## CCPR Strategy Document for Rolling Development Programme

### Date drafted: December 2017

### Period covered: 2017-2027

The original CCPR Strategy Document published on 1 March 2013, described the status of the work of the Consultative Committee of Photometry (CCPR), with focus on the activities of the CCPR Strategic Planning Working Group (CCPR WG-SP). This updated version, also prepared by the CCPR WG-SP, generally covers the relevant activities of all three of the CCPR Working Groups for the period 2017 to 2027.

### 1 General Information on CCPR

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

Date Established: 1933 as Consultative Committee for Photometry, 1971 as CCPR

Number of Members: 23 members, 3 official observers and 2 liaisons

Number of working groups: 3

Number of Participants at last meeting: 49

Periodicity between Meetings: usually 2 years for the CC, 1 year for its 3 working groups.

Date of last meeting: 22-23 September 2016

CC President: Maria Luisa Rastello, INRIM, since 1$^{st}$ January 2017

Number of KCs organized (for 1999 up to and including 2016): 10 Key Comparisons of high level have been selected and regularly organized at the level of the consultative committee, with a repeat cycle of 10 years. Adding follow-up and supplementary comparisons, a total of 26 comparisons have been organized.

Number of Pilot studies organized (from 1999 up to and including 2016): 5

Number of CMCs published in KCDB supported by CC body activities (up to and including 2016): 1291

### 2 Terms of Reference

The CCPR has the following responsibilities:

- To provide advice to CIPM on all matters concerned with photometry and radiometry;
- To establish global compatibility of related photometric and radiometric measurements through promoting traceability to the SI photometric unit, the candela, and associated derived units for photometric and radiometric quantities;

- To contribute to the establishment of a globally recognized system of national measurement standards for photometry and radiometry and development of absolute radiometry methods and facilities;

- To contribute to the implementation and maintenance of the CIPM MRA in the field of photometry and radiometry;

- To review and advise the CIPM on the uncertainties of the photometry and radiometry calibration and measurement capabilities as published on the BIPM website;

- To act as a forum for the exchange of information about the photometry and radiometry activities of the CCPR members and observers;

- To create opportunities for collaboration in the field of photometry and radiometry

In particular, the CCPR coordinates international Key Comparisons performed to benchmark claimed competencies of the National Metrology Institutes (NMIs) and Designated Institutes (DIs) for standards that are needed to underpin photometry, optical properties of detectors and sources, optical properties of materials and fiber optics. The following photometric, radiometric and spectrophotometric quantities have been identified as key measurands for this purpose: spectral irradiance, spectral responsivity, luminous intensity, luminous flux, spectral diffuse transmittance and spectral regular reflectance.

The CCPR allows Regional Metrology Organizations (RMOs) to coordinate subsequent key comparisons for NMIs or DIs in their regions to link to these CCPR key comparison reference values and also to coordinate regional comparisons of measurement standards for additional quantities related to photometry and radiometry. These have included absolute radiometers, spectral radiance, spectral radiant flux, colorimetric quantities and optical fibre quantities such as attenuation, power meters, etc.

The CCPR also acts as a forum for the exchange of information about the activities of its members and observers, to provide SI traceable measurement results with reduced uncertainties for developing or emerging activities such terahertz and single photon radiometry.

In order to carry out its responsibilities, the CCPR has currently three established Working Groups (WGs) with the following terms of references:

### 2.1 CCPR Working Group on Strategic Planning (WG-SP) (established in 2005)

- establish and maintain a strategic planning document for the CCPR in line with the CIPM guidance document for CCs;
- advise the CCPR on the optimal operational structure;
- draft and maintain admission criteria for membership of the CCPR and its working groups;
- monitor and respond to developments with respect to the future of the SI;
- regularly review and update, as needed, the *mise en pratique* for the candela.

### 2.2 CCPR Working Group on Key Comparisons (WG-KC) (established in 1997)

- establish and maintain a list of key and other comparisons in the field of photometry and radiometry, which will adequately support CMC claims by NMIs in this field of measurement in the spirit of the global MRA between NMIs;

- coordinate and schedule key comparisons, to review progress in comparisons and to recommend to the CCPR the inclusion of the results of key comparisons in Appendix B of the MRA database;
- provide supplementary guidelines and/or interpretations to the guidelines on conducting key comparisons included in the MRA, specifically for the field of photometry and radiometry;
- recommend general principles for the calculation of key comparison reference values in photometry and radiometry;
- provide advice to the WG-CMC on the range of CMCs supported by particular key comparisons;
- monitor and approve RMO key comparisons and provide advice on RMO supplementary comparison activities.

**2.3 CCPR Working Group on CMCs (WG-CMC) (established in 2003)**

- coordinate and approve the definition of service categories requested by RMOs and to maintain lists of service categories, and – where necessary – rules for the preparation of CMC entries;
- agree on detailed technical review criteria;
- coordinate and, if necessary, conduct inter-regional reviews of CMCs submitted by RMOs for posting in Appendix C of the MRA;
- provide guidance on the range of CMCs supported by particular key and supplementary comparisons;
- suggest to the WG-KC areas where additional key and supplementary comparisons may be needed;
- coordinate the review of existing CMCs in the context of new results of key and supplementary comparisons.

Within the organisational structure of these Working Groups, there are several Task Groups (TGs) that are not considered permanent but respond to a specific task or pressing issue. The current list of task groups within each of these working groups can also be found at the BIPM web-site. Information is also provided at this site on the terms of reference of these TGs and their membership.

Within WG-SP, there are currently 9 active Task Groups including one joint Task Group. Four of the WG-SP Task Groups: TG1 (Terms of Reference), TG2 (Membership Criteria), TG3 (CCPR Structure) and TG5 (*Mise en pratique*) have completed their stated aims and prepared reports that were approved by CCPR; these were dissolved in 2010, 2012, 2010 and 2015, respectively. Information about the current membership of WG-SP and the membership and terms of reference of its currently active task groups can be found on the BIPM web-site at: http://www.bipm.org/en/committees/cc/wg/ccpr-wg-sp.html.

Within WG-KC, there are currently 4 active Task Groups. One of the WG-KC Task Groups: TG2 (RMO linkage ) recently completed its stated aims of preparing input to one of the WG-KC Guidance documents (G6) and is expected to be dissolved at the next CCPR meeting. Information about the current membership of WG-KC and the membership and terms of reference of its currently active task groups can be found on the BIPM website at: http://www.bipm.org/en/committees/cc/wg/ccpr-wg-kc.html.

