Capacity Building & Knowledge Transfer

Specific guidelines for comparisons and CMCs in Length

Andrew Lewis
National Physical Laboratory (NPL)
Chair CCL's WG-MRA

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Outline

- Introduction to CCL & length metrology
- MRA: Organisational aspects within CCL
- MRA: Technical aspects within CCL
- Summary of key points

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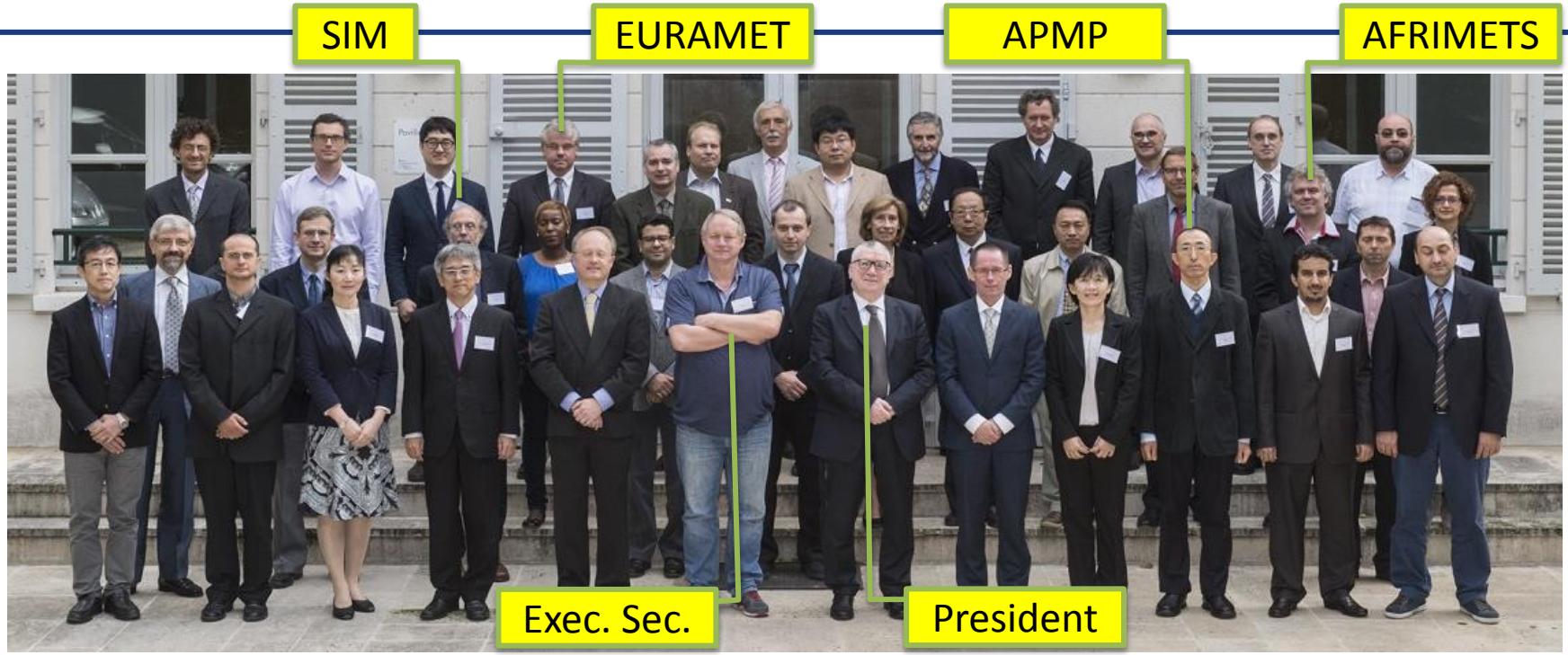
The CCL - formerly CCDM (Definition of the metre)



From the 16th meeting of the CCL (September 2015)

RMO TC-Length chairs highlighted

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CCL WG on the MRA (WG-MRA)

From the 2017 meeting of the CCL WG-MRA (October 2017)

Your important contacts in CCL !

RMO TC-L chairs

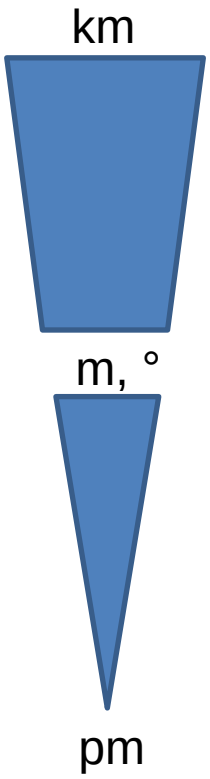
– AFRIMETS	Oelof Kruger, NMISA (ZA)	oakruger@nmisa.org
– APMP	Jariya Buajarern, NIMT (TH)	Jariya@nimt.org.th
– COOMET	Aleksandr Kostrikov, NCM (UA)	alex_kost@ukr.net
– EURAMET	Harald Bosse, PTB (DE)	harald.bosse@ptb.de
– GULFMET	Ahmad Makinudin Dahlan, ESMA (UAE)	a.dahlan@qcc.abudhabi.ae
– SIM	Karina Bastida, INTI (AR)	bastida@inti.gob.ar

Incoming WG-MRA chair

	Alessandro Balsamo, INRIM (IT)	a.balsamo@inrim.it

Length in a worldwide context – range of coverage

Geodetic-scale metrology	(100s of metres)
Large volume metrology	(1 metre to 10s of metres)
Coordinate metrology (3D)	(~1 mm to ~2 m)
Realization of the metre definition	(UV to IR wavelengths)
Angle metrology	(sub arc second to *n*×360°)
***Classical* optical metrology**	(nm flatness, 10 m RoC)
Surface metrology (form, roughness)	(1 nm to ~500 mm)
Micro-metrology	(~50 µm to 250 mm, 3D)
Dimensional nanometrology	(10 pm to 100 nm, 1D or 2D)



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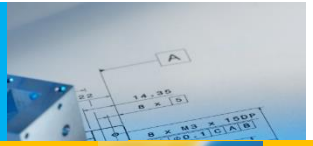
Length in a worldwide context – areas of impact

Traceability in dimensional measurements underpins all manufacturing, engineering and assembl… ensuring … intercha… the focu…

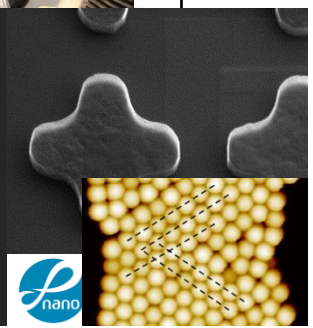


Precision engineering and dimensional metrology are key to three SI re-definitions based on fundam… dimensi… Boltzma… balance …

In aerospace, improving accuracy in aircraft assembly is reducing weight, reducing fuel burn (lower environmental impact, better energy effi… accuracy ar… up to 40 m…

For new science (particle accelerators), energy generation (wind, civil nuclear), better accuracy a… are speedi… and enabli… longer life… problems …

Surface form and texture are critical to many nano-scale devices, particularly for *in vivo* applications for health. Traceability infrastructure for 3D surface texture and simple dimensions on nano particles are focuses of the CCL and WG-Nano.



