Consultative Committee for Photometry and Radiometry (CCPR)
24th Meeting (19 - 20 September 2019)

Questionnaire on activities in radiometry and photometry

Reply from: National Institute of Standards and Technologies, USA

Delegate: Maria E. Nadal, John H. Lehman, and Yoshi Ohno

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

(a) broad-band radiometric quantities:

Broadband Radiometric LED Measurements
A broadband radiometric measurement procedure has been developed at NIST to perform uniform LED calibrations and measurements with low uncertainty. For reference-level calibrations, LED-365 irradiance source standards and UV irradiance meters have been developed. Using a low-NEP pyroelectric radiometer, a UV response function with +/- 0.2 % maximum deviation from constant has been realized between 250 nm and 420 nm. Using the constant irradiance responsivity of a reference pyroelectric radiometer, the integrated irradiance from all kinds of LEDs can be measured without using a source standard. The developed LED-365 irradiance sources and UV irradiance meters can be used to calibrate field UV irradiance meters against the working standard meter when using the same LED-365 source. Using this broadband calibration procedure, fast, inexpensive, and accurate LED measurements can be performed in irradiance, radiance, or radiant-power modes. [POCs: George P. Eppeldauer, George.Eppeldauer@nist.gov; Howard W. Yoon, HYoon@nist.gov; Carl C. Miller, C.Miller@nist.gov]

Low-NEP pyroelectric detectors for calibration of UV and IR sources and detectors
Pyroelectric radiometers with spectrally constant response have been developed at NIST with the cooperation of a few detector manufacturers. The new devices have noise-equivalent-power (NEP) values less than 1 nW/Hz$^{1/2}$ sufficiently low for use at the output of regular monochromators. Their response flatness is an order of magnitude better than that of filtered Si detectors and can be used to realize simple and low-uncertainty responsivity scales for the UV and IR wavelength ranges. Based on spectral reflectance measurements of the black coating of the pyroelectric detector, the relative spectral response was determined between 250 nm and 30000 nm. The relative response was then converted into spectral power and irradiance responsivities using absolute tie points from a silicon-trap-detector in the VIS range. The spectral power responsivity of the low-NEP pyroelectric detector is the internal standard of the NIST VIS-IR detector calibration facility for the 600 nm to 24000 nm wavelength range. The broadband radiometric measurements can be applied to IR LEDs emitting low fluxes between 750 nm and 4300 nm. All pyroelectric detector-based calibrations were performed with expanded uncertainties of about 2 % (k=2). [POCs:

Vyacheslav B. Podobedov, vyacheslav.podobedov@nist.gov; Leonard M. Hanssen, leonard.hanssen@nist.gov; Catherine C. Cooksey, catherine.cooksey@nist.gov; George P. Eppeldauer, George.Eppeldauer@nist.gov]

(b) spectral radiometric quantities:

Improvements in the spectral power and spectral irradiance calibration facility at NIST.
The Visible/NIR Spectral Comparator Facility, VisSCF, has been in operation at NIST since the mid 1990's for the calibration of detectors for spectral power responsivity. Recently, improvements have been made to this monochromator-based facility to decrease the total uncertainties of the calibrations by increasing the ultraviolet throughput, lowering the current-to-voltage converter uncertainties, wavelength uncertainties, increasing source stability and decreasing beam scatter. These improvements have resulted in a facility, when used to measure silicon diodes for power responsivity, that is capable of 20 ppm reproducibility over a two-week period and longer in the visible wavelength region. The facility is used for routine calibrations of spectral power responsivities of detectors from 300 nm to 1800 nm using a 100 W quartz-tungsten halogen lamp as a source without the use of specialized UV sources. Laser interferometers were used to calibrate displacements of x- and y-axis motion stages in the facility which has led to the implementation of direct, detector-based spectral irradiance responsivity calibrations of sensors at any wavelength from 300 nm to 1800 nm. Comparisons of aperture areas measured using this facility with the scanning technique agree with those measured in a dedicated aperture area measuring facility to < 0.12 %. [POCs: Jeanne Houston, jeanne.houston@nist.gov; Howard Yoon, howard.yoon@nist.gov]