Within WG-CMC, there are currently 3 active Task Groups. Information about the current membership of WG-CMC and the membership and terms of reference of its currently active task groups can be found on the BIPM web-site at: (http://www.bipm.org/en/committees/cc/wg/ccpr-wg-cmc.html.

Within CCPR, the concept of Discussion Forum was introduced several years ago 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, pilot studies, or new pilot or key comparisons to provide SI traceability and to underpin associated CMCs. These Discussion Forum type TGs have an expanded membership that includes not only CCPR members but also non-CCPR experts from other CCs, industry, academia and other organizations, to carry out focused scientific and technical discussions and to address specific issues. Presently, there are 4 Discussion Forum type TGs within WG-SP: TG 6 (Fibre Optics), TG7 (Few Photon Metrology), TG8 (THz Metrology) and TG12 (Use of White LED Sources for Photometry) and one within WG-KC: TG3 (Comparison Analysis).

## 3 Baseline Status

### 3.1 Definition and realization of units and related quantities

On May 20th, 2019, "World Metrology Day", the new SI will be inaugurated (see https://www.bipm.org/utils/common/pdf/SI-statement.pdf). Four of the seven base units of the SI system will be redefined: the kilogram, the ampere, the kelvin and the mole. The other three base units will be reformulated, the meter, the second and the candela. Each of these units will then be based on a fixed numerical value of a defining constant, see the 9th edition of the SI brochure (draft version of 9th edition of the SI brochure, 5 February 2018, available at https://www.bipm.org/utils/en/pdf/si-revised-brochure/Draft-SI-Brochure-2018.pdf). As a direct response to this planned revision of the SI system (see, e.g., https://www.bipm.org/en/measurement-units/rev-si/) the CCPR prepared a position paper on a possible reformulation of the candela that was published in Metrologia in 2010(http://iopscience.iop.org/article/10.1088/0026-1394/47/5/R01/meta;jsessionid=3FD460765BAF8A1821F7193F99602708.c1.iopscience.cld.iop.org). This article is also listed in the Metrologia Highlights of 2010. The CCPR WG-SP also 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.

In February 2012, the CCPR WG-SP Task Group TG5 held a workshop on the *mise en pratique* of the candela and invited representatives from the International Commission on Illumination (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. It was decided that the candela would not be redefined, but it was 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 (WGSP TG-5) and that the important companion document, the BIPM monographie on *Principles Governing Photometry* (1983) would be updated by members of WG-SP with experts from CIE in a joint CCPR-CIE Task Group on *Principles Governing Photometry* (CIPM/CIE JTC-2). The terms of reference of this joint TC 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 as well as for mesopic vision which was only recently defined by the CIE (CIE 191:2010 Recommended system for Mesopic Photometry Based on Visual Performance). This updated document will not only replace the existing BIPM Monographie (at http://www.bipm.org/utils/en/pdf/Monographie1983-1.pdf), it will serve as an update of the essentially identical CIE technical report, *CIE Publication 18.2: 1983: The Basics of Physical Photometry.*

The CCPR recently completed the updated *mise en pratique* for the definition of the candela to include an extension to associated derived units for photometric and radiometric quantities in the International System of Units (SI). It is notable that this extension also included practical realization of photon-number based units. This document was prepared by members of the WG-SP Task Group TG5 and published and available on-line in July 2015 (at: http://metrologia.bipm.org/guides-stds-conventions/2016/G1.pdf) and in *Metrologia* (Vol. 53, 2016, G1 at: http://iopscience.iop.org/article/10.1088/0026-1394/53/3/G1/meta). This paper was one of *Metrologia's* highlights for 2016.

The *Metrologia* (2010) paper prepared by members of CCPR, introduced for the first time a technical constant for photometry, $K_{cd}$, which was adopted by the CCU for the explicit-constant definition of the candela. Although no consensus was achieved at that time regarding the importance of a photon-number based definition for the candela, the members of WG-SP Task Group TG4 continue to monitor developments in the photon-based technologies and respond, as needed, to find consensus within CCPR.

The CCPR also prepared responses to CCU regarding the *Impact of Changes in the SI Units on Radiometry and Photometry* for the Consultative Committee of Units (CCU) meeting in June 2007 and on its position regarding the proposed rewording of the candela definition in explicit constant form and the subsequent text in explicit unit form (CCU/104.7.CCPR and annex to report of CCPR meeting 2012[1]).

The CCPR also provided input to 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*.

### 3.1.1 Coordination with other International Bodies

The special relationship between the CCPR and CIE, where the CIPM (CCPR) 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, was formally recognized in April 2007 with the establishment of a Memorandum of Understanding (MOU) between CIPM (CCPR) and CIE. The CIE is a liaison of CCPR.

In recognition of the cooperation between the World Meteorological Organization (WMO), the International Bureau of Weights and Measures (BIPM) and the CCPR, relating to the metrological needs of the WMO; in particular the need for space-based radiometric measurements to be traceable to SI units, the WMO is a liaison of CCPR (https://www.bipm.org/en/worldwide-metrology/liaisons/wmo.html ).

### 3.2 Key Comparisons and CMCs

There are currently ten key comparisons for the six key measurands (spectral irradiance, spectral responsivity, luminous intensity, luminous flux, spectral diffuse transmittance and spectral regular reflectance) held within the CCPR, considered to be adequate for underpinning the core photometry and radiometry measurement capabilities and associated CMCs. 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. An overview with the key comparisons is provided in section 7.

### 3.2.1 Linking and Supplementary Comparisons

Each of the ten CCPR key comparisons may be followed by a subsequent bilateral key comparison at the CC level and by linked key comparisons organized in each RMO. As a result, since 1999, there have been a total of 34 CCPR and RMO key comparisons that have been approved for equivalence, and an additional 3 comparisons are at the Draft B stage. The results of these comparisons support a total of 1291 CMCs (up to 2016) in the fields of photometry, properties of sources and detectors, properties of materials and fibre-optics.

In the same period, 17 supplementary comparisons were conducted and published, mainly within RMOs. Only three CCPR supplementary comparisons were carried out in the early 2000s. After their completion 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 additional

[1] Under publication

CCPR key comparisons since these quantities were largely realized using the same reference instruments as the existing ten KCs. Thus, participation in the closely linked KC was sufficient to underpin CMCs for these quantities. If it was desired to link directly to one of the three CCPR supplementary comparisons, these would be conducted as RMO supplementary comparisons.

