CCPR WG Strategy Document for Rolling Development Programme

Date drafted: January 2013
Period covered: 2013-2023

1. General Information on CCPR WG Strategic Planning

CC Name: Consultative Committee on Photometry and Radiometry (CCPR)

CC Working Group: CCPR Working Group on Strategic Planning (CCPR WG-SP)

Date Established: 2005

Number of Members: 12 NMI members + 5 RMO members + 2 Ex-officio members

Number of Participants at last meeting:: 32 (typically 20-25)

Periodicity between Meetings: about 1 year (about 2 years for full CCPR)

Date of last meeting (Workshop on *mise en pratique*): 22 February 2012

CC WG Chair (Name, Institute, and years in post): Joanne Zwinkels, National Research Council Canada (NRC), 6 years

Number of KCs organized (for 1999 up to and including 2012): 16

Number of Pilot studies organized (from 1999 up to and including 2012): 4

Number of CMCs published in KDB supported by CC body activities (up to and including 2012): 1224

2. Terms of Reference

A description of the scope and areas of activity of the CC body

The Consultative Committee of Photometry (CCP) was established in 1933 and became the Consultative Committee of Photometry and Radiometry (CCPR) in 1971. The CCPR is responsible for providing advice to CIPM on matters concerned with photometry and radiometry. It is presently responsible for: the practical realization of the SI photometric unit, the *candela*, and related measurement standards for photometric and radiometric quantities (luminous flux, luminous intensity, illuminance, spectral radiant flux, spectral radiance, spectral irradiance); development of absolute radiometry (absolute spectral responsivity scales); development of measurement scales for the optical properties of materials, including the provision of SI traceability for colorimetry of materials (spectral reflectance and spectral transmittance scales); and fiber optics.

The CCPR Working Group on Strategic Planning (WG-SP) was established in 2005 under the Chairmanship of Dr. Franz Hengstberger, President of the CCPR, to advise the International Committee of Weights and Measures (CIPM) on future directions in photometry and radiometry, relevant to the SI. This WG-SP was also to consider the operational structure and technical priorities of the CCPR in the context of global community needs, such as the need for new definitions/ standards and coordinated research. In 2007, the terms of reference of WG-SP were expanded to include monitoring developments with respect to the future of the SI system and a WG-SP Task

Group on the SI was established. The current membership of WG-SP is 12 NMIs (INRIM, KRISS, LNE, METAS, MSL, NIST, NMIJ, NMISA, VSL, NPL, NRC, PTB), 5 RMO technical committee chairs (AFRIMETS, APMP, COOMET, EURAMET, SIM) and 2 ex-Officio members (Executive Secretary of CCPR, President of CCPR).

Within the organizational structure of WG-SP, there are several task groups (TGs) that are not considered permanent but respond to a specific task or pressing issue. The first three WG-SP Task Groups: TG1 (Terms of Reference), TG2 (Membership Criteria) and TG3 (CCPR Structure) have completed their stated aims and prepared reports that were approved by CCPR; these were dissolved in 2010, 2012 and 2010, respectively. There are currently seven active WG-SP Task Groups; these are:

TG4: SI

TG5: *Mise en pratique*

TG6: Discussion forum on fibre optics

TG7: Discussion forum on few photon metrology

TG8: Discussion forum on THz metrology

TG9: OTDR length comparison

TG10: Ad-hoc on CCPR 2012 strategy document

Since its inception, the CCPR WG-SP has carried out the following main activities. The first output was an opinion paper on the evolving needs in the field of photometry and radiometry for the 2007 BIPM *Report on Evolving Needs for Metrology in Trade, Industry and Society*. WG-SP also prepared a short document on the *Impact of Changes in the SI Units on Radiometry and Photometry* for the Consultative Committee of Units (CCU) meeting in June 2007 and an ad-hoc task group updated *Appendix 2 of the Si brochure on the practical realization of the definition of the candela*. Members of CCPR WG-SP also prepared a review paper on *The evolution of photometry, radiometry and the candela: from the classical to the quantum world* that was published in *Metrologia* (2010). This paper introduced for the first time a fundamental constant (constant of nature) for photometry, K_{cd}, which was adopted by the CCU for the explicit constant definition of the candela. The WG-SP also prepared a response to CCU regarding the position of CCPR to the proposed rewording of the candela definition in explicit constant form and the subsequent text in explicit unit form (CCU/10-4.7.CCPR and annex to report of CCPR meeting 2012[1]).

WG-SP also introduced the concept of Discussion Forum as a new category of CCPR Task Group for discussing measurement issues and other emerging topics of interest that would benefit from broader participation of experts. These Discussion Forum task groups are intended to be short-lived and to recommend concrete tasks to CCPR, such as the establishment of a new technical CCPR working group, identify need for cooperative NMI research or new pilot or key comparisons to provide SI traceability and to underpin associated CMCs. For example, in November 2009 there was a BIPM Workshop on Physiological Quantities and SI Units. One of the recommendations from this Workshop was for CCPR and CCEM to consider the emerging need for traceable THz metrology. As a

[1] Under publication

consequence, WG-SP formed a new Task Group on Discussion Forum for THz metrology and established a formal liaison with CCEM to discuss outstanding issues and need for SI traceability in this field.

There are currently three active Discussion Forum type Task Groups within WG-SP (TG6, TG7 and TG8) and one within WG-KC (Discussion Forum on Comparison Analysis). In practice, these Discussion Forum Task Groups have organized Workshops or Conference Sessions with invited non-CCPR experts from other CCs, industry, academia, and other organizations, to carry out focussed scientific and technical discussions and address specific issues.

2009 – TG4: Workshop on SI. Number of participants: 34. *Outcome:* Draft outline for position paper on possible reformulation of the candela.

2010 – TG6: Workshop on Fibre Optics. Number of participants: 14. *Outcome:* creation of a new TG (TG9) to develop the technical protocol for a pilot comparison for optical time-domain reflectometry (OTDR) length to underpin relevant CMCs.