New National Reference Instrument for Bidirectional Reflectance Measurements.
NIST calibration services for specular and diffuse bidirectional spectral reflectance, including the 0°/45° reflectance factor scale at wavelengths from 250 nm in the ultraviolet (UV) to 2400 nm in the shortwave infrared (SWIR), have been successfully transitioned to the new Robotic Optical Scattering Instrument (ROSI). These measurements were previously performed on the Spectral Tri-function Automated Reference Reflectometer (STARR) facility. ROSI employs advanced technologies, such as high-brightness tunable light sources and a robotic arm goniometer, that have expanded the range of measurement geometries and sample reflectance levels that can be calibrated. Specular and bidirectional calibrations for white and neutral samples are currently offered at in-plane geometries, while out-of-plane bidirectional reflectance measurements can be performed for research and special tests. [POCs: Heather Patrick, heather.patrick@nist.gov; Catherine Cooksey, catherine.cooksey@nist.gov]

New Integrating sphere-based facility for relative and absolute directional/hemispherical measurements under development.
NIST has designed and is in the process of installing a new integrating sphere for 8-degree angle of incidence, specular included (8/di) directional/hemispherical reflectance. The new sphere will share a light source with the Robotic Optical Scattering Instrument (ROSI) which covers a wavelength range from 250 nm to 2400 nm. The sphere is designed to enable

realization of the absolute diffuse reflectance scale in the ROSI facility while also accommodating relative reflectance measurements for day-to-day use. [POCs: Heather Patrick, heather.patrick@nist.gov; Catherine Cooksey, cooksey@nist.gov; and Thomas Germer thomas.germer@nist.gov]

Calibration of spectral responsivity of IR detectors in the range from 0.6 µm to 24 µm

The spectral coverage of the NIST IR Spectral (Detector) Calibration Facility designed for calibration of the spectral responsivity of detectors in both radiant power and irradiance measurement modes has been extended. The responsivity is calibrated in units of V/W or VW-1cm2 in AC measurement mode at a chopping frequency of 10.5 Hz. The present ranges of 0.6 µm to 24 µm and from 0.6 µm to 12.5 µm are available for radiant power and irradiance modes, respectively. The extension of the wavelength range was enabled by new reflectance data for the reference pyroelectric detector and an upgrade of both the monochromator and radiation source. For irradiance responsivity mode, a sphereless optical geometry providing a relatively high irradiance in the detector plane, was developed and evaluated. Detectors to be tested should have a minimum detector diameter of 5 mm and acceptance angle of 20 degrees and include a preamplifier used with the detector. Typical calibration uncertainties vary over the spectral range, but generally do not exceed 2.3 % and 3.0 % (k = 2) in the radiant power and irradiance modes, respectively. The facility also provides measurements of NEP (or noise equivalent irradiance), as well as precise scanning of the detector's active area for spatial non-uniformity of response. [PCOS: Vyacheslav B. Podobedov, vyacheslav.podobedov@nist.gov; Leonard M. Hanssen, leonard.hanssen@nist.gov; George P. Eppeldauer, George.Eppeldauer@nist.gov; Thomas C. Larason, thomas.larason@nist.gov]

Optical Power at 1 KW and greater

NIST established a primary standard for measurement of laser power by means of photon momentum (traceable to the kg and Planck's constant) for 1070 nm at 1 kW and higher. This is available from NIST as a standard reference instrument (SRI6009). This has also been demonstrated at 10.6 µm. The method of measuring photon momentum is a paradigm shift from the method of direct substitution and toward calibrated sources. By implementing a mirror having very high reflectance, the optical power is measured by the standard while evaluating the device under test. This method has also been demonstrated for radio frequency and microwave sources. We have recently demonstrated self-consistency with SI measurement traceability by means of the kg and optical Watt spanning twenty orders of magnitude from a few photons per second to 100 kW. [POC: Paul Williams, Paul.Williams@nist.gov]

Optical Power for fiber-coupled radiometry

NIST completed commissioning a new, state-of-the-art cryogenic primary standard for optical fibre power measurement and calibration. It establishes for the first time, a direct traceability route between the device under test and primary standard. Two silicon micro-machined planar detectors, with vertically aligned carbon nanotube absorbers, thin film tungsten heaters and superconducting resistive transition edge temperature transducers, form the basis of the radiometer. Magnetic phase-change thermal filters ensure noise-free operation at 7.6 K. Measurement repeatability below 50 ppm is routinely achieved during a measurement cycle of 30 min. The system operates at a nominal radiant power level of 200 µW (−7 dBm). The expanded measurement uncertainty at $k = 2$ is less than 0.4%, a 20% improvement on NIST's current optical fibre power Calibration and Measurement Capability. The performance of the new standard was established at nominal wavelengths 850 nm, 1295 nm and 1550 nm. [POC: Michelle Stephens, Michelle.Stephens@nist.gov]

(c) photometric quantities:

