{\sum \frac{D_{LAB-APMP}}{u^2_{LAB-APMP}}}{\sum \frac{1}{u^2_{LAB-APMP}}}$$

Table 4

Laboratory	Deviation from CCEM-K6a Reference Value $D_{LAB\text{-}CCEM}$ and Expanded Uncertainty (95%) U_{LAB} in μV/V							
	1 kHz		20 kHz		100 kHz		1 MHz	
	δ	U	δ	U	δ	U	δ	U
NML*	**-0.2**	1.5	**0.1**	2.2	**0.2**	4.6	**5.2**	24
PTB	**0.1**	0.4	**0.1**	1	**-0.6**	2	**-13**	24

Table 5

Laboratory	Deviation from APMP Reference Value $D_{LAB\text{-}APMP}$ and Expanded Uncertainty (95%) U_{LAB} in μV/V							
	1 kHz		20 kHz		100 kHz		1 MHz	
	δ	U	δ	U	δ	U	δ	U
NML	**0.2**	0.8	**0.6**	1.9	**1.1**	5.0	**7.0**	18
PTB	**-0.1**	0.8	**0.0**	0.8	**-2.2**	2.8	**-16.7**	25

Table 6

Correction $\delta_{REF\text{-}APMP} - \delta_{REF\text{-}CCEM}$ and its Expanded Uncertainty $U_{APMP\text{-}CCEM}$ in μV/V							
1 kHz		20 kHz		100 kHz		1 MHz	
δ	U	δ	U	δ	U	δ	U
0.1	**1.6**	**0.0**	**2.7**	**1.0**	**5.8**	**-2.8**	**34**

$$u^2{}_{APMP-CCEM} = \sum\left(u^2{}_{LAB-CCEM} + u^2{}_{LAB-APMP} + 2r^2{}_{LAB}\right),$$

where r_{LAB} is the uncertainty corresponding to imperfect reproducibility of the measurements in the period elapsed between the two comparisons. This uncertainty has been determined through a separate comparison [8].

The above differences are added to the values shown in Table 3 and the graphs to obtain the values of each participant's deviation $D_{LAB\text{-}CCEM}$ from the CCEM-K6a reference value.

Pilot Laboratory – what it must do…

- **Technical protocol**
- **Register the comparison in the KCDB**
- Prepare **Travelling standards,** including determining their drift, environmental and other dependences – can be done by the support group
- **Receive measurement results from the participants.**
- In consultation with the Support Group**, calculate and evaluate the results of the comparison.**
- Prepare **Draft Report A**
- **Communicate the results to the participants.** Follow the CCEM Guidelines!
- For a Key Comparison, **Link the results with the KCRV**
- Prepare **Report B**

Many of these takes can be shared!

Pilot Laboratory – what it must have…

- **Stable standards.** The stability of the standards operated by the pilot laboratory is the only thing that an international comparison cannot check. These standards do not have to be independent.
- **Travelling standards** must have the lowest possible time drift and influence by environmental parameters and mechanical disturbances. They must be easily transportable (problems with battery-operated standards)
- **Good communication skills** and communication technology.
- **High level of judgement.** Stop and consult with support group or TC Chair when something does not seem right. Follow the guidelines when communicating with the participants.
- **Commitment to see the comparison through.** For many comparisons circulation of the standards takes less time then preparation of the reports.

Three most important things to know about comparisons

- **An international comparison is not an opportunity to calibrate your standards.** It is just a way to prove that the your standard works the way you expect.
- **Enter a comparison when you are confident in your system**, not when you are not.
- **An international comparison takes large effort from may people.** Make it count.

