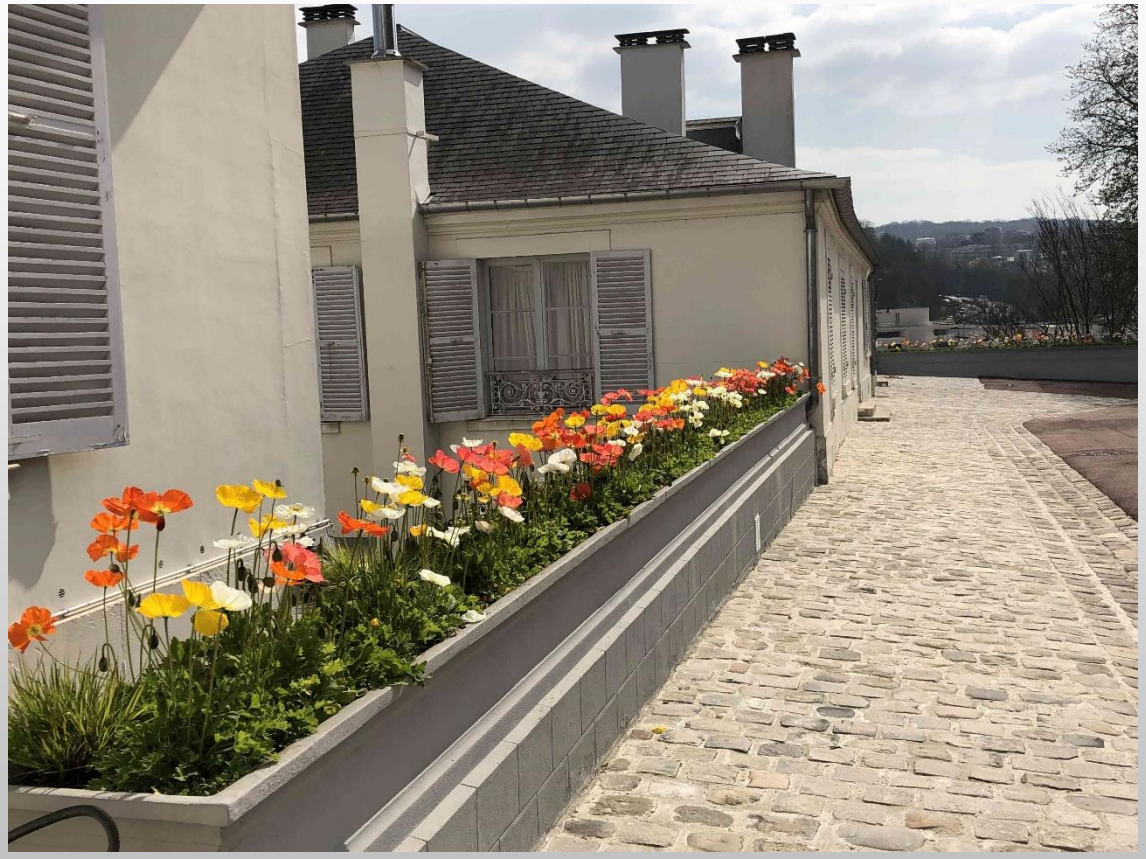
WGLF Summary to CCEM
14 April 2021

Two online meetings of the WGLF on 8th and 13th April 2021

~ 57 participants both meetings



Murray Early

WGLF chairman

Table from 2013 CCEM Strategic Plan

- 14 key comparison listed.
- K1 and K10 have been replaced by BIPM on-site comparisons.
- Need to respond to technical developments (e.g. ac PJVS), RMO needs, traceability demands etc.
- Time for an update…

9. Summary table of comparisons, dates, required resources and the laboratories already having institutional agreement to pilot particular comparisons