2011 – TG7: Special session on Few Photon Metrology at the 11th NEWRAD conference. Number of participants: more than 100. *Outcome:* 8 oral presentations about the current research activities at NMIs towards achieving SI traceability in the field of few photon radiometry.

2012 – TG5: Workshop on *mise en pratique (mep) for the candela.* Number of participants*: 35. Outcome:* Recommendation to CCPR to create a joint CCPR/CIE Task Group and decisions on how to best go forward in preparing a *mep* (see further details below).

Other mechanisms that have been used by the Discussion Forum task groups to advance its aims have been the use of surveys. Both TG6 and TG8 have conducted surveys of NMI capabilities and needs for traceability of fibre optic and THz measurements, respectively. An outcome of these surveys has been the prioritization of measurement needs and the establishment of a new Task Group, TG9, to develop the technical protocol for a pilot comparison of OTDR length and a preliminary investigation of a THz detector comparison by NMIs active in this field.

Currently, WG-SP is developing a concise *mise en pratique* document for the candela and is participating with the International Commission on Illumination (CIE) in a joint CCPR-CIE Task Group on *Principles Governing Photometry* (CIPM/CIE JTC-2) whose terms of reference are to prepare a comprehensive joint CIPM/CIE publication on 'Principles Governing Photometry' that will include all photometric quantities and units with CIE Standard spectral luminous efficiency functions for photopic, scotopic and mesopic vision. This document will replace the existing BIPM Monographie: *Principles Governing Photometry (1983)* and it is expected that this will also serve as an update of the essentially identical CIE technical report, *CIE Publication 18.2: 1983: The Basics of Physical Photometry.*

3. Baseline Status

A description of what the body has achieved since 1999 including the total number of comparisons and CMCs supported. Discussions of major changes in needs, technologies or areas of interest during the period and the effect on the activities of the body. Major

challenges and difficulties encountered and issues that require resolution. Information on repeat frequencies of any comparisons to date.

Since 1999, there have been a total of 29 CCPR and RMO key (16) and supplementary (13) comparisons that have been published and approved for equivalence, and an additional 3 comparisons are at the Draft B stage. The results of these comparisons support a total of 1224 CMCs (up to 2012) in the fields of photometry, properties of sources and detectors, and properties of materials and fibre-optics.

The three CCPR supplementary comparisons S1 to S3 that were carried out in this period were:

- S1 Spectral radiance 220 to 2500 nm
- S2 Aperture area
- S3 Cryogenic radiometers

The future of these supplementary comparisons was discussed within WG-KC and CCPR and it was decided that none of these needed to be conducted as CCPR key comparisons; these would be conducted as RMO supplementary comparisons, as necessary.

There was also considerable discussion within CCPR on the quantities and spectral ranges to be included in the 2nd round of CCPR key comparisons. These discussions included alternative ways to reduce the workload of the pilot labs and participants, e.g. by reducing the number of KCs by abandoning some of them or combining similar ones or by simplifying the comparisons (e.g. reducing the number of samples, wavelength points, etc.) From this discussion it was widely considered that the comparisons K3.a (luminous intensity) and K3.b (luminous responsivity) from the 1st round of KCs were strongly correlated and that only one comparison called “luminous intensity” should be carried out. The final decision on which artifact to use – lamps or photometers - would be determined by the dedicated comparison Task Group.

However, some NMIs called for new KCs to underpin a wider range of CMC categories. All CCPR members provided input to these plans and, after considerable debate it was determined that the 6 quantities: luminous intensity, luminous flux, spectral irradiance, spectral responsivity, spectral regular transmittance and spectral diffuse reflectance; some of them cover several different spectral ranges, giving a total of 10 key comparisons, were adequate for underpinning the core photometry and radiometry measurement capabilities and associated CMCs. These 10 key comparisons are listed in Table 7.1.

With regard to the repeat frequency of these key comparisons, this issue was discussed within the full CCPR by surveying the members and observers. There was considerable variation in the responses from a period of 5 years to 20 years. After extensive discussion, a period of 10 years was decided upon as a reasonable compromise. However, this repeat frequency interval has been used as a guideline only and other factors have been considered by WG-KC in deciding upon the actual scheduling of these 2nd round key comparisons. For example, while the key comparisons K3 and K4 on luminous intensity and luminous flux, respectively, were started in 1997-1998, and K6 on spectral regular transmittance was started in 2000-2001, it was decided that K6 should be repeated first because of problems experienced with the artifacts in the first round. The 2nd rounds for K3 and K4 could be delayed since there was not an immediate need for a repetition and because currently equivalent RMO comparisons were still in progress.

During the course of these discussions within WG-KC, the CCPR Working Group on Calibration and Measurement Capabilities (WG-CMC) highlighted the need of possible additional key and/or supplementary comparisons to support some of the CMCs, such as quantities in the fibre optics field. This was the motivation for the creation of a Task Group within WG-SP (TG6) to discuss this issue in more detail and to identify new measurement needs of the fiber optics community and to identify priorities in terms of research areas and needs for SI traceability.

With regard to the scheduling of the 2nd round of CCPR key comparisons, including determination of repeat frequency, the general view of many NMIs during the course of the first round key comparisons (KCs), was that they were taking too much time to be completed and that they increased significantly the workload and the costs for the pilot laboratories. The situation was even more difficult with the increasing demand for number of participants in these KCs. As a consequence, a Task Group on Strategy for CCPR and RMO comparisons was formed in 2004. Discussions took place in the period 2005 to 2006, leading to the following key points:

- There is a need for reducing the number of participants in CCPR KCs
- The participation in either CCPR or RMO KCs should suffice to meet MRA requirements
- A CCPR KC could be considered as a comparison restricted to those laboratories playing the role of link laboratories for RMO KCs
- Low uncertainties in CCPR KCs are desirable to ensure a reliable link with RMO KCs.