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Length in a worldwide context – future challenges

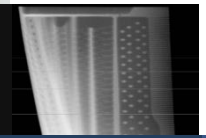
Continue to improve access to and accuracy of, realizations of the metre via optical frequency standards

Support industry's transition to Industry 4.0 (faster and cheaper digital-based production)

Develop and validate traceability routes for *in situ* metrology

Optimize length comparison portfolio to support new areas without increasing workload

Coordinate pre-normative research into novel coordinate metrology systems such as X-ray CT, micro CMMs



Extend the traceability to the metre to extreme scales: sub- nanometre and geodetic (kilometre)

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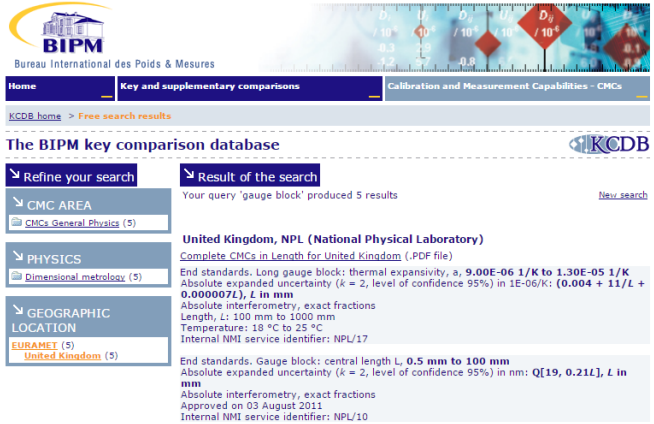
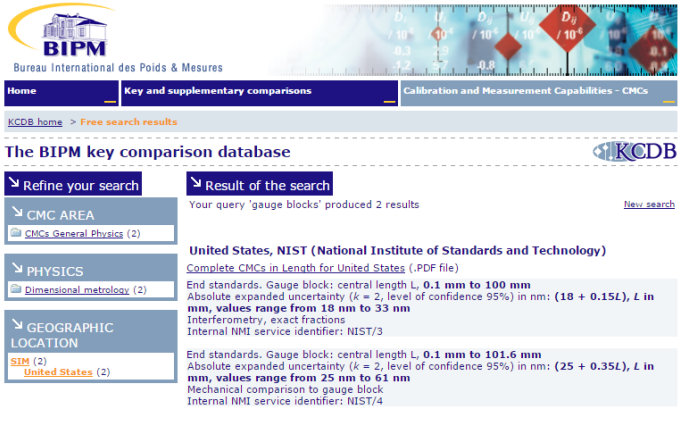
MRA underpinning measurement & calibration





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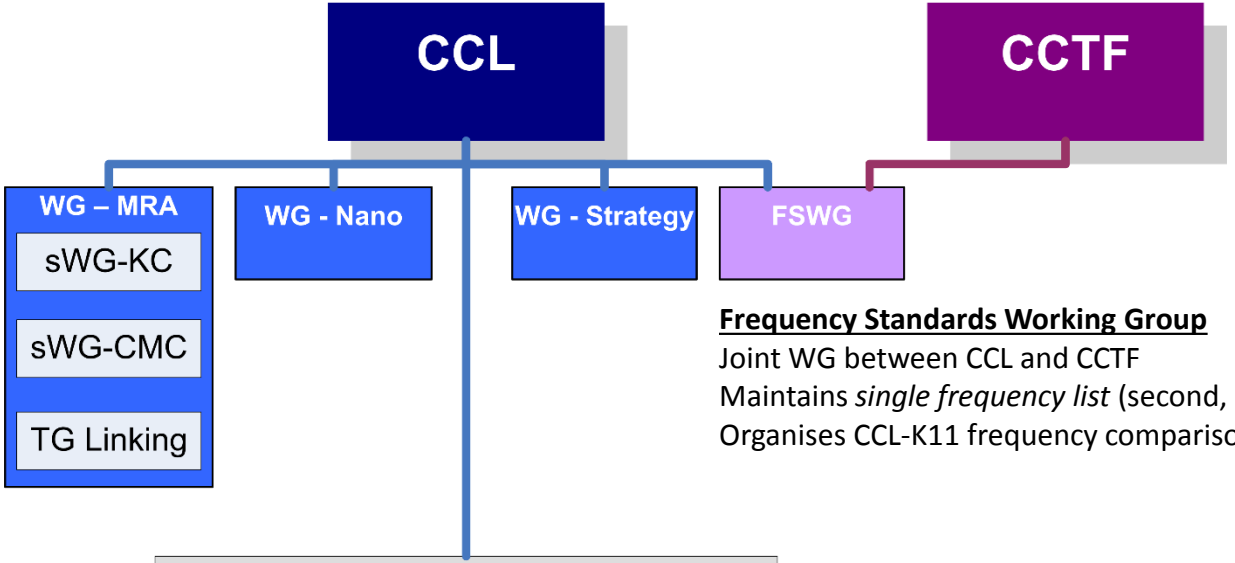
CCL organisation for MRA tasks

Working Group on the MRA
MRA delegated authority from CCL
Formed of 2 sub-Working Groups:
- Key Comparisons
- CMCs

And a Task Group on Linking
Mostly *ex officio* membership



Frequency Standards Working Group
Joint WG between CCL and CCTF
Maintains *single frequency list* (second, metre)
Organises CCL-K11 frequency comparisons

Discussion groups
Experts in KC subjects, worldwide members
Discuss latest research, trends, future needs
Ideas for comparison details
Provide technical advice to CCL
Identify principal uncertainty components
Harmonisation of terms in subject field

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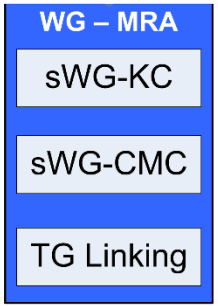
CCL organisation for MRA tasks



The majority of the MRA processes, decisions, approvals occur in WG-MRA

In 2012 CCL delegated the authority to approve key comparison protocols and reports to WG-MRA

WG-MRA reports to CCL on the work it has performed. WG-MRA meets yearly, CCL meets 3 yearly.