Coverage by Comparisons

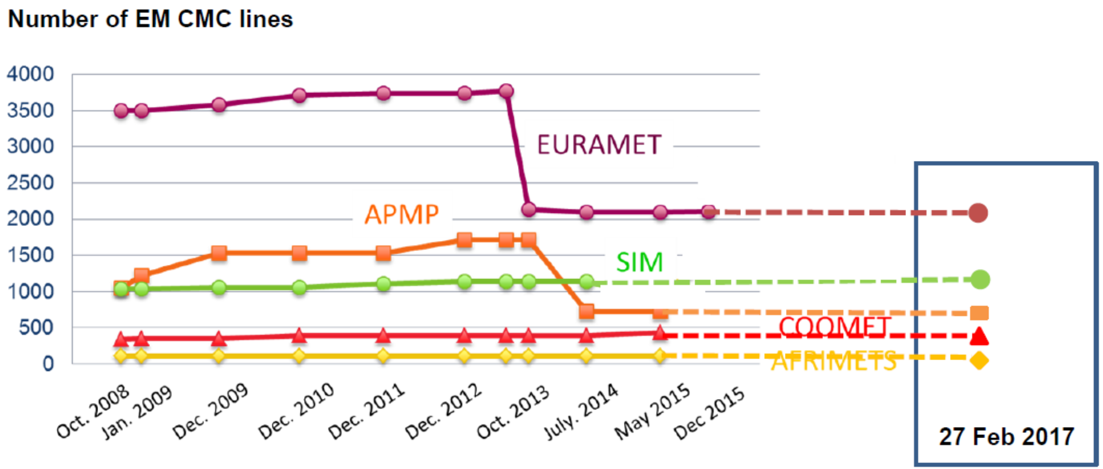
- **Electricity and Magnetism has a wide variety of quantities, ranges and influencing factors.** It is impossible to cover everything with comparisons.

- **CCEM and RMO key comparisons cover key quantities.** RMO Supplementary Comparisons and Bilateral Comparisons cover the rest as far as reasonable. E.g. Josephson voltage and Quantum Hall resistance – Key Comparisons, Digital Mutimeters (DCV, DCI, ACV, ACI, R) – supplementary comparisons.

- **Other types of evidence listed in CIPM-MRA-D-04 are important in the context of CMCs.**

CMCs in Electricity and Magnetism

- Second largest number of CMCs after Chemistry
- MRA Review Initiative 1 - Simplification of CMC format using matrices



	CMC	MTX
AFRIMETS	118	5
APMP	796	365
COOMET	455	29
EURAMET	2065	763
GULFMET	0	0
SIM	1038	149
TOTAL	4472	1311

The 1311 matrices underpin around 1750 CMCs.

CMCs in Electricity and Magnetism – example of the use of matrices

Electricity and Magnetism, Australia, NMIA (National Metrology Institute, Australia)

Calibration or Measurement Service			Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded Uncertainty							
Quantity	Instrument or Artifact	Instrument Type or Method	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage Factor	Level of Confidence	Is the expanded uncertainty a relative one ?	Uncertainty matrix	NMI service identifier	Comments
DC voltage sources: single values	Zener references	Voltage difference	1	10	V	Temperature	20 °C	0.02 to 0.04	µV/V	2	95%	Yes	Mx1.1.1	3	Approved on 31 October 2016
DC voltage sources: low value ranges (below or equal to 10 V)	DC voltage source, multifunction calibrator	Voltage difference	1E_08	10	V			0.02 to 23	µV	2	95%	No	Mx1.1.2	1.1.2	Approved on 31 October 2016
DC voltage sources: intermediate values (above 10 V to 1100 V)	DC voltage source, multifunction calibrator	Voltage difference	10	1100	V			1.1 to 2.8	µV/V	2	95%	Yes	Mx1.1.3	1.1.3	Approved on 31 October 2016
DC voltage meters: intermediate values	Digital multimeter	JAVS, calibrators	0.001	1100	V			0.1 to 500	µV/V	2	95%	Yes	Mx1.2.2	39	Approved on 31 October 2016
DC voltage ratios: up to 1000 V	Resistive divider	Potentiometry	0.001	0.5	V/V	Maximum input voltage	1000 V	0.5	µV/V	2	95%	Yes		1.3.1	Approved on 31 October 2016
DC resistance standards and sources: low values (<= 1 Ω)	Standard resistor	Resistance bridge	1E-05	1	Ω	Air or oil bath temperature	20 °C to 25 °C	0.13 to 20	µΩ/Ω	2	95%	Yes	Mx2.1	2.1.1	Approved on 31 October 2016
DC resistance standards and sources: intermediate values (> 1 Ω to 1 MΩ)	Standard resistor	Resistance bridge	> 1	1E+06	Ω	Air or oil bath temperature	20 °C to 25 °C	0.13 to 0.5	µΩ/Ω	2	95%	Yes	Mx2.1	2.1.2	Approved on 31 October 2016
DC resistance standards and sources: high values (> 1 MΩ)	Standard resistor	Resistance bridge	> 1	1E+08	MΩ	Temperature	20 °C to 25 °C	2 to 30000	µΩ/Ω	2	95%	Yes	Mx2.1	2.1.3	Approved on 31 October 2016