#### 3.2.2 Coordination within CCPR Working Groups

The need for CCPR or RMO comparisons to support SI traceability in emerging areas, such as THz radiometry and few photon radiometry, has been addressed by coordination of activities within WG-SP and WG-KC. For example, a pilot study on THz radiometry, specifically a THz laser power measurement comparison among three NMIs was identified as a priority in WG-SP TG8 (Discussion forum on THz metrology) and carried out in WG-KC as pilot comparison, P3. This work has been completed and published in 2016 (*IEEE Transactions on Terahertz Science and Technology*, Vol. 6, No. 5, September 2016). More recently, the WG-SP TG11 (Single photon radiometry) identified a comparison of detection efficiency of single photon detectors as a priority and this activity is being carried out within WG-KC as pilot comparison, P5.

#### 3.2.3 Repeat frequency

The appropriate repeat frequency of these key comparisons was discussed within the full CCPR by surveying the members and observers. There was considerable variation in the responses of different members, ranging 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 2$^{nd}$ 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 2$^{nd}$ 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.

There was also considerable discussion within CCPR on the quantities and spectral ranges to be included in the 2$^{nd}$ 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 1$^{st}$ round of KCs were strongly correlated and that only one comparison called "luminous intensity", based on lamps as artifacts should be carried out.

### 3.3 Organizing the workload of CCPR members together with RMOs

#### 3.3.1 Reducing the workload of CCPR members

With regard to the scheduling of the 2$^{nd}$ round of CCPR key comparisons, including determination of repeat frequency, the general view of many NMIs during the course of the first round 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. It was generally considered that such a large number of participants made it very difficult to run these comparisons in an efficient manner and that coordination was needed between the CCPR KCs and the RMO KCs to make this process more efficient while respecting the spirit of the CIPM MRA. 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 on how to reduce the CCPR workload, leading to the following general recommendations:

- 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 NMIs' plans for participating in the next round KCs, 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 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 specific 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+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.

#### 3.3.2 Coordination of Workload with the RMOs:

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). This practice has proven to work well.

The RMOs not only coordinate their work with CCPR but also with the other RMOs. This was originally carried out in order to reduce the number of bilateral RMO comparisons for KC quantities. However, depending upon the general interest of the measurement quantity and capacity of the pilot lab for an RMO comparison, participants from other RMOs are invited to participate in RMO supplementary comparisons (that are not carried out at CCPR level) and with linking comparisons where this is beneficial. This procedure was used very effectively for the RMO comparisons of LED measurement quantities, piloted by APMP that had participants from all interested RMOs. Currently, several spectrophotometric quantities, such as BRDF, transmittance haze and grey scale diffuse reflectance are the subject of cross-RMO comparisons. To facilitate the organization of such cross-RMO comparisons, the RMO TC-PR Chairs submit information on their planned comparisons on the BIPM website in a shared folder.

### 3.4 Guidance documents on comparisons

The CCPR has produced a number of guidelines to advice its members on the preparation and the coordination of comparisons, and on treating and reporting their results (date of publication in parentheses):

- CCPR-G1 Guidelines for membership of WG-KC (2009)
- CCPR-G2 Guidelines for CCPR KC Report Preparation Rev 3* (2013)
- CCPR-G4 Guidelines for preparing CCPR KCs (2013)
- CCPR-G5 Guidelines for CCPR and RMO bilateral KCs (2014)
- CCPR-G6 Guidelines for RMO KCs in PR (2014)
- CCPR-G7 Guidelines for RMO PR Supplementary Comparisons (Draft 2.4, June 2017)
- CCPR-G8 Guidelines for the evaluation of CMC claims in light of comparison results

Note there is currently no CCPR-G3 document. This document on the Terms of Reference of WG-KC was superseded by an updated CCPR-G1 document which includes this information. The CCPR Working Groups have also produced guidance documents to assist in carrying out their respective Terms of Reference, such as WG-CMC's responsibilities to define service categories and supporting evidence for CMCs in PR.
These include:

- Classification of Services in PR
- Supporting Evidence for CMCs in PR
- Code of procedure for CCPR Working Groups and Task Groups, CCPR-CODE
- CCPR-WG-SP Membership Criteria, 2012

The current list of approved CCPR Guidance documents can be found on the BIPM web-site at: http://www.bipm.org/en/committees/cc/ccpr/publications-cc.html#gd.

### 3.5 Workshops

In order to effectively carry out the key objectives of the CCPR Task Groups, several TG Chairs have organized Workshops in conjunction with the annual CCPR Working Group meetings or Conference Sessions at relevant specialized scientific conferences. The following is a listing of these activities over the past 8 years, the number of participants and the main outcome(s):

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

2010 – WG-SP 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.

2010 – WG-KC TG3: *Workshop on Comparison Analysis*. Number of participants: 16. *Outcome*: better understanding of dealing with issues in comparison analysis, notably regarding inconsistencies and outliers and the use of least squares analysis (rigorous) versus recipe (pragmatic) approach.

2011 – WG-SP 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 – WG-SP 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).

2013 – WG-SP TG4: *Workshop on SI units for Photometry and Radiometry*. Number of participants: 27. *Outcomes:* Recommendations from CCPR to 21st meeting of CCU (June 2013) to keep the candela as the SI base unit for photometry, to revise the text of the proposed definition of the candela in the 9th SI brochure, and that the possible reformulation of the definition of the candela in terms of photon intensity is a topic of lively debate within CCPR that is still on-going (CCU/13-06.2).

2015 – WG-KC TG3: *Workshop on Comparison Analysis*. Number of participants: 25. *Outcomes: This information will be used by WG-KC to write a guidance document on which model should be the default for analyzing KC data.*

2016 –WG-SP TG6: *Workshop on Metrology Needs in Fibre Optics*. Number of participants: 40. *Outcomes:* creation of a new TG (TG13) to organize and carry out a pilot comparison on optical fibre power responsivity using a fibre-coupled cryogenic radiometer; establishment of liaison with IEC 86 Fibre Optics and change in Terms of Reference of TG6 to include: Monitor standards developments in IEC 86 Fibre Optics. More information is publicly available on the BIPM web-site at: http://www.bipm.org/wg/AllowedDocuments.jsp?wg=CCPR-WG-SP.

2017 – WG-KC TG2: *Workshop on Models for Comparison Analysis*. Number of participants: 33. *Outcomes:* The discussion of the four models proposed by TG2 at the Workshop will be continued and the TG2 Chair will share the software for doing these calculations with pilot labs interested in resolving the outstanding issues about the choice of model. This information will be used by WG-KC to write a guidance document on which model should be the default method used for analyzing KC data.