At the 2006 meeting of WG-KC, it was agreed to conduct a survey on NMI's plans for participating in the next round KC's, as well as their willingness to serve as pilot. The survey was distributed to CCPR members and observers in March 2007. The results of this survey (CCPR-WGKC/07-03) indicated that nearly 20 laboratories wished to participate in many of these KCS. It was generally considered that such a large number of participants would make it very difficult to run these comparisons in an efficient manner and that coordination was needed between the CCPR KCs and the RMO KC's to make this process more efficient while respecting the spirit of the CIPM MRA. It was argued that limiting the number to 10 to 15 would not reduce the accuracy for the key comparison reference value (KCRV). Consequently, WG-KC proposed a set of criteria for participation in this 2nd round KCs which was planned to start in 2009.

- Firstly, this would be limited to CCPR members with an independent scale realization and CMC coverage of the quantity over the whole wavelength range and at the time of call for participants; in the case of a new KC, this final condition was not required.
- Secondly, it was proposed to have a maximum of 12 participants for each KC with a possible grouping and membership of: Group 1 (EURAMET+COOMET) with 6 participants; Group 2 (APMP+SADCMET; now AFRIMETS) with 4 participants; and Group 3 (SIM) with 2 participants.
- The inclusion of other NMIs would then be carried out through linked RMO comparisons.
- If the total number of participants which fulfil the preceding entry conditions is 12 or less, all applicants would be accepted.

These selection criteria for participation in the 2nd round KCs (CCPR/09-07) were approved by CCPR and have been implemented for the 2nd round comparisons that are on-going. Where more than the maximum number of participants for a given Group indicated their interest to participate in the KC, the final decision on limiting participation was determined by the associated RMO(s). To-date, this practise has worked extremely well.

Major changes in needs, technologies and areas of interest since 1999.

The major changes of interest to CCPR since 1999 are briefly listed below in bullet format. The response of CCPR to these events and the changes in its activities or organization are indicated in the sub-bullets.

- The establishment of an MoU between CIPM (CCPR) and CIE in April 2007 where CIPM is responsible for the definition and traceability of the candela in the SI system and the CIE is responsible for the standardization of the action spectra of the human eye.
    - The International Commission on Illumination (CIE) was made a Permanent Observer of CCPR

- Publication by CIE of a formal mesopic vision model that defines the spectral luminous efficiency function for mesopic vision (CIE 191:2010 Recommended system for Mesopic Photometry Based on Visual Performance)
    - CCPR WG-SP held a workshop in February 2012 on the *mise en pratique* of the candela and invited representatives from CIE. The Workshop had the objectives of guiding the direction and to coordinate possible joint work between the CIE and the CCPR to prepare a new *mise en pratique* for the candela. The candela will not be redefined, but it is planned to change the wording of its definition. The final decision was that a concise *mise en pratique* would be written by experts from the CCPR (WG-SP TG-5) and that an additional more extensive document *Principles Governing Photometry* should be published by a joint CCPR-CIE task group (JTC-2).

- It is expected that in the near future – four of the seven base units of the SI system will be redefined: the kilogram, the ampere, the kelvin and the mole where each of these units will be based on a fixed numerical value of a fundament constant: the Planck constant, the elementary charge, the Boltzmann constant and the Avogadro constant.
    - CCPR WG-SP prepared a position paper on a possible reformulation of the candela that was published in Metrologia (2010).
    - CCPR WG-SP created a new Task Group on SI (TG4) to look into possible ways of linking the definition of the candela to the Planck constant, h, to cater to the additional needs of emerging sectors, such as the quantum-based technologies.

- The need for energy-saving light sources. In the past decade, there has been a transformational change in light and lighting with the improved technology of light-emitting diodes (LEDs) whose application is rapidly growing to general purpose lighting, displacing traditional incandescent and fluorescent lights. This transformation will bring enormous energy savings, since lighting accounts for 20% of the world-wide energy use. LEDs have already exceeded the energy efficiency of the best fluorescent lamps, and are expected to be twice as efficient as fluorescents in a few years
    - This impacts the CCPR since the methodologies for measuring the optical measurement quantities that are most relevant to these LEDs are different from traditional light sources and need to be more fully developed.

- The need for SI traceable measurements in studies of Earth resources, the environment, human well-being and related issues.
    - A formal CCPR Resolution 4 was submitted to the 21st CGPM meeting (1999) concerning the need to use SI units in studies of Earth resources, the environment, human wellbeing and related issues

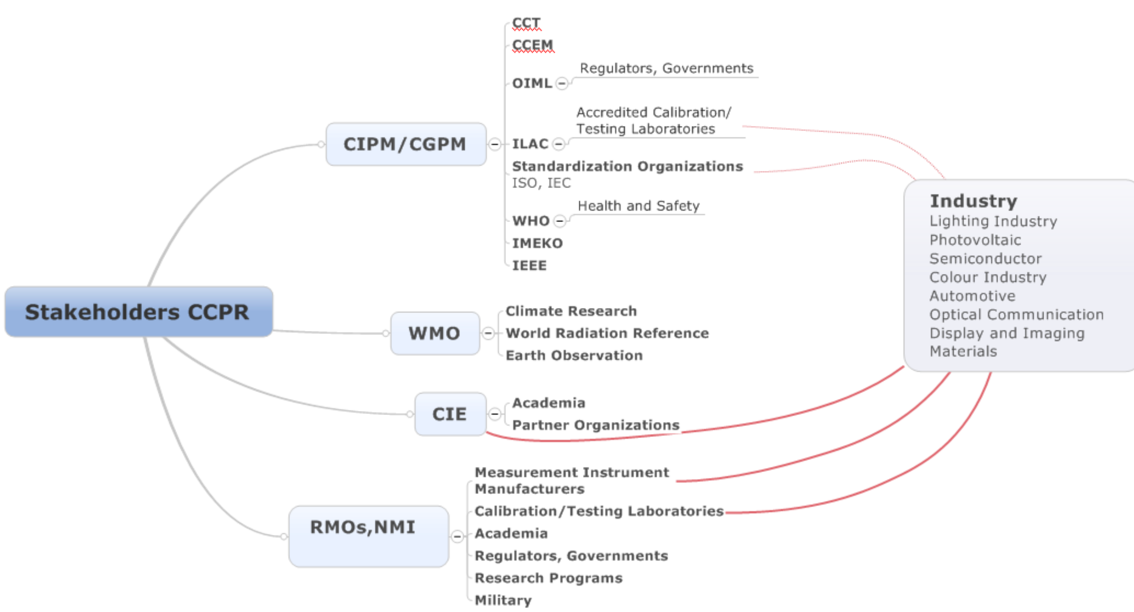
- The need for SI traceable measurements to monitor climate change.
  - A formal CCPR Recommendation P1(2005) was submitted to the CGPM "On the Importance of SI traceable measurements to monitor climate change".
  - World Meteorological Organization (WMO) is made a Permanent Observer of CCPR.