Reference number	Description	Repeat cycle	Potential start date	Estimate of resources*	How far does the light shine
CCEM-K1	Resistance, 1 Ohm and 10 kOhm	10 yr	2015	(12 labs x 1) +5	Covers resistance metrology <1 Mohm including realization of QHR primary standard
CCEM-K2	Resistance, 10 Mohm and 1GOhm	10 yr	2013	(12 labs x 1) +5	Covers resistance metrology >1Mohm
CCEM-K10	resistance, 100 Ohm	None			BIPM QHR comparisons and local QHR realisations have reduced the need for this
CCEM-K3	Inductance, 10 mH	10 yr	2020	(12 labs x 1) +5	Covers all inductance
CCEM-K4	Capacitance, 10 pF	10 yr	2015	(12 labs x 1) +5	Covers all capacitance, last comparison 1998
CCEM-K5	ac power at 50/60 Hz	10 yr	2013	(11 labs x 1) +5	Covers all electric power at 50/60 Hz
CCEM-K13	ac power harmonics	unkn	2013	(7 labs x 1.5) +6	Covers all measurement of harmonics in power systems
CCEM-K6.a	ac/dc voltage transfer, 3 V Frequency: 1 kHz, 20 kHz, 100 kHz and 1 MHz	10 yr	2014?	(12 labs x 1) +5	Covers measurement of ac/dc voltage transfer difference and ac voltage at low frequency
CCEM-K6 c	Ac/dc voltage transfer Voltage: 3 V and 4 V Frequency: 0.5 MHz, 1 MHz, 10 MHz, 30 MHz, 50 MHz, 70 MHz and 100 MHz	10 yr	2014?	(12 labs x 1) +5	Covers measurement of ac/dc voltage transfer difference and ac voltage at high frequency
CCEM-K9	High voltage ac/dc converters Voltage: 1000 V, 500 V and 200 V Frequency: 1 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz	10 yr	2016?	(12 labs x 1) +5	Covers measurement of ac/dc voltage transfer difference and ac voltage at low frequency and high voltage
CCEM-K11	ac/dc voltage transfer difference at low voltages	10 yr	2018?	(12 labs x 1) +5	Covers measurement of ac/dc voltage transfer difference and ac voltage at low frequency and low voltage
CCEM-K12	ac/dc current transfer	10 yr	2020?	(12 labs x 1) +5	Covers measurement of ac/dc current transfer difference and ac current at low frequency
CCEM-K7	ac voltage ratio	20 yr			
CCEM-K8	dc voltage ratio	20 yr			

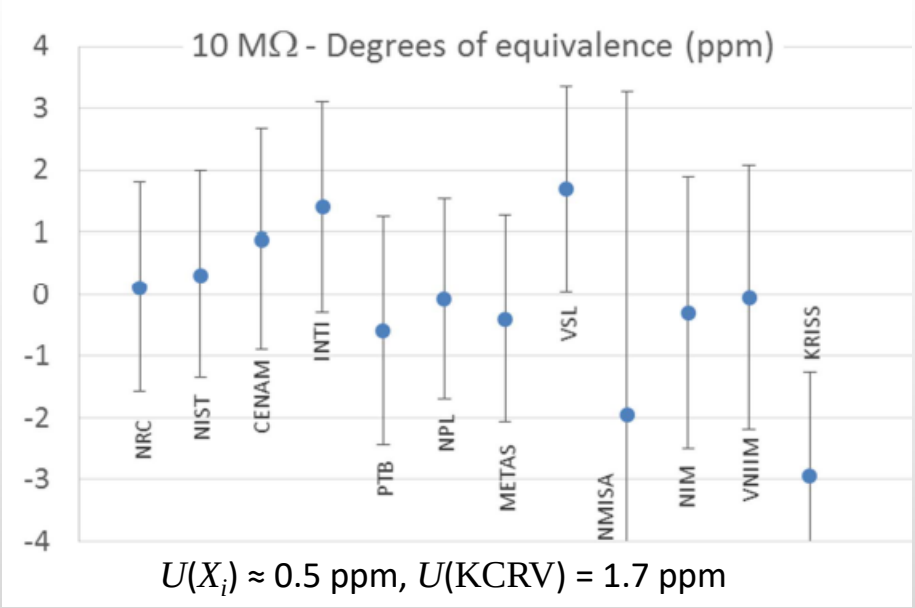
5.1 Comparison overview

NB: 6 KCs are running at present (no urgency to start more)