CMCs in Electricity and Magnetism – example of the use of matrices

Calibration and Measurement Capabilities

Electricity and Magnetism, Australia, NMIA (National Metrology Institute, Australia)

Mx2.1

	Relative expanded uncertainty / (μΩ/Ω)	Current, voltage	Standard
10 μΩ	10	32 A	Standard resistors
>10 μΩ to <100 μΩ	20	10 A to 32 A	Standard resistors
10 μΩ to <100 μΩ	200 to 20	100 A to 2000 A	DC Shunts
100 μΩ	2	10 A	Standard resistors
>100 μΩ to <1 mΩ	2	3.2 A to 10 A	Standard resistors
100 μΩ to 1 mΩ	20 to 10	100 A to 2000 A	DC Shunts
1 mΩ	1.5	3.2 A	Standard resistors
>1 mΩ to <10 mΩ	2	1 A to 3.2 A	Standard resistors
10 mΩ	1	1 A	Standard resistors
>10 mΩ to <100 mΩ	1	320 mA to 1 A	Standard resistors
100 mΩ	0.3	320 mA	Standard resistors
>100 mΩ to <1 Ω	1	100 mA to 320 mA	Standard resistors
1 Ω	0.13	100 mA	Standard resistors
>1 Ω to <10 Ω	0.3	32 mA to 100 mA	Standard resistors
10 Ω	0.15	32 mA	Standard resistors
>10 Ω to <100 Ω	0.3	10 mA to 32 mA	Standard resistors
100 Ω	0.15	10 mA	Standard resistors
>100 Ω to <1 kΩ	0.3	3.2 mA to 10 mA	Standard resistors
1 kΩ	0.15	3.2 mA	Standard resistors
>1 kΩ to <10 kΩ	0.3	1 mA to 3.2 mA	Standard resistors
10 kΩ	0.13	1 mA	Standard resistors
>10 kΩ to 1 MΩ	1	0.1 mA to 1 mA	Standard resistors
>1 MΩ to <10 MΩ	2	10 V to 100 V	Standard resistors
10 MΩ	1	10 V to 100 V	Standard resistors
>10 MΩ to <100 MΩ	2	10 V to 100 V	Standard resistors
10 MΩ to 100 MΩ	300	>100 V to 1000 V	Standard resistors
100 MΩ	2	50 V to 100 V	Standard resistors
100 MΩ to 1 GΩ	500	>100 V to 1000 V	Standard resistors
1 GΩ	5	100 V	Standard resistors
>1 GΩ to 100 GΩ	1000	100 V to 1000 V	Standard resistors
>100 GΩ to <1 TΩ	3000	100 V to 1000 V	Standard resistors
1 TΩ	2000	100 V to 1000 V	Standard resistors
>1 TΩ to 10 TΩ	3000	100 V to 1000 V	Standard resistors
>10 TΩ to 100 TΩ	30000	100 V to 1000 V	Standard resistors

The BIPM key comparison database, November 2016

- **Optimisation using matrices dramatically improves the presentation of CMCs**
- **It is mandatory for all new CMC submissions in CCEM!**

CCEM Guidance Documents on CMCs

Calibration and Measurement Capabilities in the context of the CIPM MRA
https://www.bipm.org/utils/common/documents/CIPM-MRA/CIPM-MRA-D-04.pdf

Electricity and Magnetism Supplementary Guide to the JCRB Instructions for Appendix C of MRA (incl. CMC Excel Template) https://www.bipm.org/utils/common/documents/jcrb/EM_CMC_instructions.zip

- to be updated soon

CLASSIFICATION OF SERVICES IN ELECTRICITY AND MAGNETISM
http://kcdb.bipm.org/appendixC/EM/EM_services.pdf

JCRB CMC-Review Web Page Manual
https://www.bipm.org/utils/en/pdf/jcrb_webpage_manual.pdf

