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NIST Response to the 6th CORM Report: Pressing Problems and Projected National Needs in Optical Radiometry

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Abstract

The Council for Optical Radiation Measurements (CORM) issues periodic reports relevant to the mission of the Optical Technology Division of the Physics Laboratory. The present document summarizes NIST's response to the CORM Sixth Report issued in 1995 and is timed to be contemporary with the CORM Seventh Report to be issued in 2001.

Key Words: metrology, optical properties of materials, optical radiation, photometry, radiometry, spectroradiometry

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Preface

The Council for Optical Radiation Measurement (CORM) began as a non-profit organization in 1972. CORM serves the interests of professionals and institutions engaged in optical radiation measurements, with representatives from a wide range of industrial sectors. CORM's mission includes the following:

Assessing the national requirements for standards, calibrations, and interlaboratory collaborations.

Establishing national consensus for priorities for these requirements.

Forming a liaison with the National Institute of Standards and Technology (NIST) to advise NIST of the needs of the optical technology community.

Cooperating with other organizations, both public and private, for the direct and indirect benefit of the taxpayer.

Disseminating information on standards activities in optical radiometry and spectrophotometry.

To help achieve this mission, CORM periodically surveys its membership and other technical associations to determine the pressing problems and projected national needs in optical radiation measurements. The survey results are analyzed and recommendations for action are issued in a special CORM report. The most recent CORM report, the 6th, prepared by the CORM 6th Report committee in partnership with the CORM Board of Directors and officers, was published in 1995. The needs identified from the survey were separated into three broad categories: accreditation, optical properties of materials, and radiometry.

While many of the needs clearly fall within the purview of NIST's responsibility as the nation's primary metrology and standards laboratory, other needs are better addressed by industrial or academic laboratories. The present report describes NIST's response to the needs identified by CORM. NIST's ability to respond to these needs is, of course, dependent on the available resources and laboratory mission. Following tradition, the present response to the CORM 6th report is being published coincident with the recent release of the CORM 7th Report.

For the purposes of this report quotes from the CORM 6th Report are given in bold italics.

1. Introduction

The CORM 6th Report has been circulated to the CORM membership and other interested parties both inside and outside the U.S. The CORM reports are important because they offer a list of identifiable and documented needs of NIST's customers and stakeholders. Inasmuch as the technical demands in other parts of the world are often similar to those in the U.S., the reports understandably generate interest elsewhere. These reports also provide NIST with the information necessary to ensure that its long-range planning is responsive to its customers and stakeholders. In addition to gathering data from a broad group of users of optical radiation measurements, the report is enhanced by the efforts that CORM places in prioritizing their recommendations. The following explanation of the prioritization process is taken directly from the CORM 6th report.

A formal scoring process was followed to evaluate each of the optical radiation proposals. In evaluating each proposal, the following factors were considered:

- ***Degree of Need:*** *Will the proposed development solve a significant troubling problem for a large number of users in the optical radiation measurement community?*
- ***Appropriateness:*** *How compatible is the proposal with the CORM-NIST objectives?*
- ***Probability of Success:*** *Are we proposing something that we can reasonably expect to be accomplished?*
- ***Immediacy or Urgency:*** *This category addresses the issue of timing. Will this proposal solve a problem that is disrupting the optical radiation community right now, or does the proposal address a problem that can be solved with a longer term, ongoing effort?*

A final overall priority was then assigned based on the average scores received for each proposal with the following classification in effect:

PRIORITY 1: ***CORM feels that immediate action is necessary to address the issues in this proposal.***

PRIORITY 2: ***CORM feels these proposals are important but are not as immediate as the Priority 1 proposals.***

The responses were sorted into the three categories:

- *ACCREDITATION*
- *OPTICAL PROPERTIES OF MATERIALS*
- *RADIOMETRY*

The categorization and prioritization process that CORM undertakes has increased the interest and participation of other government agencies in NIST activities. The CORM membership includes government scientists and engineers and representatives of companies that supply products and services to such government agencies as NASA and the Department of Defense. The availability of documented needs in optical radiation measurement helps to ensure that the research and development funding from these agencies are properly directed.

The expanding technical base in the U.S. results in continually increased demands for new and improved technical support from the national metrology system. It is impossible for NIST alone to respond to all the measurement needs identified by CORM. By establishing a prioritized list of needs, CORM helps other government agencies and private organizations to better identify their role and participation in optical radiation measurement service delivery. In some cases, the report can serve as a rationale for other government agencies to directly fund NIST to develop programs that satisfy specific needs of their agency that are identified in the CORM report.

As with other fundamental metrological disciplines, the use of optical radiation measurement is pervasive throughout the U.S. industry and government. Industries that use optical radiation measurements include photography, xerography, automobile, aerospace, instrument manufacturering, chemical, paper, and printing. The huge American investments in space-based observation systems for weather, earth resource, and agricultural monitoring by NASA and NOAA, and for national defense by DOD are critically dependent upon reliable and accurate optical radiation measurements and calibrations. CORM is central in defining the optical measurement and support needs that this large and diverse community requires, helping to ensure the leadership role of American technology and industry.

The NIST response to the CORM 5th report noted that the competitive pressures of international trade were pushing American industry to adopt quality programs such as defined in the International Standards Organization (ISO) 9000 series guidelines for quality assurance. As was noted then, NIST expanded the National Voluntary Laboratory Accreditation Program (NVLAP) to meet these needs (see below). NVLAP has continued to grow to satisfy the requirements of American industry and has established programs in physical, chemical, electrical, and optical testing areas. This emerging requirement to meet demands for quality assurance was an identified need in the CORM 6th report and continues to be an activity of critical interest in the technical and manufacturing community. NIST has mandated that its calibration programs should have a recognizable quality system that will help meet the requirements of a Mutual Recognition Arrangement (MRA). The MRA is an agreement among the world's metrology institutes to recognize each other's calibration certificates for the benefit of trade across international boundaries. The Optical Technology Division has established a quality system for its calibration programs based upon ISO Guide 25 (ANSI 540) and is in the process of expanding it to include the standard reference material programs within the Division.

