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

Questionnaire on activities in radiometry and photometry

Reply from: National Institute of Standards and Technology (NIST)

Delegates: Marla Dowell, Gerald Fraser, Maria Nadal (SIM), Yoshi Ohno

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

a. Broad-band radiometric quantities

Pyroelectric Standard Detectors for Broadband Radiometric Measurements of LEDs. Currently, either spectral radiometric measurements or broadband photometric measurements are used for LED evaluations. The broadband photometric measurements are based on the CIE standardized V(λ) function, which cannot be used in the UV range and leads to large errors when blue or red LEDs are measured in the wings of this function where the realization is always poor. Reference irradiance meters with spectrally constant response and high-intensity LED irradiance sources were developed at NIST to implement the earlier introduced broadband radiometric LED measurement procedure. Using a detector with spectrally constant response, the broadband radiometric quantities of any LEDs or LED groups can be simply measured with low uncertainty without using any source standard. In order to perform these detector-based calibrations, extremely-low-noise pyroelectric radiometers have been developed with an order of magnitude better spectral response-flatness than filtered-Si detectors. Integrated irradiance of UV and blue LED sources have been measured using the spectrally flat standard (reference) pyroelectric irradiance meters. For validation, the broadband-measured integrated irradiance of several LED-365 sources were compared with the spectrally-determined integrated irradiance derived from an FEL spectral irradiance lamp-standard. The disagreements were within 1.2 %. Integrated responsivity transfer has been performed from the reference pyroelectric irradiance meter to transfer standard and field UV irradiance meters. The integrated irradiance measurement uncertainties of LEDs are being decreased to a few tenths of a percent level (k = 2). [POC: George Eppeldauer, george.eppeldauer@nist.gov]

Silicon-Based Trap Detector with Long Wavelength Infrared Coverage. A new infrared trap detector has been developed and successfully tested, exhibiting quantum efficiency above 90 % for much of the range from 4 µm to 24 µm. The trap is composed of two arsenic-doped silicon (Si:As) detectors held in a wedge-shaped geometry by a mount with a 1 mm entrance aperture. By design, light entering the trap in an f/4 beam must execute at least 7 bounces before escaping the trap. The individual Si:As blocked-impurity-band (BIB) detectors exhibit significant responsivity from 2 µm to 28 µm and low noise, but have two shortcomings which are improved by a trapping arrangement. First, the detection efficiency of an individual detector is limited below 60 %, mostly due to the surface reflectance of silicon and incomplete absorption across a single detector. The trap can boost detection efficiency to near unity over wavelengths away from silicon absorptions. Second, single Si:As detectors suffer from etalon effects which can cause spectral oscillations of 10 % or more in the responsivity. The trap arrangement reduces the etalon amplitude by almost a factor of 10, resulting in oscillations near 1 % for approximately collimated sources. The Si:As BIB detector trap can serve as a secondary standard detector from 2 µm to 30 µm, with very high quantum efficiency from 4 µm to 24 µm. Although the trap must be operated at a temperature near 10 K, its high speed and wide spectral coverage make it an ideal detector for long wavelength

Fourier transform spectrometer (FTS) measurements. [POC: Solomon Woods, solomon.woods@nist.gov]

b. Spectral radiometric quantities

Laser Power Calibrations Extended to 10 kW. In late 2014, NIST launched a new measurement service for laser power that extends the upper range for NIST measurements to 10 kW, from the previous high-power limit of 1.5 kW. The service will allow NIST to meet the growing application of high-power lasers in a variety of manufacturing and defense applications, including the cutting and welding of metals in manufacturing. Researchers used the new system recently to calibrate a company's power meter at 5 kW with a $k = 2$ uncertainty of about 1%, which meets the accuracy requirements for the majority of manufacturing applications. Compared to traditional welding methods, laser welding is lower cost and has a smaller environmental footprint. Lasers could potentially be used in 25% of industrial welding applications, which could result in significant savings for U.S. manufacturers. [POC: Joshua Hadler, Joshua.hadler@nist.gov]