CMCs in Electricity and Magnetism

Classification of Services

CLASSIFICATION OF SERVICES IN ELECTRICITY AND MAGNETISM

Version No 7.6 (dated 17 March 2011)

METROLOGY AREA: ELECTRICITY AND MAGNETISM

BRANCH: DC VOLTAGE, CURRENT, AND RESISTANCE

1. **DC voltage** (up to 1100 V, for higher voltages see 8.1)
   - **1.1 DC voltage sources**
     - 1.1.1 Single values[1]: *standard cell, solid state voltage standard*
     - 1.1.2 Low value ranges (below or equal to 10 V): *DC voltage source, multifunction calibrator*
     - 1.1.3 Intermediate values (above 10 V to 1100 V): *DC voltage source, multifunction calibrator*
     - 1.1.4 Noise voltages (for noise currents see 3.1.5, for RF noise see 11.4): *DC voltage source, DC amplifier*
   - **1.2 DC voltage meters**
     - 1.2.1 Very low values (below or equal to 1 mV): *nanovoltmeter, microvoltmeter*
     - 1.2.2 Intermediate values (above 1 mV to 1100 V: *DC voltmeter, multimeter, multifuntion transfer standard*
   - **1.3 DC voltage ratios** (for input voltages up to 1100 V)
     - 1.3.1 Up to 1100 V: *resistive divider, ratio meter*
     - 1.3.2 Attenuation: *attenuators*

2. **DC resistance**
   - **2.1 DC resistance standards and sources**
     - 2.1.1 Low values (below or equal to 1 Ω): *fixed resistor, resistance box*
     - 2.1.2 Intermediate values (above 1 Ω to 1 MΩ): *fixed resistor, resistance box*
     - 2.1.3 High values (above 1 MΩ): *fixed resistor, three terminal resistor, resistance box*
     - 2.1.4 Standards for high current: *DC shunt*
     - 2.1.5 Multiple ranges: *multifunction calibrator*
     - 2.1.6 Temperature, power and pressure coefficients: *fixed resistor*
   - **2.2 DC resistance meters**
     - 2.2.1 Low values (below or equal to 1 Ω): *microohmmeter, multimeter, multifunction transfer standard, resistance bridge*
     - 2.2.2 Intermediate values (above 1 Ω to 1 GΩ): *ohmmeter, multimeter, multifunction transfer standard, resistance bridge*
     - 2.2.3 High values (above 1 GΩ): *multimeter, multifunction transfer standard, teraohmmeter*

…

The BIPM key comparison database KCDB

- 12.1.3 Semiconducting and similar materials: *reference wafers*

12.2 Dielectric properties
- 12.2.1 Relative permittivity: real and/or imaginary part: *solid materials, liquid materials*
- 12.2.2 Dielectric loss tangent: tan δ: *solid materials, liquid materials*

12.3 Soft magnetic sheet and powder materials
- 12.3.1 Specific total power loss: *Epstein, ring and single sheet sample*
- 12.3.2 Peak value of DC magnetic polarisation: *Epstein, ring and single sheet sample*
- 12.3.3 Peak value of AC magnetic polarisation: *Epstein, ring and single sheet sample*
- 12.3.4 Peak value of magnetic field strength: *Epstein, ring and single sheet sample*
- 12.3.5 RMS value of magnetic field strength: *Epstein, ring and single sheet sample*
- 12.3.6 Specific apparent power: *Epstein, ring and single sheet sample*
- 12.3.7 Relative peak permeability: *Epstein, ring and single sheet sample*
- 12.3.8 Complex relative permeability
- 12.3.9 Density: *Epstein, ring and single sheet sample*
- 12.3.10Resistivity: *Epstein, ring and single sheet sample*

12.4 Soft magnetic bulk material
- 12.4.1 Magnetic polarisation: *rod, cylinder*
- 12.4.2 Magnetic field strength: *rod, cylinder*
- 12.4.3 Remanent magnetic flux density: *rod, cylinder*
- 12.4.4 Coercive magnetic field strength: *rod, cylinder*
- 12.4.5 Magnetic saturation polarisation: *rod, cylinder*
- 12.4.6 Relative permeability: *rod, cylinder*

