Joint Biennial CNC-CIE, CIE-USNC & CORM Conference 2023

6-8 November 2023

Conference Programme

SCHEDULE OF EVENTS

Monday, November 6th

11:00 AM	**Conference Start**
11:00 AM	Introduction, Jeff Hovis, President, CNC-CIE
11:05 AM	CIE Research Strategy, Jennifer Veitch, President, CIE
11:40 AM	short break
11:50 AM	**Optical Properties of Materials, Chair: Aaron Goldfain**
11:50 AM	Material Characterization of Phantom Standards Developed by the National Institute of Standards and Technology for Quantitative Optical Medical Imaging Application and Technology for Quantitative Optical Medical Imaging Applications, *Jeeseong Hwang, NIST*
12:10 PM	μBRDF Measurement and Traceability Challenges, *Lou Gevaux, LNE-CNAM*
12:30 PM	Impact of a Finite Thickness Integrating Sphere Port on Diffuse Reflectance Measurements, *Luke Sandilands, NRC*
12:50 PM	UV-C Directional Reflectance Measurements of Common Materials, *Aaron Goldfain, NIST*
1:10 PM	break
1:40 PM	**UV Radiometry, Chair: Andrew Jackson**
1:40 PM	UV LED Measurements Using the IES-LM-92 Methods, *Jeff Hulett, Vektrex*
2:00 PM	Key Findings from Radiometric Testing of Upper-Room GUV Luminaires, *Jason Tuenge, PNNL*
2:20 PM	Field-Evaluations of Upper-Room and Whole-Room Germicidal Ultraviolet Installations, *Eduardo Rodriguez-Feo Bermudez, PNNL*
2:40 PM	short break
2:50 PM	**UV Radiometry (Cont.)**
2:50 PM	UVC and GUV Measurements in the UVSCF, *Howard Yoon, NIST*
3:10 PM	Importance of UV Spectral Distribution in Solar Simulator Applications, *Andrew Brezinski, Sciencetech, Inc*
3:30 PM	The Need for Fluence-Rate Measurement Instruments, *David Sliney, Independent Consultant*
3:50 PM	break

Monday, November 6th (continued)

4:20 PM	**Current Research at NMIs I, Chair: Angela Gamouras**
4:20 PM	A New Method for Measuring Splice Loss Uncertainty in Single Photon Detector Efficiency Measurements, *Sonia Buckley, NIST*
4:40 PM	Spectroradiometer Calibration with an UAV-Borne Light Source, *Liviu Ivanescu, NRC*
5:00 PM	Development of a New Reference Photometer, *Yuqin Zong, NIST*
5:20 PM	Infrared Radiometry for Space-Based Earth Outgoing Radiation Measurements, *Patrick McArdle, NIST*
5:40 PM	**End of Day**

Tuesday, November 7th

11:00 AM	**Educational Session on Glare Metrics, Models and Standards, Moderator: Mark Jongewaard** Speakers: Belal Abboushi and Naomi Miller (Pacific Northwest National Laboratory), Mehlika Inanici (University of Washington), and John Bullough (Mount Sinai Light and Health Research Center)
12:30 PM	break
1:00 PM	**Current Research at NMIs II, Chair: Heather Patrick**
1:00 PM	Radiation Pressure to Facilitate Measurements of High Laser Powers, *Kyle Rogers, NIST*
1:20 PM	Quantum Cascade Lasers for Measurement Science, *Nelson Rowell, NRC*
1:40 PM	NRC Cryogenic Radiometer: Scale realization from the UV to NIR, *Ka-ming Liu, NRC*
2:00 PM	Laboratory and Field Calibration Methods for Solar-Induced Fluorescence Monitoring Systems, *Julia Marrs, NIST*
2:20 PM	break
2:50 PM	**Metrology of Indoor and Outdoor Lighting, Chair: Craig Bernecker**
2:50 PM	A New Metric for Visibility of the Phantom Array Effect, *Jianchuan Tan, PNNL*
3:10 PM	Study of Non-Uniformity Corrections in Luminous Flux Measurements of Automotive Headlamps Using an Integrating Sphere Through Simulations, *Luis Prado Jr., Prado Lux*
3:30 PM	Development and Verification of a Low-Cost Handheld Spectroradiometer, *William Mills, Northern Illinois*
3:50 PM	Effect of Field of View and Cosine Correction on Spatial Efficiency for Indoor Lighting, *Parisa Mahmoudzadeh, Penn State*
4:10 PM	break

Tuesday, November 7th (continued)

4:40 PM	**Further Studies in Metrology of Indoor and Outdoor Lighting, Chair: Howard Eng**
4:40 PM	Discomfort Glare for Pedestrians: Can Any Model Get Us in the Ballpark, *Belal Abboushi, PNNL*
5:00 PM	Accuracy of the CIE Standard Observer and Other Spectral Luminous Efficiency Functions, *Wangyang Song, Penn State*
5:20 PM	Improving the M_p Metric for Evaluation of Flicker, *Jiaye Li, NIST*
5:40 PM	**End of Day**

Wednesday, November 8th

11:00 AM	**Invited talk on Cone Fundamental Photometry and Colorimetry, Lorne Whitehead, University of British Columbia**
11:30 AM	short break
11:40 AM	**Human Vision, Chair: Jeff Hovis**
11:40 AM	The Effect of Texture on Perceived Color Differences, *Zhenhua Luo, NC State*
12:00 PM	The Influence of Background on the Visual Color Difference Evaluation of Multicolored Materials, *Jiaying Wu, NC State*
12:20 PM	Visual Quality in Low-Light Environments: Effects of White, Amber and Red Lighting on Perception and Light Pollution Reduction*, Dorukalp Durmus, Penn State*
12:40 PM	break
1:10 PM	**Human Vision (Cont.)**
1:10 PM	Do Working Individuals with Color Vision Deficiencies Experience Challenges in the Digital Age?, *Sandra Mazur, Univ. Waterloo*
1:30 PM	Color Vision Testing for the Railways, *Jeffery Hovis, Univ. Waterloo*
1:50 PM	Gender Disparities in Spatial Cognition: The Influence of Stereopsis and Mental Rotation*, Sunder Bukya, Universities of Delhi, Hyderabad and Harvard*
2:10 PM	A Core Lighting Curriculum for University Students and Independent Learners, *Kevin Houser, Oregon State*
2:30 PM	break
3:00 PM	**CIE Division reports**
4:15 PM	**End of conference**

TITLES OF PAPERS, ABSTRACTS AND SPEAKER BIOS

Entries are arranged chronologically.

CIE RESEARCH STRATEGY

Jennifer A. Veitch
President, CIE

The CIE has launched a major revision of its Research Strategy, demonstrating how lighting research can support the achievement of 12 of the 17 United Nations Sustainable Development Goals. The research topics discussed in this presentation are judged by the CIE as needing immediate attention by the research community in support of developments in lighting technology and application and the next generation of lighting recommendations and standards. Topics that relate to human capabilities and ecological systems, whether fundamental or applied, would all benefit from also addressing diversity and inclusion dimensions.

The link for the CIE Research Strategy is DOI 10.25039/vudfg44z. Visit the CIE Research Strategy page (Research Strategy | CIE) to learn how the CIE can provide encouragement to research proposals that could fulfill the goals of the Research Strategy.

The CIE, as a scientific organization, will provide letters of support for research funding applications. Such letters will be written provided that the research described in the research proposal is a topic contained in the scope of the CIE and will contribute to current CIE research priorities (as listed in CIE Research Strategy) or other current CIE technical work.

To request such a support letter, please fill out the request form and send it to ciecb@cie.co.at.

Jennifer Veitch is an environmental psychologist in the Human-Building Interaction Team, National Research Council of Canada, Construction Research Centre, Ottawa, Canada. She is also the President of the CIE.