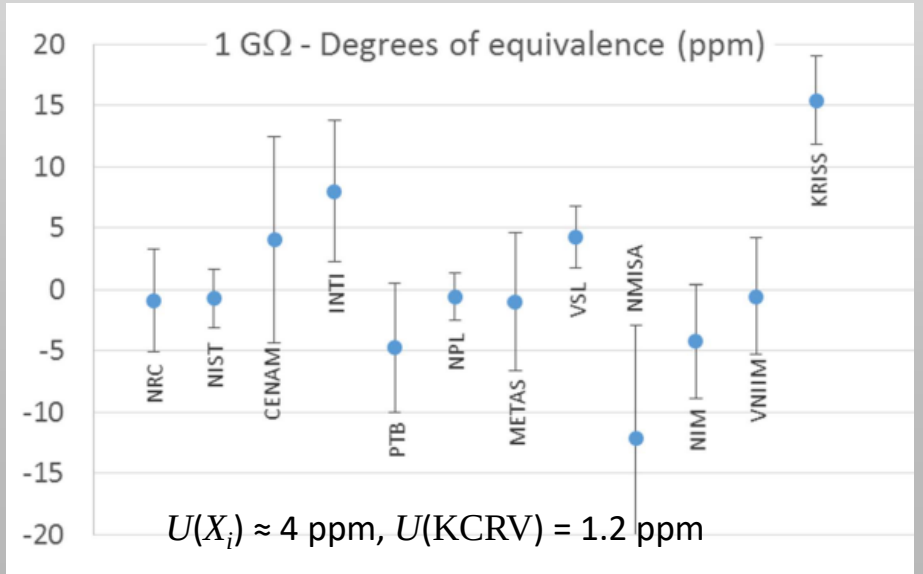
Cat	Sub-Cat	Quantity	2022	2021	2020	2019	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
1		**DC Voltage**																				
	1.1	Sources	BIPM.EM-K10, K11																			
	1.2	Meters																				
	1.3	Ratios																				K8.1 (bilateral
2		**DC Resistance**																				
	2.1.2	1 Ω to 1 MΩ	BIPM.EM-K13a/b: 1Ω/10kΩ																			K1
	2.1.3	> 1 MΩ			K2.2012: 10MΩ and 1GΩ																	
3		**DC Current to 100 A**																				
4		**Impedance**																				
	4.1	Resistance																				
	4.2	Capacitance	BIPM.EM-K14a/b: 10pF/100pF				K4: 10pF / 100pF								BIPM.EM-K14a/b: 10pF/100pF							
	4.3	Inductance		K3X: 10 mH (to start)											K3.1: 10 mH							
5		**AC Voltage**																				
	5.1.1	AC/DC <0.5 V																		K11.1: 10mV/100mV (bilate		K11: 1
	5.1.2	AC/DC 0.5 V to 5 V		K6.aX: 3V to 1 MHz																		
	5.1.3	AC/DC >5 V		K9X: 500V/1000V																		
	5.3.1	AC Ratio																				
6		**AC Current**																				
		AC/DC Current																K12: 10mA/5A				
7		**AC Power**																				
	7.1.1	Power		K5.2017: 50/60 Hz																		
8		**High Voltage and Current**																				
	8.1	High DC voltage																				
	8.3	High AC voltage and voltage transformers																				
9		**Other DC and low frequency measurements**																				
	9.3.1	Harmonics		K13: power harmonic																		
10		**Electric and magnetic fields**																				
11		**Radio frequency measurements**																				
	11.7.1	RF-DC voltage difference		K6.cX: 3V to 100 MHz																		
12		**Measurements on materials**																				

Completed Key Comparison: CCEM-K2.2012

- Measurand: DC resistance at 10 MΩ and 1 GΩ
- Pilot laboratory: **NRC**
- Other participants: **NIST, CENAM, INTI, PTB, NLP, METAS, VSL, NMISA, NIM, VNIIM, KRISS**
- Started September 2012, Final Report April 2020
- Improved uncertainties from 2002 comparison (10 MΩ dominated by resistor stability)
- Delays: usual (carnet/customs, timing, participants) but also technical (pressure coefficients required) and workload



