Consultative Committee for Photometry and Radiometry (CCPR)
23rd Meeting (22 - 23 September 2016)

Questionnaire on activities in radiometry and photometry

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

Delegate: Stefan Kück

1. Summarize the progress in your laboratory in realizing top-level standards of:

   (a) broad-band radiometric quantities

   (b) spectral radiometric quantities

Development of new calibration methods for radiometric measurements of high UV irradiance

PTB has continued its activities in development of calibration services for high UV irradiance applications, in particular UV curing processes. A joint research project with an industrial partner was started aimed at implementation of consistent and efficient testing and calibration methods and process control in the UV curing industry. The cooperation spans a time frame of three years and focuses on the development of standard broadband radiometers and standard lamps for high UV irradiance.

Spectral responsivity

Within the European joint research project SIB57 NEWSTAR “New primary standards and traceability for radiometry”, the uncertainty of optical radiant power measurement with the laser-based cryogenic radiometer facility for high-accuracy detector calibration has been reduced to 11 ppm enabling the characterization of the improved Predictable Quantum Efficient Detectors (PQEDs) with uncertainties of about 20 ppm. The main goal of NEWSTAR is to develop a new primary standard for radiometry. The PTB is leading work package 2 which aims at validating the expected ultra-low uncertainties of PQEDs with the best possible measurements using cryogenic radiometers and participates in all other work packages.

The Metrology Light Source — the PTB electron storage ring dedicated to metrology

At the Metrology Light Source (MLS), the facility for the calibration of radiation transfer sources in the spectral range from 7 nm to 400 nm, traceable to the MLS as a primary radiation standard, was validated in the spectral range from 115 nm to 400 nm and the results were recently published [R. Thornagel et al., Metrologia 51, 528 (2014)]. The shorter wavelength range below 115 nm was used to thoroughly investigate a hollow-cathode based discharge source. The operation of the MLS, at low electron beam energy of 150 MeV, which reduces the high energy part of the synchrotron radiation spectrum, has been improved in terms of electron beam lifetime as well as stability. This operation mode was used for the calibration of the engineering model of the SPICE (Spectral Imaging of Coronal Environment) spectrometer of the Solar-Orbiter mission with the direct, calculable MLS radiation, thus avoiding higher diffraction orders in the spectrometer.

Traceable calibration of single photon detectors using synchrotron radiation

The MLS was used to determine the detection efficiency of single photon detectors traceable to cryogenic radiometers of PTB. This method was employed for fiber-coupled as well as free-space single photon detectors. The MLS was used as a radiation source with a dynamic range of spectral radiant power which bridges the radiometric gap between the radiant power levels necessary for the low uncertainty operation of the reference detectors based on photodiodes and the photon fluxes suitable for single photon detectors. In this context, a bilateral inter-comparison of the detection efficiency of fibre-coupled detectors with the NIST was performed and is just being evaluated. Measurements at the MLS will also be performed within the framework of the "Pilot study on the detection efficiency of single photon detectors – Si-SPAD" (CCPR WG-SP TG 11).

Metrology for single photon sources and detectors

The work on single photon sources and detectors for quantum-based radiometry and quantum communication is ongoing. A comparison at the sub-100 fW optical power level of calibrating a single-photon detector using a high-sensitive, low noise silicon photodiode and the double attenuator technique was carried out between the Cesky Metrologicky Institut (CMI) and PTB (G Porrovecchio et al., Metrologia 53 (2016) 1115–1122). An absolute nitrogen-vacancy doped nanodiamond based single-photon source was radiometrically characterized within the frame of the EMRP-project "Single-photon sources for quantum technologies" (SIQUTE). The total output power of this source is adjustable between 55 fW and 75 fW, between a total photon flux of 190 000 photons per second and 260 000 photons per second, respectively. Also the spectral photon flux and spectral radiant flux were measured traceable to a national standard. The EMRP Joint Research Project SIQUTE was completed, the EMPIR Joint Research Project "Optical metrology for quantum enhanced secure telecommunication" was started.

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%. The facility was complemented by the feasibility to measure the wavelength- and polarisation resolved angular dependency.