Multikilowatt optical power comparison at BAM Berlin in support of laser materials processing and welding. Laser welding and materials processing are growing fields offering greater efficiencies and reduced environmental impact than traditional approaches. However, at laser powers of multiple kilowatts, traditional power meters may prove too cumbersome to allow in-situ measurements down to the necessary few percent uncertainty levels. With the support of the NIST Strategic Emerging Research Initiative funds, Drs. Paul Williams, Brian Simonds, and John Lehman have produced a prototype optical power meter based on radiation pressure which allows agile and accurate characterization of multi-kilowatt laser power without the large thermal mass and slow response of traditional high power techniques. Recently, these NIST researchers took the prototype radiation pressure power meter (RPM) to The Federal Institute for Materials Research and Testing (BAM) in Berlin to perform power measurement comparisons on BAM's 20 kW welding laser. The RPM uniquely allows the welding-laser's optical power to be measured simultaneously by two power meters (NIST's RPM and BAM's traditional power meter). Comparative measurements were made for laser powers ranging from a few hundred watts up to 20 kW. The comparison included the first-time use of a highly-reflective GaAs distributed Bragg reflector made by Dr. Ari Feldman of the NIST Communication Technology Laboratory. The mirror and the scale performed exceptionally well. The next stage of the ongoing NIST-BAM collaboration includes comparisons of the BAM optical power meter at NIST. [POC: Paul Williams, paul.williams@nist.gov]

New Facility under Development for Optical Properties of Materials Measurements at High Temperatures. TEMPS (Temperature and Emittance of Melts, Powders and Solids) is a new testbed facility under construction at NIST to address a critical measurement problem in powder-based additive manufacturing. TEMPS is designed for the accurate measurement of material emittance, reflectance and true surface temperature of metal powders as they are fused and is aimed at the establishment of measurement traceability and best practices for non-contact thermometry in additive manufacturing. This will enable improvements in the reproducibility and control of manufacturing processes. Knowledge of the optical properties of materials such as spectral emittance and reflectance is essential for non-contact thermometry, heat transfer modeling, and prediction of directed energy source coupling with targets (for example, in laser-based material processing and manufacturing). [POCs: Steven Grantham grantham@nist.gov; Sergey Mekhontsev snm@nist.gov, Leonard Hanssen

hanssen@nist.gov.]

Reflectance Factor Measurements (0°/45°) Extended into the Shortwave Infrared. A capability to measure the 0°/45° reflectance factor scale in the shortwave infrared (SWIR) from 1100 nm to 2500 nm has been realized for applications primarily in Earth remote sensing. The design, characterization, and the demonstration of a four-stage, extended indium-gallium-arsenide radiometer to perform reflectance measurements in the SWIR have been previously undertaken. This radiometer has now been incorporated into the national reference reflectometer called STARR for Spectral Tri-function Automated Reference Reflectometer. The measurements have been validated and an uncertainty budget has been established. The capability has been applied to the measurement from 250 nm to 2500 nm of three different diffuser materials, a ceramic made primarily of aluminum oxide and sintered and pressed polytetrafluoroethylene (PTFE). The 0°:45° spectral reflectance factors for these materials have been reported and compared to their respective 6°:diffuse spectral reflectance factors. All three materials exhibited reflectance properties considered desirable for reflectance standards, namely that the material is spectrally flat with high reflectance values. Choice of material for a reflectance standard then depends on factors such as cost, application, and environmental conditions. [Contacts: Catherine Cooksey, cooksey@nist.gov; David Allen, david.allen@nist.gov; Benjamin Tsai, benjamin.tsai@nist.gov and Howard Yoon, howard.yoon@nist.gov]

Advanced Electro-optical Measurements of Photovoltaic Devices. NIST's PV characterization laboratory has been developed to measure the electrical performance and optoelectronic properties of solar cells and modules. This facility consists of a monochromator-based dual light source system, an LED-coupled integrating sphere source, a tabletop solar simulator with concentrator optics, a spectroradiometer calibration facility, an RF-based photoconductivity decay apparatus for charge carrier lifetime studies, and an LED-based cell nonlinearity measurement setup based on a combinatorial flux addition method. The monochromator system along with the LED integrating sphere source is used to obtain the absolute irradiance-mode spectral responsivity of solar cells. This allows us to calibrate standard World Photovoltaic Scale (WPVS) reference solar cells for their short circuit current output under the standard reporting conditions. To-date, intercomparison measurements with a variety of national and international metrology laboratories have been performed, and agreements to within 1 % have been documented. The charge carrier lifetime facility uses a non-contact, non-destructive technique, coupled with monochromatic light sources, to determine the spectral dependence of the effective charge carrier lifetimes. [POC: Behrang Hamadani, bh@nist.gov]