Improvements to the NIST Luminous Intensity Scale
The NIST luminous intensity scale was improved by using the newly developed 5 m photometry bench that is fully automated with 50-micron distance uncertainty. Also, seven new photometers were developed and calibrated against four primary trap detectors for spectral irradiance responsivity (to derive illuminance responsivity) using a 1 kHz pulsed tunable OPO laser to reduce the uncertainty of the NIST candela unit. [POCs: Yuqin Zong, Yuqin.zong@nist.gov; Cameron Miller, c.miller@nist.gov]

Improvements to the NIST Total Luminous Flux Scale
The NIST detector-based total luminous flux scale was improved by using three newly developed photometers for measuring illuminance (to obtain the partial luminous flux) of the reference source outside the 2.5 m integrating sphere. The three photometers were also calibrated against four primary trap detectors for spectral irradiance responsivity (to derive illuminance responsivity) using the 1 kHz pulsed tunable OPO laser to reduce the uncertainty of the NIST lumen unit. In addition, the fisheye camera method is used for measuring the intensity distribution of a light source in the 2.5 m integrating sphere and thus the error resulting from the sphere's spatial nonuniformity is corrected. [POCs: Yuqin Zong, Yuqin.zong@nist.gov; Cameron Miller, c.miller@nist.gov]

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

NIST Compact Spectral Irradiance Monitor (CSIM)
NIST CSIM is a novel instrument that was successfully launched into space on a satellite on Dec 2018 as part of the SpaceX SSO-A: SmallSat Express Mission. CSIM will monitor and measure the sun's radiation for two years to help researchers understand how solar variability affects Earth's climate. This mission also is testing the effectiveness of smaller satellites that orbit for shorter lengths of time. The data from CSIM will be compared to data from a larger satellite. CSIM brings new, emerging technology advancements to maturation by demonstrating the unique capabilities of a complete SSI mission with inherent low mass and compact design. The instrument is a compact, two-channel prism spectral radiometer incorporating Si, InGaAs, and extended InGaAs focal plane photodiodes to record the solar spectrum daily across a continuous wavelength region spanning 200 nm – 2800 nm (>97% of the total solar irradiance). A new, novel electrical substitution radiometer (ESR) using vertically aligned carbon-nanotube (VACNT) bolometers serves as an absolute detector for

periodic on-orbit spectral calibration corrections. [POC: Michelle Stephens, Michelle.Stephens@nist.gov]

New calibration service of single photon detectors at 850 nm and 1550 nm
Our measurement of single-photon detector efficiencies is based on a calibrated beam splitter, a monitor power meter and transfer power meter in combination with an optical fiber attenuator to extend measurement scales to levels compatible with single-photon detectors. The method allows us to accurately control the photon flux at the detector under test with an uncertainty dominated by the calibration of our optical power meters. Our method employs optical power meters calibrated at high power levels (□□W) that can maintain high accuracy at low light levels (□pW). We achieve SI traceability through our optical fiber power meter calibration services and are able to calibrate fiber-coupled single photon detectors at wavelengths of 850 nm and 1550 nm and free-space-coupled single photon detectors at a wavelength of 850 nm. In addition, we developed reference instrumentation for our calibration service. The instrumentation is based on a superconducting nanowire single photon detector (SNSPD) system. The detector is built around a 1K cryostat design, enabling the operation of our WSi superconducting nanowire single photon detectors (SNSPDs). Currently, the system hosts two SNSPDs, optimized for 1550 nm. Our compact and robust detector packaging allows shipping of the SNSPDs inside the cryostat without noticeable degradation of the SNSPD performance over many temperature cycles. In the future, we will equip the cryostat with SNSPDs optimized for ~850 nm, 1064 nm and ~1310 nm. The system is fully automated and turn-key with a user manual. In addition, the operator does not require extensive cryogenic experience or knowledge. This facility is intended for use as internally as well as comparisons between NIST and other NMIs. [POC: Thomas Gerrits, Thomas.Gerrits@nist.gov]