12.5 Feebly magnetic, paramagnetic and diamagnetic material
- 12.5.1 DC magnetic susceptibility or relative magnetic permeability: *rod, cylinder*

12.6 Hard magnetic material
- 12.6.1 Remanent magnetic flux density: *cylinder, rectangular parallelepiped*
- 12.6.2 Coercive field strength (H_{CB}, H_{CJ}): *cylinder, rectangular parallelepiped*
- 12.6.3 Maximum energy product $(B.H)_{max}$: *cylinder, rectangular parallelepiped*
- 12.6.4 Magnetic moment: *cylinder, rectangular parallelepiped*
- 12.6.5 Magnetic flux density: *cylinder, rectangular parallelepiped*
- 12.6.6 Magnetic polarisation: *cylinder, rectangular parallelepiped*
- 12.6.7 Relative recoil permeability

12.7 Magnetic data storage media
- 12.7.1 Signal amplitude of magnetic stripes: *magnetic stripes*
- 12.7.2 Surface profile of magnetic stripes: *magnetic stripes*
- 12.7.3 Reference field of diskettes: *diskettes*
- 12.7.4 Signal amplitude of diskettes: *diskettes*
- 12.7.5 Resolution of diskettes: *diskettes*
- 12.7.6 Peak shift of diskettes: *diskettes*
- 12.7.7 Overwrite of diskettes: *diskettes*
- 12.7.8 Video and audio tapes

The Classification of services Version 7.6 in Electricity and Magnetism is available under the form of an EXCEL file by clicking here.

CMCs in Electricity and Magnetism

CMC submission process essentials

1. RMO TCEM Chair calls for a submission of a CMC set.
2. Intra-RMO review is conducted using RMO and TC Guidelines
   - RMO Guidelines https://www.bipm.org/en/cipm-mra/cipm-mra-documents/
3. RMO TCEM Chair Submits the CMC Set for the Intra-RMO Review
   - CMC Spreadsheets
   - Evidence of Coverage by QS
   - Short Report
   - Summary of new CMCs – specific to CCEM
4. CCEM WGRMO Chair organises the review
5. RMOs approve the CMCs
6. CMCs are published in the KCDB

CMCs in Electricity and Magnetism

- MRA Review Initiative 2 - Risk-based approach to Inter-RMO CMC based on sampling.

Prior to CCEM 2011:

Up to 400% review (Four RMOs each reviewing the entire set)

↓

Since CCEM 2011:

100% review (2-4 RMOs collectively reviewing the entire set)

↓

After CCEM 2015:

0 - 100% review (based on sampling)

CMCs in Electricity and Magnetism

Sampling Strategy

CCEM 2015 Decision:

Upon submission of a CMC set, a proposal for the scope of Inter-RMO review is made by the Chair of WG-RMO or designate, based on agreed criteria such as:

- Magnitude of change
- History of previous reviews
- Coverage by on-site technical reviews
- Rotation
- High-level technical judgement

The final decision on the scope of review lies with RMOs.

CMCs in Electricity and Magnetism

Implementation of Sampling Strategy (Example 1)

No	Country (NMI)		Entries in category																										
	Contact		1		2		3		4		5		6		7		8		9		10		11		12		Sum		
			entry	matrix																									
CZ	Czech Republic (CMI)	new																								3	0	3	AFRIMETS
	jstreit@cmi.cz	improved							4	4									2	2					5		11	6	APMP
		minor ch.																					1	1			1	1	COOMET
		delete																									0	0	EURAMET
FI	Finland (MIKES)	new			2	2	1										2										5	2	SIM
	Jari.Hallstrom@vtt.fi	improved			3	3			2	2							1	1									6	6	
		minor ch.			3																						3	0	
		delete																									0	0	
FR	France (LNE)	new							3	3							2	1									5	4	
	francois.piquemal@lne.fr	improved									1	1	1	1			2	2					2	2			6	6	
		minor ch.					1										1						1	1			3	1	
		delete																									0	0	
DE	Germany (PTB)	new							2	1													1	6			3	7	
	Juergen.Melcher@ptb.de	improved																					5				5	0	
		minor ch.																					4				4	0	
		delete																									0	0	
IE	Ireland (NSAI NML)	new									3	3															3	3	
	oliver.power@nsai.ie	improved																									0	0	
		minor ch.																									0	0	
		delete									22																22	0	