Other mechanisms that have been used by the CCPR Discussion Forum task groups to advance its aims have been the use of surveys and questionnaires.

**3.6 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 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 is bringing enormous energy savings, as the percentage of world-wide use of electricity by lighting has dropped from a peak of about 20 % as tungsten-based lighting is phased out in all countries. LEDs have already exceeded the energy efficiency of the best fluorescent lamps.
    - 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.

- In collaboration with the CIE, the use of SI units was recommended in a CIE technical note (TN 003:2015) that describes how to measure light with respect to non-visual effects. This TN 003 provides a freely downloadable electronic document, together with an SI-compliant version of a toolbox (downloadable at http://files.cie.co.at/784_TN003_Toolbox.xls), which is intended to support researchers in expressing their measurements as SI quantities and in SI units.

- The need for SI traceable measurements for photobiological quantities.
    - Held a BIPM Workshop on "Physiological Quantities and SI Units (November 2009)", chaired by the BIPM Deputy Director, Prof. M. Kühne.
    - A new Appendix was prepared by members of CCPR and added to the 8th edition of the SI brochure (Appendix 3) on the treatment of photobiological quantities.
    - One of the recommendations from this Workshop was for CCPR and CCEM to consider the emerging need for traceable THz metrology. As a consequence, WG-SP formed a new Task Group on Discussion Forum for THz metrology (TG8) and established a formal liaison with CCEM to discuss outstanding issues and need for SI traceability in this field.
    - A pilot comparison on THz spectral responsivity was carried out within WG-SP(2014-2015)
    - Recently, members of WG-SP, in collaboration with selected CIE experts, prepared an updated version of Appendix 3 on *Units for Photochemical and Photobiological Quantities* for the on-line version of the 9th SI brochure.

- The need for photon-based quantum standards for optical radiation
    - Establishment of WG-SP Task groups (TG7): Discussion forum on few photon metrology and (TG11): Single photon

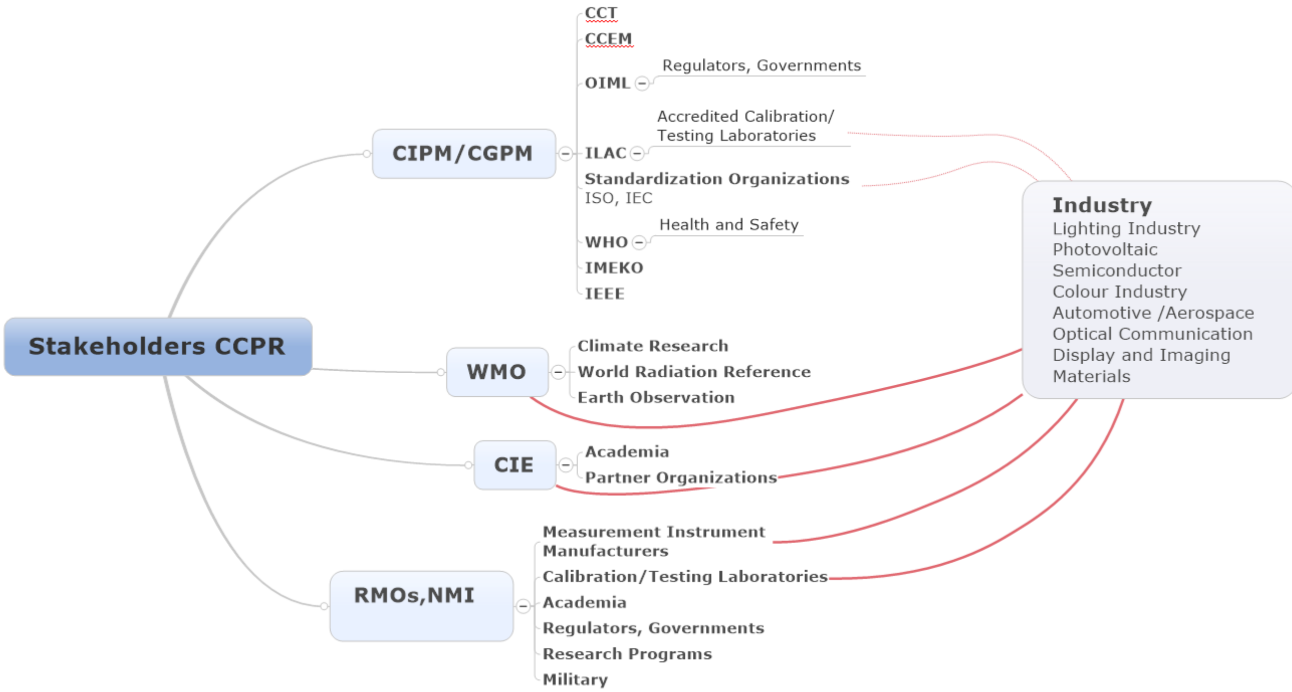
radiometry. Decision on carrying out a pilot study on the detection efficiency of single-photon detectors.

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

The stakeholders of CCPR are outlined in the graphic below. Direct stakeholders are NMIs, RMOs, international organisations with CCPR liaison 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, displays, imaging and rendering, photonics, solid-state lighting, bio-medical, quantum based information and quantum photonics, Tera-hertz, environment and climate, space, and photovoltaics.

The metrological issue for CCPR is not necessarily providing a primary scale for each of these emerging measurement needs, but how to provide the most convenient means of giving adequate traceability to the SI system. In addition, CCPR is invited to contribute to research activities outlined by different organizations. As an example, the European Metrology Programme for Innovation and Research offers collaboration to NMIs outside the EURAMET region. The need for coordinated research is also expressed in the new research strategy published by CIE (http://www.cie.co.at/index.php/Research+Strategy). CIE has identified 10 research topics requiring immediate attention by the research community in support of developments in lighting technology and application. Many of these topics are related to CCPR aims in promoting global compatibility of these associated photometric and radiometric measurements through traceability to the SI. For example, topic 4 "New Calibration Sources and Illuminants for Photometry, Colorimetry, and Radiometry" has a direct relation to CCPR WG SP TG12 (Use of White LED Sources for Photometry). Topic 9 deals with the metrology for advanced photometric and radiometric devices. There is an immediate need to define quality criteria and calibration procedures for devices such as near-field goniophotometers and array spectroradiometers, as such devices are becoming more widely used in practice. In addition guidelines are needed for the evaluation of uncertainty of optical measurements using these complex devices.

Industry is linked to CCPR 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, where 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.