First International Comparison of Single Photon Detectors. In December 2014, NIST Fellow Dr. Sae Woo Nam and Dr. Ingmar Mueller of the Physikalisch-Technische Bundesanstalt (PTB) performed the first international comparison of single photon detectors with the PTB Metrology Light Source (MLS). The MLS is a well-characterized synchrotron source traceable to the PTB cryogenic radiometer, the German primary standard for optical power measurements. In this comparison, the PTB MLS was used as a calibrated attenuated light source to bridge the gap from classical to the photon counting radiometry for the characterization of single photon detectors. An alternate NIST approach to calibrating single photon detectors has been previously demonstrated for NIST single photon detectors as well as commercially manufactured single photon detectors.[1] In December 2014, the NIST calibration approach was demonstrated in the inaugural comparison of PTB and NIST single photon detectors. The NIST and PTB comparisons were undertaken in preparation for an upcoming BIPM pilot study now underway among NMIs on the detection efficiency of single photon detectors. [POC: Sae Woo Nam; sawwoo.nam@nist.gov]

Pilot Study for the Calibration of Single Photon Detectors. Following the first international comparison of single photon detectors with the Physikalisch-Technische Bundesanstalt (PTB) Metrology Light Source (MLS) discussed above, an international pilot study for the calibration of single photon detectors has begun. This pilot study involving a number of national metrology institutes (NMI) and a number of circulating detectors-under-test, will provide a snapshot of the current detector calibration capabilities of all participating NMIs in the single-photon regime. The study involves calibration of free-space and fiber-coupled single-photon detectors. The free-space detector measurement conditions have been defined, although the mechanisms to tie the calibration to the SI are left up to the NMIs. The fiber-coupled detector measurement conditions are currently being discussed and developed. For this second round of comparisons, NIST is providing a fiber-coupled superconducting nanowire detector system, which has been built for this pilot study and can serve as a transfer standard detector system at NIST after the study is finished. The results of this pilot will be used to plan improvements in measurement capabilities and to develop best approaches for their dissemination. [POC: Thomas Gerrits, thomas.gerrits@nist.gov]

Recent Applications of Transition Edge Sensors in Metrology and Fundamental Physics. Transition Edge Sensors (TES) are extraordinary detectors. Their capabilities to detect single photons with near unity efficiency and to resolve the number of photons with unprecedented accuracy put them in a class by themselves. Two recent results have taken advantage of these capabilities. The first result demonstrates an *in situ* calibration of an attenuator on the front of a TES, which enables an extension of the dynamic range of the detector beyond its already standout capability. This is a useful step in developing a high dynamic range measurement capability, important in calibrations spanning from the single photon to conventional radiometric regimes.

The second recent result used these detectors to make a landmark test of local realism, an issue raised by Einstein concerning what he perceived as a shortcoming of quantum mechanics.[2] Experimental tests local realism began over 40 years ago, but have always suffered from loopholes due to poor detection performance. Consequently, a definitive test of this aspect of quantum mechanics has been out of reach. It is only with the development of the TES detectors and another type of cryogenic detector, both developed by NIST Fellow Dr. Sae Woo Nam, that the definitive test was finally implemented in 2015. That test, led by Krister Shalm of NIST, demonstrated that the local realistic theory that Einstein hoped would ultimately provide a better description of nature than quantum mechanics has been ruled out. [POC: Sae Woo Nam, saewoo.nam@nist.gov]

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[1] Note that NIST previously demonstrated agreement to 0.14% ($k = 1$) in an intercomparison between two absolute primary standard methods for the calibration of single-photon detectors. [S.V. Polyakov and A. L. Migdall, Optics Express 15, 1390-13407 (2007)].

[2] In a third application of a TES, [I.A. Burenkov and S.V. Polyakov, to be submitted to *Optics Express*], measured a faint light source with brightness of 0.03 photons/sec at an absolute uncertainty of 0.004 photons/sec, the best absolute uncertainty ever achieved. The authors' measurements demonstrate a new level in faint light source intensity measurement by providing better accuracy in a 100 times shorter measurement window than the Hubble Space Telescope extremely deep field data.