MATERIAL CHARACTERIZATION OF PHANTOM STANDARDS DEVELOPED BY THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY FOR QUANTITATIVE OPTICAL MEDICAL IMAGING APPLICATIONS

Jeeseong Hwang[1,*], Aaron M. Goldfain[1,2], Helen Zhang[1], & Kimberly Briggman[1]
[1]Applied Physics Division, National Institute of Standards and Technology, Boulder, CO USA
[2] Current address: Sensor Science Division Gaithersburg, MD USA
[*]Corresponding Author: jch@nist.gov

Measurement accuracy and performance reliability of medical devices determine the quality of diagnoses and therapies. We have developed tissue-mimicking materials applicable for various optical medical imaging techniques, including diffuse optical imaging, axial dimensional measurements, and photoacoustic imaging. The phantoms are composed of polydimethylsiloxane (PDMS) with both light scattering titanium dioxide (TiO_2) particles and light absorbing carbon particles included at various concentration combinations. The fluidic property of the raw PDMS material at room temperature and slow solidification time allows for manufacturing phantoms with desired shapes and structures, in addition to incorporating optical and physical properties needed for different measurement platforms. For diffuse optical imaging applications, we fabricated optically homogeneous phantoms then measured their absorption and reduced scattering coefficient spectra ($\mu_a(\lambda)$ and $\mu_s'(\lambda)$) with a broadband integrating sphere system and the inverse adding double algorithm. Analyses of μ_a (λ) and μ_s' (λ) from the broadband integrating sphere measurements demonstrate that independent control of μ_a (λ) and μ_s' (λ) is possible. For axial dimensional standards, we developed a NIST-certified standard reference material (SRM) with a layered structure appropriate for calibrating depth-resolving 3D optical systems such as optical coherence tomography. Layer thicknesses were measured by a calibrated spectral domain optical coherence tomography (SD-OCT) and independent measurement of the refractive indices of the materials used. For photoacoustic imaging applications, micro-fabricated carbon nanotube patterns whose optical absorption is nearly constant across wavelengths are transferred to the surface of PDMS to make an imaging target for resolution and local photon fluence evaluation.

Jeeseong Hwang is a senior biophysicist at the Physical Measurement Laboratory of the National Institute of Standards and Technology (NIST). His recent research focuses on developing standards and measurement technologies to promote quantitative clinical applications of various optical novel imaging devices and tissue-mimicking physical and digital phantoms. His work at NIST in 1996 began with an award of US National Research Council Fellowship on super-resolution near-field optical scanning probe microscopy of nanoscale biomimetic materials and structures. Before coming to NIST, he was a research scientist in an immunology laboratory at the biology department of the Johns Hopkins University, investigating biophysical aspects of immune response of human cells using super-resolution near-field optical microscopy and other laser-based optical imaging techniques in collaboration with the AT&T Bell Laboratories. He has served in programming committees of IEEE, SPIE, and ISO and other international conferences and organizations.

µBRDF MEASUREMENT AND TRACEABILITY CHALLENGES

Lou Gevaux, Gaël Obein, Dipanjana Saha, & Kévin Morvan
LNE-Cnam (EA 2367), La Plaine St Denis, France

A goniospectrophotometer has been developed at LNE-Cnam for performing BRDF measurements at the micrometer scale. This "µBRDF" goniospectrophotometer measures on areas smaller than one hundred micrometers in size. In addition to the technical challenges faced in measuring such small areas, another difficulty arises in validating the instrument and establishing its traceability to our national BRDF scale realized using our primary goniospectrophotometer, which measures areas of around a centimeter in diameter.

The validation of such a system cannot be carried out by direct comparison of measurements performed by both instruments on a reference sample such as a Lambertian diffuser. This limitation arises because the samples generally used do not allow for invariant BRDF between the centimeter and micrometer scales. This is due to the sample's translucency, which leads to edge-loss effects (for PTFE diffusers), or the sample's roughness, which is comparable in size to the measurement area (for metallic diffusers). Therefore, the samples used to validate very small-scale reflectance measurements must be thoroughly characterized before use, and the type of measurement performed must be appropriate.

After describing our measurement system, we will present the validation strategies we have implemented and are considering. More generally, this work leads us to question the limits of the BRDF definition when dealing with high spatial resolution measurements.

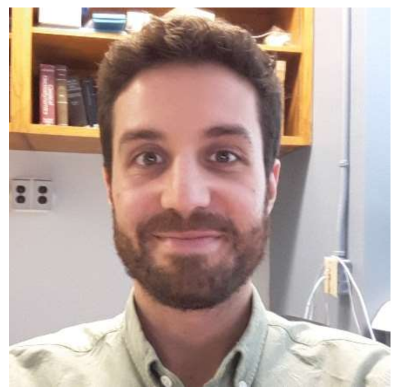
Lou Gevaux received her B.S. and engineering degree from Institut d'Optique Graduate School, France (2014), and her PhD on the topic of 3D hyperspectral imaging for the human face from the University of Lyon, France (2019). She currently works at the Conservatoire National des Arts et Métiers (Paris), in the LNE-CNAM lab, the French designated institute for radiometry, photometry and spectrophotometry references. Her research focuses on the metrological measurements of material appearance.

IMPACT OF A FINITE THICKNESS INTEGRATING SPHERE PORT ON DIFFUSE REFLECTANCE MEASUREMENTS

Luke Sandilands & Thomas Cameron
Metrology Research Centre, National Research Council Canada, Ottawa, ON, Canada

This presentation will focus on the effect of a finite thickness integrating sphere sample port on the measurement of diffuse reflectance in a directional-hemispherical geometry. For a finite thickness port, additional light losses occur due to scattering between the sphere port wall and the test sample, causing the sample reflectance to be systematically underestimated. Monte Carlo ray tracing was applied to obtain quantitative estimates of the resulting measurement error for the case of a Lambertian reflector, and the effects of sample reflectance, port geometry, and illumination beam size were explored. The numerical simulations were validated by comparison with experimental data collected with a pair of integrating sphere reflectometers with different port geometries. These results indicate that finite port thickness can be a non-negligible source of error for realistic port geometries. A strategy for minimizing this error will be outlined.

Luke Sandilands is a Research Officer in the Photometry and Spectrophotometry team at NRC. He is responsible for maintaining and developing NRC's spectrophotometric calibration services. Luke received his PhD in condensed matter physics from the University of Toronto in 2014. From 2014 to 2017, he did postdoctoral research in infrared and optical spectroscopy at the IBS Center for Correlated Electron Systems in Seoul, South Korea. He joined the Photometry and Spectrophotometry group at NRC Metrology in 2017.



UV-C DIRECTIONAL REFLECTANCE MEASUREMENTS OF COMMON MATERIALS

Aaron M. Goldfain[1,*], Grace E. Waters[1,2], Heather J. Patrick[1], & Lynn Davis[3]
[1]Sensor Science Division, National Institute of Standards and Technology, Gaithersburg, MD, USA
[2]Currently with the University of Georgia, Athens, GA, USA
[3]RTI International, Research Triangle Park, NC, USA
***aaron.goldfain@nist.gov**

UV-C germicidal radiation is attracting increased interest as a method to disinfect public spaces such as subway cars and airplanes. The radiation dose distributed throughout the space determines the germicidal efficacy as well as the safety hazards posed to potential occupants. To accurately model the dose incident on each surface it is critical to know the directional reflectance properties of materials in the space. There is currently little publicly available data for the UV-C directional reflectance of such materials.

We have measured the UV-C directional reflectance, specifically the in-plane bidirectional reflectance distribution function (BRDF), of several common building materials. The measurements were performed at wavelengths of 222 nm, 255 nm, and 280 nm using a commercial spectrophotometer with a directional reflectance accessory. We have established an uncertainty budget for absolute BRDF measurements with this instrument. We have also validated our BRDF measurements through measurements of reference materials as well as through comparisons to NIST's national BRDF reference instrument. The BRDF data will be published in an open-access database to facilitate advanced models of the efficacy and safety of UV-C germicidal systems.

Aaron Goldfain is a physicist in the Sensor Science Division of the National Institute of Standards and Technology. His research focuses on measuring the interactions of light with surfaces and developing quantitative, label-free imaging methods. He is currently measuring the bidirectional reflectance distribution function (BRDF) of materials at UV-C wavelengths and developing light-scattering-based, single-particle techniques to characterize gene delivery nanoparticles.

UV LED MEASUREMENTS USING THE IES LM-92 METHODS

Jeff Hulett
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UV LEDs often target applications where the total light dosage is precisely controlled. Designers that use UV LEDs rely on accurate irradiance data to ensure the LEDs in their products will deliver the correct dosage for the application.

The ANSI/IES LM-92 – Approved Method: Optical and Electrical Measurement of Ultraviolet LEDs, published last year, includes two new techniques for making measurements that promise better accuracy due to reduced junction heating.

This paper presents an experimental LM-92 UV-LED measurement system that implements the new DCP and M-DCP methods. This system makes high-accuracy irradiance measurements using an array spectrometer, a photodiode and a precision pulsed source/measure instrument. These instruments are controlled by Python software. For M-DCP measurements, a multi-slope integrating DMM is used.

The system architecture is presented, and measurement results for the two methods for a typical high-power UV-C LED are discussed. Error sources are listed, along with recommended best practices for implementing similar optical measurement systems.

Jeff Hulett is CTO and founder of test & measurement specialist firm Vektrex, based in San Diego, CA. Over the course of his career, Hulett has acted as chief engineer on products ranging from single-board computers for spaceflight to power supplies for DNA sequencing systems to current sources used in the LED and laser industries for product and system evaluation. Hulett holds several patents related to LED testing and has authored technical articles for publications such as LEDs Magazine, Photonics Spectra, and LED Professional. He chairs the Illuminating Engineering Society's LM-80 Working Group, he was a key contributor to the IES LM-85 and LM-92 working groups, and he is presently working within the CIE's TC2-91 group.