CCL WG-MRA

WG-MRA
Chair: Balsamo

- sWG-KC
  Chair: Lewis
- sWG-CMC
  Chair: de Oliveira
- TG Linking
  Chair: Thalmann

sWG-KC

- *RMO TC-L chairs*
- *DG Moderators*
- *KC pilots*

Organises comparisons
Approves protocols & reports

sWG-CMC

- *RMO TC-L chairs*

Looks at Executive Reports
Receives annual report from RMOs on CMC actions: pending, taken, completed

TG Linking

- *6 named individuals*

Studies which comparisons can be linked
Suggests appropriate linking mechanism

WG-MRA
Formed from 2 WGs & TG-Linking & additional named members
Coordinates across both sub WGs
Plenary session and organisation of annual meeting
Produced a range of **guidance documents and CMC categorisation**

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The ‘DimVIM’ – CMC categorisation list

- Designed September 1999
- Updated periodically (latest 2017)
- Master copy in English, but translated (& maintained) in:
  - **Chinese, Czech, Finish, French, German, Greek, Japanese, Korean, Portuguese, Spanish, Turkish, Thai**
- Version 10 (10/2017)

Ver. 10 (2017)

CLASS

Consultative Committee for Length – CCL

Working Group on the MRA – WG-MRA

CCL Length Services Classification (DimVIM)

CCL Service Category	English Language Approved Terms: Instrument or Artifact	Measurand(s)
1 Radiations of the Mise en Pratique		
1.1 Laser Radiations		
1.1.1	frequency stabilized laser.	vacuum wavelength; optical frequency.
1.1.2	other stabilized laser.	vacuum wavelength; optical frequency.
1.2 Lamp Radiations		
1.2.1	spectral lamp.	vacuum wavelength.
2 Linear Dimensions		
2.1 Length Instruments		
2.1.1	(laser, length) interferometer (system, optics, refractometer).	error of indicated displacement; wavelength compensation.
2.1.2	EDM instrument.	error of indicated distance.
2.1.3	1-D measuring machine.	error of indicated [size; displacement].
2.1.4	height measuring instrument.	error of indicated [vertical size; displacement].
2.1.5	1-D displacement [transduscer, actuator] (LVDT, PZT,…)	error of indicated displacement.
2.1.6	gauge block comparators	error of indicated displacement.
2.1.7	dial-indicator tester.	error of indicated displacement.
2.2 End Standards		
2.2.1	gauge block.	central length; variation in length; thermal expansivity; length difference of gauge block pairs.
2.2.2	length bar (long gauge block).	central length; variation in length; thermal expansivity.

1 实现米的辐射		
1.1 激光辐射		
1.1.1	实现米的稳频激光.	真空波长；光频
1.1.2	其他稳频激光	真空波长；光频
1.2 灯辐射		
1.2.1	光谱灯	真空波长；光频
2 线性尺寸		
2.1 长度仪器		
2.1.1	(激光, 长度) 干涉仪 (系统, 光学, 折射计).	位移示值误差；波长补偿.
2.1.2	光电测距仪	距离示值误差
2.1.3	一维测量仪器	（尺寸，位移）示值误差
2.1.4	高度仪器	（垂直尺寸、位移）示值误差
2.1.5	一维位移［传感器，发生器］(LVDT，PZT，…)	位移示值误差
2.1.6	量块比较仪	位移示值误差
2.1.7	指示表检测仪	位移示值误差
2.2 端度标准器		
2.2.1	量块	中心长度；长度变化量；热膨胀
2.2.2	长度棒(长量块).	中心长度；长度变化量；热膨胀

9 CCL Guidance documents on comparisons & CMCs

Document	Title
CCL-WG/-MRA-GD-1	Running of MRA comparisons in length metrology and monitoring their impact on CMCs
CCL-WG/-MRA-GD-2	CCL comparison scheme
CCL-WG/-MRA-GD-3	Guide to preparation of Key Comparison Reports in Dimensional Metrology
CCL-WG/-MRA-GD-3.1	Comparison technical protocol template
CCL-WG/-MRA-GD-3.2	Comparison report template
CCL-WG/-MRA-GD-3.2b	Template bilateral report
CCL-WG/-MRA-GD-3.3	Executive Report Template
CCL-WG/-MRA-GD-4	KC planning [frequently updated] – timeline/scheduling
CCL-WG/-MRA-GD-5	Guide to formatting CMC entries v2

Comparison portfolio: choosing what & how many

Principal Techniques	CCL-K1	CCL-K2	CCL-K3		CCL-K4	CCL-K5		CCL-K6	CCL-K7	CCL-K8
	gauge block	length bar	poly	gau.	diameter	ball	step	2D CMM	linescale	surf tex.
Realizing the Metre definition										
Interferometry	2	2			2	2		2	2	1
Wavelengths in air	2	2			2	2		2	2	1
Gauge Issues										
Temperature of Gauge	1	2			2	2		2	2	1
Mounting & Aligning	1	2	2		2	2		2	2	1
Wavefront Probing										
Reflection Phase Effects	2	1								
Wringing	2	1								
Mechanical Probing										
Stylus contacting at surface, 1-D					2	1	2	1		2
Bi-directional probing for size					2		2			
Probing for 3-D center coordinates						2		2		
Image Probing										
Sensing Line Centres									2	
Angle Metrology										
Measuring small angles (autocoll.)			1	2						
Large Angle Gen: Circle Dividers			2	1				1		
Small Angle Gen: SineBar, CircDiv.				2						
Formal mathematical processing of data sets										
ISO parameter extraction										2
Form Metrology										
Flatness										1
Roundness					1					
Thread, Gear Profile										
3-D Surface										1

Most CMCs are based around classes of artefact (& lasers – later)

Too many artefacts for one comparison each

Looked at key skills needed to perform length metrology at the highest level

Used these to reduce number of artefacts and hence limit number of comparisons

Table comes from CCL Strategy Document

2 = strong test of skill by comparison
1 = weaker test of skill
0 = no link

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Comparison portfolio: participation

- Strike a balance on number of participants

More participants

- Ensure inter-RMO linking
- Robustness against problems/withdrawals
- Fewer comparisons overall
- Better accuracy KCRV

Fewer participants

- Shorter duration (less time for pilot)
- Results available sooner
- Reduced artefact wear (*)
- Easier to coordinate

(*) High quality artefacts normally calibrated on 2 to 3 year interval.
In a comparison, they are calibrated every month for 1.5 to 2 years.
Some artefacts are no longer measurable at the end…

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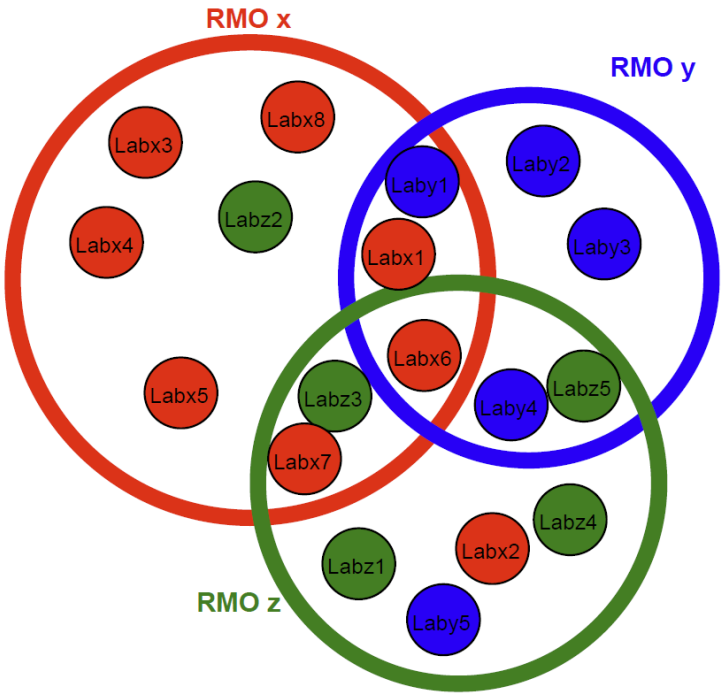
2 comparison schemes: *classical*, *inter-RMO*