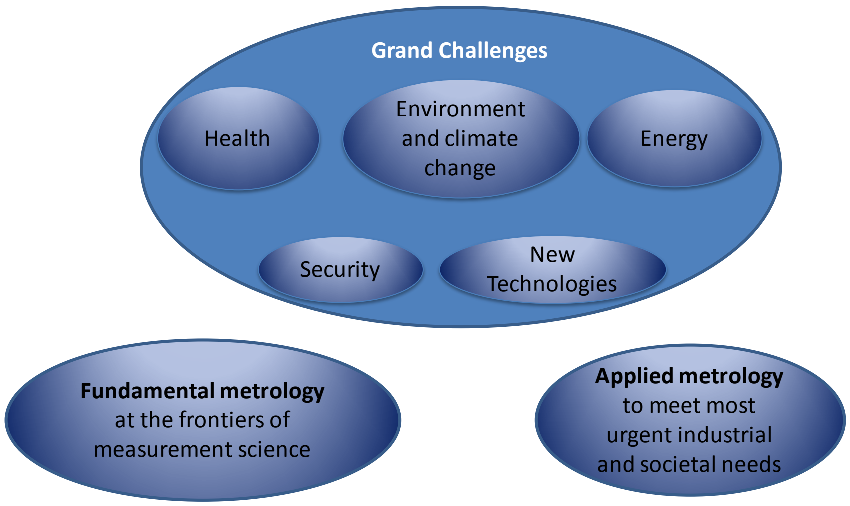

CCT
CCEM
Regulators, Governments
OIML
Accredited Calibration/
Testing Laboratories
CIPM/CGPM
ILAC
Standardization Organizations
ISO, IEC
Health and Safety
WHO
IMEKO
IEEE
Industry
Lighting Industry
Photovoltaic
Semiconductor
Colour Industry
Automotive /Aerospace
Optical Communication
Display and Imaging
Materials
Stakeholders CCPR
WMO
Climate Research
World Radiation Reference
Earth Observation
CIE
Academia
Partner Organizations
Measurement Instrument
Manufacturers
Calibration/Testing Laboratories
RMOs,NMI
Academia
Regulators, Governments
Research Programs
Military

## 5 Future Scan (2017-2027)

### 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 1980s and 1990s 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, remote sensing, etc. and as a complimentary or diagnostic tool/facilitator in many sectors including other metrology domains. For the most part, the requirements in these fields have not significantly pushed at the uncertainty levels needed in primary scales as compared to those already achieved. However, many specific fields and applications require tailored measurement techniques that should meet challenging requirements. They also continue to place significant demands on how to gain convenient and cost effective access to the required uncertainties for particular applications.

### 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 higher resolution and biocompatible standards and establishing calibration chains that integrate different measurement techniques and novel extremely high sensitivity detection including new optical quantum standards also affecting fundamental metrology.

### 5.2.1 Low-cost, high-accuracy transfer standards

The growing demand for lower-cost transfer standards that maintain high accuracy requires the development 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, such as the ratio of the Josephson constant, $K_J$ to $2e/h$, and thereby, support 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.

- Primary standards at the cost of standard detectors
- Improved performance of cryogenic radiometers and silicon-based standards to strengthen SI

### 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.

With the efforts of many NMIs and CCPR activities (e.g., the pilot study conducted by TG11 of WG-SP), the quantities for calibration of photon counting detectors are expected to be included in the CMC list around 2020. This will be the first practical step towards the extension of radiometric standards down to the few photon level, followed by improvement of accuracy and extension of the wavelength range for calibration of photon counting detectors. In addition, accurate techniques for measuring the photon number statistics of a source operating at the few photon level have been developed driven by the technical advance of photon number-resolving detectors. The metrology related to the single and multiple photon counting detectors will open a new field of photon-based “quantum” radiometry.

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. This is particularly important for some emerging applications, e.g. quantum optics, to consider the full quantum nature of electromagnetic radiation as a primary traceable route to the SI. For this reason, a section of the updated *mise-en-pratique* for the definition of the candela describes the practical realization of these photon-number-based units.

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 or quantum imaging) or opto-mechanical systems (e.g. micro-cavities or gravitational wave detectors), in the quantum regime, beyond the SQL.

- Measurement of optical radiation at very low light levels down to single photon level
- Improved accuracy and extension of wavelength range for few photon detection
- Quantum enhanced optical techniques to push the uncertainty limits

### 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 new single-photon 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, ideally with a self-consistency within $10^{-5}$. 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.

- Development and validation of highly efficient single-photon sources as new standard sources for radiometric application

### 5.2.4 New high power accurate or low uncertainty radiometers

Very high power lasers (>1 kW) are being developed to transform matter and because of this application, they cannot be easily measured with radiometers based on absorption of radiation without causing damage to the radiometer itself. New radiometric standards based on other principles, e.g. on photon force, are needed to measure lasers at these high power levels.

- Very high power laser measurement (>1 kW)

### 5.2.5 Solid-state lighting as primary source

The development of solid-state light (SSL) sources as an energy efficient successor of the incandescent source has completely changed the lighting market. However, primary reference sources for (ir)radiance and (il)luminance are still based on incandescent technology (e.g. FEL lamps). In the future the manufacturing of these sources may terminate and alternative primary reference sources need to be made available. The development, characterization and validation of stable SSL based primary sources is required to prepare for the replacement of the incandescent primary standards by SSL standards.

- Development, characterization and validation of primary light sources based on SSL to replace incandescent sources.

## 5.3 Grand 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 Energy: production and efficiency

**Photovoltaics,** are a key, and growing, optical technology for energy production and its metrological needs are relevant to the responsibilities of the CCPR. Driven by the desire to reduce dependency on fossil fuels to reduce carbon emissions, sustainability photovoltaics are the subject of worldwide research. Small gains in the relative cost to watt ratio can have major impact in terms of commercial exploitation and also in viability of deployment. 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. For example, organic solar cells can be produced in a variety of colours, transparencies and shapes, which requires the development of new performance metrics beyond those used for today's standard photovoltaic technologies. 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 an international effort to ensure consistency and traceability at the uncertainty levels required. Because of the wide range of photovoltaic designs and technologies new metrics, based on energy-rating, are needed to evaluate both their "initial" and "on-going" energy rating performance.