The traditional lamp-based DSR facility is used for routine operation for the calibration of the absolute spectral irradiance responsivity of solar cells, photometric detectors and UV detectors, traceable to the PTB's cryogenic radiometer. The long-standing monochromator-based DSR setup covers the total spectral range from 210 nm to 1900 nm. This facility is actually pilot of the EURAMET.PR- S5 (Comparison of reference solar cells).

Using the current obtained by the (Laser-) DSR measurements, an accurate IV-characteristics under STC can be determined.

The portfolio was complemented by the possibility to measure shunted solar cells and detectors. The result is a voltage at Standard-Test-Conditions (STC) instead of a current. A new amplifier and a new traceability chain had to be developed for this option.

Diffuse Reflectance

The robot-based gonioreflectometer for measuring diffuse reflection in directed/directed geometries, operating in the wavelength range 250 nm to 1700 nm, is regularly used for calibration service. A proof of principle test was performed with a laser driven light source giving evidence for a greatly enhanced signal to noise figure in the short wavelength regime.

The standard use however was hampered by the extreme calibration workload and a technical problem with the source.
The goniometric system was successfully tested and applied for measurements of diffuse transmittance. Although a wide range of in and output angles can be realized investigations are under way to extend the system for almost all practically important geometries.
The European Metrology Research Program (EMRP) project “xD-Reflect, Multidimensional Reflectometry for Industry" is in its final phase. The measurements for intercomparison are finished. Results on all activities in XD-reflect will be presented at the *4th CIE Expert Symposium on Colour and Visual Appearance*. For 2017 it is planned to start a follow-up project within the EMPIR framework which will transform the gathered knowledge into (pre-)-standards in the key fields of gloss, sparkle, and goniochromatic measurement.

Regular spectral transmittance and reflectance
The regular spectral transmittance part of the reference set-up successfully took part in CCPR-K6 comparison on regular transmittance.
The measurement capabilities of the set-up were used for scattering experiments in the visible as well as for investigations of the fluorescence of nano-dots. Absorption and fluorescence methods will be increasingly applied within a project exploring the suitability of semiconductor nanoparticles as reference material for particle sizes below 10 nm, a project which started in spring 2016.

(c) photometric quantities

Luminous flux and LED measurement facility
A first LED-based Multiple Transfer Standard has been developed put into operation. Traditionally, classical photometric transfer standards represent only one single calibrated measurement quantity which is set by one defined electrical operation condition, which is sometimes complemented with other quantities of subordinated priority. As an example, incandescent lamps designed as luminous flux or luminous intensity standards may be used to transfer the quantity distribution temperature in addition to the unit lumen or candela. Beyond that, the LED Multiple Transfer Standard is designed to operate at different operating conditions with respect to its spectral, spatial light distribution as well as to its time-dependent light output. In the framework of the EMRP Project MeSaIL several of these newly developed transfer standards are currently under test at different NMIs.
In addition to the robot-based goniophotometer, where lamps or luminaires are not moved during measurement, PTB permanently improves its versatile LED measurement setup for goniophotometric measurements, which can be used for sources which are insensitive with respect to position and movement.

Luminous intensity
The Photometric Bench System of PTB was successfully used for the measurements of the group of PTB luminous intensity travelling standard lamps within the CCPR-K3.2014, piloted by NRC. To improve and shorten the traceability chain from the cryogenic radiometer to the luminous intensity lamps for the realisation of the unit of the quantity luminous intensity, PTB started to build a special transition-trap-based photometer ($V(\lambda)$-Trap) which can be calibrated using a coherent light beam as well as incoherent incandescent light sources. In this way, the same $V(\lambda)$-Trap device will be calibrated against the cryogenic radiometer and

used to determine the temperature of a black body and used to determine the distribution temperature of a luminous intensity transfer standard which is than calibrated by the $V(\lambda)$-Trap. The development is supported by simulations and test measurements which are very promising.

2. What other work has taken place in your laboratory in scientific or technological areas relevant to the CCPR?

Characterisation of reference instruments from global monitoring networks for the total column ozone (TOC)

Global networks for ground-based TOC observations are based on two common instrument types: the so called Dobson and Brewer spectrophotometers. Results of the TOC measurements using the Dobson and the Brewer instruments have shown discrepancies, which have been partly traced back to uncharacterised instrumental features. The algorithms used to derive the TOC from the measurement data require the bandwidths and the centre wavelengths of the bandpass functions of the spectrophotometers. Within the EMRP ENV59 project ATMOZ "Traceability for the total column ozone" both the world reference Dobson operated by NOAA, USA and the European reference Dobson instruments maintained by DWD, Germany were characterised at PTB in Braunschweig for these characteristics using a narrow band spectrally tuneable laser radiation. Also a reference Brewer instrument from the European Brewer Reference Centre (RBCC-E) was characterized with respect to wavelength, bandpass as well as its temperature coefficients.