KEY FINDINGS FROM RADIOMETRIC TESTING OF UPPER-ROOM GUV LUMINAIRES

Jason Tuenge
Pacific Northwest National Laboratory, Portland, OR, USA

The U.S. Department of Energy (DOE) launched the CALiPER program in 2006 to address a need for unbiased, trusted performance information for solid-state lighting (SSL) products, including those incorporating LED emitters. DOE testing and analysis, conducted by qualified test labs using industry-approved test procedures, helped to encourage high-quality products and discourage inflated performance claims. Early CALiPER testing also contributed fundamentally to the development of standardized photometric test methods specifically for SSL and the associated accreditation of testing laboratories.

The COVID-19 pandemic led to a similar environment for germicidal ultraviolet (GUV) products, where unsubstantiated performance claims proliferate, new technologies and test methods are in development, and the capabilities of commercial test laboratories are limited. In response, and further motivated by the desire to improve resilience to any future pandemics, the CALiPER program recently expanded its scope to include GUV products used to treat air and surfaces in occupiable spaces.

This presentation shares key findings from Round 2 of GUV product testing, which focused on electrical and radiometric characteristics of upper-room luminaires. Products of this type are designed to safely treat occupied spaces by irradiating the volume above occupants. Eight wall-mounted luminaires rated to produce UV-C were tested, five using low-pressure mercury lamps and three using LED technology. UV-C radiant intensity distribution was measured far-field using a mirrored gonioradiometer, and spectral distribution in the 200–400 nm range was measured in the direction of maximum intensity. Performance claims are compared with measurements taken after 0, 100, and 500 hours of operation.

Jason Tuenge joined PNNL in 2008 as a Lighting Research Engineer, with experience ranging from applications engineering for a luminaire manufacturer to lighting design at engineering firms. He leads radiometric and electrical testing of germicidal ultraviolet products through the U.S. Department of Energy's CALiPER program, and supports related field measurements of GUV systems. Jason serves on multiple relevant committees including ANSI C137.12, IES TPC, and UL 8802. He has a B.S. in architectural engineering from the University of Colorado-Boulder, and a Master of Information and Data Science degree from the University of California-Berkeley.

FIELD-EVALUATIONS OF UPPER-ROOM AND WHOLE-ROOM GERMICIDAL ULTRAVIOLET INSTALLATIONS

Eduardo Rodriguez-Feo Bermudez, Belal Abboushi, & Jason Tuenge
Pacific Northwest National Laboratory, Portland, OR, USA

Germicidal ultraviolet (GUV) technologies are installed in buildings to mitigate the risk of airborne pathogen transmission. Pacific Northwest National Laboratory (PNNL) will conduct field evaluations of 12 sites across the US that have implemented upper-room or/and whole-room GUV systems to evaluate their safety, energy consumption, and effectiveness. The evaluations will provide novel research on how GUV systems are installed and performed in settings outside of curated laboratory spaces. The sites were selected based on the potential for people to congregate and their community impact. Sites include schools, places of worship, airports, restaurants, and healthcare facilities. At each site, PNNL will create a horizontal grid in the rooms where systems are installed. Irradiance measurements will be compared to safety limits published by the American Conference of Governmental Industrial Hygienists in 2022. Additionally, irradiance measurements will be taken at two heights for each grid point to infer the system's germicidal effectiveness.

In this presentation, we will discuss the objectives of the field evaluations and explain how the data can be used to better characterize GUV systems and their effectiveness. By the time of the presentation, we will have completed half of the planned field evaluations; we will present the developed measurement protocol and share preliminary results.

Eduardo Rodriguez-Feo Bermudez received his Master of Science in Applied Physics from Michigan Technological University and Bachelor of Science in Physics from the University of South Florida. As a graduate student he has participated in optics-based experiments for Michigan Tech Cloud Chamber group and interned at the US Naval Observatory (D.C.). This has allowed him to accumulate a wealth of knowledge in the science of light scattering along with coding/investigative skills needed to aid and execute experiments.
Now Eduardo is an Associate Scientist at Pacific Northwest National Laboratory in the Lighting Science Research group. Within the group, he helps the progression of projects and experiments that try to illuminate our knowledge in the subjects of Light Uniformity, Glare, Flicker, Connected Lighting, and Germicidal ultraviolet systems.

UVC AND GUV MEASUREMENTS IN THE UVSCF

Jeanne Houston, Tom Larason, Vladimir Khromchenko, & Howard Yoon*
National Institute of Standards and Technology, Gaithersburg, MD, USA
***Presenter**

The need for UVC and particularly germicidal UV, GUV, spectral power responsivity (ASR) calibrations of optical detectors [A/W], have been increasing. Calibrations from 200 nm to 300 nm are required for nondestructive testing, disinfection, and the semiconductor industry. NIST has a facility for the power responsivity and irradiance calibration of detectors in this wavelength range called the UV Spectral Comparator Facility (UVSCF). The original design and build of the UVSCF had measurement limitations and large uncertainties. The UVSCF has recently been redesigned and rebuilt to improve its calibration performance.

The focus of the new UVSCF designs is to increase the signal throughput for the UVC range using UV rich sources, decrease reflective losses using optical coatings optimized for the UV range. The facility has a 1 to 1 imaging system that reduces the impact of aberrations. Both the spectral and dimensional scanning abilities are improved to reduce the uncertainties in the spectral power responsivity calibrations as well as irradiance calibrations. Results of the UVSCF's performance testing for scattering, repeatability, reproducibility, NEP, as well as other uncertainty contributors will be presented. Examples of GUV and UVC ASR and irradiance calibrations will be presented with their resulting uncertainties.

Howard Yoon is the Group Leader of the Temperature Group in the Sensor Science Division at NIST. He is the US national representative for thermometry on the Consultative Committee for Thermometry at the BIPM. He received his Ph.D. in solid-state physics from the University of Illinois at Urbana-Champaign and his BA from Swarthmore College. He has coauthored over 130 technical publications, mostly in the areas of spectroradiometry and radiation thermometry. He also has 4 patents in the area of spectroradiometry. He has twice won the NIST Astin Award for measurement science, NIST Judson French Award, 2023 Edward Bennett Rosa Award and is also the recipient of the US Department of Commerce silver medal for scientific achievement.

IMPORTANCE OF UV SPECTRAL DISTRIBUTION IN SOLAR SIMULATORS APPLICATIONS

Andrew Brzezinski
Sciencetech Inc., London, ON, Canada

UV light is present in sunlight and in most solar simulators. However, solar simulator standards, which are primarily for testing photovoltaics, have historically ignored UV light or they simply group UV into a wide band, overlooking the detailed structure of the UV solar spectrum. Applications that require considering a more detailed UV spectrum include MIL-STD-810 testing, sunscreen testing, materials testing in extraterrestrial environments, and experiments in atmospheric photochemistry. These application areas will be examined and the spectral requirements important to each application will be discussed and compared across applications.

Andrew Brzezinski studied Engineering Science at the University of Toronto and earned a PhD in Materials Science and Engineering in the topic of 3D photonic materials. Currently he works at Sciencetech. Inc. in the role of Scientific Applications Manager.

THE NEED FOR FLUENCE-RATE MEASUREMENT INSTRUMENTS

David H. Sliney
Consulting Medical Physicist, Fallston, MD 21047-USA

Fluence rate is particularly important to measure or calculate in photobiology. Fluence rate probes have been developed in past decades to measure internal body tissue exposure rates for photoactivation of drugs (as in photodynamic therapy, PDT). Today, with the increased interest in the application of indoor germicidal ultraviolet (GUV) inactivation of aerosolized viruses and bacteria, there is a true need to actually measure ultraviolet-C fluence-rate rather than to measure simple UV-C irradiance within the disinfection irradiation zone. The reason that fluence and fluence rate are important in photobiology relates to the fact that backscatter or photons arriving from different sources at a sensitive biological molecule – a chromophore – are equally effective regardless of direction; hence cosine-response irradiance detectors greatly underestimate the fluence-rate. Fluence-rate probes developed for use in biomedical laser applications made use of a spherical integrator tip at the end of an optical fiber which transmitted light to a detector. In medical applications, the photobiological effect could be measured, but in indoor atmospheres, it is very difficult to measure inactivation of microbes. Alternatively, fluence detectors have measured the photochemical change within a quartz vial suspended in air. But this leads to a big challenge on how to calibrate these types of detectors. Radiometric standards are needed!.