- The need for SI traceable measurements for photobiological quantities
  - Held a BIPM Workshop on "Physiological Quantities and SI Units " Chaired by the BIPM Deputy Director, Prof. M. Kühne.
  - A new Appendix is added to the new edition of the SI brochure (Appendix 3) on the treatment of photobiological quantities.

- The need for photon-based quantum standards for optical radiation
  - Establishment of a WG-SP Task group (TG7): Discussion forum on few photon metrology

4. Stakeholders (who they are and their level of involvement)

A list and/or description of who are the end-user beneficiaries and whether (and if so how) they are involved in identifying measurement needs, and in prioritization, particularly for comparisons.



The stakeholders of CCPR are outlined in the above graphic. Direct stakeholders are NMIs, RMOs, international organisations with CCPR observer status (CIE and WMO), and the CIPM/CGPM. On the second level are other CCs that CCPR has established liaisons (notably CCT and CCEM on radiation thermometry and THz metrology, respectively), international organisations that are linked to CCPR through CIPM/CGPM agreements (WHO, IMEKO, IEEE), standardization organizations (ISO, IEC), regulators, optical radiation instrument manufacturers, calibration and testing laboratories, the military, and the research community. CCPR traditionally serves a wide range of industries including lighting, space, semiconductor, optical communication, automotive, color industries which span manufacturing colored goods (textiles, paints, plastics) to industries reproducing color (printing, photography), and in health and safety. Emerging Industrial areas include appearance, display and imaging, photonics, solid-state lighting, bio-medical, quantum based information, Tera-hertz, environment and climate, space, and photovoltaics.

There is no direct mechanism for feedback from the end-user to CCPR. Industry is linked mainly through the calibration and testing laboratories to the NMIs. In addition, industry uses measurement standards defined by standardization organisations. In the field of light and lighting there is an alternative link from industry to CCPR through CIE. Industry can directly participate in the preparation of measurement recommendations and standards. The need of comparisons at lower levels of uncertainty or for application-specific metrology, such as testing of solid state lighting, is mainly formulated by the NMIs or RMOs. At the industrial or secondary calibration laboratory level, comparisons are organized mainly through national accreditation programs.

The metrological issue for CCPR is not necessarily providing a primary scale for each of these measurement needs, but how to provide the most convenient means of giving adequate traceability to the SI system.

5. Future Scan (2013-2023)

A future vision of the landscape and consequent requirements and measurement challenges, identifying; likely ongoing requirements; requirements that will appear or develop in the next 10 years, particularly identifying potential major/disruptive step changes.

5.1 Background

Radiometry and Photometry is a technically wide field, where metrological research and development is addressed along

- ✓ Fundamental metrology at the frontiers of measurement science
- ✓ Grand challenges, where the identified measurement and metrology needs are health, energy supply, environment and climate change, security, and new technologies
- ✓ Applied metrology to meet the most urgent industrial and societal needs

For most of the traditional sectors using optical radiometric/photometric techniques, there has been a slow evolutionary progress in terms of demand for new or improved measurement capability, standards, quantities or units. The last major step forward was triggered by the redefinition of the candela in 1979 and the move towards greater exploitation of detector based scales and, in particular, semi-conductor based devices. The advent and widespread adoption of cryogenic radiometry as the primary standard of choice in the 1980’s and 1990’s enabled around an order of magnitude reduction in uncertainty in many of the optical primary scale realisations and disseminations.

There has been and continues to be major and rapid development and use of optical radiometric based techniques in instrumentation, consumer products, healthcare, etc and as a complimentary or diagnostic tool/facilitator in many sectors including other metrology domains. However, for the most part, these issues have not significantly pushed at the uncertainty levels needed in primary scales as compared to those already achieved. They do, on the other hand, continue to place significant demands on how to gain convenient and cost effective access to these uncertainties for particular applications and this is perhaps the major theme underpinning future metrology requirements.

5.2 Fundamental metrology

Over the previous decades, discoveries associated with new technologies, mainly in quantum physics, have led to important changes in thinking for metrology in the future, in particular for fundamental metrology. Quantum optics technologies have demonstrated improved measurements capabilities beyond the boundaries of classical optical radiation metrology. Thus, research and development on photon quantities has the potential to result in a step change to the SI.

The present Photonics era is based on rapidly developing optical technology and photon devices especially applied in the field of secure communication and quantum computing, but also in the emerging field of biophotonics, which requires optical metrology based on better standards and calibration chains including new optical quantum standards also affecting fundamental metrology.

5.2.1 Low-cost, high-accuracy transfer standards

The main goal is the progress and validation of new primary standards for radiometry which have approximately the same cost and functionality as current transfer standard detectors. This would enable NMIs to build the primary standard into different applications (in-line references), thereby taking full advantage of its properties.

Improving the performance of cryogenic radiometers and silicon-based standards could enable radiometry to measure fundamental constants and thereby supporting other techniques through this different route. Such results would contribute to the basis upon which the CIPM fixes the fundamental constants in their future revision of the SI base units.

5.2.2 Few Photon Metrology and Quantum Enhanced Measurements

There is an increasing need in many sectors to measure optical radiation at very low intensity levels, sometimes down to single photons. Emerging Industries using quantum key distribution for secure communication, bio-photonics and fluorescence, nano/mems photonic devices, astronomy and quantum research are some examples where radiometric measurements involving few photons are of increasing importance.

