# Consultative Committee for Photometry and Radiometry (CCPR)

25th Meeting (on-line 10-11 May 2022)

## CCPR member report on activities in radiometry and photometry since the last CCPR meeting (2019)

**Reply from: Physikalisch-Technische Bundesanstalt (PTB), Germany**

**Delegate: Stefan Kück**

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1. Summarize the recent progress in your laboratory with respect to measurement standards, research projects, and metrology services to fulfill the demands of customers in:

(a) broad-band radiometric quantities:

- A research project (DINoLED) was started to investigate the boundary conditions to replace Mercury discharge UV-sources for water disinfection by LED sources.
- A working group at DIN was established to develop a standard for the specifications of UV-C air disinfection.
- The EMPIR Project 19ENV04 MAPP started to provide metrology for aerosol optical properties
- A new mobile setup for calibration of pyrgeometers and other broad-band hemispherical infrared detectors:
  A new mobile setup was established at PTB to allow the direct calibration of pyrgeometers, and other broad-band hemispherical infrared detectors typically used to measure the downwelling longwave radiation of the atmosphere directly against calculable blackbody radiation with uncertainties of 0.5 W/m$^2$. Pyrgeometers are operated worldwide in networks like the Baseline Surface Radiation Network (BSRN). Their traceability is currently realized against one blackbody operated at PMOD/WRC Davos. The main component of the new setup of PTB is the Hemispherical Blackbody (HSBB) specifically designed to meet the needs of hemispherical detectors, i.e., showing no angular dependance of the effective emissivity. This blackbody provides an independent path of traceability of pyrgeometers to the SI. Meanwhile an intercomparison between the blackbody of PMOD and the HSBB was also conducted very successfully which verifies the existing route of traceability. This independent traceability to the SI is a topic long requested by the WMO. The new setup featuring the HSBB is now available for service and further intercomparisons.

(b) spectral radiometric quantities:

- The EMPIR JRP 19NRM02 started to provide input for the revision of standards, where one work item belongs to the implementation of correlations with respect to spectral measurements

- The TULIP setup at PTB for the laser-based measurement of the spectral responsivity of broadband detectors was improved by a quasi-continuous laser system based on a picosecond pulse laser with a bandwidth in the one-nanometer range which is ideal for such investigations.
- The measurement setup the total spectral radiant flux of PTB's robot goniophotometer was successfully improved by implementation of new array-spectroradiometers covering now the spectral range from 360nm to 1050 nm. This will expand PTB's measurement capability accordingly.
- Spectral responsivity of thermal detectors in the mid-infrared region:
  The spectral responsivity of a set of thermopile detectors and pyroelectric detectors has been calibrated in the near-infrared and mid-infrared region by using a cryogenic substitution radiometer as a detector standard and a blackbody as a radiation source standard. The application of two different kinds of primary standards enabled to verify each method and to extend the wavelength range for detector calibrations in the mid-infrared region up to 14 µm. Additionally, PTB has set up a detector comparison facility dedicated for the near- and mid-infrared spectral region. The set of calibrated thermal detectors may be used as secondary detector standards for the dissemination of the spectral responsivity to customer detectors at this facility. The particularities of pyroelectric detectors when used for absolute measurements of chopped radiation have explicitly been investigated within the mentioned calibration measurements.
- Radiometry for remote sensing:
  The Reduced Background Calibration Facility 2 of PTB is strongly involved in realizing radiometric traceability and characterisation of optical components for ESA's ESA Earth Explorer 9 FORUM mission and the LIBERA mission of NASA, NIST and LASP due to its worldwide unique ability to provide traceable spectral radiance up to 100 µm. To meet the ambitious needs of both missions the RBCF2 is continously improved. Current developments are a new Variable Reference Blackbody and a Coldscreen offering a temperature controlled and uniform scenery. Both combined will reach radiometric uncertainties in-lab below 10 mK in the FIR region.
  The installation of a newly developed, improved monochromator beam line for the (vacuum-) ultraviolet spectral range from 40 nm to 400 nm is in the final phase. This will enhance the capabilities for detector calibration.
  The CCPR KC K2d (10 nm -200 nm) have not started so far. Besides PTB (pilot), two other NMI (NIST, VNOFII) have stated their interest. Current work is underway to identify suitable artefacts for the comparison regarding their uniformity, stability and availability.
- Metrology for single photon sources and detectors:
  An InGaAs quantum dot based single-photon source was applied for the absolute detection efficiency calibration of a silicon single-photon avalanche diode. The single-photon source delivers up to $2.55 \times 10^6$ photons per second inside a multimode fiber at the wavelength of 929.8 nm for above-band pulsed excitation with a repetition rate of 80 MHz. The purity of the single photon emission,