Direct calibration of ground based instruments to measure solar spectral irradiance in the near infrared.

A double-monochromator-based spectroradiometer and a 6-channel filter radiometer operated by the Royal Belgian Institute for Space Aeronomy have been calibrated in terms of spectral irradiance responsivity using the high-temperature blackbody of the PTB as primary standard for spectral irradiance. The instruments were then used at the PYR-ILIOS campaign carried out in June to July 2016 at the Mauna Loa Observatory (Hawaii, USA, 3396 m a.s.l.). This ground based instrumentation was used for measurements of solar spectral irradiance of the Top Of Atmosphere (TOA), obtained through atmospheric NIR windows using the Bouguer-Langley technique.

Upgrade of measurement capabilities for characterisation and calibration of array spectroradiometers

For spectral characterisation of array spectroradiometers, Pulsed Laser for Advanced Characterization of Spectroradiometers (PLACOS) facility has been in operation at PTB since ten years. Recently a new setup was taken into use based on an optical parametrical oscillator operating at 1 kHz pulse repetition rate. The new setup offers an advantage of shorter measurement times, broader dynamic range and improved stability. Characterisation and calibration of array spectroradiometers can be carried with respect to stray light, bandpass characteristics as well as wavelength calibration over the spectral range from 210 nm to 2600 nm. The new laser based setup is also prepared for absolute radiometric calibrations.

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Development of a UV-LED based source for tracking radiometric stability of array spectroradiometers

Within the EMRP ENV59 project ATMOZ "Traceability for total column ozone", efforts are being made to develop, characterise, and apply array spectroradiometers to measure the direct solar UV irradiance. One of the key requirements for array spectroradiometers in solar ultraviolet measurement applications is their radiometric stability. For this purpose a compact and stable reference source based on state-of-the-art commercially available light emitting diodes (LEDs) has been developed at PTB. The UV-LEDs based source system will allow tracking radiometric stability and wavelength scale of the array spectroradiometers.

Fourier transform spectroradiometers for solar UV irradiance measurements

A new Fourier transform spectroradiometer has been calibrated against different standard lamps and in parallel radiation against other spectroradiometer. The Fourier transform spectroradiometer is used for outdoor measurements of the direct sun light with a high wavelength resolution of 0.05 nm. The facility will complement an array spectroradiometer with lower wavelength resolution during the measurement campaign in Izana as a part of the ATMOZ EMRP project. The objective is the determination of the ozone column.

Radiometry for remote sensing

The GLObal Limb Radiance Imager of the Atmosphere (GLORIA), as one of the most advanced limb sounding instruments, has been given strict traceability to the SI. The spectral radiance and radiation temperature of the two large aperture in-flight reference blackbodies of the hyperspectral imager have been calibrated in the wavelength range from 5 µm to 15 µm and in the relevant temperature range for climate research from -60 °C to 30 °C at an uncertainty level of 100 mK. A uniformity of better than 35 mK over the whole aperture at an operating temperature of -30 °C of the in-flight reference blackbodies was achieved.

A traceability concept for the worldwide operating Network of Detetion of Mesopheric Change (NDMC), which aims to detect longterm temperature trends in the Mesopause, has been developed. For inherent redundancy it consists of a traveleling reference source and a traveling reference spectrometer. Both are designed to enable the traceable calibration of the ground based measurement stations of the NDMC for spectral responsivity at 1.55 µm with an uncertainty of 0.5 % at a radiance level of 350 W sr^{-1} m^{-2} m^{-1}.

The German Aerospace Centre (DLR) is operating the Calibration Home Base (CHB) as a facility for the radiometric calibration of airborne hyperspectral sensors and field spectrometers. The calibration concept relies on the application of both absolutely calibrated source- and detector-based radiometric transfer standards.