New Facility for the Calibration of Infrared Detectors Realized. A new facility, called the NIST Infrared Spectral Comparator Facility (IR-SCF), has been developed for the calibration of infrared detectors and is being made available to customers through NIST Measurement Services. The IR-SCF facility extends present ultraviolet and visible calibration services, performed using UV-SCF and VIS-SCF, respectively, into the infrared to wavelengths as long as 25 micrometers. A wavelength of 25 micrometers corresponds to approximately 12 THz. The 25 micrometer limit is at the edge of the far-infrared region of the spectrum, defined as 25 micrometers to 300 micrometers by astronomers. This new detector calibration capability is made possible by implementation of a monochromator-based spectrally tunable radiation source and development of effective optical geometries to obtain a higher calibration accuracy with standard IR detectors. New low-noise pyroelectric detectors were specially developed for this application. [POC: George Eppeldauer, george.eppeldauer@nist.gov; Vyacheslav Podobedov, vyacheslav.podobedov@nist.gov]

New Reference Instrument for the Diffuse Optical Properties of Materials. Diffuse optical properties are critical parameters for understanding the interaction of light with tissues and other optically diffusive materials. NIST has developed a national reference instrument dedicated to the measurement of the diffuse optical properties of samples at room temperature. A double integrating sphere setup was implemented to measure the hemispherical reflectance and transmittance of solid and liquid samples. A custom model-based analysis program has been developed to determine the optical coefficients with the associated uncertainties. For further details, see "Development of traceable measurement of the diffuse optical properties of solid reference standards for biomedical optics at National Institute of Standards and Technology," P. Lemaillet, J.P. Bouchard, D.W. Allen, *Applied Optics* **54** (19), 6118-6127. [POC: David Allen, david.allen@nist.gov]

New Beamline Installed on the NIST Synchrotron Ultraviolet Radiation Facility (SURF III). A new beamline has been installed on the NIST Synchrotron Ultraviolet Radiation Facility (SURF III). The new facility was designed to allow continuous radiometric and optical properties measurements from 4 nm to 400 nm, eliminating a previous measurement gap in photodetector calibrations between 92 nm and 116 nm. Continuous photodetector calibrations with uncertainties < 1 % (compared to as high as 8 % previously) are possible. Reflectometry measurements previously limited to between 11 nm and 35 nm can now be performed over the full 3 nm to 400 nm range. The beamline was initially installed at Brookhaven National Laboratory and was moved to NIST following the shutdown of the vacuum ultraviolet (VUV) ring of the National Synchrotron Light Source (NSLS) . A technical description of X24C as it was installed at NSLS can be found at http://beamlines.ps.bnl.gov/beamline.aspx?blid=X24C. [POCs: Jack Rife, jack.rife@nist.gov; Edward Hagley, edward.hagley@nist.gov; Alex Farrell, alex.farrell@nist.gov; Robert Vest, robert.vest@nist.gov]

Diffraction Corrections at the NIST Synchrotron Ultraviolet Radiation Facility (SURF III). A detailed theoretical and experimental study was undertaken of diffraction effects and approximations associated with the use of the standard Schwinger equation for synchrotron radiation on the radiometric measurements provided by Beamline 2 of the NIST Synchrotron Ultraviolet Radiation Facility (SURF III). Beamline 2 was specifically designed to calibrate space-based instruments that measure the Sun, using the Schwinger equation together with knowledge of the electron energy, beam current, and beam radius and various geometric factors to provide the absolute magnitude of the incident flux on the radiometer under calibration. The nearly 18 m distance between the electron storage ring tangent point and the measurement location together with the multiple apertures along the optical pathlength suggest that diffraction effects could play a significant role on Beamline 2 measurements. The present study led to a more exact theoretical formulation for the absolute flux emitted by SURF III at a function of wavelength, angle, and tangent point-radiometer distance, that explicitly incorporates the radiofrequency fuzz applied to the electron bunches to improve beam lifetime and reduce amplitude noise on the radiation, and its validation against measurement. Diffraction effects were determined to be a significant, even in the ultraviolet, increasing the magnitude of the incident radiation at the radiometer aperture by approximately 1 % at 334 nm. [POC: Eric Shirley, eric.shirley@nist.gov]