expressed by the value of the 2nd order correlation function $g^{(2)}(\tau = 0)$, is between 0.14 and 0.24 depending on the excitation power applied to the quantum dot. The single-photon flux is sufficient to be measured with an analog low-noise reference detector, which is traceable to the national standard for optical radiant flux. The measured detection efficiency using the single-photon source remains constant within the stated uncertainty for different photon fluxes. The standard uncertainty in the calibration of the detection efficiency is around 1.2 %.
A single-photon source based on dibenzoterrylene in anthracene (DBT:Ac) was developed, whose photon flux is traceably measured to be adjustable between 144 000 and 1320 000 photons per second at a wavelength of (785.6 ± 0.1) nm, corresponding to an optical radiant flux between 36.5 and 334 fW. The high purity of the single-photon stream is verified, with a second-order autocorrelation function at zero time delay below 0.1 throughout the whole photon flux range. Such a molecule based single-photon source was used for the calibration of a single-photon avalanche detector against a low-noise analog photodiode traceable to the primary standard for optical radiant flux (i.e., the cryogenic radiometer). Due to the narrow bandwidth of the source, corrections to the detector efficiency arising from the spectral power distribution are negligible. With this major advantage, the developed device may finally realize a low-photon-flux standard source for quantum radiometry. The standard uncertainty in the calibration of the detection efficiency is around 2 %.
The angular-dependent emission of different single-photon emitters, based on nitrogen-vacancy centers in nano-diamond and on core-shell CdSe/CdS quantum dot nanoparticles, was characterized. The angular-dependent emission was measured using a back focal plane imaging technique. A theoretical model of the angular emission patterns of the 2D dipoles of the emitters was developed to determine their orientation, which predicts the experiment well.
The precise estimation of a detector´s response to the incoming light is necessary to avoid security breaches in quantum communication. The typical working regime uses a free-running single-photon avalanche diode in combination with attenuated laser pulses at telecom wavelength for encoding information. An analytical model for this regime, which considers the effects of dark counts and dead time on the measured count rate was developed.

- **Laser radiometry**
  A measurement of laser power can be performed by the measurement of its photon momentum. For this the viability and precision of the photon-momentum-based optical power measurement method that employs an amplification effect caused by a multi-reflected laser beam trapped in an optical cavity was reviewed. An comparison was carried out for an optical power range between 1 W and 10 W at a wavelength of 532 nm, which corresponds to a force of approximately 2000 nN at the upper limit, yielding approximately 2.3% relative standard uncertainty in the case of 33 reflections. This method enables especially the extension to the range of highest laser power.
  A bilateral comparison between NIST and PTB laser power standards for scale realization confidence by gravitational wave observatories was performed.  The

gravitational wave (GW) observatories calibrate interferometer displacement using photon momentum, with laser power serving as the measurand. These observatories are traceable to the International System of Units through a primary standard maintained by the US's National Metrology Institute (NMI), the National Institute of Standards and Technology (NIST). The bilateral degree of equivalence of laser power measurements for various NMIs indicated in the 2010 EUROMET.PR-S2 supplementary comparison reveals scale realization uncertainty unacceptably large for GW event parameterization. In this work the analysis to identify the source of the discrepancy between the PTB and NIST results was carried out. Using an improved transfer standard in a bilateral comparison, with representatives of the Laser Interferometer Gravitational-Wave Observatory (LIGO) receiving results prior to their comparison, NIST and PTB demonstrated a degree of equivalence of −0.15% with an uncertainty of 0.95% (k = 2) for combined 100 mW and 300 mW.