2. Discussion of the CORM 6th Report Proposals for Action

There was one proposal for action in the accreditation portion of the CORM 6th report, eight proposals in the optical properties of materials, of which four were priority one and the rest priority two, and six in the radiometry category, of which three were priority one and the rest priority two. We will discuss the proposals for action in the order they appeared in the CORM 6th Report and discuss NIST activity as appropriate.

a) Accreditation

As discussed in the Introduction, there has been an upsurge in interest by American industry to become compliant with ISO 9000 Series Registration and in the accreditation of calibration and testing laboratories. Over 70 % of the respondents of the CORM questionnaire indicated a need for the accreditation of testing and calibration laboratories. This proposal is labeled A-1 in the report and is introduced as follows:

A-1: Accreditation for Optical Radiation Measurements

Over the past several decades a shift has occurred from domestic markets to a more open and global marketplace. International competitiveness and the ability to manufacture and market on a global scale has become the new battlefront for the industrialized nations in the world. Within this global marketplace is a sustained drive by many nations to harmonize standards and measurement practices that are used to manufacture goods and products. Issues such as international traceability, registration to the ISO 9000 series of standards and accreditation have become important processes that must be achieved in order to compete and survive in this global arena.

Specifically, the CORM 6th Report recommended the following for NIST:

CORM recommends that the U. S. firmly establish and maintain an internationally recognized accrediting body for measurements in the field of optical radiation measurements. The current efforts at NIST through the National Voluntary Laboratory Accreditation Program (NVLAP) need to be enlarged to provide accreditation for the following optical radiation measurements:

RADIOMETRY

Luminance
Illuminance
Luminous Flux

Color Temperature
Spectral Radiance
Spectral Irradiance

Spectral Responsivity
Radiance Temperature
Optical Pyrometry
Laser Power
Laser Energy

OPTICAL PROPERTIES OF MATERIALS

Regular (specular) Transmittance
Diffuse Transmittance (ISO 5-2:1991)
Bi-Directional Transmittance Distribution Function (BRTF)
Bi-Directional Reflectance Distribution Factor (BRDF)
Specular Reflectance
Reflectance Factor (45/0 or 0/45, near-normal/ hemispherical)
Coefficient of Luminous Intensity Retroreflectance

NIST administers the National Voluntary Laboratory Accreditation Program (NVLAP). NVLAP provides third-party accreditation to testing and calibration laboratories. NVLAP's accreditation programs are established in response to Congressional mandates or administrative actions by the Federal Government or from requests by private-sector organizations. NVLAP is in full conformance with the standards of the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), including ISO/IEC 17025 and Guide 58. NVLAP identifies its accredited laboratories in a published directory, NIST Special Publication 810, and on its web site. NVLAP is comprised of a series of laboratory accreditation programs (LAPs) which are established on the basis of requests and demonstrated need. Each LAP includes specific calibration or test standards, or both, and related methods and protocols assembled to satisfy the unique needs for accreditation in a field of testing or calibration. NVLAP accredits public and private laboratories based on evaluation of their technical qualifications and competence to carry out specific calibrations or tests.

Accreditation criteria are published in the U.S. Code of Federal Regulations (CFR, Title 15, Part 285) as a part of the NVLAP Procedures and General Requirements, and encompass the requirements of ISO/IEC 17025 and the relevant requirements of ISO 9000:2000. Accreditation is granted following successful completion of a process which includes submission of an application and payment of fees by the laboratory, an on-site assessment, resolution of any deficiencies identified during the on-site assessment, participation in proficiency testing, and technical evaluation. The accreditation is formalized through issuance of a Certificate of Accreditation and Scope of Accreditation and publicized by announcement in various government and private media.

NVLAP accreditation is available to commercial, manufacturers, university, and federal, state, and local government laboratories. Laboratories located outside the United States may also be accredited if they meet the same requirements as domestic laboratories and pay any additional fees required for travel expenses. NVLAP provides an unbiased third-party evaluation and recognition of performance, as well as expert technical guidance to upgrade laboratory performance.

As for international recognition, NVLAP is a full member of the International Laboratory Accreditation Council (ILAC). ILAC is an international cooperation between the various laboratory accreditation schemes operated throughout the world. Founded twenty years ago, ILAC was formalized as a cooperation in 1996 when 44 national bodies signed a Memorandum of Understanding (MOU). This MOU provides the basis for the further development of the Cooperation and the eventual establishment of a multilateral recognition agreement between ILAC member bodies.

NVLAP's purview includes the field of optical radiation. The scope of NVLAP's field of accreditation for optical radiation is covered in the Calibration Laboratories Technical Guide, NIST Handbook 150-2. The Handbook 150-2 was published originally in 1994 and was recently revised and is available from the NVLAP business office. The scope of the LAP for optical radiation includes: radiance temperature, photometry, spectrophotometry, spectral radiance and spectral irradiance, spectral responsivity, laser power and energy, and optical-fiber power measurements. The Technical Criteria for Optical Radiation Calibrations in NIST Handbook 150-2 was written and edited by the NIST calibration experts from the Optical Technology and the Optoelectronics Divisions. Additionally, NIST's calibration experts engaged in the field of optical radiation measurements have participated in NVLAP training and are qualified and prepared for technical assessments. Several such experts have already served as assessors.

NIST's calibration experts also have quality systems expertise and can assist laboratories in the development of their own quality programs. NIST has recently adopted a system for assuring quality in the results of measurements delivered to customers in calibration and measurement certificates. Several divisions at NIST, including the Optical Technology Division, have implemented or are in the process of developing quality systems for their calibration activities based on the ISO/IEC 17025.