Intense laser-driven plasma light sources improve optical radiation measurement services. Inexpensive ultraviolet radiation sources based on laser-driven plasmas provide intense levels of broadband ultraviolet radiation from 200 nm to 450 nm and beyond, without the high-voltage hazards of laboratory-built argon arc sources. A laser-driven plasma source when combined with a supercontinuum fiber-laser source, can furnish continuous optical radiation over the full reflected solar band (200 nm in the ultraviolet to 2400 nm in the infrared), critical for the calibration and characterization of materials and sensors important in Earth remote sensing for climate research, weather forecasting, and land-use studies. A laser-driven plasma source was successfully demonstrated for precision optical radiation measurement in the Sensor Science Division Ultraviolet Spectral Comparator Facility (SCF) used to calibrate ultraviolet radiation detectors. More recently, a laser-driven plasma source was incorporated into the Division's Robotic Optical Scattering Instrument (ROSI) used in the measurement of the reflectance of materials and standards as a function of sample illumination and viewing angles, and in the Division's Reference Transmittance Facility, used for measurement of various neutral density and spectral filters. The laser driven plasma source is coupled with a monochromator to provide a spectrally tunable ultraviolet light source. The laser-driven plasma source with monochromator provides tens to hundreds of times the output power of a traditional lamp-monochromator light source in the ultraviolet wavelength range. Together, the laser driven plasma source and supercontinuum source provide tunable optical radiation from 200 nm to 2400 nm for goniometric reflectance and transmittance measurements, with fluxes ranging from 10's of microwatts in the UV to 2 milliwatts in the infrared. The high source power will enable reflectance measurements over a wider range of geometries and for lower reflectance samples than currently performed and increase the dynamic range and lower the uncertainty for measurements of neutral density filters below 400 nm. [POCs: Heather Patrick, heather.patrick@nist.gov; Clarence Zarobila, clarence.zarobila@nist.gov; Catherine Cooksey, catherine.cooksey@nist.gov]

Wide-Field-of-View Fisheye Camera Advances the Application of Integrating Spheres in Photometry & Radiometry. Integrating spheres are widely used in radiometry and photometry to make optical radiation measurements. Integrating spheres are hollow spheres that are coated on the inside with a highly reflective, highly scattering material such as barium sulfate, and have one or more apertures for coupling light into or out of the sphere. A properly designed integrating sphere when illuminated by the light from a lamp or a laser will provide a spatially uniform source of light at its exit apertures due to the many reflections that the light undergoes before it exits the sphere. This uniform source of light can be used to calibrate radiometers and photometers. The installation of an inward-looking, wide-field-of-view fisheye camera into the wall of the sphere, provides a new approach to measure the non-uniformity of the integrating sphere, an often dominant source of uncertainty for many optical radiation measurements. The camera installation also allowed the demonstration of a new approach to measure the absolute angular intensity distribution of the light source, an important measurement in photometry, particularly for solid-state lighting components. [POC: Yuqin Zong, yuqin.zong@nist.gov, x2332]

High Accuracy Refractometer Extended to Wavelengths in the Mid-Infrared. The NIST UV/vis refractometer facility has been upgraded to enable high-accuracy index measurements for wavelengths out to 15 µm. The diffraction-limited, minimum-deviation-angle design enables index measurements with an absolute accuracy of < 0.0001% in the UV, scaling to about 0.005% at 15 µm, at transmitting wavelengths of materials of sufficient size and quality. Measurements of optical materials at this accuracy are required for the latest-generation design of precision optical systems ranging from semiconductor lithography tools in the deep UV to satellite-based infrared telescopes. A database of the UV-IR indices of the most important optical materials, at higher-accuracy than previously available, is being developed and publicly disseminated. Measurements of customer materials with appropriate geometry can be made at these accuracies, depending on the material quality, through NIST measurements services. [Contact: John Burnett john.burnett@nist.gov.]