- Improved accuracy for photovoltaic efficiency measurements under "real conditions" and at production level spatial scales.
- Consistent international traceability for all types of photovoltaic cell
- New metrics for photovoltaics based on energy-rating

**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 practice, 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 partial move towards OLEDs and lighting panels will require further evolution and standardisation of techniques. The associated challenges for CCPR are the diminishing availability of incandescent light sources for use as primary standards, the selection and evaluation of alternative standard lamps including LED-based standard lamps and careful consideration of choice of artefact for future key photometric comparisons (e.g. as being investigated in the EMPIR PhotoLED project).

- Standardisation of specification of measurement conditions for new lighting types (SSL, OLEDs)
- Development of new and/or improved metrics to meet consumer needs
- Selection of alternative standard lamps for future key comparisons of photometric quantities

**Radiative energy transfer**, i.e. the transport of energy via electro-magnetic radiation is an important quantity for energy efficiency. The energy efficiency of buildings (zero-energy buildings) is strongly determined by radiative energy transfer through insulation materials, windows etc. Radiative energy transfer is also a key parameter for solar-thermal power plants.

Parameters that are relevant to radiative energy transfer like transmission, reflection and emissivity need to be measured over a wide wavelength range, from the visible to the thermal infrared. More accurate measurement of these quantities will enable technological development of materials, which is currently hampered by insufficient measurement capabilities to prove material performance.

- Transmission, reflection and emissivity measurements over a wide wavelength range (VIS to thermal infrared) and for potentially complex materials.
- Reference standards for comparative testing

### 5.3.2 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 for standardization which is needed by both manufacturers and users of this medical equipment to ensure reliable test results.

Quantitative instead of only qualitative diagnostics includes medical imaging, modern microscopy and traceable multimodal measurement procedures. Diagnostical and therapeutical instrumentation includes the use of photo-biosignals, and fluorescence optics. For these wide dynamic range and extreme-low-light applications, metrological R&D is needed for calibrating these novel image and fluorescence sensors.

**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 photobio-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 biotechnological measurement methods that are fit-for-purpose are vital to driving production efficiency, product safety and improved therapy and diagnostic tools.

- exploitation of photo¬bio-technology by industry

**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.

- Provide traceable measurements at single photon level for instrumentation and applications of single molecule biophysics and applied biophotonics.

**Agriculture and Fisheries:** Human health is intricately linked to nutrition. In order to meet the need to feed an increasing human population, whilst also reducing the impact of agriculture on the environment (See Section 5.3.3 below), agriculture and fisheries are increasingly relying on smart technologies. These smart technologies often use optical measurement methods, for example the use of spectrometers on satellites, aircraft and drones for monitoring crop health and supporting automated farming, with satellite observations critical for sustainable forestry, agriculture and fisheries applications.

- Develop optical measurement methods for monitoring crop health and supporting automated farming.

### 5.3.3 Environment and Climate

There is a growing consensus that we have entered the Anthropocene [http://quaternary.stratigraphy.org/workinggroups/anthropocene/ ]: the geological epoch in which the actions of human beings are the most significant force of change on the planet. As a society we are also at a crucial moment: we now have sufficient evidence to understand how we are approaching (or overshooting) the "planetary boundaries" [W. Steffen et. al., *Science*, **347** (6223): 1259855] while still having the time to make the necessary changes to bring our actions back within those boundaries. The key challenge is the need to ensure sustainable social and economic growth for all while minimising our negative environmental impact. The United Nations has defined 17 Sustainable Development Goals [https://sustainabledevelopment.un.org/] covering social, economic and environmental areas to describe the commitment of the governments of the World to meeting this challenge.

There are several areas for which photometry and radiometry can have a significant role in supporting the UN Sustainable Development Goals and these key environmental challenges. These include measurements to support the introduction of technologies for the sustainable generation and use of energy, for example photovoltaics, LED lighting and building energy efficiency material measurement (Section 5.3.1). They also include measurements to support smart agriculture (Section 5.3.2).

**Monitoring the Earth's environment**

One of the most significant ways that radiometry can support this societal challenge is through monitoring the changing environment. The changes in the climate are due to subtle changes in the radiation balance of the Earth (incoming 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. Due to the complexity of the Earth system, and non-linear feedbacks, temperature measurements alone are not a reliable predictor of impact. Environmental monitoring therefore 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) [https://public.wmo.int/en/programmes/global-climate-observing-system], and more than 2/3 of the ~50 involve some form of optical radiation measurement: emitted, direct, absorbed or reflected.

To provide global observations, , such environmental monitoring requires satellite observations, with *in situ* observations of biogeophysical quantities providing both complementary local information and validation reference sets for the satellite observations. Many satellite sensors making measurements for the ECVs measure, as a basic measurand, spectral or band-integrated radiance of Earth-emitted (thermal infrared, passive microwave) and solar-reflected (visible, shortwave infrared) radiation. For practical purposes many visible/shortwave infrared sensors also provide measurements of reflectance.

In order to detect small long-term environmental changes, data sets spanning many decades, and therefore multiple satellites, are needed. Combining data from different satellites requires a robust and stable measurement infrastructure and metrological traceability of satellite Earth observations to SI through improved pre-flight calibration, in-orbit references and in-field ground measurements of radiance and reflectance.

The metrological challenge in this sector is to achieve uncertainties in radiance and reflectance measurements that are close to those of laboratory standards, in the field and from orbit, while understanding the specific challenges of Earth observation from the ever-changing atmosphere (e.g. repeat measurements are impossible). Other challenges involve providing reference standards that can operate in environmentally-challenging conditions (pre-flight in clean rooms and vacuum, in the field in deserts, ice-sheets, oceans and for the measurement of vegetation in forests) and for instruments with field of views that are typically much larger than those of other applications. The uncertainties required by this theme are probably the most demanding for CCPR and also require highly-specialized expertise of the specific requirements of the satellite community.

Thus, the key challenges in this sector are:

- Development of techniques which can make SI-traceable standards and instruments that can be used for remote monitoring on-board satellites/airborne

- Development of transfer standards to be used in satellite pre-flight calibration (large area, clean rooms, vacuum systems) and in-field instrument calibration (deserts, ice sheets, oceans, forests) for radiance and reflectance

- Provision of “fiducial reference measurements” to the Earth observation community: SI-traceable reference standards for biogeophysical parameters such as ocean and land surface temperature (thermal infrared), reflectance and radiance of deserts, ice and of vegetation, radiance measurements at ocean sites and for transmittance/scattering/emission of atmosphere and its constituent molecules.