NVLAP has many resources available on their website that can assist laboratories in the development and implementation of quality systems. The NIST Handbook 150-2, Assessor checklists, and web-based training on the 17025 can all found at the NVLAP website http://ts.nist.gov/ts/htdocs/210/214/214.htm

b.1) Optical Properties of Material-Priority One Proposals

b.1.1) O-1: New Standards for Regular and Diffuse Transmittance

The CORM report recommended that NIST provide various standards for regular and diffuse transmittance in the infrared to the ultraviolet. These standards are required for the calibration of spectrophotometers and densitometers, used for quality and process control in a variety of industries. Specifically, CORM recommended that:

- ***SRM's be developed with a wide range of absorbance (0.05- 6 absorbance units in the visible/UV range, 0.05- 4 absorbance units in the NIR).***

- ***Highly accurate standards for diffuse transmittance, primarily in the UV and visible regions of the spectrum, with absorbance in the 0.05-4 A range, also be developed.***

- ***The overall wavelength range of the standards of high absorbance should be 190-850 nm and 850-2500 nm, respectively. The wavelength range for the diffusely transmitting standards should be from 190-850 nm.***

NIST presently provides standards for a wide range of absorbances for the wavelength range 250 nm to 2500 nm through Calibration Service 38061S, Special Test of Spectral Transmittance. The Division prefers to offer these capabilities through a calibration service instead of through SRM's, as this allows the customer to specify the desired absorbance and wavelength range.

Accurate standards for diffuse transmittance are offered in the visible wavelength range through SRMs 1001 and 1008. These SRMs are x-ray and photographic-film step tablets in which the absorbances of the various steps vary from 0.1 to 4 and are measured to an expanded uncertainty of 0.004 ($k = 2$).

b.1.2) O-2 Colored Standard Reference Materials

The report recommended that NIST provide a set of color reflectance samples to allow industry to accurately calibrate their instruments. The U.S. produces many high-quality color measurement instruments, but NIST does not currently supply appropriate calibration artifacts for use by this industry. The burgeoning e-commerce area as well as traditional display and graphics industry are presenting new demands for national standards for color measuring instruments. Specifically, CORM recommends that NIST produce a set of color tiles (plaques) that satisfy the following criteria:

A calibrated set of colored SRM's must be spatially uniform, and non-thermochromic, while being capable of diagnosing the following systematic errors:

Wavelength
Bandpass
Photometric Scale
Geometric Sensitivity
Stray Radiation

This set should be appropriate for total hemispherical and bi-directional (45/0 or 0/45) reflectance factor measurements in order to correspond to instruments in common industrial use. Industry is currently in need of reflectance uncertainties on the order of +/- 0.0003, a full order of magnitude better than what is currently available from NIST. CORM recommends that the National Institute of Standards and Technology and US equipment/materials manufacturers work together to meet the needs of industry.

The Optical Technology Division has nearly completed the construction of a new colorimeter for the high-accuracy measurement of reflectance color. The instrument has the capability to perform measurements on customer-supplied color tiles for the standard 0/45 geometry and over the full hemisphere using a goniometer. We expect to make the capabilities of the colorimeter available through a formal calibration service to be launched near the end of 2002. The Division is exploring the possibility of obtaining high quality colored tiles for use as colorimetric standards as well as exploring other possible measurement services to meet the needs of these industries.

b.1.3) O-3: Measurement of Fluorescence

Fluorescence measurements are often essential to completely characterize the appearance of an object when it is illuminated. For example, many paints or coatings when exposed to sunlight will not only reflect the light according to their pigmentation, but will also fluoresce. The appearance of the object is a combined effect of the reflected and fluorescent radiation. CORM recommends the following activities for NIST:

- ***Provide at the national level, a referee measurement service using accurate two-monochromator calculated methods and including goniometric capability for measurement of the color appearance of fluorescent materials.***

- *Initiate a measurement assurance program for calibration and testing laboratories to establish their traceability to the national level and improve their measurement uncertainty.*

- *Provide a series of fluorescent Standard Reference Materials for use by industry and academia in confirming the adequacy of laboratory measurements.*

The new NIST colorimeter discussed above has been designed to allow modification for the measurement of the color of fluorescent materials. Additional funding will be sought to support the implementation of these capabilities. Once the instrumentation is developed and validated, fluorescence-color calibrations will be offered to customers through a formal service instead of through a set of SRM's to provide the needed flexibility for the customer to specify the details (geometry, wavelengths, etc.) of the measurements.

b.1.4) O-4: New Standards for Bi-directional Reflectance Distribution Factor (BRDF) and Bi-directional Transmittance Distribution Factor (BTDF)

The needs for BRDF and BTDF reference materials have been expressed in previous CORM reports, but in the past were of lower priority. The increased need, as identified in the CORM 6th Report, is driven by the growing use of optical scattering techniques for characterizing the appearance of materials and for assessing the quality of reflecting surfaces for precision optical instruments.