The source-based SI traceability to the CHB facility is provided by PTB via a dedicated portable radiance standard (RASTA). The latter has been calibrated at the PTB with respect to its spectral radiance in the wavelength range from 350 nm to 2.5 µm employing two independent calibration methods with relative standard uncertainties (k=1) ranging from 0.8 % to 7.5 % depending on wavelength.

To provide redundancy to the source-based calibration and to take advantage of the superior stability of detector-based radiometric transfer standards, the RASTA design includes a multiple detector unit consisting of five individual filter radiometers (FRs). Three of these FRs are filters based with centre wavelengths at 400 nm, 550 nm and 850 nm whilst the remaining two FRs are of broad-band design for covering the wavelength range from 850 nm to 1.7 µm and 850 nm to 2.5 µm, respectively.

The spectral irradiance responsivity calibration of these FRs was performed at the spectral comparator facility of PTB. In the wavelength range from 250 nm to 1.7 µm, this was accomplished by comparison with absolutely calibrated transfer detectors, traceable to the primary detector standard, the cryogenic radiometer. In the wavelength range from 1.7 µm to 2.5 µm a relative calibration was done by applying a thermopile-detector with a previously characterized, spectrally flat absorbing layer. The achieved relative standard uncertainties (k=1) range from below 0.3 % in the UV and VIS up to 1% in the NIR (2.5 µm).

Synchrotron radiation based solar and atmospheric research

The activities regarding characterization and calibration of space instrumentation for solar and atmospheric research has been pursued. In close cooperation with the instrument-building research institutes, measurements were carried out for the SPICE (Spectral Imaging of Coronal Environment) and EUI (Extreme Ultraviolet Imager) instruments of ESA's future Solar Orbiter mission. Besides characterization and calibration of single components (i.e., mirrors, filters and detectors) regarding spectral reflectance, transmission, and responsivity in the whole EUV and VUV spectral range from about 5 nm up to 200 nm, the calibration regarding irradiance of the full instruments either against the Metrology Light Source (MLS) as a primary source standard, or secondary detector standards was realized.

Spectral and total emissivity

PTB continues to extend its capabilities to determine total directional and total hemispherical emissivity of surfaces from directional spectral emissivity measurements. Now spectral emissivity from 1.1 µm to 200 µm under variable angles of observation in a temperature range from -40 °C to 1000 °C can be measured.

Absolute diffraction efficiencies of infrarede gratings

The European Southern Observatory (ESO) is currently performing a significant upgrade of its cryogenic, high-resolution infrared Echelle spectrograph (CRIRES) which is part of the instrumentation of the Very Large Telescope (VLT). Within a cooperation between PTB and the Landessternwarte (state observatory) Thüringen, PTB has developed a dedicated setup for the measurement of absolute efficiencies of diffraction gratings in the infrared. Applying the new setup, PTB has measured the absolute efficiencies of the gratings to be used in the upgraded VLT spectrograph CRIRES+, in the wavelength range from 1 µm to 6 µm with relative standard uncertainties (k=1) below 5%.

Status of the CCPR-K2.a.2015

PTB participates in the comparison CCPR-K2.a.2015. "Spectral Responsivity" (wavelength range 900 nm to 1600 nm). The technical protocol is currently under discussion.

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). The technical protocol has been approved by CCPR. The measurements of PTB are scheduled for 2017.

Status of the CCPR K3

The measurements campaign for the CCPR K3 "Luminous Intensity" at PTB has been finished. The final result for all 6 WI41/G lamps of PTB was sent to the pilot laboratory (NRC) in July

2015. In th meantime, the pilot distributed all relative results with respect to the pilot measurement. No outliers could be identified so far.

Status of the CCPR K6.2010
Draft B was submitted by the pilot lab to be reviewed by CCPR WG-KC.

Status of the CCPR pilot comparison "Spectral Responsivity in the Terahertz Spectral Range"
In 2015 the CCPR pilot comparison "Spectral Responsivity in the Terahertz Spectral Range" between NIST, NIM, and PTB took place at PTB at two frequencies, namely 2.52 THz and 0.762 THz. The results are published in 2016.

Status of the CCPR "Pilot study on the detection efficiency of single-photon detectors – Si-SPAD"
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, it is currently planned that the study ends in 2018 with the final report.