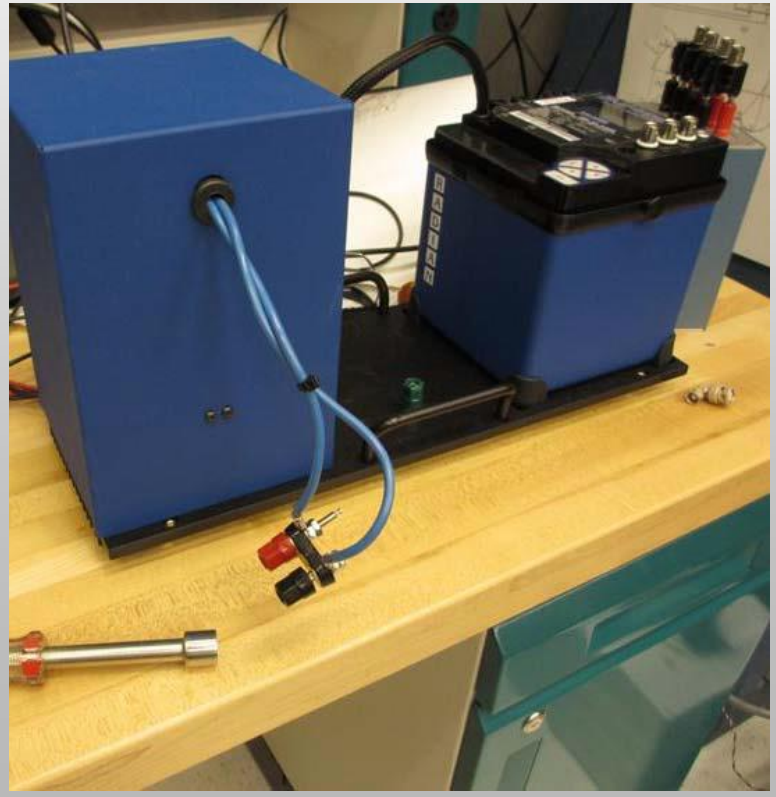
$U(X_i)$ ≈ 0.5 ppm, U(KCRV) = 1.7 ppm



$U(X_i)$ ≈ 4 ppm, U(KCRV) = 1.2 ppm

Ongoing Key Comparisons: CCEM-K5.2017

- Measurand: Primary power at 120 & 240 V, 5 A, 53 Hz; phase 0°, ± 60°, ± 90°,
- Artefact: two Radian travelling standards (thanks to NIST)
- Support group: **PTB** (pilot measurements), **CENAM** (logistics) and **VSL** (analysis and reporting)
- Other participants: **NIST, INMETRO, LNE, SP, NIM, NMIA, VNIIM, NMISA**
- Aimed uncertainty level < 20 µW/VA, performing at 2-3 ppm level (pilot) – more than 5 times better than previous K5!
- Final measurements: April 2021 – significantly affected by COVID
- Draft A report: first half 2022



Ongoing Key Comparisons: CCEM-K6.a/K6.c/K9

- Measurand: ac/dc voltage transfer:
  - K6.a: 3 V, 10 Hz - 1 MHz
  - K9: 500 V and 1000 V, 10 Hz – 100 kHz
- Artefacts: NIST PMJTC + Fluke Range Resistor
- Support group: **RISE** (logistics), **INTI** (reporting), **NIST** (pilot measurements), **PTB** and **NMIA**
- Other participants: **RISE, INTI, PTB, NMIA, NIST, NRC, JV, NMIJ, NIM, LNE, NMISA, INMETRO, VNIIM**
- Running in parallel with K6c
- Started end of 2018, measurements underway again through to May 2022 after several device failures and COVID delays

- Measurand: ac/dc voltage transfer:
  - K6.c: 3 V, 500 kHz - 100 MHz
- Artefact: NIST PMJTC
- Support group: **RISE** (protocol), **NIST** (pilot measurements), **PTB**
- Other participants: **NRC, NIM, LNE, VNIIM, A*STAR**
- Running in parallel with K6a/K9
- Started at the end of 2018, measurements underway again through to May 2022 after COVID delays