David Sliney holds a Ph.D. in biophysics and medical physics from University College London, Institute of Ophthalmology. He managed the Laser/Optical Radiation Program at what is now the Army Public Health Center until retirement. He is a faculty associate at the Johns Hopkins School of Public Health. His research interests focus on subjects related to ultraviolet effects, photobiological hazards of intense optical sources and lasers, and optical safety of medical devices. He is chair of the IES Photobiology Committee and was President of the American Society for Photobiology in 2008-2009 and a past Director of CIE Division 6 (Photobiology and Photochemistry) and a past Grum Awardee.

A NEW METHOD FOR MEASURING SPLICE LOSS UNCERTAINTY IN SINGLE PHOTON DETECTOR EFFICIENCY MEASUREMENTS

Sonia Buckley, Megan Hurley, Sae Woo Nam, & John Lehman
National Institute of Standards and Technology, Boulder, CO 80305 USA

During a calibration, a single photon detector and a calibrated power meter are alternately spliced to a setup, and the relative powers used to calibrate the single photon detector. Differences between the quality of the splices during this measurement contribute to the uncertainty in the single photon detector efficiency calibration, but are usually only accounted for in the standard deviation of subsequent measurements. This is because conventional techniques, such as OTDR, cannot be used to evaluate these splices, as the distance from the splice to the detector/power meter is typically shorter than the resolution. Here we discuss a new technique using an integrating sphere and a photodiode to measure the power emitted from the splice. The device can be separately calibrated by measuring transmitted power through the fiber versus photodiode current for different splices. The difference between the splices can then be quantitatively accounted for in the uncertainty budget. The technique may prove useful in other applications where splice evaluation is relevant but challenging.

Dr. Sonia Buckley is a physicist at the National Institute of Standards and Technology (NIST) in Boulder, Colorado in the Sources and Detectors group of the Applied Physics Division. Her research interests are in metrology for future technologies and industries, with a current focus on developing a single photon detector efficiency calibration service. She has over 40 publications in the areas of quantum optics, integrated photonics, and hardware for artificial intelligence. Sonia received a PhD in Applied Physics and an MS in Electrical Engineering from Stanford University in 2014, and her undergraduate degree in Physics from Trinity College Dublin in 2009.

SPECTRORADIOMETER CALIBRATION WITH A UAV-BORNE LIGHT SOURCE

L. Ivănescu[1,2], C. Marseille[2], N.T. O'Neill[2], & J.E. Albert[3]
[1]National Research Council Canada, Ottawa, ON, Canada
[2]Université de Sherbrooke, Sherbrooke, Canada
[3]University of Victoria, Victoria, Canada

We investigated the feasibility and the limitations of using a UAV-borne (Unmanned Aerial Vehicle) light source for calibrating a starphotometer (essentially a telescope mounted spectroradiometer). This is a proof-of-concept experiment for future use of satellite- and balloon-borne calibration light sources. We measured a narrow-band, three-colour LED source at three fixed UAV positions between 700 and 1500 m distance and at 115 m altitude over a 5–10° elevation angle range above the horizon (equivalent to a 0.09–0.19 airmass range). While the calibration was deemed to show good potential, the use of a narrow-band light source revealed some limitations. Line-of-sight extinction profiling appeared to be a very interesting product that can be extracted from these types of measurements.

Liviu Ivanescu is a Research Officer in the Photometry and Spectrophotometry team at the NRC Metrology Center. He is responsible for developing and maintaining photometric and optical radiometric measurement standards, while also providing related calibration services. Liviu holds a B.Sc. in Physics, with focus on "Optics, Spectroscopy, Plasma, Lasers", from University of Bucharest, as well as a M.Sc. from UQAM in "Atmospheric Sciences". He received a Ph.D. in atmospheric remote sensing from University of Sherbrooke in 2020, with topic "Accuracy in Starphotometry", followed by a postdoc at the same institution until joining NRC in 2023.

DEVELOPMENT OF NEW REFERENCE PHOTOMETER

Yuqin Zong
National Institute of Standards and Technology, Gaithersburg, MD, USA

To achieve a small measurement uncertainty in photometry, preferably, a photometer is calibrated for spectral irradiance responsivities directly against a standard trap detector using a uniform tuneable laser source. However, most photometers cannot take this advantageous calibration method because of their interference fringes when they were exposed to a coherent laser source. In addition, most of photometers were susceptible to environment conditions (e.g., temperature, dust, and moisture). These limitations of photometers make it difficult to achieve a small calibration uncertainty of illuminance responsivity. To address these issues, we developed a new generation of reference photometers, which are calibrated against standard trap detectors using a 1 kHz pulsed tuneable laser. The uncertainty of illuminance responsivity is reduced from >0.4 % to 0.20 % (k = 2). Also, the new photometer is sealed and temperature-controlled, which makes it long-term stable and is much less susceptible to environment conditions. The change of illuminance responsivity is on the level of 0.05 % per year.

Yuqin Zong is an optical engineer and the photometry project leader at the Sensor Science Division, National Institute of Standards and Technology, USA. His research covers calibrations of optical sensors and imagers using tunable lasers, measurement methods for LEDs and solid-state lighting products, and correction of stray light for array spectroradiometers and imaging instruments.Ivanescu is a Research Officer in the Photometry and Spectrophotometry team at the NRC Metrology Center. He is responsible for developing and maintaining photometric and optical radiometric measurement standards, while also providing related calibration services. Liviu holds a B.Sc. in Physics, with focus on "Optics, Spectroscopy, Plasma, Lasers", from University of Bucharest, as well as a M.Sc. from UQAM in "Atmospheric Sciences". He received a Ph.D. in atmospheric remote sensing from University of Sherbrooke in 2020, with topic “Accuracy in Starphotometry”, followed by a postdoc at the same institution until joining NRC in 2023.

INFRARED RADIOMETRY FOR SPACE-BASED EARTH OUTGOING RADIATION MEASUREMENTS

Patrick McArdle, Nathan Tomlin, Chris Yung, John Lehman, & Michelle Stephens
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The Earth energy imbalance (EEI) is the difference between the amount of solar energy reaching the Earth to the amount leaving Earth. Therefore, an accurate measurement of the EEI can inform the dynamics of the Earth's changing climate. EEI measurements are composed of total solar irradiance (TSI) and earth outgoing radiation (EOR) measurements. TSI is mainly composed of shortwave (UV-Near IR) and the EOR is split into a solar reflected shortwave (UV-Near-Infrared) and emitted longwave (Near-Infrared – far infrared) components. For EOR measurements, part of the challenge is developing detectors that are sensitive across both the shortwave and longwave bands. Work being done at NIST is in developing next generation micro-bolometers based on vertically aligned carbon nanotubes (VACNTs). VACNTs have many ideal properties for use as the absorbing element in bolometer type detectors including near unity absorption from UV-far infrared wavelengths, high thermal diffusivity, and VACNTs can be lithographically grown in a two-dimensional form factor1. One disadvantage is the properties of the VACNTs can differ as the substrate selection changes, and due to high fabrication temperatures material selection is limited. In addition, next generation EOR measurements are looking to improve spatial resolution which requires shrinking detector size. With shrinking sizes and hyper-black properties, it is difficult to optimize and characterize the optical properties of these detectors. In this work we describe efforts to develop characterization methods for these next generation VACNT microbolometers and discuss results.

1. Lehman, J., Yung, C., Tomlin, N., Conklin, D. & Stephens, M. Carbon nanotube-based black coatings. *Applied Physics Reviews* **5**, 011103 (2018).

Patrick McArdle is a National Research Council postdoc at NIST in Boulder, Colorado with the Sources and Detectors group in the Applied physics Division of the Physical Measurement Laboratory. Patrick completed his Ph.D. at William and Mary in physics and is currently developing methods for characterizing the infrared properties of vertically aligned carbon nanotube microbolometer

EDUCATIONAL SESSION ON GLARE METRICS, MODELS AND STANDARDS.

Chair: Mark Jongewaard, LTI Optics, Westminster, CO, USA

MODELING AND PREDICTING GLARE IN LIGHTING APPLICATIONS

John Bullough
Light and Health Research Center, Icahn School of Medicine at Mount Sinai, Albany , NY, USA

Glare control is important for both interior and exterior lighting applications to ensure good visual performance and provide for occupants' visual comfort. Disability glare, the reduction in visual performance from light sources in the field of view, is mainly addressed in exterior lighting. Discomfort glare, the sensation of annoyance or pain from bright lights, can be experienced in both exterior and interior lighting applications. Different systems are used to assess discomfort glare in different applications, but is this necessary? This presentation will review the factors that influence both disability and discomfort glare in the hopes of stimulating discussion about an integrated approach to measuring glare.