New Facility for Spectral Radiance and Radiation Thermometry Calibrations. A new facility for calibrating spectral radiance sources and radiation thermometers has been nearly completed at NIST. This facility consists of a double prism-grating monochromator with photomultiplier tube, Si and extended InGaAs detectors for spectral radiance measurements from 200 nm to 2500 nm with a variable-temperature blackbody standard whose temperature can be varied from 800 K to 3200 K. Two NIST-designed, detector-based radiation thermometers with multiple, spectral filters are used to determine thermodynamic temperatures of the variable-temperature blackbody. Integrating sphere sources and other radiance standards are calibrated using the blackbody with measured temperatures. The radiation thermometers can also be calibrated using fixed-point cells which are placed inside the blackbody which is then used as a furnace for operating fixed-point cells. The spectroradiometer and radiation thermometers are mounted on an optical table with a total length of travel of 6 m using open-faced linear motors and absolute linear encoders for determining positions to an uncertainty of 2.5 µm over the entire length of travel.
[POCs: Howard Yoon howard.yoon@nist.gov, Charles Gibson Charles.gibson@nist.gov]

International comparison of THz laser power measurements. The first international comparison of THz laser power measurements took place at the Physikalisch-Technische Bundesanstalt (PTB). Dr. Andreas Steiger of PTB-Berlin hosted the comparison with visiting scientists Dr. John Lehman of the National Institute of Standards and Technology (NIST) and Drs. Yuqiang Deng and Qing Sun from the National Institute of Metrology (NIM) of China. The measurement results from each participant agreed very well with the reference value and to each other within the stated uncertainties. Unlike earlier comparisons, this one was undertaken in a relatively short period. Organized in a new manner, the participants met in Berlin to compare their standards at one place at one time. The measurement infrastructure such as the laser source and other instrumentation provided by PTB were critical to meeting the proposed schedule. Measurements of THz power are important for a variety of technical areas including climate science, security, medicine, communications and manufacturing. This milestone will greatly benefit commercial development of instrumentation and sensors for remote sensing, THz imaging, high-speed telecommunications and time-domain spectroscopy. [POC: John Lehman, john.lehman@nist.gov]

(c) photometric quantities

NIST photometry bench being upgraded. NIST has a photometry bench that has been used for over 25 years to perform calibrations for absolute outputs of light sources and to quantify the responses of various photometers and detectors. Increased demand for calibration services and for lower uncertainties has motivated NIST to build a new, improved photometry bench. The new bench is halfway through its development. The bench follows the shape of an H where one side is a stage that will move various sources including lamps, sphere sources, and flashing light sources into the optical axis. The opposite side is a stage that will move various detectors (illuminance meters and luminance meters among others) into the optical axis. The detector stage will have the ability to move along a supporting rail system automatically. It is anticipated that the improvements in the bench will allow NIST to implement a SI candela scale with an expanded uncertainty of 0.25 % (k = 2). [POC: Cameron Miller, c.miller@nist.gov; Yuqin Zong, yuqin.zong@nist.gov; Maria Nadal, maria.nadal@nist.gov; John Curry, john.curry@nist.gov]

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

Measurement Assurance Program (MAP) Assesses industry's Ability to Measure the Performance of Solid-State Lighting Products. NIST in partnership with the Department of Energy and the Environmental Protection Agency Energy Star program developed a MAP in solid state lighting measurements to advance national and international capabilities for the testing of solid-state lighting products in support of the rapid growth in commerce in this area, driven by energy efficiency gains, long product lifetimes, and decreasing product costs. The first version of the MAP program in this area was made available from January 2010 to December 2014, and included 118 labs distributed as follows: US (49), China (45), Taiwan (9), Korea (4), Canada (3), and one each from The Netherlands, Brazil, Singapore, India, Malaysia, Hungary, Italy, and Germany. The MAP used a set of solid-state lighting products to test laboratory capabilities to perform the series of photometric and electrical measurements described in the Illuminating Engineering Society (IES) standard LM-79-08, "Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products," developed under NIST technical leadership. A report on the results from this study, accepted on May 12, 2016 for publication in the IES journal LEUKOS, demonstrates that labs generally agree within ±4% (k = 2) on measurements for total luminous flux and luminous efficacy, with the latter number being a critical measure of the energy efficiency of a product. Larger discrepancies were seen in some of the accompanying electrical measurements, with the specific causes still being studied. With the first solid-state lighting MAP program now completed, the Sensor Science Division started a second such program using a new set of artifacts to more accurately represent products now being offered in the rapidly advancing solid-state lighting market. [POCs: Maria Nadal, maria.nadal@nist.gov; Benjamin Tsai, benjamin.tsai@nist.gov]