- **Differential Spectral Responsivity facility (DSR and Laser-DSR)**
  The laser-based Differential Spectral Responsivity (DSR) facility is used for high precision calibrations of the spectral irradiance responsivity of large area detectors like solar cells with an uncertainty of 0.4%. With the activities of the last three years, the uncertainty was reduced to 0,32%. Current activities are aimed at a traceable measurement of cell size, which is required for an extension of the portfolio to include efficiency measurements. The final report of the EURAMET Comparison PR-S5 (Project No. 1226) about the "Calibration of reference solar cells at standard test conditions" was published in 2021.
- **Competence Centre for PV-Metrology**
  The PTB is establishing a competence center for PV metrology. It will offer a unique infrastructure of laboratory and free-field calibration procedures with the lowest measurement uncertainties worldwide and it will serve the metrological support of the energy transition. With the PV Metrology Competence Centre, PTB is extending their activities from the area of solar cells to solar modules. It will cover all required parameters for a comprehensive calibration regarding all yield-relevant quantities and the energy rating according to IEC 61853, e.g., the power measurement of modules as well as its dependency on the temperature, irradiance, angle, spectrum and wind speed. In 2021 the calibration of solar modules according to their power measurement was successfully audited. In addition, a metric for the determination of the shading tolerance of PV modules was developed and tested.
- **Diffuse Reflectance**
  The goniometric primary set-up as well as the sphere-based facility are constantly asked for calibration tasks on a high level.
  The wavelength range of the gonio-setup was enhanced to cover the NIR range >1700 nm to 2500 nm by implementing new measurement schemes and radiation sources. The uncertainty in blue and UV wavelength range was reduced by substitution of the halogen lamp by LEDs.
  The EMPIR project "BiRD, Bidirectional Reflection Definition" was successfully finalized. In May 2019 the EMPIR program BxDiff ("Bi-directional measurements in

extra dimensions of diffusing materials", call SI broader scope) was started in which the European measurements capabilities for BRDF-measurements will be improved, first NMI reference set-ups for BSSRF will be created, and dedicated BTDF primary facilities will be implemented at Aalto and PTB.

- **Regular spectral transmittance and reflectance**
  The primary facility is constantly booked out by calibrations, not few being performed on special items from optical industry, research institutions or industry. Therefore, a continual effort is made especially in adding new radiation sources. E.g., a quantum cascade laser for measurements in the MIR was successfully integrated as well as small spot laser sources to supply calibrations in the growing field of micro-samples.

(c) photometric quantities:

- A special robot arm with 6 degrees of freedom (CaRo) as a detector positioning system for characterising the directional luminance of luminance standards was installed at the photometric bench of PTB and successfully tested. It is used to determine unavoidable non-uniformities in the amplitude of the luminance as a function of location and direction when calibrating ILMDs with luminance standards, separately for the non-uniformity of the luminance standard and the non-uniformity of the camera.
- An extension of PTB's network of standard lamps by LED-based artefacts for luminance, luminous intensity and luminous flux is started.
- The EMPIR JRP 20NRM01 MetTLM started to provide input for the standardization of temporal light modulation (TLM) and temporal light artefacts, where one work package belongs to the development and demonstration of new measurement modes regarding imaging luminance and (multi-) spectral TLM measurements.
- The Partnership JRP 21NRM01 HiDyn to perform research about luminance distribution measurements for assessing glare and obtrusive light using high-dynamic-range imaging systems was selected for funding.

(d) other area(s) relevant to CCPR:

- Status of the CCPR-K2.a.2015:
  PTB participates in "Pilot study on the comparison CCPR-K2.a.2015. "Spectral Responsivity" (wavelength range 900 nm to 1600 nm). PTB has finished its measurements and has sent the result report to the pilot. detection efficiency of single-photon detectors – Si-SPAD" (EURAMER Project 1468)
- Status of the CCPR-K2.b.2016:
  PTB participates in the comparison CCPR-K2.b.2016. "Spectral Responsivity" (wavelength range 300 nm to 1000 nm). PTB has finished its measurements and has sent the result report and the technical report to the pilot.
- The "pilot study on the detection efficiency of single-photon detectors – Si-SPAD" started in May 2016 at PTB with the first measurements. This pilot study is carried out within the frame of the CCPR-WG-SP Task Group 11. There are 11 participants

in this pilot study, from which 10 have already carried out their measurements. It is planned that the study ends in 2023 with the final report.