CORM therefore recommends that:

- *Standard Reference Materials (SRM's) be developed for bi-directional reflectance distribution factor (BRDF) , both of nominally high and low reflectance for both high and low scatter samples, covering the wavelength range from the UV to the mid-IR (approx. 190 - 25,000 nm). These standards should have minimal reflectance structure (and thus, a series of standards, each with differing spectral reflectivity, should be considered) in the area of interest.*

- *SRM's be developed for bi-directional transmittance distribution factor (BTDF), both of high and low nominal transmittance and with both high and low degrees of forward scatter. Such standards need not cover as wide a spectral range as the BRDF SRM's, but should be usable over a fairly wide range in the UV-VIS-NIR (190-2500 nm).*

- *NIST work with U.S. industry, military and NASA to develop and maintain SRM's for these measurement techniques.*

Bi-directional reflectance and transmittance distribution factor standards are available by submission of the appropriate artifact for calibration through NIST Calibration Service Special Tests 38060S and 38061S [4]. BRDF and BRTF measurements can be made for the wavelength range from 250 nm to 2500 nm. A calibration service offers the advantage that the customer has the flexibility of specifying the angles, wavelengths, transmittance, and reflectance of interest, whereas a SRM would be available only for a specific set of angles and wavelengths; we thus do not anticipate offering any additional SRM's for BRDF or BRTF standards. When high demand is anticipated for a specific set of angles and wavelengths we will offer SRM's, such as our SRM 2040 which is a 0/45 reflectance standard. In addressing the desire that NIST work with industry, military, and NASA to develop and maintain SRM's for BRDF and BRTF, we note that NASA has funded NIST to participate in a round-robin test of BRDF capabilities in support of the EOS (Earth Observing Satellite) program. The results from this round robin have been published. [5]

b.2) Optical Proprieties of Materials - Priority Two Proposals

b.2.1) O-5: Measurement of Retroreflectance

Retroreflectance measurements quantify the ability of a material to reflect light back in the incident direction. Retroreflectance is important for road signs and other devices in which a significant fraction of the incident light must return in the direction the illumination, regardless of the incident angle. Retroreflectance is usually measured photometrically with standard illuminants to assess the use of the material for human vision. CORM recommended the following:

A recommendation is made that NIST initiate the following.

- ***Develop a set of SRM's consisting of calibrated colored retroreflective materials for signing at the key measurement angles for maintenance purposes which are 0.2 degree observation and minus 4 degrees entrance angle.***

- ***Develop a set of SRM's with established chromaticity coordinates for both daytime and nighttime measurement geometries for use by performance testing laboratories for verification of color performance in both ordinary and fluorescent retroreflective materials.***

- ***Establish a new Measurement Assurance Program for the measurement of the retroreflectance of road striping materials at the angles used for maintenance*** *inspections and acceptance testing including 88.76 degree entrance angle and 1.05 degree observation angle.*

A further recommendation is made that NIST continue the existing Measurement Assurance Program and integrate its use into an accreditation program for calibration and testing laboratories.

The construction of a laboratory for the measurement of retroreflectance is being planned, supported by funding from the National Highway Cooperative Research Program. The services of this laboratory will be offered through our calibration programs instead of through SRMs as this is the fastest route to disseminating its capabilities to our customers. In addition, a calibration service allows the customers to more fully request the details of the measurements to be made to accommodate their specific technical requirements.

The planned instrument will consist of source, goniometer, and detector systems. To meet current standards, the source system will consist of a stable tungsten strip lamp that produces uniform illumination of the material under test with Standard Illuminant A and an appropriate set of apertures necessary to meet all of the requirements. The output of the source system will be monitored. The goniometer will be able to handle signs with diameters up to 75 cm and pavement striping with angular resolutions of the entrance and rotation angles better than those specified in the standards. There will also be provision made to mount a detector at the location of the material under test to measure the incident light, and the distance from the goniometer to the detector will be adjustable from 10 m to 30 m. The photopic detector will be mounted on stages to allow observation angles from 0.1° to 4° at 15 m and 0.05° to 2° at 30 m.

Several modifications will be implemented to accommodate additional spectral and geometrical capabilities. A Xe arc lamp source will be added, producing nearly 100 times more lumens than the tungsten strip lamp, thereby significantly increasing the sensitivity of the instrument. Additional standard illuminants, such as C, can be achieved by using appropriate filters. A spectral detector will provide measurements of the spectral characteristics of the retroreflected light, which will allow the color of the sample to be computed under a variety of illumination conditions. A beamsplitter will be used for relative measurements to an observation angle of 0°, which will provide an additional ability to characterize the retroreflecting properties of a sample.

The most important modification will be to permit measurements of the BRDF of a retroreflective sample. This capability for the reference instrument will link it to the broader area of spectrophotometry. More importantly, knowing the BRDF of a sample, its retroreflecting characteristics under the geometrical conditions specified in the documentary standards can be calculated. Therefore, the response of the sample to different illumination and viewing conditions can be modeled. This will be important for materials that are not flat, such as tape on garments, and for simulating driving conditions.

b.2.2) O-6: The Measurement of Appearance

The appearance of an object is determined by the spectral and angular dependence of the reflectivity of the coating or surface of an object and the spectral properties of the illuminating source. If the coating is fluorescent, the appearance can be affected by the extent and nature of the fluorescence and its relationship to its illuminating radiation. The spectral reflectance and other optical properties, such as gloss and haze, play a role in determining the appearance of an object. CORM recommends the following actions for NIST.

The National Institute of Standards and Technology can play an important role by doing the following:

- ***Establish a laboratory program directed toward appearance measurement, this effort should include research into the human factors affecting visual evaluations so that the importance of these attributes is understood.***

- ***Develop a system of SRM's on gloss, contrast, texture, translucency, and other appearance attributes that can be disseminated to user laboratories. Where scales appear for such attributes, the emphasis should be upon visual interval scaling.***

Through special funding from the NIST Director, the Optical Technology Division has been expanding its capabilities in characterizing appearance properties. This funding has been used to develop a new goniophotometer laboratory for appearance measurements [6] and a Calibration Service for specular gloss, 38090S. We hope in the future to expand our capabilities to include texture. We do not anticipate getting involved in human factors affecting visual evaluations, as we do not presently have the facilities, personnel, infrastructure, or institutional mandate to undertake studies on human subjects.

b.2.3) O-7: Effect Material SRM's

Effect materials are those coatings that change appearance depending on the viewing angle and incident angle of the illumination. This geometric sensitivity to appearance introduces new demands for the calibration of traditional spectrophotometric instruments used for measuring optical properties. In addition to the calibration problem, there are issues of agreeing upon a set of measurements that are useful for the characterization of the materials. CORM requested NIST to undertake the following tasks.