REFLECTIONS ON DAYLIGHT GLARE EVALUATIONS IN BUILT ENVIRONMENTS

Mehlika Inanici
University of Washington, Seattle, WA, USA

Successful daylighting designs can support human visual comfort, productivity, and health while reducing energy consumption. Evaluation of visual comfort is one of the most researched topics in lighting, yet we have not reached a consensus on how to evaluate it in emerging designs or existing spaces. This talk focuses on daylight glare in work environments. Strategies for controlling daylight glare, while maximizing the potential benefits of daylight, will be discussed. The presentation will conclude with an outlook on gaps in research and discrepancies between research and practice.

WHY IS OUTDOOR GLARE SUCH A STUBBORN PROBLEM?

Naomi Miller & Belal Abboushi
Pacific Northwest National Laboratory, Portland, OR, USA

Decades of work have gone into solving the snarly issue of quantifying outdoor discomfort glare. Here are a few issues:

- How does a pedestrian experience the glare? Looking at the pavement ahead, glancing at different heights around the space, or looking upward at the luminaire?
- What are the factors that contribute to discomfort glare? How are these variables measured? Do we have instruments to measure them? How difficult is it to get consistent values? How do we measure luminance of the source? Do luminance patterns (like LED arrays) in the aperture affect the glare response? Does diffusion help? Is there a distance above which the luminance pattern converges to a point source?
- Does the position index have relevance outdoors? If glare cuts off at 60 degrees above the line of sight, why does a baseball cap improve comfort so effectively?
- How much precision do we need in an outdoor glare metric? What’s good enough? Are there simple approaches that can get us in the ballpark for both predicting and measuring discomfort glare in the field?
- What’s the next critical issue to study?

RADIATION PRESSURE TO FACILITATE MEASUREMENTS OF HIGH LASER POWERS

Kyle Rogers
National Institute for Standards and Technology, Boulder, CO USA

We measure the output power of high-power CW lasers by using the light's radiation pressure. In recent years, we have found radiation pressure to be an accurate method of laser power measurement that allows for minimal perturbation of the laser beam. Our Radiation Pressure Power Meter yields low overall uncertainty values and is a portable, reliable tool for high power measurements. This device does have limitations, some of which have been addressed in multiple new design geometries. Implementation of these new geometries has also allowed for other beam aspects (eg. transverse profile) to be monitored while high power measurements take place. Additionally, the multiple-bounce geometry known as the High Amplification Laser-pressure Optic has allowed for best-in-class uncertainty that is being pushed further to the level of the cryogenic radiometer. In this presentation, I will describe the use of radiation pressure for laser power measurements and delve further into the various geometry configurations and their design aspects, applications, and results.

Kyle Rogers received the B.S. degree in mechanical engineering in 2016, and the M.S. degree also in mechanical engineering in 2023 from the University of Colorado, Boulder. He began his research at the National Institute for Standards and Technology in 2015, where he has focused his efforts on Radiation Pressure and other radiometry techniques. He has been heavily involved in the research and development of the bulk Radiation Pressure Power Meter (RPPM), which has allowed for focused efforts in LabVIEW development, sensor design, and fabrication. He currently is working on future generations of the sensor, which has allowed for expanded work with high power applications.

Kyle is also the Calibration Leader for multiple calibration services at NIST Boulder. These services include fiber optic power meters, both absolute measurements and linearity measurements, as well as high-power calibrations in the kilowatt regime. This work has allowed Kyle to expand his expertise in both fiber optics and high-power laser metrology, where he hopes to continue development of measurement techniques for the future of NIST.

QUANTUM CASCADE LASERS FOR MEASUREMENT SCIENCE

Nelson Rowell, Robert Rinfret, & Li-Lin Tay
Metrology Research Center, National Research Council of Canada, Ottawa, ON, Canada

The impact of quantum cascade lasers (QCLs) in infrared (IR) metrology will be illustrated in this presentation with three example applications. In the first example, QCLs operating in the 5.9 to 9.3 μm range were used to measure the total reflectance values (ρ) for relatively low reflectance diffuse materials, with 0.001% < ρ < 1%. Here QCLs were tunable IR sources for an IR integrating sphere, with samples wall mounted and measurements done with the substitution method. The reflected signal was detected with a cooled mercury cadmium telluride (MCT) detector on a sphere port. The reflectance spectra were obtained by varying the laser wavenumber over its tuning range with a laser linewidth of 1 cm^{-1}. The advantages of using QCL sources are their high brightness and collimation. The restricted QCL tuning range is a disadvantage. In the second example, QCLs were deployed as high brightness sources for IR microscopy, for spectrometer-free, hyper-spectral imaging of small samples with a MCT focal plane array detector. An important limitation in IR imaging is the IR spot size, which is diffraction limited to several micrometers. Attenuated total reflectance can reduce the spot size four-times, but with severe sampling constraints. In the third example, we show how the spatial resolution can be improved by combining a QCL with a visible laser in the pump-probe method, optical photothermal infrared (O-PTIR) spectroscopy. This method provides IR spectra spatially resolved at the visible diffraction limit, which is 20x smaller than the IR limit. We will describe how such an apparatus was assembled and show spectral IR images obtained with it.

Nelson Rowell is a Principal Research Officer in the Photometry and Spectrophotometry team at the National Research Council, which he joined in 1978 after his studies at the University of Toronto. Rowell's research concerns optical spectroscopic methods for materials characterization. Rowell's developments include: Brillouin scattering from thermal phonons in optical waveguides; Fourier transform infrared photoluminescence from the semiconductor epilayers of Si and Si1-xGex; Berreman-mode far infrared reflectance from phonons in the sub-monolayer thick mixing layers within III-V semiconductor superlattices; Attenuated total reflection for the identification of monolayer-thick organic layers on silicon. Rowell is the author of 275 refereed publications.

NRC CRYOGENIC RADIOMETER: SCALE REALIZATION FROM THE UV TO NIR

Ka-ming Liu
Metrology Research Center, National Research Council of Canada, Ottawa, ON, Canada

Recent work at the National Research Council (NRC) Canada has involved the primary scale realization of optical radiant power down to 250 nm using the NRC monochromator-based absolute cryogenic radiometer system. This presentation will discuss the cryogenic radiometer measurement apparatus used at NRC for primary radiometry, the scale realization from the UV to NIR spectral regions, and how the calibrations are transferred down to industry, following the traceability chain.

Ka-ming Liu is a Research Council Officer at the NRC, currently working with the Thermometry and Radiometry Group in the realization of optical power. Since joining he has been working on the cryogenic radiometer alongside Angela Gamouras and Derek Li. He has previous experience at NPL, working with optical fibers and fiber-based radiometer measurements.

LABORATORY AND FIELD CALIBRATION METHODS FOR SOLAR-INDUCED FLUORESCENCE MONITORING SYSTEMS

Julia K. Marrs, Taylor S. Jones, B. Carol Johnson,
Stephen E. Maxwell, Lucy R. Hutyra, & David W. Allen
National Institute of Standards and Technology, Gaithersburg, MD, USA

Solar-induced chlorophyll fluorescence (SIF) is the emission by plant leaves of photons not used in photosynthesis. SIF is an increasingly popular method that aims to remotely track photosynthesis and carbon assimilation in tower-based remote sensing systems, complementing SIF measurements from nine satellite platforms that have been launched to date. The last decade has seen a proliferation of SIF instrumentation installed in field settings worldwide, but the intercomparability of these data are currently limited by the diverse instrumentation and calibration methods used across systems, as well as by the uncertainty in measurements of the faint SIF signal. At the Forested Optical Reference for Evaluating Sensor Technology (FOREST) site at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD, SIF is measured alongside numerous complementary remote sensing and environmental parameters. Here, we present a radiometric calibration of a SIF-measuring system performed at in laboratory facilities at NIST. Wavelength calibration, detector linearity, and characterization of stray light were evaluated with an uncertainty budget. Additionally, we assessed additional sources of uncertainty relevant to field-deployed systems, including sensitivity to variability in optical components and component- and system-level alignment sensitivities. Finally, progress toward a portable, SI traceable calibration system that can be deployed onsite at field systems is also presented. Such calibration systems offer the potential for more accessible and affordable alternatives to frequent laboratory calibrations, as well as for instrument intercomparisons across sites, in support of satellite validation and improvements to future Earth system models.

Julia Marrs is a postdoc in the Remote Sensing Group at NIST Gaithersburg. She is interested in hyperspectral sensor characterization and field instrumentation standardization for validating space-based measurements of biospheric greenhouse gas fluxes. She is currently making field measurements of solar-induced chlorophyll fluorescence (SIF) to examine controls on its relationship with biogenic carbon cycling. She is developing calibration methods for SIF systems and quantifying sources of uncertainty that can hinder accurate measurements the faint and dynamic SIF signal, with the overall goal of establishing best practices for SIF instrumentation and characterization protocols traceable to SI scales.