NIST develops an in-house capability to grow vertically aligned carbon nanotubes for radiometry applications. Vertically aligned carbon nanotubes (VACNTs) are one of the blackest substances available. They are a key technology for radiometry applications that rely on conversion of light to heat for precise radiometric power and energy measurements. As part of an effort to develop new radiometric standards for visible laser power measurements, Nathan Tomlin and Chris Yung along with Mark Keller have recently demonstrated in-house growth of VACNTs. When this process is fully developed, NIST will have the capability to manufacture micro-fabricated laser radiometers completely in-house. In-house development of next generation radiometric standards will be accelerated from months to days, providing new opportunities for NIST for collaboration with the radiometric standards community, and enable research into the applicability of VACNTs for standards over a wide range of power and wavelength, as well as harsh environments such as space. (POC: Michelle Stephens; michelle.stephens@nist.gov]

SIRCUS Study of Virus Deactivation by Ultraviolet (UV) Radiation Published. UV radiation is increasingly being used to deactivate pathogens during water treatment, in large part because it reduces the amount of chemicals required during the treatment process. Commercial opportunities in this area have led to significant industry innovation in UV lamp technology, including lamps with different spectral outputs in the UV. In an effort to better understand the wavelength dependence of the UV deactivation of pathogens, the University of Colorado, Tetra Tech, and the Water Research Foundation (WRF) entered into a collaboration with NIST to use the NIST Traveling-SIRCUS capability to measure the wavelength dependent dosages of UV radiation required for the deactivation of pathogens. In the present investigation the virus MS2 was chosen. This virus has an RNA-based genome and is used as a model for cryptosporidium and adenovirus. The effort required deploying Traveling SIRCUS to Tetra Tech in Vermont to expose the MS2 phage virus to accurate dosages of UV radiation between 210 nm and 290 nm. The measurements revealed that the primary deactivation method was RNA damage and that for a fixed dosage level the shortest wavelength used (210 nm) was generally the most effective, with approximately an order of magnitude difference between 290 nm and 210 nm. For further details see S.E. Beck et al., "Comparison of UV-Induced Inactivation and RNA Damage in MS2 Phage across the Germicidal UV Spectrum," *Applied and Environmental Microbiology* **82**, 1468 (2016). [POC: Tom Larason, thomas.larason@nist.gov]

Laser-Based Manufacturing of Photovoltaic Cells. The Laser Radiometry Project in Quantum Electronics and Photonics Division, in collaboration with researchers from the University of New South Wales (Sydney, Australia), has demonstrated three processes that should improve the cost and efficiency of mass-manufactured photovoltaic (PV) cells. The collaboration leveraged the lasers available in NIST's laboratories with the material fabrication and analysis capabilities of the university. The first process involves using laser heating to crystalize amorphous silicon substrates. Amorphous silicon is a less expensive material from which PV cells can be made, as compared to crystalized silicon, but which produces cells of lower efficiency. The researchers demonstrated liquid-phase crystallization of thin-film silicon on glass, a technology that could eliminate several costly production steps. The second process involves using lasers to produce deep dopant diffusion in the crystalline silicon in a matter of seconds, a process that currently takes hours in industry. Finally, pulsed and continuous wave (CW) lasers were used to develop next-generation quantum dot-based solar cell technology, which promise much higher efficiency than current technologies. The fast heating and cooling rates (> 1010 K/s) involved with pulsed laser excitation enable material modification unattainable by other means. This fact was exploited to improve dopant activation, which is a current technological barrier. CW laser processing was also investigated for rapid nucleation of quantum dot films, giving researchers greater control over the process, as well as achieving nucleation in seconds as opposed to hours. [POC: Brian Simonds, brian.simonds@nist.gov]