Ongoing Key Comparison: CCEM-K13

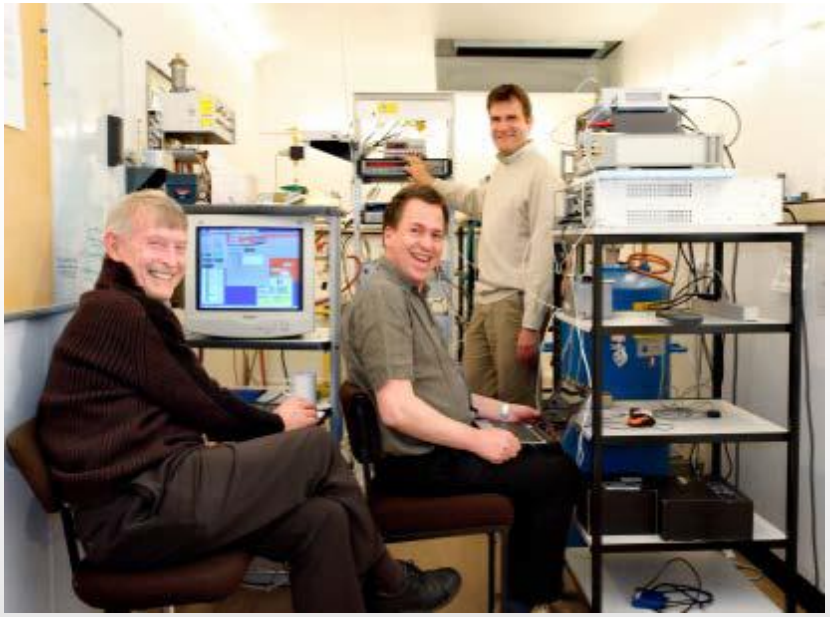
- Measurand: power harmonics with 3 waveforms:
  - Sine wave at 120 V, 5 A, unity power factor
  - IEC62053-21 signals: voltage 10%, current 40%, 5th harmonic
  - Field-recorded waveform
- Artefact: Fluke 6105
- Support group **NIST** (technical support), **NRC**, **RISE** (logistics), **NPL** (analysis and report), **NIM** (pilot measurements)
- Other participants: **PTB, VNIIM, NMIA**
- Started end of 2018, measurements underway again through to Aug 2022 after several device failures and COVID delays

New Key Comparison: CCEM-K3

- Measurand: inductance 10 mH and 1 kHz
- Artefacts:
  - Two standards provided by PTB
  - Air-worthy temperature-controlled enclosures provided by shipping company. Estimated cost per shipping €2.5k - need to decide to ship hot or cold
- Support Group:
  - PTB – Dr Rolf JUDASCHKE
    characterisation of standards, pilot laboratory measurements
  - NIM – Dr YANG Yan
    logistics, including liaising with NMIs on schedules, artefact movements and participant report submission
  - NMIA – Dr Leigh JOHNSON
    comparison protocol, KCDB registration, analysis and reporting

PARTICIPANT	COUNTRY	REGION
KRISS	Korea	APMP
NMIA	Australia	APMP
NIM	P.R. China	APMP/COOMET
VNIIM	Russia	APMP/COOMET
LNE	France	EURAMET
VTT	Finland	EURAMET
PTB	Germany	EURAMET/COOMET
INMETRO	Brazil	SIM
NIST	USA	SIM
NRC	Canada	SIM
NMISA	South Africa	AFRIMETS

BIPM Comparisons



Onsite Comparisons

- BIPM.EM-K10.a/b JVS on-site comparison
- BIPM.EM-K12 QHR on-site comparison
- Developing on-site PJVS comparison of ac voltages

Artefact Comparisons

- BIPM.EM-K11.a/b Zener voltage: 1.018 V and 10 V
- BIPM.EM-K13.a/b resistance: 1 Ω and 10 kΩ
- BIPM.EM-K14.a/b capacitance: 10 pF and 100 pF

BIPM participation

- GULFMET.EM.BIPM-K11 and APMP.EM.BIPM-K11.3 (Zener)

Calibration Services

- Zeners, resistors, capacitors

WGLF Future Comparisons: Survey Results

Cat	Sub-Cat	Quantity	Key Comparison
1		**DC Voltage**	
	1.1	Sources	
	1.2	Meters	Yes: 8
	1.3	Ratios	Yes: 8
		Measurand	
		Artefact	
2		**DC Resistance**	
	2.1.3	> 1 MΩ	Yes: 10
		Measurand	
		Artefact	
8		**High Voltage and Current**	
	8.1	High DC voltage	Yes: 11
	8.3	High AC voltage and voltage transformers	Yes: 10
		Measurand	
		Artefact	
6		**AC Current**	
		AC/DC Current	
		Measurand	
		Artefact	

Tentative Conclusions

1. K8: DCV ratio should repeat – start 2023?
2. Strong interest in 1000 V dc – could try DVM collapsing star using 3458A or similar (supplementary?)
3. Strong interest in 1 TΩ or higher – optional point(s) in next K2? (could start 2025?)
4. Strong interest in both dc and ac voltage at 100 kV (or higher) – aim to start 2023?
5. AC-DC Current – call for pilot/support group and participants to get underway 2023

Notes

- Consider low current (ULCA) rather than 1 T Ω or higher

Proposed Future Key Comparisons

To be presented at the CCEM- WGLF meeting 2023:

- New KC to support high voltage (DC/AC)
  - Task group of VTT, NMIA, RISE, INTI, VNIIMS to make a proposal (measurand and artefact)
- K12 AC-DC Current (10 mA and 5A to 100 kHz)
  - Task group of INTI, PTB, CENAM, ?