Status of COOMET.PR-K1.b.1: Bilateral comparison of spectral irradiance of deuterium lams between PTB and VNIOFFI
A bilateral comparison of spectral irradiance measurements of deuterium lamps in the spectral range between 200 nm and 350 nm is being carried out between PTB and VNIIOFI. The comparison was planned to be accomplished within the framework of RMO COOMET intercomparison where VNIIOFI acts as a pilot laboratory. PTB acts as link laboratory to the CCPR-K1.b.

Status of COOMET.PR-S6
The trilateral comparison on fibre optic power responsivity covering the wavelength 1310 nm and 1550 nm and the power levels 0.3 mW to 1 mW was completed, the results were published in *Svetlichny et al. "Final report on COOMET.PR-S6.2012: Supplementary comparison on fiber optic power responsivity", Metrologia, 51 (2014), 1A, Tech. Suppl., 02003*.

Status of EURAMETPR-S5
The measurements of EURAMET Supplementary Comparison S5 about the short circuit current under Standard-Test-Conditions of reference solar cells are finished. The confirmation of the data of the participants and the evaluation has been succeeded. The completion of the Pre-Draft A is planned for 2016.

CCT NCTherm "High-temperature fixed point research plan"
Metal carbon eutectic high temperature fixed points (HTFP) prove themselves to be promising reference sources for radiometry, photometry and thermometry. To implement these fixed-points in a future high-temperature scale as standard radiation sources, the CCT NCTherm formulated a HTFP research plan. Within the EMRP project InK "Implementing the new Kelvin" absolute radiometry at NIST, LNE-CNAM, VNIIOFI, NRC, NMIA, NIM, CEM, NRC, NMIJ and PTB determined the thermodynamic temperatures of the point of inflections of

the melting transitions of Re-C, Pt-C and Co-C eutectics to be 2747.84□(*U*= 0.35 K), 2011.43□(*U*= 0.18K) and 1597.39□□(*U*= 0.13 K), respectively, and the thermodynamic temperature of the freezing transition of Cu to be 1357.80□(*U*= 0.08 K), all ***k***=2. Additionally, within the framework of the EMRP INK project, PTB hosted a comparison in 2015 to test the level of agreement for absolute radiometric temperature measurement in the temperature range between 1300 K and 3000 K using absolutely calibrated filter radiometers in radiance and irradiance mode provided by LNE-CNAM, MIKES, CEM, and PTB.

Short Course in Photometry

In November 2016, PTB will organise the 2016 short course in photometry for German speaking participants. This 9th 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.

Traceability of the detection efficiency of fibre-coupled single photon detectors to national standards

PTB and the "Sources and Detectors" group at NIST Boulder are working in a joint effort to validate the traceability of the detection efficiency of fibre-coupled single photon detectors to national standards, i.e. the cryogenic radiometer. The aim is to identify suitable corrections that have to be applied when fibre-coupled detectors are calibrated against free-space standards, such as the reflection at the fibre end which occurs only during free-space measurements. Two calibration campaigns have been performed at NIST Boulder laboratories and PTBs Metrology Light Source. The results are currently under evaluation. The relative agreement of the different calibration techniques is expected to be better than 5 %.

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

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4. What are present, new or emerging needs of users of your services that are not being supported sufficiently by current CCPR activities or initiatives? In the light of this information please suggest desirable changes in the future working program of the CCPR.

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5. What priorities do you suggest for new research and development programmes at NMIs in the area of Photometry and Radiometry?

- The development of single photon standard sources to be used as standards for single photon and low photon flux radiometry.
- The development of transfer standards sources for LEDs and OLEDs to be used as secondary standards in photometry.

- The development of transfer standard sources and spectral irradiance calibration procedures for high-power UV spectral irradiance.
- The development of transfer standard detectors and calibration procedures for high-power UV spectral responsivity.
- Near-field goniophotometry, imaging photometry (ILMDs) and imaging radiometry are important technologies for the future. True traceability of measured sources or plots cannot be provided currently. Although European NMIs tried to establish joint projects in the framework of the European Metrology Research program more than once, these JRPs were rejected by the reviewers and the attempts failed.
- The development of a method for the accurate measurement of angular dependency of solar *modules* to fit the needs of the energy rating standards.

6. Are there any 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?

Within Europe this is currently almost completely covered by the EMRP and EMPIR research programmes and projects.

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

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8. Bibliography of radiometry and photometry papers of your laboratory since the last CCPR (September 2014)?

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