A recommendation is that the National Institute of Standards and Technology initiate the following work:

- ***Improve the referee capability to measure spectrally and calculate the chromaticity of effect materials at multiple angle combinations with uncertainties of less than 0.5 CIELAB color difference unit.***

- ***Plan and initiate a measurement assurance program suitable for verification of the measurement capabilities of calibration and testing laboratories at the multiple angle combinations needed to test effect materials.***

- ***Issue a series of calibrated SRM's of various colors and material types with spectrophotometric and chromaticity values at the angles needed for effect materials measurement.***

The Division is researching methods for the quantitative characterization of pearlescent coatings, important for the appearance of a variety of commercial products. A quantitative specification for pearlescent coatings will aid national and international commerce by ensuring the ability to accurately reproduce a coating in a variety of locales.

As part of the Division's effort to quantify the properties of the pearlescent coatings, a series of coating samples supplied by manufacturers were examined using the Division's Spectral Tri-function Automated Reference Reflectometer (STARR [4]). STARR measured the reflectance of the samples for incident wavelengths from 380 nm to 780 nm in 10 nm increments and incident angles of 15°, 25°, 45°, 65°, and 75°. Viewing angles were chosen from –80° to 80° in 5° steps. For each pair of incident and reflected angles, colorimetric values of lightness, *a*, *b*, hue, and chroma were calculated. The STARR-determined colorimetric quantities validated the qualitative expectations by exhibiting a strong dependence on the incident and reflected angles. Empirically, it was found that measurements at a subset of the reflectance angles, 15°, 35°, 45°, 70°, and 85° for each incident angle provide sufficient information to furnish a full characterization of the pearlescent coatings.

Building on this background research, future Division efforts are directed at further developing the metrology for characterizing pearlescent coatings. This will help guide the Division's response to the needs of industry, academia, and government laboratories for calibration services in this area.

b.2.4) O-8: Specular Reflectance

The wavelength dependence of the specular reflectance is an important property in describing optical elements such as mirrors or windows in optical systems and the the color or appearance of an object. Standard reflectance materials are used to calibrate a range of process control instruments in the visual arts, printing, painting, and coating industries. While standard reference materials are available from NIST for some reflectance applications, CORM recommends the following additional efforts by NIST:

SRM's should be available that cover a wide wavelength range (UV to mid-IR) as two separate standards. The current standard SRM 2003h (aluminum mirror) is acceptable for the UV-VIS-NIR, while SRM 2011 (gold mirror) is an acceptable artifact for the mid-IR region. Both the range, measurement interval and the option of additional geometries needs to be increased to make these SRM's more useful to the customer.

NIST presently offers three SRMs (2003, 2011, and 2023) for specular reflectance at an incident angle of six degrees and wavelength range from 600 nm to 2500 nm for 2011 (first-surface gold mirror) and from 250 nm to 2500 nm for 2003 (first-surface aluminum mirror) and 2023 (second-surface aluminum mirror). As noted by CORM, our customers desire additional flexibility in specifying both the measurement interval and the geometries for the measurements. Indeed, these expanded capabilities are presently available through Special Test Calibration Service 38060S. To ensure our customers the maximum flexibility that they desire, we plan on discontinuing SRMs 2003, 2011, and 2023, and offering these services instead through Special Test 38060S.

c.1) Radiometry - Priority One Proposals

Radiometry is the science of measuring electromagnetic radiation (usually called optical radiation) and involves the characterization of optical sources and detectors. Photometry, as a subfield of radiometry, is the measurement of optical radiation weighted by the response of the human eye. Colorimetry, a related subfield, is the measurement of optical radiation weighted by the appropriate color function. Radiometry issues have been heavily emphasized in the CORM reports over the years. This emphasis reflects the importance of radiometry to a number of science and engineering endeavors, spanning earth remote sensing by satellites to the manufacture of microelectronics by lithography and rapid-thermal processing.

c.1.1) R-1: Detector-Based Radiometry

There has been a continual demand by CORM for improved quality and accuracy photodetectors. NIST has recommended performing radiometric measurements using photodetectors with known absolute spectral responsivities [7], i.e., the so called detector-based radiometry. Recommendations for improvements in detectors have been a key ingredient of the last several CORM Reports and continues to be an area of considerable activity at NIST and the other national laboratories. The CORM 6th Report requested that NIST undertake the following:

The need continues for further development, particularly for extending the technology into the ultraviolet and near-infrared regions, and developing a detector-based total luminous flux standard.

The following have been identified as areas for further work:

- ***Develop detector standards for the UV and IR.***

Various detector standards have been demonstrated in the infrared to the ultraviolet spectral regions. In a collaboration with International Radiation Detectors, Inc., nitrided, thin-oxide, silicon photodiodes with and without Pt-silicide front windows have been developed as stable ultraviolet detector standards for the 180 nm to 400 nm wavelength range. The detectors have enhanced UV-damage resistance and can maintain the spectral power responsivity scale with an uncertainty of 0.5 % (k=1). [8]

Also, in collaboration with the Optoelectronics Division, $LiNbO_3$ and $LiTaO_3$ near-infrared to ultraviolet pyroelectric radiometers have been designed with a spectral power responsivity uncertainty of 0.1 % (k=1) between 250 nm and 1600 nm. [9] Again with the Optoelectronics Division, Ge trap radiometers have been developed to convert power responsivity into irradiance responsivity for operation between 800 nm and 1600 nm. In the infrared, InGaAs radiometers have been constructed for the 1 μm to 2.5 μm wavelength range to measure radiant power or irradiance. Large-area InSb radiometers have been developed in cooperation with Judson Technologies, Inc. to maintain the NIST spectral power and irradiance responsivity scales between 2 μm and 5.1 μm with an uncertainty of 1 % (k=1). [10]

- ***Improve all detector standards for greater long-term stability, spatial uniformity and response.***

New generation tunnel- and reflectance-type Si trap radiometers have been developed at NIST with improved spatial response uniformity to transfer and maintain the spectral responsivity scales. [11] Si, InGaAs, pyroelectric, and HgCdTe detectors have been selected from different manufacturers to obtain improved long-term stability and spatial response uniformity.