In these few photon regions, classical standards and techniques can, in some cases be conceivably scaled downwards, their uncertainties and potential non-linearity are likely to be limiting metrologically. The requirement for a set of radiometric realisations at photon levels commensurate with need is clear and with it brings the opportunity for an independent physical basis for these quantities based on the counting of photons.

Recent discussions within the CCPR have indicated that there is some desire to make the photon more visible within the definition of the units commensurate with its underlying foundation in physics by stating explicitly the quantum relationship in the definition of the candela.

- Establish radiometric standards and techniques useable at the few photon level.

Quantum enhanced optical measurements e.g. the exploitation of quantum techniques such as entanglement or the non-classical state correlation to yield sensitivity and accuracy better than purely classical approaches, are among challenging targets for basic science. The statistical scaling of uncertainties with $n^{-1/2}$ (where n is the number of uncorrelated and independent measurements) is referred to as the Standard Quantum Limit (SQL) or "shot noise" in quantum optics. A more favorable statistical scaling of uncertainties can be achieved if quantum effects such as entanglement are used to correlate the probes field before letting them interact with the system to be measured, allowing the SQL boundary to be exceeded. The target is to develop theoretical and technological capabilities for operating imaging system (e.g. sub-shot noise imaging, ghost imaging) or opto-mechanical systems (micro-cavities), in the quantum regime, beyond the SQL.

5.2.3 New single-photon source standards with self-consistency within 10^{-5}

The target is the development of highly efficient single-photon sources (SPS) for the realization of SI traceable radiometry at the single photon level. In radiometry, a predictable single-photon source i.e., a source that emits a calculable number of photons at a specific rate and wavelength could act as standard source. Validation of these sources as primary standards will require the development of proper methodologies for the careful characterization of the efficiency of the entire photon collection system and finally the comparison with existing standards. In the quantum communication applications the request for this source is that of a pure single-photon source, i.e. the emitted photons are single and well separated in time from each other. The photon statistics of the source play a key role in the security of the communication.

5.3 Challenges and future photometry and radiometry metrology themes

The following sections are summaries of anticipated metrological requirements for the next two decades based in part on a recent assessment by the EURAMET Technical committee on Radiometry and Photometry (TCPR) https://www.euramet.org/index.php?id=roadmaps , discussions within technical task groups of CCPR WG-SP and the 11th International Conference on New Developments and Applications in Optical Radiometry, NEWRAD 2011. It is not intended to be complete or detailed but more as an overarching framework to scope the major challenges and metrology themes that are likely to be of importance to CCPR. In many cases there are significant overlaps in technologies and consequential metrological requirements but for brevity and to avoid unnecessary duplication an attempt has been made to consider the driving requirement and categorise accordingly. More details can be found in the roadmaps and associated notes indicated above on the EURAMET web site.

5.3.1 Industrial needs (manufacturing and communications)

For most industrial needs existing standards, uncertainties and procedures are likely to remain adequate but with an increasing demand for lower costs and flexible standards to allow traceability to be established and disseminated during production at the work place. For example, the move towards hand-held spectrally resolving instrumentation, where on-board software can compute differing weighting functions as opposed to fragile lamps or a range of bespoke detectors as transfer standards is likely to be increasingly the norm.

“Appearance” is perhaps the greatest challenge in this theme i.e. the need to establish robust measurement systems, transfer standards and descriptive metrics to measure the reflective properties of complex shapes and surfaces in order to describe their “visual appearance” to a human observer under differing illumination conditions. The drivers being consumer perceptions of “quality”, “suitability” and “desirability” and the means to assess these at the design, production and test phases of the product development and production cycle independent of the human observer. In this context, products range from food stuffs, textiles, manufactured items like cars, etc through to products developed specifically to aid sustainability e.g. artificial wood.

- Gonio-metric measurements of spectrophotometric properties of complex shapes and surfaces
- Radiometric measurements under simulated environmental/illumination conditions
- Metrics to describe “perceptual” properties
- Characterisation of radiometric properties of imaging systems

Photonic/optical based sensors are being developed for a wide range of applications particularly in process control/monitoring situations. Here the metrology challenge is more about ensuring that the characteristics of the sensor can be characterised under operational conditions and often at very small scales. In some cases novel photonic properties of materials are being exploited which may involve highly non-linear processes adding complexity to the metrological characterisation

- Small spatial scale application of radiometric techniques and standards

Communications based on fibre optics has pushed the uncertainty requirements traditionally required in the visible spectrum to the near IR spectral region and for ever increasing power levels. The increasing drive for bandwidth leads to multi-wavelength systems and the means to discriminate relative performance of systems under such operational conditions.

- “Golden” reference standard fibres
- Fast optical pulse characterisation

Extreme UV lithography (EUVL) for the future manufacture of semiconductor chips using short wavelength radiation of 13.5 nm requires advanced radiometry for the characterization and calibration of EUV radiation sources and detectors. Higher accuracy wavelength measurements of the spectral reflectance of multilayer mirrors used in the EUV are also urgently needed.

5.3.2 Energy: production and efficiency

Photovoltaics, In the context of CCPR, are the key technology for energy production. Driven by the desire to reduce dependency on fossil fuels to reduce carbon emissions and sustainability photovoltaics are the subject of worldwide research. Small gains in the relative $ to Watt ratio can have major impact in terms of commercial exploitation and also in viability of deployment. While semiconductor-based devices continue to be the most efficient, their manufacturing cost while falling, is still large and efforts to develop other technologies based on organics continues to be a future goal.

Although the key infrastructure, standards, and traceability frameworks exist to support this sector, the commercial demands are driving the need for improved accuracy and more tailored solutions. These are needed to ensure that there is commonality of performance assessment for different technology types and under deployment conditions and at spatial scales consistent with production devices. In metrological terms, it can be considered evolutionary as the key measurement principles exist. However, practical implementation of these and the development of appropriate cost-effective transfer standards and measurement/lab simulation systems needs some international effort to ensure consistency and traceability at the uncertainty levels required.