- Response to **criticism** from CCL members of **workload**
- CCL comparison then RMO comparison: **double work**
- Worse for smaller RMOs – few CCL members, always have double workload
- RMO TC chairs agreed to **share duties across regions**
- ***Inter-RMO*** comparisons: multiple RMOs in one comparison
- No CCL comparison unless necessary
- Retain ***classical*** organisation (CCL then RMO) for **large circulation** comparisons in popular topics (*e.g*. gauge blocks K1, diameter K4)
- Inter-RMO comparisons for other topics *e.g.* step gauges (K5)

Inter-RMO comparisons



This comparison scheme offers the following advantages:

- It guarantees equal status of CCL and RMO comparisons.
- It provides more flexibility in grouping laboratories of different regions in order to achieve comparisons of similar size and to run comparisons with adequate artefacts at different levels of uncertainty.
- It allows for an optimized and possibly reduced number of comparisons, and consequently requires lower expenses for purchasing suitable artefacts, fewer pilot laboratories and reduced workload for CCL members.
- It gives more flexibility and more frequent opportunities for any laboratory to join a comparison when needed to support its CMCs.

If required, a virtual CCL comparison may be formed for analysis purposes by the CCL members which take part.

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CCL Key Comparison Portfolio

No.	Artefact	Type
K1	gauge blocks	[*classical*]
K2	long gauge blocks (merged into K1)	[*classical*]
K3	angle	[*classical*]
K4	diameter	[*classical*]
K5	step gauges	[*inter-RMO*]
K6	2D CMM artefacts (on hold after cycle 1, $$$)	[*inter-RMO*)
K7	linescales	[*classical*]
K8	surface texture	[*inter-RMO*]
K11	lasers (yearly ongoing participation)	[classical]

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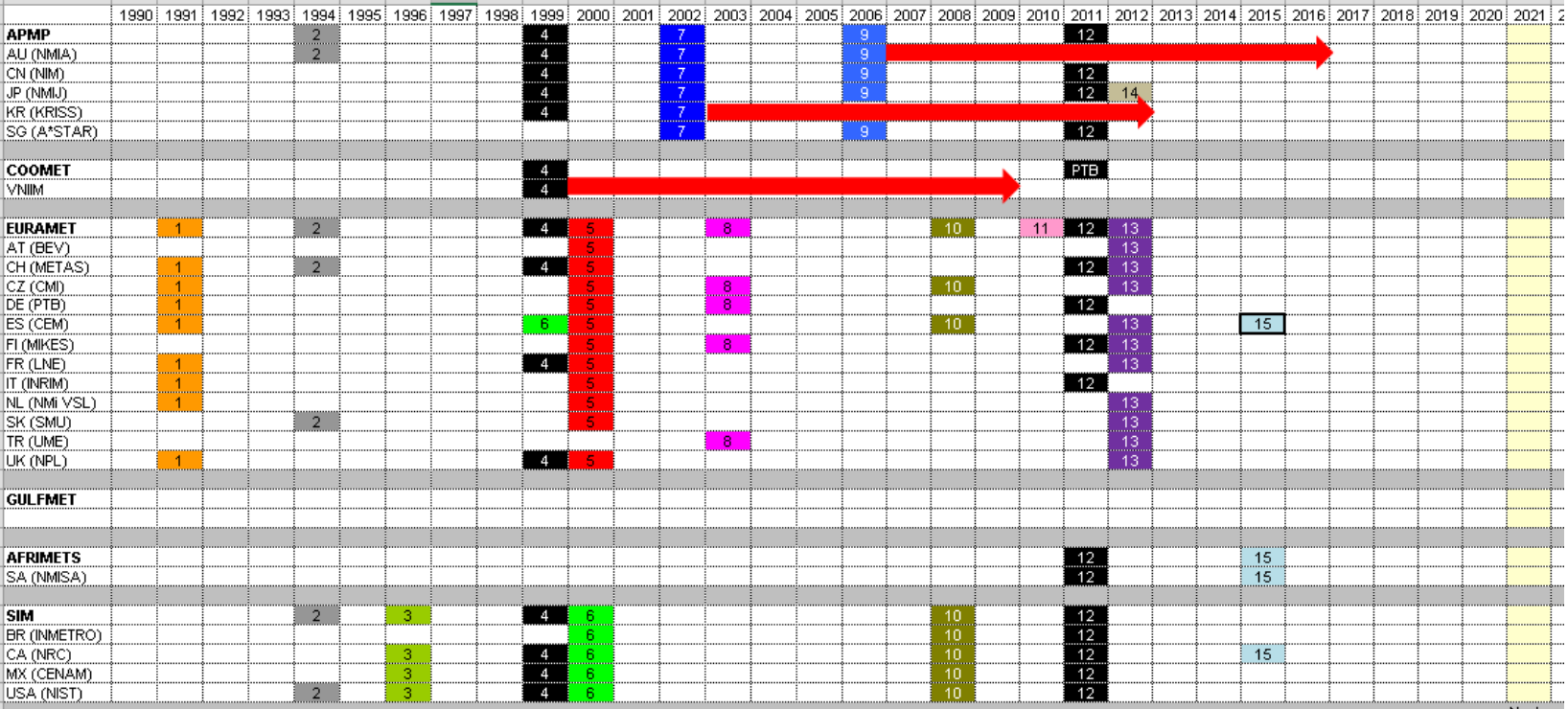
K11 was the number of the former BIPM laser comparison

Comparison frequency

- Originally tried to achieve **7 year repeat cycle** but difficult to conclude all comparisons within this period.
- Changed to **10 year cycle** which is being **achieved**.
- WG-MRA has the task to organise comparisons with a view to offering participation to all CCL members at least once every 10 years.
- WG-MRA also assists RMOs to achieve 10 year repeat (inter-RMO) by coordinating inter-RMO participation.
- Aim to **avoid bilateral comparisons** (big workload for reviewing reports, gains for only 2 or 3 participants).
- Allow 'stretch' of 10 year periodicity if new comparison cycle starting soon or comparison in another RMO will start soon.
- 2017 - Accepted APMP proposal for 'paid for/commercial calibrations' as reference values for NMI needing to urgently prove a CMC claim.