2. What work in PR has been/will be terminated in your laboratory, if any, in the past /future few years? Please explain the reasons and provide the name of the institution if it has been/will be substituted by a DI or accredited laboratory.

   none

3. Summarize the Capacity Building and Knowledge Transfer activities undertaken by your institute in photometry and radiometry (courses, training, …):

   - In November 2019, PTB organized the 11$^{th}$ short course in photometry for German speaking participants. This short course comprises the most relevant topics of metrology and traceability in the field of photometry and colorimetry and targets lighting engineers and scientists working in the field of metrology.
   - In May 2022, PTB will hold the 12$^{th}$ Photometry short course in Braunschweig.
   - PTB is also coordinating the EMPIR small collaborative project SmartPhoRa.

4. Summarize the research projects currently performed within a collaboration with one or more NMIs or Dis (name of the project, participants):

   - EMPIR JRP 18SIB10 *chip*S·CAL*e* “Self-calibrating photodiodes for the radiometric linkage to fundamental constants”, participants: JV, Aalto, CMI, CNAM, INRIM, Metrosert, PTB, TUBITAK, IFE, SINTEF, USN
   - EMPIR JRP 19NRM02 RevStdLED “Revision and extension of standards for test methods for LED lamps luminaires and modules”, participants: PTB, Aalto,CSIC, IPQ, LNE, TUBITAK, DTU, KIT, NSC-IM, candelTec, JETI, NMISA, TechnoTeam
   - EMPIR JRP 19ENV04 MAPP “Metrology for aerosol optical properties”; Participants: SFI Davos, Aalto, CMI, NPL, PTB, VSL, AEMET, CNR, CNRS, GRASP SAS, Our, UV, UVa,
   - EMPIR SCP SmartPhoRa “Smart specialization and stakeholder linkage in photometry and radiometry”; Participants: PTB, Aalto, BIM, CNAM, CSIC, GUM, INM-MD, Metrosert, TUBITAK.
   - EMPIR JRP 20NRM01 MetTLM “metrology for temporal light modulation”; Participants: VSL, Aalto, PTB, RISE, CSTB, DTU, ICCS, TU-E, VHK, GGO, LMT, Signify
   - Partnership JRP 21NRM01 HiDyn “support for the standardisation of luminance distribution measurements for assessing glare and obtrusive light using high-dynamic-range imaging systems”; Participants: PTB, Aalto, CMI, CNAM, CSIC, ICCS, TUB, EPFL, METAS (status: selected for funding, negotiation ongoing)
   - EMPIR JRP 20IND04 ATMOC “Advanced Traceable Metrology for Optical Constants; Participants:17FUN06 SIQUST “Single-photon sources as new standard sources”, PTB, Aalto, BAM, DFM, TUBITAK, VSLCMI, INRIM, Metrosert, NPL, VTT, CEA, CNRS, FSU Jena, FVB, IMEC, JCM, JKU, TU DelftCNR, CSIC, FAU, INFN, TUB, U Twente, RWTH, ZeissUdS, UNITO, USTUTT

- EMPIR JRP 20FUN05 SEQUME “Single and entangled photon sources for quantum metrology”, PTB, Aalto, CMI, DFM, JV, Metrosert, TUBITAK, CNR, CSIC, FAU, INFN, KBFI, TUB, UdS, UNITO, USTUTT, ZIB, INRIM
- EMPIR 19NET02 EMN-Quantum, “Support for a European Metrology Network on quantum technologies”, CMI, GUM, INRIM, LNE, LNE-SYRTE, NPL, PTB, UME
- EMPIR 19ENV07 MetEOC-4 “Metrology for Earth Observation and Climate”, NPL, Aalto, CMI, PTB, SFI Davos, FZ-Jülich, JRC, NLS, Rayference, SURREY, Our, UZH, BUW, HUK, KIT, UGent

5. Are there any other research projects where you might be looking for collaborators from other NMIs or are there studies that might be suitable for collaboration or coordination between NMIs?

   none

6. Have you got any other information to place before the CCPR in advance of its next meeting?

   none

7. Bibliography of radiometry and photometry papers of your laboratory since the last CCPR (September 2019):

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