A simple, robust design for an optical frequency comb described. A recent invited publication serves as a tutorial for building a robust optical frequency comb from low-cost commercially available components [L. C. Sinclair, J.-D. Deschênes, L. Sonderhouse, W. C. Swann, I. H. Khader, E. Baumann, N. R. Newbury, and I. Coddington, "A compact optically coherent fiber frequency comb," *Rev. Sci. Instrum.* **86**, 081301 (2015).] A frequency comb is the optical spectrum formed by an ideal regular train of optical pulses and comprises a series of repeating, equally spaced spectral lines. Applications that can benefit from a compact, robust comb include 1) precision spectroscopy of greenhouse gas concentrations in real world environments as well as manufacturing settings, 2) sub-fs level timing synchronization of timing/navigation networks, 3) calibrated 3D imaging in noisy manufacturing environments using comb sources for laser radar, and 4) broadband optical calibration sources for astronomical telescopes. The NIST article describes the design, fabrication, and performance of a laptop-sized frequency comb that can operate outside of a laboratory environment. The goal of the article is to enable other research groups in the world to build their own high-performance frequency combs and explore additional applications of this versatile laser tool. [POC: Laura Sinclair; laura.sinclair@nist.gov]

NIST continues to supports the radiometric calibration of U.S. weather/climate satellite sensors. NIST provided calibration support for the infrared and optical sensors for several satellite missions from the infrared through the ultraviolet, including for space weather applications. Efforts included collaboration with instrument teams for the Joint Polar Satellite System (JPSS), Geostationary Operational Environmental Satellite - R Series (GOES-R), and the Orbiting Carbon Observatory (OCO). The Deep Space Climate Observatory (DSCOVR) launched on Feb. 11, 2015, included the NIST Advanced Radiometer (NISTAR), a three-channel radiometer for quantifying the infrared and optical radiation balance for climate science studies. NIST also continues to support satellite ocean color measurements through the continued calibration and characterization of the Marine Optical Buoy located off the coast of Hawaii. [POCs: Steven Brown, steven.brown@nist.gov; Mitch Furst, mitch.furst@nist.gov; Carol Johnson, carol.johnson@nist.gov; Stephen Maxwell, stephen.maxwell@nist.gov; Joseph Rice, joseph.rice@nist.gov; John Woodward, john.woodward@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.

N/A

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.

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.]

Measurement Capabilities beyond the Visible & Near Infrared. Customers and other stakeholders are also interested in expanded availability of calibrations/standards at wavelength regions outside of the near-infrared and visible region for applications such as materials processing and sterilization using UV LEDs and THz and thermal imaging and spectroscopy. [Needed: International comparisons that emphasize spectral windows outside the near-infrared and visible]

Standardized Atmospheric Models with Validated Uncertainties. The provision of radiometric standards/calibrations, particularly in the infrared/far infrared/THz, are complicated by changes in atmospheric composition (water vapor and aerosols) or atmospheric pathlength between calibration and application. Improved and standardized tools to aid accurate, traceable atmospheric corrections to radiometric measurements are desired. [Needed: Robust tests and comparisons of atmospheric models, particularly against high quality measurements, for a variety of scenarios appropriate to CCPR stakeholders would be useful.]

Calibration Services and Standards for Low-Cost Imaging Systems Deployed on CubeSats and UAVs. Miniature satellites and unmanned air vehicles potentially offer government, non-government organizations, and industry low-cost tools to develop a variety of data products to support environment monitoring, land usage, emissions monitoring, water security and usage, urban development, national and regional security, etc. The data products have the potential to be the foundation for numerous local, national, regional, and international decisions with major environmental and financial impacts. Radiometric calibration and standards tools are needed to establish the traceability and comparability of the measurements being provided by the various low-cost and compact radiometric sensors (thermal infrared, hyperspectral, chemical spectroscopy, etc.) that are being deployed and will be deployed on these platforms. These calibrations and standards need to be a fraction of the cost of the sensors. [Needed: Low cost calibrations and stability monitoring tools that can be incorporated into sensors during manufacture. CCPR could aid such innovation through the development of procedures and comparisons among laboratories of low-end hyperspectral imager calibrations and stability monitoring methods.]

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.]

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?

See the items identified in section 4 above.

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 working with PTB, NRC, and NPL to undertake an international comparison of single photon detector efficiency.

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

NIST will be hosting the Single Photon Workshop in summer 2017 on the University of Colorado at Boulder campus. Invitations will be forthcoming. For information about the workshop or to get on the mailing list contact Dr. Thomas Gerrits (thomas.gerrits@nist.gov). NIST will also be hosting a workshop on laser-based manufacturing in July 2017 at the NIST Boulder campus. For more information about the workshop contact Dr. John Lehman (john.lehman@nist.gov).

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

Note : List below is from the NIST publication database, and the first author listed (NIST researcher) is not necessarily the first author of the publication.

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