A NEW METRIC FOR VISIBILITY OF THE PHANTOM ARRAY EFFECT

Jianchuan Tan, Ph.D., Naomi J. Miller, M.S., Lia Irvin, M.S., & Michael Royer, Ph.D.
Pacific Northwest National Laboratory, Portland, OR, USA

Temporal light modulation (TLM) has three different visual effects on observers depending on the TLM frequency and waveform characteristics generated by the dimming system and LED driver. When observers move their eyes widely across the modulating light source or across a scene lit by such a source, they may experience a series of repeated images at frequencies between 80 and 11,000 Hz (and probably up to 20,000 Hz according to past research from another lab). This phenomenon is known as the phantom array effect. In some circumstances, particularly when there is nighttime traffic, the phantom array effect may result in nausea, migraines, or even dangerous perceptual confusion.

Sensitive populations and design experts are becoming more conscious of the need for a metric addressing the phantom array effect. To address this gap, a new metric is being proposed: the phantom array visibility measure (PAVM). It is based on recent findings from laboratory experiments, and it follows a mathematical framework similar to that used for FVM and SVM, which divides the time-domain TLM waveform into its Fourier components, evaluates each component using a sensitivity response curve, and then sums the components using an equation with a Minkowski norm.

This presentation will provide background on the phantom array effect, describe recent experimental work, present a new sensitivity function for the phantom array effect, introduce PAVM and its interpretation, and document required measurement protocols.

Jianchuan Tan (JT) joined PNNL in 2021, as a Systems Engineer in the Lighting Science Research team. He is a Ph.D. from Lighting Research Center at Rensselaer Polytechnic Institute, with areas of expertise in Lighting and Architectural Science. He is a PMP, LC and WELL AP. JT's Ph.D. dissertation topic is on reducing flicker from AC LED lighting system with electrical and optical methods by using phase-shift technology and slow-decay phosphors. In PNNL, he is actively contributing to TLM related research, as well as IES and CIE committees for TLM measurement and standard making, and for lighting control standard works.

STUDY OF NON-UNIFORMITY CORRECTIONS IN LUMINOUS FLUX MEASUREMENTS OF AUTOMOTIVE HEADLAMPS USING AN INTEGRATING SPHERE THROUGH SIMULATIONS

L. Prado Jr, R. C. F. de Lima, & C.E. Anderson
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The study employs computer simulations to investigate the effects of the Sphere Response Distribution Function (SRDF), following a methodology similar to that presented by Ohno, Y., and Daubach, R.O. [1]. The simulations are applied to a 1.5-meter integrating sphere in our automotive photometric laboratory. The research primarily focuses on evaluating non-uniformity correction for three distinct samples, with their respective Luminous Intensity Distributions (LID) accurately measured using an automotive goniophotometer. Additionally, this study underscores the significance of correctly aligning the optical axis of the device under test in the setup to minimize the correction factor and associated uncertainties in the process.

1. Yoshi Ohno & Ronald O. Daubach (2001) Integrating Sphere Simulation on Spatial Nonuniformity Errors in Luminous Flux Measurement, Journal of the Illuminating Engineering Society, 30:1, 105-115, DOI: 10.1080/00994480.2001.10748339

Dr. Luis Name Prado, Jr., PhD, is a visionary leader with an illustrious career spanning academia and the automotive industry. As the CEO of Pradolux-Luxparts Group, he brings 18 years of invaluable experience to the optical and light measurements conference. Dr. Prado excels in photometry, energy-efficient product development, and LED technology. With a diverse skill set that includes leadership, a deep understanding of the physics of light, and expertise in Lean Manufacturing, Dr. Prado is a dynamic, multitalented professional. His educational background, which includes a Doctorate in Natural Sciences from the University of Bonn, reflects his unwavering commitment to excellence.

DEVELOPMENT AND VERIFICATION OF A LOW-COST HANDHELD SPECTRORADIOMETER

William J. Mills, Kevin B. Martin, Justin L. Cathey
Department of Engineering Technology
Northern Illinois University

Existing spectroradiometers are inclined to be relatively large in size and relatively expensive compared to standard light photometers (light meters). Existing low-cost spectrometers provide spectral information on a relative basis only. However, radiometric data is required to properly characterize environmental lighting. This work developed and verified a low-cost (approximately $400) spectroradiometer system. The system consists of a low-cost, miniaturized visible light spectral sensor connected via USB cable to a Raspberry Pi (RPi) small board computer with a small (smartphone-sized) touchscreen. The system can be powered by a battery or wall plug. The spectral power distribution and other measured light metrics (e.g., lux) are displayed on the touchscreen, stored locally, and accessible remotely via Local Area Network or Wi-Fi. The developed system can be held in a single hand and operated in stationary and wearable modes. The response of the low-cost spectrometric sensor was characterized across the visible spectrum, under varying intensities, against a reference calibrated radiometric spectrometer. Spectrometric correction factors were developed from comparison characterization. The low-cost system was found to be “Fit for Purpose” to characterize light sources and calculate visible light exposure metrics. Due to the flexibility of communication protocols, this spectroradiometer was integrated into an existing prototype building management system.

EFFECT OF FIELD OF VIEW AND COSINE CORRECTION ON SPATIAL EFFICIENCY FOR INDOOR LIGHTING

Parisa Mahmoudzadeh & Dorukalp Durmus
Pennsylvania State University, University Park, PA, USA

Lighting application efficacy (LAE) characterizes the effectiveness of indoor lighting systems by quantifying light reaching a target (i.e., surface(s) or occupant(s)' eye). Within the LAE framework, spatial efficiency denotes the amount of radiant flux emitted by the luminaire(s) that reflects off surfaces and reaches occupants' effective field of view (FOV) [1]. However, the human visual system's sensitivity to light changes with retinal eccentricity. Previously, it was proposed that a cosine correction could be applied to account for the effectiveness of rays coming from different angles noting that light distribution on the retina is closer to a cosine pattern [2], while others argued otherwise [3].

Here, the effect of FOV (30-, 90-, and 160-degrees) and cosine correction on spatial efficiency is investigated. Spatial efficiency ($\eta_{spatial}$), the integrated radiance across the FOV divided by the total amount of radiant flux emitted to the space, can be formulated as

$$\eta_{\text{spatial, FOV}} = \frac{\int_0^{\Omega} L_e \, d\Omega}{\phi_{e,total}} \quad (1)$$

where L_e is the radiance reaching the target FOV (unit: $W \cdot sr^{-1} \cdot m^{-2}$), Ω is the solid angle, and $\Phi_{e,total}$ is the total radiant flux emitted in a room (unit: W). Two sets of simulations were generated using Radiance simulation software: homogenous sensitivity across the FOV and a cosine correction. Results suggest significant differences between cosine corrected and uncorrected calculations for 90- and 160-degrees FOV. Spatial efficiency and its variation increased with the FOV (160-degrees homogenous FOV had the largest spatial efficiency). Future research will validate these results through a visual experiment.

References

[1] D. Durmus, W. Hu, and W. Davis, "Lighting application efficacy: A framework for holistically measuring lighting use in buildings," *Front Built Environ*, vol. 8, Aug. 2022, doi: 10.3389/fbuil.2022.986961.

[2] A. C. Kooijman, "Light distribution on the retina of a wide-angle theoretical eye," *J Opt Soc Am*, vol. 73, no. 11, p. 1544, Nov. 1983, doi: 10.1364/JOSA.73.001544.

[3] S. He, H. Li, Y. Yan, and H. Cai, "Capturing Luminous Flux Entering Human Eyes with a Camera, Part 1: Fundamentals," *LEUKOS*, pp. 1–19, Dec. 2022, doi: 10.1080/15502724.2022.2147942.

Parisa Mahmoudzadeh is a PhD candidate and research assistant in Architectural Engineering at Pennsylvania State University, where she specializes in lighting. She holds a bachelor's degree in Architectural Engineering and a master's degree in Interior Architecture and Environmental Design. Her research interests include visual perception, circadian lighting, user-centered lighting systems, environmental psychology, and applications of immersive virtual environments. Currently, she is working on developing a computation method for lighting application efficacy of indoor environments.

DISCOMFORT GLARE FOR PEDESTRIANS: CAN ANY MODEL GET US IN THE BALLPARK?

Belal Abboushi
Pacific Northwest National Laboratory, Portland, OR, USA

After dark, pedestrians may experience discomfort from glare caused by outdoor lighting. While several models for measuring discomfort have been proposed, there is no consensus as to which model should be used. In this presentation, we will share findings from recent studies that focused on identifying practical and reliable metrics for nighttime glare. We will first provide an overview of the problem of nighttime glare, models to quantify it, and guidelines to promote consensus on an effective metric. Second, we will share results of a recent study that evaluated the performances of seven models were investigated using datasets from four independent studies, comparing the degree of association between model predictions and subjective ratings, and the ability of a model to distinguish between discomfort and non-discomfort situations. Of the models tested, the best performance was found using either the model proposed by Bullough et al. in 2008 or by direct illuminance at the eye.