CMCs in Electricity and Magnetism

Implementation of Sampling Strategy (Example 2)

SIM.EM.9.2015 **Submitted Entries**

Deadline for submission: 10/30/2015 Version: date 04/07/2016

Intra-RMO review: Start 1/1/2016 End: 6/30/2016

No	**Country (NMI)**		**Entries in category**																										
	Contact		**1**		**2**		**3**		**4**		**5**		**6**		**7**		**8**		**9**		**10**		**11**		**12**		**Sum**		
			entry	matrix																									
																													AFRIMETS
CENAMEP	Julio Gonzalez	new																									0	0	APMP
	jgonzalez@cenamep.org.pa	improved													2												2	0	COOMET
		minor ch.																									0	0	EURAMET
		delete																									0	0	SIM
NRC	Carlos Sanchez	new																									0	0	GULFMET
	Carlos.Sanchez@nrc-cnrc.gc.ca	improved	7	7	7	2				1	5	1	1	1	4		18	11					8	2			50	25	
		minor ch.							7																		7	0	
		delete																									0	0	
		new	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
		improved	7	7	7	2	0	0	0	1	5	1	1	1	6	0	18	11	0	0	0	0	8	2	0	0	52	25	
	Total	minor ch.	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	
		delete	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

CMCs in Electricity and Magnetism

CCEM Inter-RMO Reviews

		AFRIMETS	APMP	COOMET	EURAMET	SIM	GULFMET	Notes
Sharing	AFRIMETS.EM.1.2013		No	Yes	Yes	No		1 lab only (NIS - Egypt)
	APMP.EM.7.2011	Yes		No	Yes	Yes		CMCs from 9 NMIs
	APMP.EM.8.2013	Yes		Yes	Yes	Yes		CMCs from 5 NMIs
	COOMET.EM.6.2013	Yes	Yes		No	No		1 NMI (Belarus - BelGim)
	COOMET.EM.7.2014	Yes	No		Yes	No		CMCs from 5 NMIs, **ongoing**
	EURAMET.EM.8.2012	No	Yes	Yes !		Yes		CMCs from 15 NMIs, sharing between APMP a
	EURAMET.EM.12.2014	Yes	Yes	No		Yes		CMCs from 18 NMIs, **ongoing**
	SIM.EM.7.2014	Yes	No	Yes	No			1 NMI (INTI - Argentina)
Samling and Sharing	**COOMET.EM.8.2015**		**Yes**			**Yes**		**2015-03-16 - 2015-05-21**
	EURAMET.EM.13.2015	**Yes**	**Yes**			**Yes**		**2015-08-31 - 2016-04-21**
	SIM.EM.8.2015			**Yes**	**Yes**			**2015-10-23 - 2016-04-29**
	APMP.EM.9.2015			**Yes**	**Yes**	**Yes**		**2015-12-21 - 2016-12-05**
	COOMET.EM.8.2015		**Yes**			**Yes**		**2015-03-16 - 2015-05-21**
	COOMET.EM.9.2015							**2015-12-21 - Re-submitted using matrices**
	COOMET.EM.10.2015	**Yes**	**Yes**					**2016-01-04 - 2016-03-25**
	COOMET.EM.11.2016							**2016-06-07 - 2016-09-07**
	SIM.EM.9.2016		**Yes**	**Yes**	**Yes**		**Yes**	**2016-10-04 - 2017-05-04**
	AFRIMETS.EM.2.2016					**Yes**	**Yes**	**2016-10-05 - 2016-12-05**
	SIM.EM.9.2016				**Yes**			**2017-03-27 - 2017-05-31**
	COOMET.EM.12.2017					**Yes**	**Yes**	**2017-05-29 - 2017-06-20**
	AFRIMETS.EM.3.2017		**Yes**	**Yes**		**Yes**	**Yes**	**2017-09-22 - 2017-10-12**

Conclusions

- CCEM and RMO Technical Committees for Electricity offer wide-range support for comparisons, development and publications of CMCs.
- Work is under wat to make the Comparison and CMC processes as efficient as possible.
- Hopefully, proving international equivalence with comparisons and CMCs will be easier for developing NMIs than capacity building.

Capacity Building & Knowledge Transfer

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