- Improved accuracy for photovoltaic efficiency measurements under "real conditions" and at production level spatial scales.
- Consistent international traceability for all types of photovoltaic cell

Solid-state lighting is now making major inroads into consumer applications with phased removal of energy inefficient incandescent lamps spreading across the globe. In the main, there are radiometric/photometric metrology challenges associated with the new light source technologies (LED, OLED) that are evolutionary in nature. However, in current practise, they are more about ensuring that an appropriate metric is associated to devices that are relevant to the customer and the intended application and ensuring that industry can standardise on measuring conditions, etc. The longer term move towards OLEDs and lighting panels will require further evolution and standardisation of techniques but no fundamental drivers in terms of CCPR, primary standards and key comparison, other than careful consideration of choice of artefact for future comparisons.

- Standardisation of specification of measurement conditions for new lighting types
- Development of metrics to meet consumer needs

Solar-powered energy systems are considered one of the most effective ways to address energy challenges by using less energy. As a major proportion of energy is used to heat and cool buildings, simple innovative methods of improving energy use in the build environment are urgently required. Research will be used for the improvement of the measurement of the efficiency of the energy generation in renewable sources using solar sources. Capabilities have to be improved on the conversion efficiency of solar-powered energy systems for adding renewable energy sources to national power networks. The application or indirect use of energy should also be addressed: improvement of the standards used for the efficiency of lighting is such an example. The development of new or better sensors by the manufacturers for improving the efficiency and savings for buildings, services and industrial users will need improved standards, better calibration capabilities, modelling and comparability of the sensors.

5.3.3 Health and Life Sciences

Medical/Health sectors continue to make increased use of optical radiation for both diagnosis and treatment. However, other than possible scientific evaluations of interactions of tissue etc. to optical radiation and/or application specific issues such as measurements in-vivo, most of the metrological issues at CCPR level are likely to be covered by existing capabilities or more stringent developmental needs for other applications.

Metrology for health underpins the more reliable and efficient exploitation of diagnostic and therapeutic methods and the development of new techniques, which is needed to improve health care, limit costs and foster the competitiveness of the related industries and services.

In this framework the “virtual human” refers to a model of the human eye and the human vision functions as a comprehensive reference standard for manufacturers of medical instrumentation, medical R&D, modelling and training. The incorporation of human physiology in physical measurements beyond the spectral sensitivity of the human eye will be a great challenge.

Quantitative instead of only qualitative diagnostics includes imaging, modern microscopy and traceable multimodal measurement procedures.

Diagnostical and therapeutical instrumentation includes the use of photo-biosignals, and fluorescence optics.

Biotechnologies: Photon metrology is of increasing importance to the biotechnology community and is in increasing demand. The context is the need to create a sound international basis for accurate and reliable comparable measurements underpinning the development and exploitation of photo-bio-technology by industry. Thus the emerging field of photo-bio-metrology is placing new and growing demands on the metrology research community which needs a co-ordinated approach at this early stage to maximise potential. The specific requirements are to provide the metrology to ensure compliance with related regulation, and to help innovation through the development and validation of new and novel measurement methods. Reliable and valid measurement methods that are fit-for-purpose are vital to driving production efficiency, product safety and improved therapy and diagnostics.

Single molecule biophotonics: Single quanta of light have been relevant for illustrating fundamental quantum principles but they are also ubiquitous in the life sciences. The most efficient detection techniques for fluorescent biomolecules are sensitive on the single photon level. Individual particles of light are also of direct relevance in biological processes as they may affect the structure of individual molecules which in turn can transduce signals in living organisms. The retinal molecule can switch its conformation after absorption of very few photons and thus turns the human eye into one of the most sensitive light detecting devices that exist. Single molecules can also be considered to be single-photon sources. We still have to learn about the relevance and evolutionary advantage of quantum physics in photosynthesis. The target is to investigate interactions between single molecules and quantum optical fields.

5.3.4 Environment and Climate

A key challenge is the need to ensure sustainable growth while reducing negative environmental impact. The Earth’s environment and climate are changing and the consensus is that mankind is making a significant contribution to these changes. Research into innovative new systems and technologies that mitigate environmental impacts will require measurements that validate claims of high-efficiency transportation, construction and energy technologies. These include the energy efficiency of buildings and reduction strategies for lighting noise in living environment.

The changes in the climate are due to subtle changes in the optical radiation balance of the Earth (in-coming to out-going) leading to a resultant increase in global temperature. Although, in principle, absolute change in temperature can be measured through a global network of “thermometers” this is not by itself a reliable metric due to sampling issues, local changes, as well as sensing techniques, themselves. The community thus makes use of a variety of indicators to monitor and infer change or the impact of change. These are the so called Essential Climate Variables (ECVs), more than 2/3 of the 50 involve some form of optical radiation measurement: emitted, direct, absorbed or reflected. This will require new measurement standards for environmental changes and the environmental performance of new technologies.

As climate change needs to be monitored globally, this drives the need for satellite observation of the Earth and Sun system and the key metrological challenge. The basic measurands and thus underpinning standards for this sector are well-established and in the main trace back to spectral radiance and irradiance, although many key parameters are actually reflectances that are for practical purposes measured as radiances. In order to reliably detect changes in the environment and to monitor the climate, a robust and stable measurement infrastructure is required. These typically involve measurements at very low levels and over long timescales. The activities to be addressed most urgently through research include validated and traceable measurement techniques, sensors and measurement standards related to detecting change and monitoring climate and the assessment and management of environmental noise.

The metrological needs are for:

- ✓ Novel sensors and underpinning measurements for global surface and ocean temperatures and stable long-term trends in the composition of the ocean and atmosphere.
- ✓ Provision of a distributed system capable of providing traceability to SI units for measurement data from global ground and satellite-based networks.