Improvements in the design of thermal-infrared radiation thermometers and sensors
Most commonly used radiation thermometers operate in the 8 µm to 14 µm wavelength range to measure objects which are near or at room temperatures including human body temperatures. NIST has recently reported the construction and characterization of a new thermal infrared radiation thermometer design which implements the size-of-source effect reduction designs of visible and near-infrared radiation thermometers. This radiation thermometer is constructed with zinc-selenide (ZnSe) lenses for collecting and focusing the thermal-infrared radiation onto a pyroelectric detector. The pyroelectric detector has a window with a 8 µm to 14 µm filter for spectral selection, and the detector and preamplifier are packaged into a hermetically sealed container and temperature stabilized. Critical optical elements such as the field stop, Lyot stop, collimating lens, and detector, are placed inside a thermally stabilized assembly that is controlled using thermo-electric coolers (TEC) and thermistors. The assembled radiation thermometer is calibrated using both variable-temperature fluid-bath and heat-pipe blackbodies from -45 °C to 75 °C and the use of a modified-Planck function and these blackbodies. This new design, which does not need cryogenic cooling, demonstrates sub millikelvin temperature measurement resolution with few millikelvin, weeks-long or months-long stable operations while measuring room-temperature objects. This design can be used for long-term monitoring of sea- or land-

surface temperatures or for calibration and validation of ambient-temperature blackbodies. [POC: Howard Yoon, howard.yoon@nist.gov]

Establishment of Refractometry System with Diffraction-Limited Accuracy from 0.14 μm to 14 μm
NIST has made fully operational a unique refractometry system achieving diffraction-limited index measurements for wavelengths from the vacuum ultraviolet at 0.14 to the mid-infrared at 14 μm, near room temperature. For measurements through this wavelength range, with samples having sufficiently high sample homogeneity and surface flatness, all other components of uncertainty have been reduced below the size-limited diffraction components, giving 1-sigma uncertainties ranging from 5×10^{-7} at the shortest wavelengths to 5×10^{-5} at longest wavelengths for prism samples with surfaces of about 1 cm on a side. These capabilities have recently been focused on developing a publicly-disseminated index database for technologically important IR materials, starting with Ge and ZnSe. Measurements of high-quality customer samples with appropriate geometry can be made at these accuracies through the NIST measurements services. [POC: John Burnett john.burnett@nist.gov]

Structured Illumination Mueller Matrix Imaging
NIST has developed a new optical imaging method that combines structured illumination imaging with polarimetric imaging in a manner that may be particularly useful for biomedical and other turbid media diagnostics. In structured illumination (SI) imaging, an irradiance with a given spatial frequency is incident upon the medium, and the reflected radiance modulations are imaged. SI imaging shows potential for discriminating tissues with different scattering lengths and depths in the tissue. In Mueller matrix (MM) imaging the polarimetric characteristics of the scattering processes are probed. MM imaging has been shown to be particularly useful for characterizing tissue orientation and alignment. By combining the two imaging methods, NIST has developed a new method that not only differentiates tissues by scattering length, orientation, and alignment simultaneously, but increases the sensitivity of the polarimetric imaging by increasing the signal from singly scattered light. [POCs: Thomas Germer, thomas.germer@nist.gov; Maritoni Litorja, maritoni.litorja@nist.gov]

Gain Calibration of Current-to-Voltage Converters
Current-to-voltage converters (CVCs) are used in many photometric and radiometric applications. To achieve small uncertainties and agreement between detectors, calibration uncertainties of CVCs on the order of 0.005 % (k=2) are required. NIST developed a calibration service for CVCs in the range of 100 pA to 1 mA DC photocurrents. The calibration service is based on two transimpedance amplifiers that have been designed such that the gain resistors can be calibrated in situ. The transimpedance amplifiers are used to calibrate stable low current sources which are used to calibrate test units. The calibration of test unit involves 21 different current levels on each gain level. [POCs: Thomas C. Larason, thomas.larason@nist,gov; Cameron Miller, c.miller@nist.gov]

Full four-dimensional and reciprocal Mueller matrix bidirectional reflectance distribution function of sintered polytetrafluoroethylene

NIST measured the Mueller matrix bidirectional reflectance distribution function (BRDF) of a sintered polytetrafluoroethylene (PTFE) sample over the scattering hemisphere for six incident angles (0◦ to 75◦ in 15◦ steps) and for four wavelengths (351 nm, 532 nm, 633 nm, and 1064 nm). The data for each wavelength were fit to a phenomenological description for the Mueller matrix BRDF. This description is designed to be complete, to obey the appropriate reciprocity conditions, and to provide a full description of the Mueller matrix BRDF as a function of incident and scattering directions for each wavelength. This dataset and its parameterization provide a comprehensive on-demand description of the reflectance properties for this commonly used diffuse reflectance reference material over a wide range of wavelengths. [POC: Thomas Germer, thomas.germer@nist.gov]