- ***Develop calibrated detector standards packages that can be easily used by NIST customers.***

Modular working-standard Si, Ge, and InGaAs radiometers and photometers have been developed with cooled temperature control for the detectors and heated temperature regulation for the filters. A five-channel Si radiometer has been constructed with a temperature controlled filter-wheel and a Si tunnel-trap detector for high accuracy (0.1 % uncertainty level) power, irradiance, and radiance measurements.

- ***Continue work on development of detector-based candela to improve photometric scales***

A new Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) Facility has been constructed at NIST to improve the accuracy of spectral responsivity scales. [12,13] The standard photometers will be calibrated on this facility against the reference tunnel-trap irradiance meters using tunable laser-based point sources. The SIRCUS-calibrated standard photometers are expected to lead to a factor of two decrease in the uncertainty of the NIST candela.

- ***Promote the application of detector-based radiometric standardization in research and industry***

Twelve detector-based scales have been demonstrated at NIST in the past decade. Most of these scales were developed since the last CORM report. The traditional spectral power responsivity scale has been extended for the 200 nm to 20 μm wavelength range. The power responsivity scale has also been extended to irradiance and radiance measurement modes. Improved accuracy transfer and working standard radiometers have been developed to realize the improved accuracy responsivity scales and to propagate the scales to industry, military, and academia.

- ***The methodologies for the use of these standards needs to be improved and standardized so that they will be used in a uniform and consistent way***

NIST has improved detector (radiometer) standards in power, irradiance, and radiance measurement modes. Irradiance and radiance responsivity calibrations require uniform point and extended sources. A traveling SIRCUS (high intensity, tunable-monochromatic, and uniform source with an irradiance-mode detector standard) has been developed to help the community to make field-level irradiance and radiance mode calibrations in a uniform and consistent way. A detector-based tristimulus color scale has been worked out at NIST to calibrate tristimulus colorimeters with decreased chromaticity uncertainty. The spectral-responsivity-based calibration method can be applied for existing tristimulus meters and will result in more uniform and consistent color measurements than traditional lamp-based calibrations.

c.1.2) R-2: Radiometry: Sources and Standards

NIST maintains a program to supply spectral irradiance and radiance lamps for use by scientific and industrial customers. These lamps are used for calibrating sensor systems that rely upon spectral information for the generation of their data product. These sensor systems could be a satellite used for weather and earth resource monitoring looking for small temporal variations. The improvement of both the quality of the lamps issued, as well as the scales that NIST uses to calibrate the lamps, has been a subject of CORM proposals in past reports. High-quality lamps and detectors form the cornerstone of modern radiometry and hence their improvement is a natural outgrowth of their importance. The CORM 6th Report recommended that NIST undertake the following.

CORM recommends that:

- ***Measurement scales be converted from the currently used source standards***

The source-irradiance (spectral irradiance) scale was recently realized against a group of filter-radiometer (detector) standards. The spectral irradiance responsivity of the broad-band filter-radiometers was derived from the primary standard cryogenic radiometer. The temperature of the transfer-standard blackbody-source was determined from irradiance measurements with the filter-radiometers. The uncertainty of the source-irradiance scale was decreased by about a factor of ten at 2.4 μm and a factor of two at 250 nm, as compared to the source-based irradiance scale realization in 1990. [14] At present, the source-radiance (spectral radiance) scale is still derived with radiance ratios from the melting point of gold using a narrow-band radiance meter and a variable-temperature blackbody source.

- ***Detector standards be improved (see Detector-Based Radiometry section).***

Efforts at improving detector standards have been discussed above in the Detector-Based Radiometry sections.

- ***Hybrid standards, consisting of a combination of stable optical filter, detector, and transimpedance amplifier, be developed as standards at specific wavelengths***

NIST develops narrow-band (filtered) Si radiance meters with temperature-controlled cooled detectors and heated filters for high sensitivity and stability. Tunnel-trap detectors are also used to avoid back-reflectance from detectors to filters. Blackbody temperatures can be determined from narrow-band radiance measurements. The output signal of a narrow-band radiance meter can be calibrated in (radiance) temperature.

- ***Special emphasis be placed on lowering uncertainties in the UV and in the IR beyond 1000nm.***

The SIRCUS-UV-VIS-NIR and SIRCUS-IR Facilities are being developed to lower the measurement uncertainties in the ultraviolet and infrared ranges. A new beamline at SURF III has lowered the uncertainties in spectral radiant power from 125 nm to 400 nm to ~0.5 %. A new IR comparator facility has allowed lower uncertainties out to 20 μm.

- ***The methodologies for the use of these standards be improved and standardized so that all users are using them in a uniform and consistent way (see R-3: Methodology: Photometry and Radiometry).***

Irradiance and radiance mode measurements have been introduced recently to decrease the uncertainty of power mode measurements caused by poor spatial response uniformity of detectors. NIST continues to publish recent results on new methodologies in various journals, including the Journal of Research at NIST.