The metrological challenge in this sector is to achieve the very high accuracies required at the point of measurement i.e. the satellites or in-situ at some point on the surface of the globe or its atmosphere. Uncertainties close to those of current primary standards are required for long time scales and where re-calibration in the laboratory is not possible. Other challenges involve the practical means of providing traceability which is typically under environmentally challenging conditions, e.g. vacuum/extremes of temperature and for instrumentation which is spatially large in scale. The uncertainties required by this theme are probably the most demanding for CCPR, but also due to their highly specialised nature do not necessarily warrant major effort by all NMIs at the potential exclusion of the other themes. It is critical that these issues are addressed and that the NMI community work effectively to meet the global need and ensure international consistency but this can probably best be done by coordinated action and comparison amongst a few NMIs focussed on the specific traceability issues. Thus, the key challenges in this sector are:

- Development of techniques which can make possible a set of SI-traceable radiometric standards and instruments to make such measurements in space.
- Difficulty of demonstrating and maintaining traceability to the SI in the space environment because the levels of accuracy needed are often more demanding than those needed to satisfy current industrial requirements.
- Establishing full traceability to SI units in space and at remote locations on the Earth.

5.3.5 Security

Metrology is central to the development of instrumentation at the technological frontiers to meet the growing public **security** needs.

Security-related metrology includes development and characterization of Terahertz (THz) sources and detectors. The Terahertz (**THz**) region is the last part of the non-ionising EM spectrum to be exploited technologically. An emerging THz industry is developing rapidly. Major drivers for this rapid growth are – besides security applications – medical imaging, biological screening, e.g. of toxins in the atmosphere, and biological and pharmaceutical spectrometry of solids and liquids. At present, little metrological support can be provided to this activity, although requested by industry. The growth of this industrial need will require the e*stablishment* of traceable radiometry in the THz range

Another research option is underpinning quantum cryptography by entangled photon-sources which are also of interest in radiometry, and by validation procedures for information integrity, which also affects legal metrology.

The extremely strong privacy properties of Quantum Key Distribution (QKD) can be used as PET to enforce protection of personal data, as it is foreseen in the legal framework. The standardisation initiative active for QKD judges as mandatory the need of traceable measurement at single photon level. The target is to develop the metrological expertise and capabilities to meet the needs of future developments in QKD components such as sources, detectors, true physical quantum random number generators and quantum repeaters.

5.3.6 New Technologies

Nanotechnology is a key enabling technology. The driving forces behind are the demand for ever increasing integration, e.g. in electronics and information technology, as well as the possibility of achieving new functionalities which are not possible otherwise such as through photonic crystals, optical meta-materials, and nano-sources. In many cases in nanotechnology, quantum-mechanical effects prohibit a scaling-down of properties of micro systems and thus require new scientific approaches. The metrological key challenge is the characterization of nano-sources and nano-detectors.

Metrology for new materials: Materials developments are pervasive in our lives as the building blocks for everything around us contributing enormously to improvements in health, the environment and wealth creation through, for example, modern medical implants, cheap renewable energy from photovoltaics or major changes in telecommunications. Material science is undergoing a revolution, with new materials “designed for function” offering the potential to generate products and provide services that would be impossible with conventional materials.

However such materials, in particular higher performance nano-materials, bio-materials metamaterials and hybrid materials bring particular metrological challenges due to their very nature, scale and special properties and the combination of two or more functions in a single material. It is important to be able to quantify the complex interplay of the microscopic state and the resultant properties. Progress is dependent on our ability to validate and inter-relate our measurements in four areas:

Metrology priorities will include the development and application of traceable measurements and predictive modelling to structure, property and performance of materials throughout their lifecycle. There are major challenges in these measurements, such as the relationship between mapped, multiple property variations and micro-structural variations, including intercomparison of different mapping techniques. These activities will provide the appropriate tools and techniques to aid innovative developments and ensure full, effective and safe exploitation of new materials.

Technical Innovations: EUV, VUV and THz are logical extensions of the electromagnetic spectrum increasingly being exploited for scientific analysis, manufacturing, imaging and sensing. To underpin these innovative applications, the establishment of a unified radiometry from the EUV to the THz range is required. There will also be a need to extend all the radiometric measurement systems of CCPR (except of course photometry) into these spectral domains and consequential extension of the key comparisons into these regions.

- Radiometric techniques and standards into EUV, VUV and THz spectral regions
- Key comparisons to underpin these EUV, VUV and THz measurements

In the optical frequency range, various technical innovations require improved metrological capabilities. Due to the multi-dimensional character of the radiation quantities in many of the applications, a variety of parameters has to be measured simultaneously, e.g., wavelength spectrum, power level, angular and spatial distribution, coherence, polarization or quantum state. The final goal is to provide highest level realisations of the basic and derived radiometric units combined with a rapid, low-cost dissemination via the calibration chains.

5.4 Applied metrology

The fields that need to be addressed most urgently are

- ✓ Novel optical radiometric capabilities for industry and quality of life: a better knowledge of innovative complex light sources will require developments on 3D metrology for optical light sources such as LEDs, OLED-arrays and displays to be characterised and calibrated with low uncertainty. The research challenges are the development of measurement techniques for large-volume and pixellated light sources, near-field to far-field transitions, and the development of camera-based photometry and radiometry.
- ✓ Fibres for communication technologies, as high speed communication, quantum computing and processing rely on optical fibres and complex all-in fibre distribution systems. The development and use of such systems requires a complex characterisation in term of spectral, temporal and polarisation properties.

Physical measurements of visual perception for product quality and security purposes: Product quality requests a quantifying metrology on what was a subjective assessment of appearance. Manufacturers request a quantifying metrology in this new field for more cost-effectiveness, reliability and thus competitiveness. To replace visual perception for product quality, most of the physical measurement methods, standards, instrumentation, modelling and simulation have to be developed for appearance metrology including research projects in reflectometry, colorimetry, fluorescence microscopy, and fluorometry.

6. Rationale for various activities (2013-2023)

The CCPR and member NMIs are very active in working to meet the current and future metrology needs of its user community. In the short term, the existing portfolio of key comparisons is considered to be adequate to underpin these needs, but within the next two decades, extensions into different spectral regions will become necessary. For example, semiconductor industries require SI-traceable measurement of extreme UV radiation. The field of high energy radiation requires radiometric standards down to the X-ray range. Mid- and far-infrared radiometry has become more important in order to increase the accuracy of earth and climate observations. The THz-radiation has found commercial applications in remote sensing. To allow the extension of measurand range, various activities to validate the methods and the equivalence of each laboratory should follow.