**Monitoring change in radiation balance**

Change in the Earth’s temperature and consequential impact on climate is due to change in the balance of Energy entering the Earth system and that leaving, which should be monitored on both sides of the balance (Earth emission and Solar irradiance). The Sun is the key driver of the Earth climate, providing the principle source of energy to the system. There is thus a need to measure the total (spectrally-integrated) solar irradiance incident upon and reaching the surface of the Earth and to monitor any change in this on climatological timescales (multidecadal). There is clear historical evidence that relatively small changes in total solar irradiance (<<1 %), after correcting for the 11 year cycle, have significant impact on the climate.

Measurements of total solar irradiance are currently traceable to the World Radiometric Reference (WRR) of the WMO maintained at the WRC in Davos, Switzerland. This scale is not only the environmental reference but also has a role in underpinning photovoltaic efficiency measurements. Efforts to ensure the long term stability of this reference and ensure and improve its accuracy to SI remains one of the key priorities for the CIPM/WMO MOU and has led to significant effort from the NMI community including the development of the Cryogenic Solar Absolute Radiometer as a candidate to replace or complement the radiometers currently defining the WRR.

Similarly, measurements of the absolute value and variance of spectral content of solar irradiance, particularly, but not exclusively, in the UV is of importance to attribute how this variation, even on short timescales, interacts with the atmosphere affecting its chemistry e.g., water vapour and ozone. There is still significant debate between the modelling community about such processes, and the robustness of the measurement data from both ground and space observations and about how this might impact short term climate events such as El-Niño.

On the other side of the balance, Earth-emitted radiance also needs significant effort and in addition to measurements of the Earth's surface temperature the WMO are keen for the NMI community to provide support to improving the traceability of the global radiation networks particular infrared radiation emitted from the sky. In a similar manner to the WRR traceability is currently to the mean of a group of instruments, World Infrared Standard Group (WISG) maintained by the WRC in Davos. This artefact based scale has a weak link to SI which needs to be strengthened and sustainable for the long term.

The key challenges are:

- Development of high accuracy transfer standards and spectrometers to reliably measure spectral solar irradiance (terrestrially, in field locations, and in space)

- Improved instruments, standards and methods to enable WMO networks, particularly in the IR domain, to make SI traceable measurements of sufficient accuracy in a variety of environmental conditions

- Establishment of high accuracy (NMI primary uncertainty level) SI-traceable total solar irradiance measurements in space and terrestrially through upgrading of the WRR

#### 5.3.4 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, besides security applications, are medical imaging, biological screening, e.g. of toxins in the atmosphere, and biological and pharmaceutical spectrometry of solids and liquids. In response to growing demand from industry for traceable radiometry in the THz range, there has been an increase in metrological R&D activities at some NMIs to establish new measurement systems, methods and novel THz detectors. Within the CCPR, there has also been a recent pilot comparison of THz laser power measurements undertaken by three NMIs (https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7530930).

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 Privacy Enhancing Technologies (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.

- Radiometric traceability for THz sources and detectors for security
- Entangled photon sources for quantum cryptography

- Measurements at single photon level for Quantum Key distribution

#### 5.3.5 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 nanodetectors**.

**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 these measurements.

Metrology priorities will include **the development and application of traceable optical measurements and predictive modelling to characterise the structure, properties and performance of materials** throughout their lifecycle. Key measurands that are used to predict performance of these materials, e.g. for electrotechnical and environmental applications, are their optical properties. 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.

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

### 5.4 Applied metrology

#### 5.4.1 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, key conditions of observation and illumination and descriptive metrics to measure the reflective and transmissive 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 production cycle independent of the human observer and rendered images for e-commerce and virtual reality. In this context, products range from food stuffs, textiles, manufactured items like cars, cosmetics, 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 and realization of metrological scales for appearance properties (as with colour)
- Characterisation of radiometric properties of imaging systems
- Standardisation of measurement conditions such as irradiation and observation beam parameters.
- Establishment of minimal sets of measurement geometries for a complete description of samples.
- Standardisation of data representation and data file structure for a common exchange of information.
- Measurement systems and methods for new quantities such as bidirectional sub-surface reflectance distribution function to characterise translucency.

**Photonic/optical based sensors** are being developed for a wide range of applications particularly in process control/monitoring situations and for health applications. 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
- Measurement of optical power and spectral distributions within optical integrated devices

**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. Furthermore, 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.

- "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 measurements of the spectral reflectance of multilayer mirrors used in the EUV are also urgently needed.

**Novel optical radiometric capabilities for industry and quality of life**: a better knowledge of innovative complex light sources will require developments on 3D metrology using imaging measurement devices, such as camera-based luminance and radiance measurement devices, for pixelled optical light sources such as LEDs, OLED-arrays and displays to be characterised and calibrated with low uncertainty.

- Development of measurement techniques for large-volume and pixelated light sources, near-field to far-field transitions, and the development of traceable camera-based photometry and radiometry.

### 5.4 Overview of future scan on requirements and measurement challenges for CCPR

| | THEMES | Grand Challenges | | | | Fundamental | Applied Metrology | |
|---|---|---|---|---|---|---|---|---|
| **Radiometry/ Photometry FIELD** | **Energy** | **Climate and Environment** | **Security** | **Health** | **New Technologies** | **Basic SI and fundamental science** | **Industry** | **Communication technology** |
| **Radiometric responsivity scale** | | Sensing and Earth obser-vation | THz sources and detectors | | Radio-metric standards for EUV, VUV and THz | | EUV litho-graphy | |
| **Few/single photon metrology** | | | Quantum crypto-graphy, Quantum Key Distri-bution | Photo-bio-technol.<br><br>Single molecule bio-photonics | | Single photon source as standard<br><br>Quantum enhanced measurements<br><br>Astronomy | Nano/<br><br>mems photonic devices | |
| **New/ improved primary detector standards** | | (close to) primary level sensors for SI trace-ability in space | | | | Fundamental constants | In line measure-ments | |
| **High power laser calibration** | | | | | | Link to fundamental constants via photon momentum | Manu-facturing (cutting, welding etc) | |
| **Solid state lighting metrology** | Energy saving | | | Optical Flicker | | New sources for radiometry and photometry | | |
| **Imaging & goniometry** | | | | | | | 3D metrology for optical light sources. Camera based near and far field measure-ment | |
| **PV metrology** | Improved | | | | | | | |

| | THEMES | Grand Challenges | | | | Fundamental | Applied Metrology | |
|---|---|---|---|---|---|---|---|---|
| **Radiometry/ Photometry FIELD** | **Energy** | **Climate and Environment** | **Security** | **Health** | **New Technologies** | **Basic SI and fundamental science** | **Industry** | **Communication technology** |
| | PV rating | | | | | | | |
| **Fiber metrology** | | | Quantum key distribu-tion | | | | Sensing | 'Golden fiber' reference standards<br><br>Optical pulse characteriz ation |
| **Optical properties of materials** | Transmissi on, reflection, emissivity for energy saving and energy genera-tion. | | | | Optical character-ization of new materials | | Appearance | |
| **Optical and photonic sensors** | | | | Optical sensors for health applica-tions | Nano detectors and sources | | Process control | |
| **Distributed sensing networks** | | Earth observa-tion, SI trace-ability in space | | | | | | |