KC planning document – K1 topic example

Similar Excel files used in RMO TC-L committees

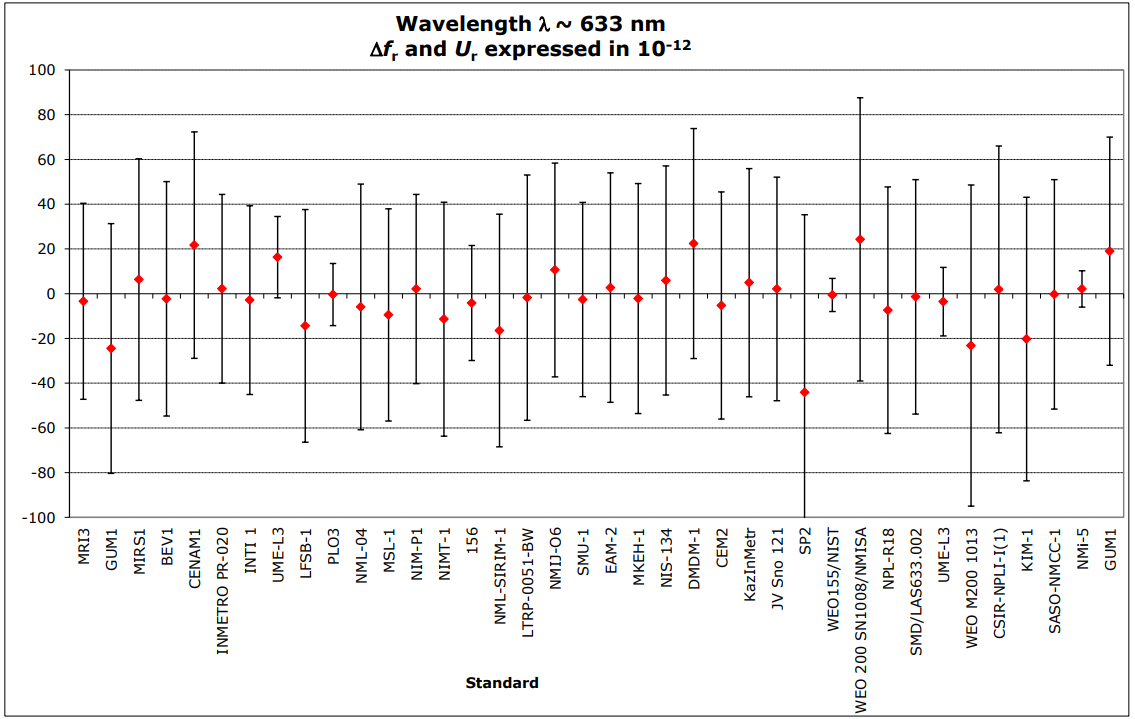


	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
APMP					2					4			7				9					12										
AU (NMIA)					2					4			7				9					12										
CN (NIM)										4			7				9					12										
JP (NMIJ)										4			7				9					12	14									
KR (KRISS)										4			7																			
SG (A*STAR)													7				9					12										
COOMET										4												PTB										
VNIIM										4																						
EURAMET		1			2					4	5			8					10		11	12	13									
AT (BEV)											5												13									
CH (METAS)		1			2					4	5											12	13									
CZ (CMI)		1									5			8					10				13									
DE (PTB)		1									5			8								12										
ES (CEM)		1								6	5								10				13			15						
FI (MIKES)											5			8								12	13									
FR (LNE)		1								4	5												13									
IT (INRIM)		1									5											12										
NL (NMi VSL)		1									5												13									
SK (SMU)					2						5												13									
TR (UME)														8									13									
UK (NPL)		1								4	5												13									
GULFMET																																
AFRIMETS																						12				15						
SA (NMISA)																						12				15						
SIM					2		3			4	6								10			12										
BR (INMETRO)											6								10			12										
CA (NRC)							3			4	6								10			12				15						
MX (CENAM)							3			4	6								10			12										
USA (NIST)					2		3			4	6								10			12										

	start	stop	KCDB number	Status	Publication reference	Next CCL-K1
1	1991	1992	EUROMET.L-K1.Prev		(Metrologia, 1995, 32, 79-86)	
2	1993	1994	CCDM gauge block comparison		(Metrologia, 1998 35, 97)	
4	1998	1999	CCL-K1		(Metrologia, 2002, 39, 165-177)	
5	1998	2000	EUROMET.L-K1		(KCDB, EUROMET project #471 Final report)	
8	2002	2003	EUROMET.L-K1.1		(KCDB, EUROMET project #643 Final report)	
7	2001	2002	APMP.L-K1		(Metrologia, 2006, 43, Tech. Suppl. 04004)	
9	2005	2006	APMP.L-K1.1		(Metrologia, 2009, 46, Tech. Suppl. 04005)	
3	1994	1996	SIM.L-K1.Prev.		(Metrologia, 1999, 36, 421-432)	
6	1998	2000	SIM.L-K1		(Metrologia, 2007, 44, Tech. Suppl. 04001)	
10	2008	2010	SIM.L-K1.2007		(Metrologia, 2012, 49, Tech. Suppl. 04010)	
11	2010	2010	EURAMET.L-K1.2		(Metrologia, 2012, 49, Tech. Suppl. 04005)	
12	2011	2013	CCL.K1-2011	Draft A.1		
13	2012	2014	EURAMET.L-K1.2011		(Metrologia, 2016, 53, Tech. Suppl. 04003)	
14	2011	2012	APMP.L-K1.1.2011		(Metrologia, 2013, 50, Tech. Suppl. 04002)	
15	2015		AFRIMETS.L-K1	Planning		

Ongoing CCL comparison

- CCL-K11 – comparison of standard laser frequencies
- 5 node labs:
  - BEV, MIKES, NIMT, NMIJ, NPL
  - Doing the work previously offered by BIPM length section
- Protocol being rewritten – not really like a comparison



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Progress: 116 comparisons, 88 completed

Comparison totals complete/run

BIPM	02/**02**	
CCL-K	07/**10**	(3 in running cycle 2)
CCL-S	04/**04**	
AFRIMETS-K	00/**01**	(starting)
AFRIMETS-S	01/**03**	
APMP-K	09/**12**	(3 running in cycle 2)
APMP-S	05/**08**	
COOMET-K	01/**01**	
COOMET-S	16/**20**	
EURAMET-K	12/**19**	(4 running in cycle 2)
EURAMET-S	23/**26**	
GULFMET-K	00/**00**	
GULFMET-S	00/**01**	(starting firs ever)
SIM-K	04/**05**	
SIM-S	04/**04**	