Will also discuss in 2023:

- Develop Process for implementing BIPM Onsite PJVS ac voltage comparison
  - Presentation by Stephane Solve – ready to start discussing protocol matters
  - Task group of BIPM, MIKES, KRISS, NRC, NMIA, PTB, NPL, METAS, CENAM, NMIJ
- Develop ideas to initiate K8: DC voltage ratio
  - Traditional artefacts (e.g. Datron 4902S) no longer produced
  - New artefacts available but yet to be proven
  - Task group: NMIA, PTB, NMC, VSL
- Extend K2 to include 1 TΩ or more (optional), proposal due by 2025
  - Consider NMIJ development of new artefacts

Proposed Future Key Comparisons

To be considered at future CCEM- WGLF meetings

- Possible needs to support new linearity measurands
- SI redefinition suggests measurement of very low current could become more important – future KC?
  - Interest in findings of CCEM-CCRI task group on small currents
- Agreed DMM for DCV up to 1 kV in collapsing star pattern – interesting but premature for now
- AC and DC ratio are longer term KCs – do RMOs want these?
- Rationalise the four ac-dc voltage comparisons in light of future on-site PJVS for ac voltages

Future Comparison Schedule

CCEM Key Comparisons	Repeat	Next	RMO
K14: high ac voltage	15	2023	?
K12: ac-dc current, 10mA/5A	15	2023	Y
K8: dc voltage ratio?	20	2025	?
K11: low ac-dc voltage, 10mV/100mV	15	2025	Y
K2: high dc resistance, 10MΩ, 1GΩ and 1TΩ?	15	2025	Y
K7: ac voltage ratio, 1kHz	20	2027	?
K5: single phase ac power, 50/60Hz	15	2029	Y
K6.a: mid ac-dc voltage, 3V to 1MHz	15	2031	Y
K6.c: RF-dc voltage, 3V to 100MHz	15	2031	Y
K4: capacitance, 10pF/100pF	20	2035	Y
K9: high ac-dc voltage, 500V/1000V (was K6.b)	15	2031	Y
K3: inductance, 10mH	20	2041	Y
K1: dc resistance, 1Ω and 10kΩ	-	-	-
K10: dc resistance, 100Ω	-	-	-
K13: power harmonics	-	-	-