## 6 Rationale for various activities (2017-2027)

The following list of priority activities are planned by CCPR over the next 10 year period, in addition to the CCPR key and RMO PR key comparisons listed in Section 7:

- Pilot study of single detection efficiency of single-photon detectors (WG-SP TG 11)
- Pilot comparison for spectral regular transmittance measurements in the UV region (WG-KC TG1)
- Pilot study on the use of a new portable cryogenic radiometer for calibration of optical fibre power meters (WG-SP TG13)
- Investigate the use of white LED sources for photometry (WG-SP TG12)
- Pilot study for the use of alternative standards for photometric comparison (WG-KC TG4)
- Finalise and publish the updated BIPM monograph on The Principles Governing Photometry (Joint CIE/CCPR JTC-2)
- Achieve a consensus within CCPR of a photon-based definition of the candela (WG-SP TG4)
- Complete preparation of Guidance documents for CCPR key and RMO PR key comparisons (WG-KC), for RMO linkage (WG-KC TG2) and Comparison analysis (WG-KC TG3)
- Update Excel PR CMC Supporting Evidence (WG-CMC TG2)
- Achieve a consensus within CCPR on the CMC reviewing process and "how far the light shines" for future CCPR CMCs (WG-CMC TG3)

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 reference instruments / methods 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 CC comparisons of key comparison quantities under specialist conditions may become allowable under the MRA.

RMO pilot studies, RMO supplementary comparisons and other unregistered comparisons of related quantities are indicative of perceived future needs and have a bearing on the allocation of resources by NMIs to this type of activity; as a consequence, many of these arise from large collaborative projects such as through EMPIR funding. Lists of such planned comparisons are maintained by RMOs and are publicly available at the CCPR website (https://www.bipm.org/en/committees/cc/ccpr/rmo.html) to offer members of other RMOs an opportunity to participate if no such comparison is planned within their own RMOs and they have urgent need for comparison results to support their CMC claims.

As NMIs develop capability to respond to specialized needs such as these, inter-regional comparisons need to be encouraged and indeed the wider CCPR has been quite successful in this approach. These comparisons are important during the establishment phase of new technologies in order to build confidence in measurement techniques. However, it is clear that the incorporation of new quantities to the list of Key comparisons would have to be very carefully considered, taking into account the demand and uncertainty level required of a quantity, its independence from other quantities already covered, and the structuring of the major service categories of the CMCs.

Many of the fields considered above are highly multidisciplinary and there is a recognition that photometry and radiometry specialists must work in close collaboration with experts from other technical domains and closer to those applications. Demands for cooperation with other international organisations will be stronger in the near future. This will include the need to work closely with the Earth Observation community through links with the Space Agencies and their international organizations such as CEOS and GEO. In the display and lighting industries, improved reliability of science and technology related to human vision and cognition are needed to support better product design and process control. For example, the newest displays for virtual reality will require metrology beyond the current measurement standards of photometry. In the medical/health sector, the development of quantitative diagnostic and therapeutic biophotonics instrumentation requires metrology experts in optical radiation measurements collaborating in multidisciplinary work with experts in biotechnology and health and life sciences. 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.

The BIPM continues to serve the needs of CCPR by providing Executive Secretary and organizational support for CCPR sessions, working group meetings, as well as Workshops and training.

## 7 Required Key comparisons and pilot studies 2017-2027 with indicative repeat frequency

There are currently ten key comparisons held within the CCPR. These are in the main conducted at a high level. The current schedule for these comparisons is given in Table 7.1. The start dates that are listed for these key comparisons are the plans according to the 2016 CCPR meetings. The key comparisons that include a date in their ID have 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.

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

The published results of all the CCPR and RMO key comparisons can be found in the KCDB and a summary table of all CCPR key comparisons, completed and on-going, can also be found at the following publicly available CCPR webpage (https://www.bipm.org/en/committees/cc/ccpr.html).

A list of planned RMO comparisons is publicly available on the CCPR webpage (http://www.bipm.org/utils/en/lsx/CCPR-RMO.xlsx). At the end of 2016, 15 comparisons were planned to start in 2017-2018. This document is to be updated every year.

**Table 7.1 CCPR Key comparisons (2013-2023).**

| Start | ID | Quantity | Pilot | Status |
|---|---|---|---|---|
| 2013 | CCPR K6:2010 | Spectral regular transmittance | MSL | Completed. Results published. |
| 2014 | CCPR K3:2014 | Luminous intensity | NRC | On-going |
| 2017 | CCPR K4:2017 | Luminous flux | NMIJ | On-going |
| 2016 | CCPR K2.b:2016 | Spectral responsivity, 300 nm to 1000 nm | KRISS | On-going |
| 2016 | CCPR K2.a:2016 | Spectral responsivity, 900 nm to 1600 nm | NPL | On-going |
| 2017 | CCPR K1.a:2017 | Spectral irradiance, 250 nm to 2500 nm | VNIIOFI | On-going |
| 2017 | CCPR K5 | Spectral diffuse reflectance | MIKES | On-going. Technical protocol being developed. |
| 2018 | CCPR K1.a | Spectral irradiance, 200 nm to 350 nm | NIST | Planned |
| 2019 | CCPR K2.c | Spectral responsivity, 200 nm to 400 nm | PTB | Planned |
| 2019 | CCPR K2.d | Spectral responsivity, 10 nm to 200 nm | PTB | Planned |

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

- Fibre optic properties, specifically OTDR length (Pilot: METAS; Start Date: 2016) and fibre optic power responsivity (Pilot: NIST; Start Date: TBD)

- Regular spectral transmittance in the UV (Pilot: NMISA; Start Date: TBD)

- Detection efficiency of single photon detectors (Pilot: PTB; Start Date: 2017)

- Use of white LED sources as transfer standards (Pilot: MIKES; Start Date: TBD).

## 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 (see Section 3.4).

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

Minor revisions are expected every two years; a major revision is expected every four years with the extension of the period covered by the rolling programme.