- ***Improved documentation, training and networking on the use of these standards needs to be implemented.***

NIST has started a long-term effort to develop improved detector-based calibration methods, procedures, and transfer/working standard radiometers. Simultaneously, NIST started a publication effort (twelve detector-based scales have already been published) to educate the radiometric community about the advantages and propagation possibilities of the new scales. NIST short courses on radiometric, photometric, and temperature measurements are organized on a regular basis.

c.1.3) R-3: Methodology: Photometry and Radiometry

As the quality of detectors and sources improves and as the availability of new radiometric techniques enter the marketplace, it is necessary that the procedures and methodology of using the new capability be conveyed to the potential users. This need is not solely directed at NIST as it calls for activity by CORM as well. Universities and organizations like the CIE, SPIE, and OSA also have a potential role in this area. CORM suggests the following technical areas could use improved methodology.

Improved measurement procedures and techniques are particularly needed in the following areas:

- ***Ultraviolet Radiometry and Spectroradiometry.***

- ***Quantification of polarization and stray light in measuring systems.***

- ***Gonio-Photometric measurements.***

- ***Calibration of spectroradiometers.***

NIST has instituted two short courses held annually: 1) Radiation Thermometry and 2) Photometry and Colorimetry. These well-attended courses help to disseminate the latest and most up-to-date methodology used by NIST into industry and government. We are in the process of instituting another short course on spectroradiometry within the next year.

c.2) Radiometry -Priority Two Proposals

c.2.1) R-4: Colorimetric Measurement of Displays

The technology for displays has evolved with the addition of LED displays and liquid-crystal displays, replacing the venerable CRT display in many applications. They all have their unique measurement problems and challenges. The consumer demand for correct color rendering of images on computer displays and on the printed output have spurred the development of calibration procedures unique to these devices. Previous CORM Reports have mentioned the need for display colorimetry improvements and this problem continues to be a topic in the CORM 6th Report. The CORM 6th Report summarizes the requests as follows:

The measurement of displays was a concern of a number of the respondents to the questionnaire. Most of the measurement needs were the determination of luminance, color and image contrast for cathode ray tube (CRT) displays, liquid crystal displays (LCD) and light emitting diode (LED) displays. The concerns of the respondents fell into two general categories; the desire for better standards to calibrate measurement equipment and the desire for standardized measurement procedures for the determination of display performance parameters.

The Optical Technology Division established a project on this subject in 1997, and devoted major efforts to establish a capability of color and luminance calibrations for displays. There was also a concern in the Air Force for color measurement of cockpit displays, and this project was funded by the Air Force from FY97 to FY99. There were large variations in color and luminance measurements of displays; the discrepancies were several times larger than the manufacturers' specifications for CIE Illuminant A. Early tests at NIST proved discrepancies of 0.005 to 0.0015 in chromaticity x, y and more than 10 % in luminance among different commercial instruments measuring various colors of a CRT and LCD, though manufacturer's specifications showed "accuracies" of ±0.001 to 0.003 in x, y and ±2 % in luminance for Illuminant A. Another test showed errors of more than 0.05 in x, y and 30 % in luminance for an LCD measured with a contact type colorimeter. The main problem was that there were no standards available (with known uncertainty) to calibrate or check these instruments. In addition, there were no good guides on the measurement practice.

To address the first issue, we developed a reference spectroradiometer specially designed for color measurement of displays. It consisted of a double monochromator with input imaging optics incorporating a depolarizer for LCD measurement. With thorough characterization of the instrument, we achieved the expanded uncertainty (k=2) within 0.002 in x, y and 1 % in luminance for any color of a CRT or LCD. [15,16] The errors for chromaticity and luminance readings depend on the color of display being measured, and it was very difficult to apply corrections for many different colors. To solve the difficulty, we developed the Four-Color Method, which allows correction of a colorimeter for any colors of a display with calibration using three primary colors plus white of the display. [17,18] This method proved to be useful and is being introduced by several companies. We have established a NIST calibration service for calibration of colorimeters for displays, where we calibrate colorimeters for four colors of a CRT and/or LCD and provide the Four-Color correction matrix.

To address the second issue, two staff members, Yoshi Ohno and Steve Brown, took an active part in the development of international standards including IEC 61966-3 measurement on CRTs

(2000), IEC 61966-3 measurement on LCDs (2000), VESA flat panel display measurements standard, and CIE TC2-42 document (still in preparation). Steve Brown has taken the chair of CORM CR-5 Electronic Displays.

c.2.2) R-5: Photometry: Improved Measurement Capability

Improvements in photometric measurements have been a consistent request of CORM and other NIST customers. NIST has made considerable progress in improving the fundamental SI unit, the candela. The CORM 6th report has requested the following:.

It is important that NIST now turn its attention to the immediate need for improvements to luminance, luminous flux and color temperature scales and the supporting measurement services.

As the photometry community begins to use detector-based standards, rather than source based photometry standards, a need for additional education on the proper methodology becomes of particular importance. This lack of understanding is causing some confusion within the community and a need exists for an educational seminar or workshop to disseminate the information on detector based photometry. A recommendation is made that NIST update its SP 250 publication on Photometry and consider holding a seminar/workshop on Photometry in the next few years.

Since 1995 when the CORM 6th report was issued, the Optical Technology Division has made a number of improvements in photometry. These improvements include the development of the the Absolute Integrating Sphere Method, the basis for the new NIST luminous flux unit realized in 1995. [19] The new scale has been disseminated since 1996. The magnitude of the NIST lumen increased by 1.1 % at this time, but turned out to be in better agreement (within 0.2 %) with the world mean, as demonstrated by the 1998 CCPR intercomparison of photometric units. The absolute sphere method has the advantage of realizing the lumen using an integrating sphere, with no need of a goniophotometer, and is being introduced by other national laboratories, including BIPM [20] (international bureau), HUT (Finland), and VNIIOFI (Russia).