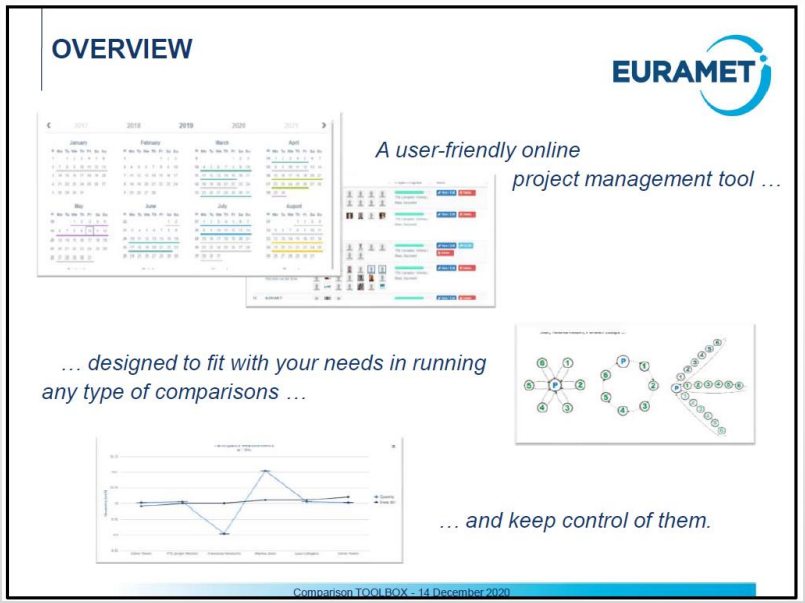
Future Priority (proposed start)	Branch	Key Comparisons		Cat	Sub-Cat	Quantity	2022	2021	2020	2019	2018	2017	2016	2015	2014	2013	2012
	DC VOLTAGE, CURRENT, AND RESISTANCE			1		**DC Voltage**											
BIPM					1.1	Sources											
Not yet					1.2	Meters											
#3 - 2025 (K8)		1	K8		1.3	Ratios											
				2		**DC Resistance**											
BIPM					2.1.2	1 Ω to 1 MΩ											BIPM.EM-K13a/b: 1Ω
#5 - 2025 (K2)		2	K2		2.1.3	> 1 MΩ			K2.2012: 10MΩ and 1GΩ								
				3		**DC Current to 100 A**											
NB: not a key quantity																	
	IMPEDANCE UP TO THE MEGAHERTZ RANGE			4		**Impedance**											
NB: not a key quantity					4.1	Resistance											
2035? (K4) BIPM		3	K4		4.2	Capacitance		BIPM.EM-K14a/b: 10pF/100pF			K4: 10pF / 100pF						
starting 2021		4	K3		4.3	Inductance		K3X: 10 mH (to start)									
	AC VOLTAGE, CURRENT, AND POWER			5		**AC Voltage**											
#4 - 2025 (K11)		5	K11		5.1.1	AC/DC <0.5 V											
active BIPM (PJVS?)		6	K6.a		5.1.2	AC/DC 0.5 V to 5 V		K6.aX: 3V to 1 MHz									
active		7	K9		5.1.3	AC/DC >5 V		K9X: 500V/1000V									
#6 - 2027 (K7)		8	K7		5.3.1	AC Ratio											
				6		**AC Current**											
#2 - 2023 (K12)		9	K12			AC/DC Current											
				7		**AC Power**											
active		10	K5		7.1.1	Power		K5.2017: 50/60 Hz									
	HIGH VOLTAGE AND CURRENT			8		**High Voltage and Current**											
#1b - 2023 (K14?)					8.1	High DC voltage											
#1a - 2023 (K14?)					8.3	High AC voltage and voltage transformers											
	OTHER DC AND LOW FREQUENCY MEASUREMENTS			9		**Other DC and low frequency measurements**											
not repeated		11	K13		9.3.1	Harmonics		K13: power harmonic									
	ELECTRIC AND MAGNETIC FIELDS			10		**Electric and magnetic fields**											
NB: not a key quantity																	
	RADIO FREQUENCY MEASUREMENTS			11		**Radio frequency measurements**											
active		12	K6.c		11.7.1	RF-DC voltage difference		K6.cX: 3V to 100 MHz									
	MATERIALS			12		**Measurements on materials**											
NB: not a key quantity																	

5.2 Other Information from WGLF

- Brief update on updated CIPM documents particularly CIPM MRA-G-11 [Michael]

- EURAMET Toolbox development [Marko]
  - could significantly help project management of (initially) EURAMET comparisons

- GULFMET.EM.BIPM-K11[Stephen Yang]
  - Nice example of using generalised least squares for comparison analysis which could be of benefit to CCEM



Analysis Model of Intercomparison Results

- Analysis model: $\boldsymbol{y} = \boldsymbol{X}\,\boldsymbol{\beta} + \boldsymbol{e}$ (1)

The solutions ($\boldsymbol{\beta}$) of equation (1) can be calculated by equation (2), with an uncertainty matrix ($\boldsymbol{C}$) as given by equation (3).

- $\boldsymbol{\beta} = \boldsymbol{C}\,\boldsymbol{X}^{\mathrm{T}}\boldsymbol{\Phi}^{-1}\boldsymbol{y}$ (2)
- $\boldsymbol{C} = \left(\boldsymbol{X}^{\mathrm{T}}\boldsymbol{\Phi}^{-1}\boldsymbol{X}\right)^{-1}$ (3)

where

- $\boldsymbol{y}$ is a vector of the measurement results,
- $\boldsymbol{X}$ is a design matrix,
  $\boldsymbol{\beta}$ is a vector of unknowns,
  $\boldsymbol{e}$ is a vector of random errors or disturbances,
- $\boldsymbol{\Phi}$ is the input covariance matrix.