It may also become necessary to consider alternate or a range of comparison artefacts to ensure that the full dynamic range of a quantity can be evaluated particularly as the needs of the few photon community start to become significant. As the properties of light in this extreme range are completely different from the classical ones, the SI-traceable measurement at the few photon level requires further research and development activities. The CCPR can provide technical guides or solutions to academia and industry for the measurement issues in the new field of few photon metrology. Alternative strategies of supplementary comparisons of key comparison quantities under specialist conditions may become allowable under the MRA.

For specialized services like photovoltaics, appearance, optical fibres, etc., inter-regional comparisons need to be encouraged and indeed CCPR has been quite successful in this approach. It is clear that the need for increasing the number of Key comparisons would have to be very strong and that even at the RMO level, careful consideration needs to be taken of the value and necessity of large numbers of comparisons for other than the major service categories of the CMCs.

Demands for cooperation with other international organizations will be stronger in the near future, as improved reliability of science and technology related to human vision and cognition are needed to support better product design and process control in the display and lighting industries. The newest displays for virtual reality will require metrology beyond the current measurement standards of photometry. The CCPR needs to link the experts of science with the experts of industry through joint activities with the relevant global organisations such as CIE and the Society for Information Display (SID) to promote the development of measurement standards which can meet the urgent practical demands.

In terms of units and definitions, there remains an on-going discussion within CCPR as to the choice of base unit with suggestions that the current candela might be better replaced with the lumen. The relative merits of this will not be discussed here. However, it is important to note that irrespective of the choice of base unit, it would have little impact on the nature and type of comparisons performed to support the MRA although the CCPR community would be impacted by the change in definitions and relationships of the traceability chain.

Several years ago, the BIPM closed its radiometric and photometric laboratories so it would take considerable effort and resources to have it become a viable active contributor to the sectors served by CCPR NMI members and/or provide a means to run any key comparisons. The BIPM should continue to serve as a coordinating entity for these comparisons and, where appropriate, can become a representative voice of the NMI community through use of expertise loaned, seconded or acting on its behalf from an NMI with relevant expertise.

7. Required Key comparisons and pilot studies 2013-2023 with indicative repeat frequency

There are currently ten key comparisons held within the CCPR. These are in the main conducted at a high level and cover the areas of radiometry and photometry of sources and detectors and spectrophotometry of materials. The CCPR has agreed upon a ten year cycle for the 2nd round key comparison process starting in 2012. The current schedule and status of these comparisons are given in Table 7.1 At this time, only one of these comparisons (K6-2010) has officially started after completion of the following tasks: 1) formation of a task group and appointment of a pilot lab; 2) call for participants; and 3) preparation of technical protocol.

Table 7.1 CCPR Key comparisons and their status (2013-2023).

Start	ID	Quantity	Pilot	Status
2012	K6 -2010	Regular spectral transmittance	MSL	Registered. Filters being stabilized.
2012	K3	Luminous intensity	NRC	Protocol being developed
2012	K4	Luminous flux	NMIJ	Protocol being developed
2013	K2.b	Spectral responsivity 300 nm to 1000 nm	KRISS	Call for participants complete.
2013	K2.a	Spectral responsivity 900 nm to 1600 nm	NPL	Call for participants complete.
2014	K1.a	Spectral irradiance 250 nm to 2500 nm	KRISS	Call for participants to be prepared in 2012
2015	K5	Diffuse spectral reflectance	MIKES	
2016	K1.b	Spectral irradiance 200 nm to 350 nm	NIST	
2017	K2.c	Spectral responsivity 200 nm to 400 nm	PTB	
2019	K2.d	Spectral responsivity 10 nm to 200 nm	PTB	

Consideration as to the need for key comparison in extended wavelengths and for other materials would depend upon the closeness in the relationship for the measurement methodologies and artifacts for these measurement capabilities.

Pilot studies currently being undertaken or investigated within the CCPR include:

- Fibre optic properties, specifically OTDR length
- THz radiometry
- Regular spectral transmittance in the UV.

8. Resource implications for laboratories for piloting comparisons

The CCPR key comparison quantities and spectral ranges in the 2nd round (2013-2023) are nearly identical to those carried out in the 1st round. Thus, the main resource implications for laboratories for piloting comparisons are: development of the technical protocol with the dedicated Task Group, carrying out modifications of the experimental set-up, if necessary, to accommodate artifacts that are different from routine calibration services; re-doing uncertainty budgets with special consideration of establishing the stability of the Pilot lab scale in measuring the transfer artifacts over the time period of the comparison; carrying out the actual measurements; and preparation of the various comparison reports and communication with participants, WG-KC and the RMO P&R TC chairs.

The time required for development of improved measurement facilities is not included in these estimates because the key comparisons are intended to be a test of the status quo situation that would be available to clients of these measurements. As previously discussed, the time required for the measurements by the pilot lab has been reduced by the fact that the number of participants has been limited to 12. The time required for the analysis of the comparison data and the preparation of the reports at the Pre-draft A, Draft A and Draft B stages, is also expected to be considerably reduced compared to the first round by the fact that CCPR WG-KC has prepared several informative guideline documents including worked examples. The CCPR Guidelines that have been published and that are being developed are:

- CCPR-G1 Guidelines for membership of WG-KC (Oct. 2005)
- CCPR-G2 Guidelines for CCPR KC Report Preparation Rev 3 (Rev.2 Sep. 2009)
- CCPR-G3 Guidelines for acceptance of CCPR KC participants (Sep. 2009)
- CCPR-G4 Guidelines for preparing CCPR KCs (Draft 2.0)
- CCPR-G5 Guidelines for CCPR and RMO bilateral KCs (Draft 3.1)
- CCPR-G6 Guidelines for RMO PR KCs (Draft 2.2)
- CCPR-G7 Guidelines for Supplementary Comparisons (Draft 1.1)

For details of the estimated resources (PMs) for the NMIs piloting these key comparisons, see attached Excel spreadsheet

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

See attached Excel spreadsheet

10. Document Revision Schedule