Belal Abboushi is a Lighting Research Engineer at the Pacific Northwest National Laboratory. Belal is involved in projects examining visual discomfort and glare, lighting uniformity, spatial brightness perception, and germicidal ultraviolet disinfection. Belal earned a PhD in Architecture from the University of Oregon where he conducted studies investigating lighting and occupant's visual comfort in office buildings. He is a member of the IES Discomfort Glare in Outdoor Nighttime Environments committee.

ACCURACY OF THE CIE STANDARD OBSERVER AND OTHER SPECTRAL LUMINOUS EFFICIENCY FUNCTIONS

Wangyang Song & Dorukalp Durmus
Pennsylvania State University, University Park, PA, USA

Electric lighting enables occupants to accomplish tasks while ensuring safety and enhancing visual comfort. Evaluating the amount of light in architectural spaces is a critical part of building systems design. The CIE 1924 photopic luminous efficiency function ($V(\lambda)$, also called 2° standard observer) has been historically used to model human spectral sensitivity to light stimuli. However, several studies highlighted its shortcomings, spurring the exploration of alternative luminous efficiency functions. Despite the evidence exhibiting its limitations, the lighting industry continues to rely on the $V(\lambda)$ for photometric measurements (e.g., illuminance, luminance) to characterize light sufficiency in architectural spaces.

A visual experiment was conducted to evaluate the accuracy of the CIE standard observer and its alternatives, namely CIE 10° photopic photometric observer, CIE cone fundamentals-based alternative spectral luminous efficiency functions. Seven pairs of nominal white light conditions (approximately 2700 K) were generated using a multi-primary LED system. The pairs were generated using genetic algorithms to match the illuminances for $V(\lambda)$, by widely differ for alternative spectral luminous efficiency functions. The pairs also included null conditions to test potential bias. Participants judged the brightness of the stimuli using 2afc in a simultaneous presentation. Results indicate that illuminance based on the CIE 10° photometric observer can potentially predict scene brightness better than the CIE 2° standard observer. Future research will utilize other chromaticities (4000 K and 6500 K) to test accuracy of CIE standard observer and alternative functions.

Wangyang Song is a PhD student in the Department of Architectural Engineering at Penn State University. His research focuses on architectural lighting, color science, energy efficiency and spatial brightness. Wangyang has a bachelor's degree from University of Nottingham, majoring in Architectural Environmental Engineering. During his undergraduate studies, he has become interested in lighting and decided to pursue a PhD in lighting research. Wangyang Song is currently investigating the impact of spectral sensitivity functions on spatial brightness using computational and human factors research methods.

IMPROVING THE M_P METRIC FOR EVALUATION OF FLICKER

Jiaye Li[1], Yoshi Ohno[1], & Andrew Bierman[2]
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[2]Consultant, Albany, New York, USA

Recently TLM (temporal light modulation) related measurements and calculations have regained high interest, with new regulations by European Commission and other regional regulations requiring limits for TLA (temporal light artefacts) quantities for LED lighting products. In these regulations, P_{st}^{LM} (IEC TR 61547-1-2020) for flicker and SVM (TR 63158-2018) for stroboscopic effects are commonly used. However, due to complexity of P_{st}^{LM}, attentions are paid to another metric for flicker, M_p (ASSIST vol. 11, 2015). This metric works in frequency domain and requires a much shorter measurement time (>2 sec) compared to 3 minutes for P_{st}^{LM}. M_p is already used in some commercial TLM measuring instruments. However, for some types of lamps, large variations in M_p results are found for repeated light measurements using different waveform sampling parameters.

Both simulated waveforms and measured waveforms were used to evaluate M_p. The impact of waveform duration (from 2 sec to 180 sec), sampling rates, and starting phase of the measured waveform on the M_p values were investigated.

The results show that the waveform duration and starting phase have significant impact on the M_p values when using the original formulae in the ASSIST document. The variation of calculated M_p due to these two factors was largely reduced after adding a Hann window before the FFT transform. However, applying a Hann window led to a different M_p value from the one obtained with the original formulae, since the Hann window reduces the effect of spectral leakage while enhancing the FFT spectrum peak due to the added window function. The sampling rate can also have a noticeable effect on the M_p value depending on the waveform. Further investigation into the cause of these and possible solutions is in progress to improve the metric.

Dr. Jiaye Li received her Ph. D. in engineering from Katholieke Universiteit Leuven (KU Leuven) in Belgium. Her research area is color vision: color matching, color rendering, color difference, contrast perception. She worked as a Ph. D. researcher supervised by Prof. Kevin Smet and Prof. Peter Hanselaer in the Light & Lighting Lab of KU Leuven from 2018 to 2022. She is now a Postdoc researcher at NIST, working with Dr. Yoshi Ohno on Vision Science projects in Sensor Science Division.

INVITED TALK ON CONE FUNDAMENTAL PHOTOMETRY AND COLORIMETRY

Lorne Whitehead, University of British Columbia, Vancouver BC Canada

Lorne Whitehead is a professor in the Department of Physics at the University of British Columbia, and he serves as UBC's special advisor on innovation. His research focuses on applied physics, energy efficiency, color, illumination and information display.

THE EFFECT OF TEXTURE ON PERCEIVED COLOR DIFFERENCES

Zhenhua Luo & Renzo Shamey*
Color Science and Imaging Labs, TECS Dept., North Carolina State University, Raleigh, USA
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In color difference evaluation of textured stimuli, parametric factors, $k_L = 2$, $k_C = 1$, and $k_H = 1$ are commonly employed in formulas (such as CIE94 and CIEDE2000) to adjust the relative role of lightness difference component in the overall model. Visual color difference data were obtained through psychophysical experiments on an LCD monitor for textured stimuli representing ten common knitting patterns around 11 color centers using a panel of 26 observers. Tolerances for each combination of texture pattern and color center were established using the method of adjustment. Additionally, visual tolerances for the homogenous samples were determined for comparative purposes. Statistical analysis revealed that specific textures significantly increased lightness tolerances compared to the uniform stimuli. However, the texture effect varied across color centers and was pronounced in specific textures. Similar trends were observed for chroma and hue tolerances, although the texture effects on chroma and hue tolerances were generally less prominent than on lightness tolerances. Using the current visual dataset, the performance of CMC, CIE94, and CIEDE2000 formulas with $k_L = 2$ or 1 were tested using F-tests and the STRESS metric. The results revealed that CIE94(1:1:1) significantly outperformed other models. Formulas with parametric factors (2:1:1) exhibited significantly worse performance than their counterparts with (1:1:1) ratio. These findings suggest the necessity for model optimization to accommodate various textures in different regions of the color space.

Zhenhua Luo is a Ph.D. candidate at the Wilson College of Textiles, North Carolina State University. She obtained her Master of Science degree in Textile Engineering from NC State in 2018. Following her graduation, she embarked on a journey to continue her academic pursuit by working towards a Ph.D. in Fiber and Polymer Science. In 2018, Zhenhua became a part of the Color Science and Imaging Laboratory, working under the mentorship of Dr. Renzo Shamey. Her primary research interests focus on color psychology, color quality control, color difference perception, digital color imaging, and colorimetric measurement.

THE INFLUENCE OF BACKGROUND ON THE VISUAL COLOR DIFFERENCE EVALUATION OF MULTICOLORED MATERIAL

Jiaying Wu[1] & Renzo Shamey[1]*
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The perception of color is significantly influenced by its surrounding context, raising the question of how the background affects the magnitude of the perceived differences. This work focused on assessing color differences in multicolored materials, specifically those composed of colors from the MARPAT camouflage pattern. Our previous study highlighted significant color differences for a color patch surrounded by a checkerboard background versus a color-averaged background. This underscores the challenges in evaluating colors in a complex background, indicating that it cannot be approached in the same manner as that used for unrelated colors. In this study, psychophysical experiments were conducted to quantify perceived color differences between pairs of stimuli containing preset color differences, either connected on one side or separated, and surrounded by either a checkerboard, or a color-averaged, or a gray background. Results emphasized significant visual color differences between the pairs of stimuli when connected versus separated, regardless of the backgrounds examined. Observers consistently reported smaller perceived differences with a gray background. Colored pairs on a gray background exhibited a substantial decrease in visual difference when separated, as opposed to being connected. Meanwhile, sample pairs with checkerboard or color-averaged backgrounds showed a relatively smaller decrease in visual difference under similar conditions. The performance of several color difference models in quantifying color differences for different backgrounds was also assessed. All tested models exhibited relatively high STRESS values (33.12-45.10), suggesting room for improvement in predicting human visual perception of color differences of sample pairs within complex surrounds.