Characterization of New Planar Radiometric Detectors using Carbon Nanotube Absorbers under Development at NIST
Carbon nanotube technology, in conjunction with silicon micro-fabrication techniques, has enabled NIST to develop planar radiometric detectors, which has led to the establishment of a new generation of primary standards. The goal is to develop compact, fast, and easy-to-use, radiometric calibration systems, spanning the wavelength spectrum from the ultraviolet to the THz region in a single detector, suitable for use with both coherent and incoherent sources, and encompassing open beam and fibre-coupled modes of operation, with utility beyond that of the laboratory environment. Successful comparison of scales derived from two new table- top systems, to existing radiant power and optical fibre power scales, traceable to SI has been completed. [POCs: Solomon I. Woods, Solomon.woods@nist.gov,; John H. Lehman, John.lehman@nist.gov; Igor Vayshenker, Igor.Vayshenker@nist.gov]

Detector-based Array Spectrometer Calibration Methodology
NIST developed a detector-based method to realize the spectral irradiance scale or spectral radiance scale on an array spectroradiometer using a 1 kHz pulsed tunable OPO laser. The preliminary result shows the new detector-based scale agrees with the conventional source (FEL lamp) based scale, but the detector-based scale is expected to have significantly smaller uncertainties due to its single-step, straightforward realization approach. [POCs: Yuqin Zong, Yuqin.zong@nist.gov; Cameron Miller, c.miller@nist.gov]

Luminous Intensity Distribution Measurement using an Integrating Sphere
NIST developed a differential goniophotometer by using a fisheye camera on a conventional integrating sphere to measure the intensity distribution of a test light source. The differential goniophotometer is a one-shot, fast goniophotometer without any moving parts. [POC: Yuqin Zong, Yuqin.zong@nist.gov;

LED Based Luminous Intensity Standards
NIST have conducted research for many years on developing LED based transfer standards to disseminate scales to industry. The first type of LED standards has been developed, which is based on 3 mm × 3 mm large-chip specialty LEDs. The measurement results show the new LED standards have superior short-term and long-term stabilities measured in years. [POC: Yuqin Zong, Yuqin.zong@nist.gov;

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.

NIST is working to replace the liquid-cooled open beam cryogenic radiometer with a mechanically cooled fiber-coupled cryogenic radiometer.

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.

NIST is considering the needs of the gravitational wave measurement community and measurement of laser power near 1 W and 1047 nm

Next Generation Source Standards - The conventional incandescent lamps, used as primary transfer standards by NMIs to disseminate photometry and radiometry scales to industry, have been discontinued. The new LED based transfer standards are in urgent needs. Developing these new standards require collaboration between NMIs scientists and industry experts.

Reference Data and Reference Materials to Facilitate the Sourcing and Specification of Optical Materials within the International Supply Chain. Optical instrument manufacturers are challenged by the variable quality of the UV/optical/infrared materials and components sourced within the international supply chain. High quality reference data (index of refraction, transmittance, reflectance, nonlinear optical coefficients, scatter) and standard reference materials are required to improve and validate the specifications of UV/optical/infrared materials throughout the international supply chain. [CCPR can promote the development of high-quality data on UV/optical/infrared materials and encourage the development through measurement comparisons of high-quality infrared index of refraction measurements.]

Accurate Measurements in Complex Environments. Customers/stakeholders of NIST Measurement Services are not seeking calibrations/standards with lower uncertainties, but rather desire low-cost standards/calibrations that allow accurate photometric or radiometric measurement in a complex or non-pristine environment: space/aerospace (satellites, CubeSats, UAVs), ocean (optical buoys), factory (laser welding, additive manufacturing, process monitoring), astronomical facility, clinic/operating room, surface monitoring stations, etc. [Needed: International comparisons that represent more closely how NMI calibrations/standards are actually delivered to the customers and how the customers actually use these standards.]

Improved Optical Properties of Materials Measurements to Support Laser-Based Advanced Manufacturing. The increasing use of high-power lasers in advanced manufacturing for the cutting and welding of materials and for the additive manufacture of parts requires high-quality optical properties of materials data on materials at high temperature, in the molten state, and as powders. Such data would facilitate the development and improvement of processes and process monitoring tools. Also needed are traceable measurements of laser optical power, laser beam mode quality, and irradiances at high laser intensities. [CCPR should lead the development of intercomparisons of materials optical properties at high temperatures, including the molten state, and high intensity laser measurements].

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

   Fiber-coupled absolute radiometry at communications wavelengths (1310, 1550, “L-band,” etc.)

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?***

   NIST is actively collaborating with other NMIs

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

   N/A

8. ***Bibliography of radiometry and photometry papers of your laboratory since the last CCPR (September 2016)?***

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