Summary of progress on all length comparisons

Identifier	REGISTRATION: Comparison proposed (RMO, CCL)	REGISTRATION: Comparison accepted (RMO, CCL)	REGISTRATION: Registered with KCDB	PROTOCOL: Protocol submitted to WG-MRA for approval	PROTOCOL: Protocol approved by WG-MRA	MEASUREMENTS: Start of artefact circulation	MEASUREMENTS: End of artefact circulation	MEASUREMENTS: Final results received	REPORTING: Draft A report to participants only	REPORTING: Draft B report V1 to participants	REPORT APPROVALS: Final report (agreed by participants) sent to WG-MRA for approval	REPORT APPROVALS: Final report approved by WG-MRA	KCDB ENTRY: Final report sent to KCDB	KCDB ENTRY: Data files (Excel) sent to KCDB	EXEC. REPORT: Executive report prepared and sent to CCL or WG-MRA for discussion	EXEC. REPORT: Executive report finalised and sent to CCL Exec. Sec. for website storage
BIPM.L-K10	1988	1988	Y	Y	Y	1988	2000	Y	Y	Y	Y	Y	Y	Y	N/A	N/A
BIPM.L-K11	2004	2004	Y	Y	Y	2004	2006	Y	Y	Y	Y	Y	Y	Y	N/A	N/A
CCL-K1	Sep-97	Sep-97	Y	Y	N	Mar-98	Sep-99	Y	Sep-99	01-Jan	Sep-00	Sep-00	Y	Y	N	N
CCL-K1.2011	Sep-09	Sep-99	Y	Jun-10	Sep-09	2011	Jun-13	Y	exp 11/2014							
CCL-K2	Sep-97	Sep-97	Y	Y	N	Sep-99	Aug-01	Y	Sep-01	Y	Mar-03	Sep-03	Y	Y	Sep-03	Y
CCL-K3	Sep-97	Sep-97	Y	Y	N	Jul-00	Aug-02	Y	Y	Y	Aug-07	Sep-07	Y	2008/9	Y	Y
CCL-K3.2016	CCL 2015															
CCL-K4	Sep-97	Sep-97	Y	Y	N	Nov-00	Dec-02	Y	Jul-03	Jul-05	Jan-07	Sep-07	Y	Y	Aug-07	Y
CCL-K4.2014	Oct-14	Oct-14	06/10/2015	Aug-15	Sep-15	Aug-15	exp 3/17									
CCL-K5	Sep-97	Sep-97	Y	Y	N	Apr-99	Mar-02	Y	Y	Jul-03	Sep-03	May-05	Y	Y	Sep-03	Y
CCL-K6	Sep-97	Sep-97	Y	Y	N	Feb-01	Aug-04	Y	Jul-06	May-07	Oct-08	Sep-09	2009	2009	Mar-13	Nov-14
CCL-K11	2011	2011	Y	Y	N	2011	ongoing	-	-	-	-	-	-	-	-	-
CCL-S1	Jun-98	Jun-98	Y	N/A	N/A	Feb-99	Jun-00	Y	Y	Nov-00	Nov-00	Y	Y	N/A	N	N
CCL-S2	Jun-98	Jun-98	Y	N/A	N/A	Sep-00	Jul-02	Y	Y	Feb-03	Aug-03	Sep-03	Y	N/A	Jul-03	Y
CCL-S3	Jun-98	Jun-98	Y	N/A	N/A	May-00	Apr-02	Y	Y	Aug-03	Aug-03	Sep-03	Y	N/A	N	N
CCL-S4	Jun-98	Jun-98	Y	N/A	N/A	Jan-05	Mar-06	Y	Y	Oct-07	Mar-08	2008/9	2008/9	N/A	N	N
AFRIMETS.L-K1																
SADCMET.L-S1	Y	Y	Y	N/A	N/A	2007										
SADCMET.L-S2	Y	Y	Y	N/A	N/A											
AFRIMETS.L-S3	Y	Y	Y	N/A	N/A	Nov-12	May-13	Y	Y	Y	15/04/2015	06/05/2015	17/08/2015	N/A	N	N
AFRIMETS.L-S4	Y	Y	Y	N/A	N/A	Aug-12	Y	Y								
APMP.L-K1	Aug-98	Y	Y	N	N	Jan-01	Jul-02	Y	Y	Y	Mar-05	Sep-05	Y	Y	N	N
APMP.L-K1.1	Oct-04	Y	Y	N	N	May-05	Aug-06	Y	Y	Y	Jul-09	Sep-09	Sep-09	Y	N	N
APMP.L-K1.1.2011	Y	Y	Y	N	N	2011	Dec-12	Y	Feb-12	Y	13/02/2013	##########	11/04/2013	22/04/2013	##########	21/11/2013
APMP.L-K2	Aug-98	Y	Y	N	N	May-00	Apr-03	Y	Y	Y	Dec-03	Y	Dec-03	Dec-03	Mar-08	Y
APMP.L-K3	Y	Y	Y	N	N	2005	2007	Y	Y	exp 11/2014	18/07/2016	########	23/08/2016	N		
APMP.L-K4	Y	Y	Y	N	N	2008		Y	2012	Nov-13	15/05/2014	18-Jun-14	18-Jun-14	17/07/2014	16/02/2015	06/05/2015
APMP.L-K5.2006	2003	Y	Y	N	N	2006	2010	Y	Y	Nov-10	11/03/2011	Oct-11	Jan-11	N	07/03/2013	11/04/2013
APMP.L-K5.2006.1	22/08/2012	Y-RMO	22/08/2012	N	N	27/08/2012	Y	Y	Y	Dec-14	16/10/2016					
APMP.L-K5.2014	Y	Y	26/11/2014	03/12/2014	12/12/2014	15/12/2014			due 11/2015							
APMP.L-K6	Oct-05	Y	Y	N	N	2008	2008	Y	Y	Y	22/01/2014	11-Feb-14	10-Jul-14	N	01/09/2015	29/09/2015

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Current & future comparisons

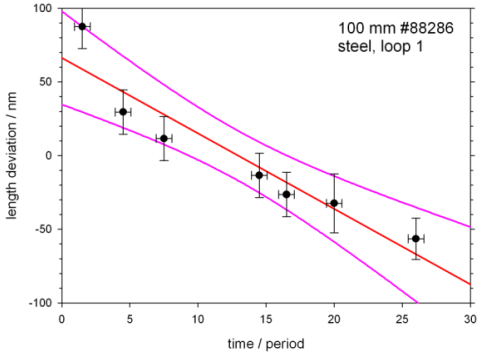
No.	Artefact	
K1	gauge blocks	AFRIMETS planning, CCL 2021
K3	angle	CCL 2017 planning
K4	diameter	CCL & EURAMET running, CCL 2026
K5	step gauges	EURAMET ending, APMP 2025?
K7	linescales	CCL planning
K8	surface texture	APMP 2019, EURAMET 2021
K11	lasers	(yearly ongoing participation)

CCL Pilot Studies

- Some pilot studies in nanometrology were re-classified as CCL supplementary comparisons – no longer allowed to do so!
  - CCL-S1 – one dimensional nano gratings
  - CCL-S2 – step height standards
  - CCL-S3 – line scale standards
  - CCL-S4 – two-dimensional gratings
- Several pilot studies in the RMOs were *post hoc* elevated to be RMO supplementary comparisons – this is no longer allowed also!