5.2 Other Information from WGLF

- Efficiency of comparison reviews [Murray]
  - Large number of RMO key and supplementary comparisons needing editorial review
  - Taking too long (sorry!), also review by committee not effective
  - Agree for chair to request specific WGLF member (or colleague) to do a thorough review on behalf of WGLF (only ~1 review per year per person)
- Review of recently completed, current, and planned RMO comparisons [RMO TCEM chairs]
  - Available on WGLF Web pages
  - Useful to monitor upcoming supplementary comparisons to encourage collaboration
- Membership of the WGLF
  - Gert encouraged CCEM members to apply to join WGLF

WGLF survey results

Cat	Sub-Cat	Quantity	Key Comparison	NMIJ			PTB			LNE			INMETRO			NRC			NIST			NMC			MIKES VTT			KRISS			INRIM			CENAM			RISE			IPQ			VSL			METAS			NIIM, VNIIM		
				Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise	Key Comparison	Participate	Organise
1		**DC Voltage**																																															
	1.1	Sources																																															
	1.2	Meters	Yes: 8							N	N	N	Y	Y	N	Y	Y	M				Y	Y	Y	Y	N	N	Y	Y	N										Y	Y		Y	Y	N		N	N	Y	Y	
	1.3	Ratios	Yes: 8				Y	Y	N																						N	N	N	Y	Y	N	Y	Y	N										
		Measurand					voltage ratio						1 µV to 1kV			ratio?																																		
		Artefact					RVD (Datron 4902S)						NVM/DVM			MIL1340A						Divider/DVM						DVM			covered by K8			Divider			RVD (Datron 4902S)			Supplementary?										
																																		Supplementary?														
2		**DC Resistance**																																															
	2.1.3	> 1 MΩ	Yes: 10	Y	Y	N	N	N	N	N	N	N				N	M	N	Y	Y	Y	Y	Y	Y	Y	N		Y	Y	N	N	N	N	Y	Y	N	Y	Y	N				Y	Y	N	N		Y	
		Measurand		10GΩ to 100TΩ															10TΩ, 100TΩ option			1TΩ, 10TΩ						1TΩ or 100TΩ						1TΩ																
		Artefact		NMIJ/Finechem dev						EURAMET.EM-S32 2009-11									NIST/FinCh/MII/Gildline			Star candidate?						3-terminal & Guard			EURAMET.EM-S32 low current? (UCLA)												CCEM-K2 just finished					
8		**High Voltage and Current**																																															
	8.1	High DC voltage	Yes: 11																						Y	Y	Y	Y	Y	N							Y	Y	Y										
	8.3	High AC voltage and voltage transformers	Yes: 10				Y	Y	N	Y	Y	Y	Y	Y	N	Y	Y	N				Y	Y	Y							Y	Y	N	Y	N	N				N			Y	Y	N				Y	Y	Y
		Measurand											DC, 50Hz, 60Hz			DC, 50Hz, 60Hz						DC, 50Hz			DC Ratio																		AC ratio								
		Artefact											RVD/VT									RVD/VT			NMIA 150kV RVD			DC Divider			could be RMO comparison			50 Hz Divider or capacitor			100kV/200kV 200 KV divider available Alf-Eng willing						conventional transformer						100 kV DC, 1kV 50Hz Meas. Syst., Dividers help with analysis		
6		**AC Current**																																														
		AC/DC Current																																Y																
		Measurand																																															
		Artefact																																															

WGLF Terms of Reference

Activities:

- To advise the CCEM and the WGRMO on matters related to its technical area; [CCEM and WG Meetings, ongoing]
- To identify the major future problems challenging the national metrology institutes in electromagnetic measurement in its technical area and to provide input to the CCEM on the BIPM's technical program on electrical metrology; [CCEM Strategy document]
- To establish and maintain a list of key and other comparisons in its technical area, which will adequately support CMC claims by NMIs in this field of measurement in the spirit of the global MRA between NMIs; [Agenda items 3, 4]
- To coordinate and schedule key comparisons, to review progress in comparisons and to recommend to the CCEM the inclusion of the results of key comparisons in Appendix B of the MRA database; [Agenda items 4, 5]
- To provide supplementary guidelines and/or interpretations to the guidelines on conducting key comparisons included in the MRA, specifically for the field of electricity and magnetism; [CIPM and CCEM documents, ongoing]
- To provide advice to the WGRMO on the range of CMCs supported by particular key comparisons; [Agenda item 4b]
- To recommend RMO key comparisons to the CCEM for approval and to provide advice on RMO supplementary comparison activities. [Ongoing]