The additional and important step has been taken to use the Absolute Integrating Sphere Method for routine calibration of lamps using a new 2.5 m integrating sphere, to further reduce our calibration uncertainty for luminous flux of lamps to 0.5 % (k=2), one of the lowest in the world. [21] NIST is also taking the equally important step of working with industry in reducing their uncertainties in luminous flux measurements. [22,23] Along these lines, one of the Division's staff members, Dr. Yoshi Ohno, is leading the project by the IESNA Testing Procedures Committee to produce a guide for luminous flux measurements. The Division also started the annual NIST Photometry Short Course in 1998, which consists of lectures and hands-on laboratory sessions. Also, as requested in the CORM 6th report, the NIST Publication 250 in photometry was completely revised and published as SP250-37 in 1997.

Finally, in expanding its photometry capabilities, the Division established a scale for the flashing light photometric unit, $lx \cdot s$, with support from the Federal Aviation Administration. [24] The project was carried out in 1996 and 1997 to address the need for accurate calibration of flashing-light photometers used to maintain aircraft anticollision lights. A new calibration service, 37110S, has been established as a result of this project.

c.2.3) R-6: Improved Spectroradiometric Instrumentation

This request is directed at both NIST and the scientific instrument manufacturers to develop new spectroradiometers with improved performance and better long-term stability in selected wavelength regions. Some of the radiometric measurements, such as in the solar ultraviolet, have particular problems that ordinary radiometric instrumentation does not satisfactorily solve. Emerging industrial demands for ultraviolet processing and deep ultraviolet lithography also offer challenges. The CORM 6th Report recommends the following:

A low cost, portable, highly accurate spectroradiometer is needed for solar ultraviolet spectral irradiance measurements from 280 to 400 nm and a single instrument covering the wavelength range of 300 to 3000 nm or longer is required for research relating to solar energy.

CORM recommends that industry, with guidance from NIST:

- ***Develop a low-cost, portable and highly accurate spectroradiometer with improved system sensitivity, stability, faster scanning speed, ease of calibration, flexible software and extended wavelength coverage with well defined optical performance specifications.***

- ***Improve the documentation and training associated with the use of the improved instrumentation.***

- ***Promote the advantages and disadvantages of different types of measurement systems for specific measurement applications.***

Perform additional research on the use of multi-channel based instruments used for spectroradiometric measurements. While it is possible to produce meaningful spectroradiometric measurements from multi-channel instruments, the practical difficulties

are generally ignored in system implementation and treatment of data, leading to incorrect or misleading results.

This is an area that is more the responsibility of instrument manufacturers, as developing commercial instruments is not within the mission of the Division. However, NIST has developed, along with industry, several Fastie-Ebert spectroradiometers. [26] These portable double monochromators feature high throughput, high wavelength accuracy, and low out-of-band stray light. They have been used to measure spectral irradiance and radiance in a number of different projects, such as the UV monitoring network program, [27] intercomparisons of synchrotron radiation and deuterium lamps, [28] and calibration of remote sensing instruments.

3. Conclusions

The interaction between CORM and NIST via the recommendations in the various CORM reports has, over the years, provided an important ingredient in NIST's program planning. The responses outlined in this report are indicative of this fact and prove the value of the efforts that CORM undertakes on a periodic basis to perform these surveys. As documented in this report, since the CORM 6th report was issued in 1995, the Optical Technology Division has made tremendous strides in improving all aspects of optical radiation measurements. The integration of the intrinsic high accuracy of the cryogenic radiometer into all aspects of the Division's measurement services has been completed and a new laser-based facility, SIRCUS, has been constructed to extend the improved measurement capability into other areas of radiometry. Included in this effort has been the placement of the radiometric source-based scales upon a detector-based scale that is directly related to the cryogenic radiometer.

The radiometry efforts are complemented by new programs in optical properties. These programs are being designed to meet the new demands in this area driven by advances in digital imaging, recording, and display technology. The recent widespread use of LEDs in displays and lighting was foreseen in the CORM 6th report and in its immediate predecessor, the CORM 5th report, and consequently NIST is presently disposed to meet many of the needs of this important area.

The CORM 7th report is due to be released later this year and we look forward to studying its recommendations to gain guidance on future opportunities for NIST programs. We view this response to a CORM report as an essential mechanism to complete the cycle of recommendation, evaluation, action, and assessment and we are hopeful the optical radiation measurement community finds our report useful. The authors thank the staff of the Optical Technology Division for assisting in the writing of this report by furnishing updates on their projects.

4. Acronyms

ANSI	American National Standards Institute
BIPM	Bureau International des Poids et Mesures
BRDF	Bi-directional Reflectance Distribution Function
BRTF	Bi-directional Transmittance Distribution Function
CCPR	Consultative Committee for Photometry and Radiometry
CFR	Code of Federal Regulations
CIE	Commission Internationale de L'Éclairage
CORM	Council for Optical Radiation Measurements
CRT	Cathode ray tubes
DoD	Department of Defense
EOS	Earth Observing System
HUT	Helsinki University of Technology
IEC	International Electrotechnical Commission
IESNA	Illuminating Engineering Society of North America
ILAC	International Laboratory Accreditation Council
IR	Infrared
ISO	International Standards Organization
LCD	Liquid crystal display
LED	Light emitting diode
MAP	Measurement Assurance Program
MOU	Memorandum of Understanding
MRA	Mutual Recognition Arrangement
NASA	National Aeronautics and Space Administration
NHCRP	National Highway Cooperative Research Program
NIR	Near Infrared
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NVLAP	National Voluntary Laboratory Accreditation Program
OSA	Optical Society of America
SI	International System of Units
SIRCUS	Spectral Irradiance and Radiance responsivity Calibrations using Uniform Sources
SP	NIST special publication
SPIE	The International Society for Optical Engineering
SRM	Standard Reference Material
STARR	Spectral Tri-function Automated Reference Reflectometer
SURF	Synchrotron Ultraviolet Research Facility
UV	Ultraviolet
VESA	Video Electronics Standards Association
Vis	Visible
VNIIOFI	Institute for Optico-Physical Measurements, Gosstandart of Russia

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