Specifics of CCL KC protocols

- Usual items: participants, timetable, artefacts, SI traceability,
- Insurance for artefact(s)
- How to handle/transport (often include thermal logger)
- Definition of measurand(s), reference conditions (*e.g*. ISO 1: 20 °C)
- How to report results (preferred units)
- Reporting timescale (max 6 weeks)
- How the KCRV will be calculated (usually weighted mean)
- Potential datafitting for artefact instability (confirm drift, model drift)
- Correlation between participants
- Main uncertainty contributions
- Request for ‘no extreme’ measures
- One or two loops and linking



- WG-MRA approves all key comparison protocols - including RMO ones

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Traveling standards – length artefacts

- Use *normal* artefacts
  - Ideally with stability history
  - Occasionally trial novel artefacts
  - Have used an instrument (autocollimator)
- Artefacts often become damaged
  - Sometime multiples/backups needed
- Accelerated wear rate
  - Can be issue for last participants – see most damaged items
- Protection for transport
  - Early days – hand transport in aircraft cabins

Comparison reports – Final & Executive

Process

- GD-3.2 Report Template
- GD-3.2b Bilateral report Template
- GD-3.3 Executive Report Template
- **Draft A** (Excel file of results) – simple confirmation of data
- **Draft B** contains first analysis
  - iterated until concluded then becomes **Final Report**
- **Final** sent to WG-MRA for discussion and approval
- **Executive Report** follows soon (private)
  - Simplest summary of main results (usually DoE and U(Doe))
  - Comparison of uncertainty with relevant CMCs – good/bad
  - Contains CMC actions and any outcomes so far
  - Copied to Exec. Sec (to website), copied to RMO TC-L chairs

Pragmatism vs strict rules

- *Results changeable to **before Draft A** with no concern (ideally reason given), no comment in report*
- ***After Draft A** correction of obvious **blunders** caused by 'comparison intricacies' (noted in report)*
- ***Technical revision** of results with clear justification and approval of participants (detailed note in report, calculation before and after) – prevents bilateral*
- *CMC action – has to be agreed by RMO TC-L as appropriate and signed off by them:*
  - *Greying out of CMC*
  - *Increase uncertainty in CMC*
  - *Voluntary withholding of service*
  - *Internal comparison evidence*
  - *Informal bilateral*

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Review of CMCs in light of comparison results

- *Poor* results are investigated
- *Poor* means too many with *En* >> 1 (*En* = 'difference'/'uncertainty')
- A few with 1 < *En* < 1.5 may be OK (accreditors use same criterion)
- More than one with *En* > 1.5 not OK
- Described in detail in Executive Report
- Seek explanation, discuss, approve within RMO
- No solution, grey CMC, increase uncertainty, suspension, ?actions?
- Yearly report from RMO to sWG-CMC
- Lists of actions (action pending, action done, issue solved)
- Unsolved issues – WG chair emails local TC-Q chair to investigate

How to be a good pilot in CCL comparisons

- Use the template documents
- Register with RMO, KCDB, WG-MRA
- Accept extra-RMO participants (if needed)
- Get protocol approved by WG-MRA (detect errors, problems)
- Seek donation of artefacts
- Keep communicating
- Prepare outline analysis early- populate Excel file as results come in
- Draft A release within 1 week of final results (just the Excel file – check blunders)
- Draft B very soon after confirmation of Draft A
- Use existing analysis spreadsheets for KCRV, *En*, etc.
- Fully detailed Final Report (can be up to 70 pages!)
- Short and succinct Executive Report (ideally 4-6 pages) – with recommendations on CMCs

Outline

- Introduction to CCL & length metrology
- MRA: Organisational aspects within CCL
- MRA: Technical aspects within CCL
- Summary of key points

Key Comparison Reference Values

- Use weighted mean unless known issues (over-dominant NMI)
- Bilateral comparisons do not generate KCRV, just DoE, *U*(DoE)
- Iterative process
  - Calculate KCRV (weighted mean of contributing results)
  - Calculate *En* values = DoE/U(DoE) taking '-' for correlation
  - Examine Birge ratio – consistent results?
  - If not, remove highest En result
- Re-calculate *En* for excluded results taking '+' in uncertainty
- Plot graphs, generate table of *En*
- For Executive Report, generate tables of DoE, *U*(DoE), *U*(CMC)
- Do not calculate mutual DoE (12 participants, 50 measurands, …6600 numbers…)

Full details in **CCL-WG/-MRA-GD-3.2**

KCRV: the mathematics (1/2)

ITERATE BASED ON DECISION ON NEXT SLIDE

Compute the normalised weight, w_i , for each result x_i given by: $w_i = C \cdot \frac{1}{[u(x_i)]^2}$ where the normalising factor, C, is given by: $C = \frac{1}{\sum_{i=1}^{I} \left(\frac{1}{u(x_i)} \right)^2}$

Then calculate the weighted mean, $\bar{x}_w$, which is given by: $\bar{x}_w = \sum_{i=1}^{I} w_i \cdot x_i$

The uncertainty of the weighted mean is calculated by: $u(\bar{x}_w) = \frac{1}{\sqrt{\sum_{i=1}^{I} \left(\frac{1}{u(x_i)} \right)^2}} = \sqrt{C}$

After deriving the weighted mean and its associated standard uncertainty, the deviation of each laboratory's result from the weighted mean is determined simply as $x_i - \bar{x}_w$

The uncertainty of this deviation is calculated as a combination of the uncertainties of the result, $u(x_i)$, and the uncertainty of the weighted mean $u(\bar{x}_w)$ $u(x_i - \bar{x}_w) = \sqrt{[u(x_i)]^2 - [u(\bar{x}_w)]^2}$

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KCRV: the mathematics (2/2)

For each iteration, check for consistency using *Birge Ratio*, R_B

$$R_B = \frac{u_{ext}(\bar{x}_w)}{u(\bar{x}_w)}$$ where $u_{ext}(\bar{x}_w)$ is the external standard deviation $$u_{ext}(\bar{x}_w) = \sqrt{\frac{1}{(I-1)} \cdot \frac{\sum_{i=1}^{I} w_i (x_i - \bar{x}_w)^2}{\sum_{i=1}^{I} w_i}}$$

The Birge ratio has an expectation value of $R_B = 1$, when considering standard uncertainties. For a coverage factor of $k = 2$, the expectation value is increased and the data in a comparison involving I (number of) laboratories are consistent provided that

$$R_B < \sqrt{1 + \sqrt{8/(I-1)}}$$

If the check fails, calculate the *En* values for all laboratories, remove the result with the largest *En* from contributing to the weighted mean, then re-iterate until the test is passed.

$$E_n = \frac{x_i - \bar{x}_w}{\sqrt{[U(x_i)]^2 - [U(\bar{x}_w)]^2}}$$

Any results no longer contributing to the weighted mean are no longer correlated so the uncertainty of their difference from the mean uses a '+' sign:

$$u(x_i - \bar{x}_w) = \sqrt{[u(x_i)]^2 + [u(\bar{x}_w)]^2}$$

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“dark uncertainty” - dispersion of results > expected from lab uncertainties?