Jiaying Wu is a PhD candidate and a member of the Color Science and Imaging laboratory at North Carolina State University under the direction of Prof. Renzo Shamey. She received a BS in Textile Chemistry from Zhejiang Sci-Tech University (2015) and an MS in Textile Chemistry from NC State University (2018). Her main research interests include color and vision science, visual perception, digital color imaging, colorimetry and color management.

VISUAL QUALITY IN LOW-LIGHT ENVIRONMENTS: EFFECTS OF WHITE, AMBER, AND RED LIGHTING ON PERCEPTION AND LIGHT POLLUTION REDUCTION

Dorukalp Durmus[1] & Annika Jägerbrand[2]
[1] Pennsylvania State University, University Park, PA, USA
[2]University of Gävle, Gävle, Sweden

In the pursuit of mitigating light pollution and its environmental impact, the use of specific outdoor lighting chromaticities, such as amber and red, has gained attention. However, the implications of these lighting choices on visual quality under low lighting conditions remain relatively unexplored. In this study, a controlled visual experiment was conducted simulating outdoor lighting conditions with reduced light pollution.

Twenty-nine participants (14 female, 15 male) were exposed to lighting conditions ranging from very low illumiance (1 lx) to slightly higher levels (33 lx) under white (~4500 K, λ_d = 570 nm), amber (λ_d = 590 nm), and red lighting (λ_d = 623 nm). All light sources were generated using a multi-primary LED lighting system in a controlled lab environment. Findings reveal a significant impact on visual quality, with objects perceived most poorly under red and amber lighting (9 lx), followed by very dim white lighting at 1 lx. Importantly, an illuminance-dependent relationship was observed, indicating that as lighting levels increased, visual quality improved.

These results shed light on the intricate interplay between light source chromaticity, illuminance, and visual quality in low-light settings, providing valuable insights for lighting design, urban planning, and light pollution reduction efforts. These findings advocate for a nuanced approach to outdoor lighting, considering both color and intensity to optimize visual quality while minimizing environmental impact. This research contributes to the ongoing dialogue on responsible lighting practices, offering practical guidance for designers and policymakers seeking to balance aesthetics, safety, and sustainability in outdoor lighting scenarios.

Dr. Alp Durmus is an assistant professor in the Department of Architectural Engineering (AE) at Pennsylvania State University. He completed his PhD in architectural sciences at the University of Sydney, Australia before moving to the USA to join Pacific Northwest National Laboratory (PNNL) as a postdoctoral researcher and later Senior Associate Lighting Research Scientist. He later joined Penn State AE department as a professor in architectural lighting. Alp's research and teaching interests are color science, visual perception, emerging lighting systems, and image quality assessment

DO WORKING INDIVIDUALS WITH COLOR VISION DEFICIENCIES EXPERIENCE CHALLENGES IN THE DIGITAL AGE?

Sandra Mazur & Jeffery K Hovis
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Purpose: There are several careers that are reliant on an individual's ability to make color-related judgments. Numerous studies have shown that selecting a career becomes a common obstacle for most color defectives. However, there is limited research that directly analyzes the effect that this defect has on their use of digital displays at work.

Methods: An online survey was administered to 381 color defectives (280 males) in Canada and the USA which included a section on the experiences of 215 respondents (167 males) when using digital displays at work/volunteering.

Results: The majority (96%) of respondents reported experiencing at least a little difficulty with at least one color-related task when using a digital display at work or volunteering. Based on the median ranking of difficulty, the males had more challenges (i.e., reading, interpreting, reviewing, creating, or editing) with maps (51%-some difficulty), photos (49%-some difficulty), and spreadsheets (42%-some difficulty). For the females, the most difficult tasks were color-coded diagrams (53%-some difficulty), graphs (50%-some difficulty), and color-coded plans/instructions (45%-some difficulty). Although there were slight differences between sexes in their rankings, the differences were not statistically significant (Kruskal-Wallis test; $p \geq 0.26$). Most of these challenges were experienced when using desktops/laptops (38% males), cell phones (26% males), and tablets (19% males).

Conclusions: Although there were some minor differences in the ranking of difficulty of the various colored images by both sexes, nearly all color defectives did experience some level of difficulty with at least one of the color-related tasks when using digital displays at work or volunteering.

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COLOR VISION TESTING FOR THE RAILWAYS

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Introduction: Correct identification of railway wayside signal color lights is critical for safe operation of equipment on the tracks. However, evaluating color discrimination using only a screening test may not be occupationally relevant. CIE 143:2001 recommended a lantern test as an alternative to a screening test. However, lantern tests are scarce and often do not have face validity with the signal lights.

Methods. A lantern test (CNLAN) was designed to provide a functional assessment of color discrimination for the rail industry. It was validated against a simulated field trial. Additional experiments examined how viewing distance affected the pass-fail results and whether clinical color vision tests could predict the lantern results.

Results: Using a failure criterion based on the worst-normal performance, 97% of the individuals with a color vision defect failed both the CNLAN and simulation trial. The pass rate for individuals with color vision deficiencies increased to 62% as the viewing distance for the lantern test decreased from 4.6m to 0.57m. Failure of the Farnsworth- Munsell D15 color vision test predicts that the individual will fail the lantern at the furthest test distance. Individuals with a mild defect can pass the lantern test at closer viewing distances.

Conclusion: Identifying railway signal lights is challenging for most individuals with a color vision defect at longer viewing distances. Individuals with a mild color vision defect may be able to identify the signal light colors at closer viewing distances, which typically occur in railway yards.

Dr. Jeff Hovis is a faculty member of the University of Waterloo School of Optometry and Vision Science. He has an active research program developing performance-related vision standards for law enforcement, aviation, maritime and railway industries. He has been a member of several panels and research groups reviewing vision standards for civilian pilots in Canada. He is currently President of the Canadian National Committee of the Commission Internationale de l'Eclairage.

GENDER DISPARITIES IN SPATIAL COGNITION: THE INFLUENCE OF STEREOPSIS AND MENTAL ROTATION.

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This study aimed to investigate the impact of the mental rotation task and stereopsis on gender disparities in spatial cognition. A total of 60 individuals, including both males and females, participated in the stereoscopic evaluation and mental rotation task trials. The results of Experiment 1 indicated that participants from both gender groups exhibited similar binocular function parameters and normal depth perception. In Experiment 2, when spatial skills were assessed using the Mental Rotation Task, male individuals demonstrated superior spatial abilities and outperformed female participants. Furthermore, it was found that the male advantage in mental rotation tasks extended across various levels of rotation, suggesting that differences in the degree of this advantage between tests may be influenced by varying levels of complexity. Additionally, the study revealed that developing prototype-based tasks for spatial abilities can enhance spatial cognitive functions.

Dr. Sunder Bukya is a guest faculty at the Center for Neural and Cognitive Sciences, University of Hyderabad. Holding a PhD in Cognitive Sciences from the same institution, he has authored four research publications. His passion lies in the realm of cognitive science, cognitive linguistics, psycholinguistics, neuroscience language, and applied linguistics, where he explores the intricate nuances of human cognition and language processing. With a strong foundation in academia, he brings valuable insights and expertise to the field of cognitive sciences, continually advancing our understanding of the human mind.

A CORE LIGHTING CURRICULUM FOR UNIVERSITY STUDENTS AND INDEPENDENT LEARNERS

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In collaboration with a group of lighting professionals, learning outcomes were defined, prioritized, organized, and mapped to a three-course sequence of lighting courses within a Bachelor of Science in Architectural Engineering degree program. Syllabi and educational exercises were developed to support the learning outcomes—including classroom activities, homework assignments, and design projects. The learning exercises balance the technical foundations of applied illuminating engineering with the artistic aspects of applied lighting design and are intended to promote significant and lasting learning by providing students with realistic, contemporary, and contextual educational experiences. The process for identifying and prioritizing lighting content is described, a process that could be adapted by other lighting educators to other pedagogical contexts. The syllabi and learning exercises are disseminated for reuse or adaptation, or for self-study by independent learners.

If interested, you could also learn more about the project here:
https://blogs.oregonstate.edu/kevinhouser/nuckolls-project

Kevin Houser (PhD, PE, FIES, LC, LEED AP) is a Professor at Oregon State University with a joint appointment as Chief Engineer at Pacific Northwest National Laboratory, co-founder of Lyralux, Inc., and former editor-in-chief of LEUKOS, the journal of the Illuminating Engineering Society (IES). He has published more than 125 publications about light and lighting. He has been awarded the CIBSE Leon Gaster and Walsh Weston Awards, IES Taylor Technical Talent Award three times, Edison Report Lifetime Achievement Award, the IES Presidential Award, and is a Fellow of IES. His work focuses on human perceptual and biological responses to light.

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