- Yes – this sometimes occurs
- Analytically confirmed by Birge Ratio being exceeded
- Sometimes a check on artefact drift is positive and this must then be taken into account
- Sometimes correlated with high *En* values for one or more measurands – suggesting artefact-specific problem
- In one comparison (*), detailed analysis revealed an uncertainty contribution never considered before in many decades of use!

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(*) EURAMET.L-K3.2009 revealed autocollimators are affected by the weather, more specifically the air density and its refractive index

Underpinning of CMCs by comparisons: step 1

- Determining "how far the light shines“ : step 1 - skills matrix

Principal Techniques	CCL-K1	CCL-K2	CCL-K3		CCL-K4	CCL-K5		CCL-K6	CCL-K7	CCL-K8
	gauge block	length bar	poly	gau.	diameter	ball	step	2D CMM	linescale	surf tex.
Realizing the Metre definition										
Interferometry	2	2			2	2		2	2	1
Wavelengths in air	2	2			2	2		2	2	1
Gauge Issues										
Temperature of Gauge	1	2			2	2		2	2	1
Mounting & Aligning	1	2	2		2	2		2	2	1
Wavefront Probing										
Reflection Phase Effects	2	1								
Wringing	2	1								
Mechanical Probing										
Stylus contacting at surface, 1-D					2	1	2	1		2
Bi-directional probing for size					2		2			
Probing for 3-D center coordinates						2		2		
Image Probing										
Sensing Line Centres									2	
Angle Metrology										
Measuring small angles (autocoll.)			1	2						
Large Angle Gen: Circle Dividers			2	1				1		
Small Angle Gen: SineBar, CircDiv.				2						
Formal mathematical processing of data sets										
ISO parameter extraction										2
Form Metrology										
Flatness										1
Roundness					1					
Thread, Gear Profile										
3-D Surface										1

From CCL Strategy Document

Skills matrix from early days of MRA

2 = strong test of skill by comparison
1 = weaker test of skill
0 = no link

One comparison may test a skill that underpins several CMCs

Underpinning of CMCs by comparisons: step 2

- Pragmatic approach
- Use all positive evidence available:
  - Quality System (internal comparisons, cross-checks)
  - Comparisons evidence (where available)
  - DimVIM (similar classes of CMCs have similar skills)
  - Published papers in journals describing technique and testing
  - EURAMET: CMC review experts (usually KC pilots of similar topics)
  - Blind comparison using commercial calibration to get a reference

CMC formatting for CCL: DimVIM & GD-5

Column C, enter a short phrase that conveys the "Instrument Type or Method" used to make the measurement. The phrase should suggest (to an expert) the main scale, how the gauging features are probed, and any differential scale. These factors, combined with the identification of the reference standards used (Column L), tell an expert much about your procedure. Examples:

Artifact: Measurand	Instrument Type or Method	Reference Used
gauge blocks: central length	interferometry, exact fractions	stabilized lasers
stage micrometer: line spacing	video microscope & 1-D comparator	length interferometer
index table: angle	index table & one autocollimator	index table, autocollimator

- Avoid zero (minimum) or non-specified maximum in ranges (unless true!)
- Use of the Q[a, b*L*] short form notation for quadrature sum (root sum square)

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Quantity equations *vs* numerical value equations

The KCDB currently uses *numerical value equations* for CMC uncertainties:

$U = (25 + 1.2\ L)$ nm , L in mm

Many accreditation bodies require the use of *quantity equations*:

$U = 25\ \text{nm} + 1.2 \times 10^{-6}\ L$

Raised for discussion under KCDB 2.0

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Outline

- Introduction to CCL
- MRA: Organisational aspects within CCL
- MRA: Technical aspects within CCL
- Summary of key points

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Key points (1/2)

- Slight bending of the rules to save time and money ☺
  - Not always KCRV
  - No mutual DoEs
  - Minimal numerical linking of comparisons
  - Not always '*classical*' comparison scheme, Inter-RMO used as well
- Organise and structure CC & WGs to achieve efficiency
  - Ensure good communications with the RMO TCs
  - Maximise use of experience, encourage new members
- Be flexible and put some trust in quality systems & experts
- Use template documents/Excel files to make things easy for pilots

Key points (2/2)

- Expect delays in some (all?) comparisons
- Be as open & inclusive as possible
  - Guidance documents, Final Reports, Strategy, Planning, Templates,
- Provide feedback to:
  - Strategy WG - Issues may show need for new research
  - WG-MRA (via RMO TC chairs) – willing to help you
  - Discussion Groups (anyone can be a member) – talk about experiences
- Ask for help – either someone has done it before or we can learn something new together!

Capacity Building & Knowledge Transfer

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http://www.bipm.org/wg/AllowedDocuments.jsp?wg=CCL-WG

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Image credits

metre bar & laser - A Lewis, UK.

meeting of the CCL – (http://www.bipm.org/jsp/en/CCPicture.jsp?cc=CCL) BIPM.

meeting of the CCL WG-MRA 2017 – VTT-MIKES

part & engineering drawing - NPL, UK; *Si sphere* - PTB, DE; *Boltzmann resonator* - NPL UK; *Airbus wing* – M McCarthy, UK; *gear* – NimTECH workshop presentation R Thalmann, METAS, CH (http://www.nimtech.ptb.de/nimtech/fileadmin/documents/nimtech/pdf/Keynote_Thalmann.pdf); *nanomark* - Industrial Development Bureau, Ministry of Economic Affairs, TW (http://www.nanomark.org.tw/Eng/).

ion trap – NPL, UK; *freeform scanner* – NPL, UK; *aero engine* – NPL, UK; *gauge blocks* – NPL, UK; *XCT image of turbine blade* – Nikon Corporation (http://www.nikon.com/products/industrial-metrology/lineup/xray_ct/ct/xth450/index.htm); *Si X-ray Interferometer* – NPL, UK.

part & engineering drawing - NPL, UK; *Gauge Block Interferometer* – NPL, UK; *KCDB extracts* – BIPM; *gauge comparator* – Willrich Precision (https://willrich.com/product/tesa-upd-gauge-block-comparators/); *gauge on tool* – Frank Ford, US, (http://www.frets.com/HomeShopTech/Tooling/LatheSineFixture/sinefixture05.jpg); *gauge block set* – NPL, UK; *API thread gauges* – NPL, UK.

CCL Working Group schematic diagram – A Lewis, NPL, UK & CCL WG-MRA.

extract from DimVIM – sWG-CMC of the CCL WG-MRA.

skills matrix extract from CCL Strategy document – CCL WG-S and CCL WG-MRA.

inter-RMO comparison scheme – CCL WG-MRA.

comparison topic K1 planning sheet – CCL-WG-MRA.

CCL-K11 graph – M Matus, BEV, AT & KCDB, BIPM.

length comparisons Excel sheet – A Lewis, NPL, UK.

EURAMET.L-K1.2011 graph – M Matus, BEV, AT.

EURAMET.L-K1.2011 transport boxes– M Matus, BEV, AT;

mathematics - from WG-MRA Guidance Documents, A Lewis & CCL WG-MRA.

skills matrix extract from CCL Strategy document, ibid.