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**NIST Response to the 7th CORM Report:
Pressing Problems and Projected National
Needs in Optical Radiation Measurement**

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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 Seventh Report issued in 2001 and is timed to be contemporary with the CORM Eighth Report to be issued in 2005.

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

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Preface

The Council for Optical Radiation Measurement or 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 purpose as stated on their website, www.corm.org, is

- To establish (and publish) consensus among interested parties on national, industrial and academic requirements for physical standards, calibration services, and inter-laboratory collaboration programs in the fields of optical radiation measurement, including measurement of the transmittance and reflectance properties of materials, measurement of radiant sources, and characterization of optical detectors used for the measurement of these properties.
- To establish national consensus on the priorities for these requirements.
- To maintain liaison with the National Institute of Standards and Technology (NIST) and to advise the Institute of requirements and priorities.
- To cooperate with other organizations, both public and private, to accomplish these objectives for the direct and indirect benefit of the public at large.
- To assure that information on existing or proposed standards, calibration services, collaboration programs, and its own activities is widely disseminated to interested parties.
- To answer inquiries about such standards activities or to forward such inquiries to the appropriate agencies.

To establish a consensus on issues in the optical radiation measurement community, CORM periodically surveys its members and other interested parties on needs in optical radiation measurements. This community encompasses diverse interests from the university or government scientist using remote sensing satellites to study the earth to industrial scientists and engineers using optical measurement to assess the performance and quality of products after manufacture. The survey results are analyzed and recommendations for action are issued in a special CORM report. The most recent CORM report, the 7th, prepared by the CORM 7th Report committee in partnership with the CORM Board of Directors and Officers, was released in 2001 [1]. The needs identified from the survey were separated into three broad categories: radiometry, optical properties of materials, and measurement uncertainty.

Many of the needs fall within the purview of NIST's mission as the Nation's primary measurement and standards laboratory, while other needs are better addressed by industrial or academic laboratories. The present report presents 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 synergy with the laboratory mission.

For the purposes of this response, quotes from the CORM 7th Report are given in bold italics.

1. Introduction

The CORM 7th report was issued in late 2001 and was circulated to the CORM members and other interested parties worldwide. Over the years, the CORM reports have generated considerable interest among managers at government, industry, and university laboratories because of their ability to anticipate needs in optical radiation measurements. The CORM reports have served as an important tool for NIST management as some of the identified requirements and needs are within the mission of NIST. It has become a tradition for NIST to discuss its efforts to meet the needs identified by CORM in the form of an internal report [2]. It is the purpose of the present document to discuss NIST's response to the CORM 7th Report. The present response only considers areas within NIST's mission.

The CORM reports, in addition to defining critical needs, place the needs in a priority order to facilitate planning. The following explanation of the prioritization process is taken directly from the CORM 7th 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?*
- *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?*
- *Economic Factor: This category addresses the importance of the proposed work with regard to its impact on US industry, trade or other national priority.*

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 final prioritized proposals were broken down into the following three categories:

- ***RADIOMETRY***
- ***OPTICAL PROPERTIES OF MATERIALS***
- ***MEASUREMENT UNCERTAINTY***

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, DoD, and DHS. The availability of documented needs in optical radiation measurement helps managers at these agencies in ensuring that the funding they provide to the research and development community is optimally used.

The expanding technical base in the U.S. increases the demand 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 provide funding to NIST to develop programs in areas identified in the CORM report that satisfy specific needs of their agency.

The use of optical radiation measurement is pervasive throughout U.S. industry and government. Industries that use optical radiation measurements include photography, lighting, xerography, automobile, aerospace, defense, homeland security, instrument manufacturing, chemical, paper, and printing. The space-based observation systems developed for weather, earth resource, and agricultural monitoring by National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA), and for national defense applications by Department of Defense (DoD) are critically dependent upon reliable and accurate optical radiation measurements and standards for their success. CORM is central in defining the optical measurement and standards needs that this large and diverse community requires, helping to ensure the continued leadership role of U.S. technology and the global competitiveness of U.S. industry.

CORM has been a leader in identifying the need for calibration laboratories to adopt appropriate quality programs. Their efforts, and that of others, have led NIST to adopt an ISO 17025 standard for its measurement services [3]. NIST additionally responded to the need for measurement quality assurance by expanding the National Voluntary Laboratory Accreditation Program that serves a wide range of U.S. industry. CORM's identification of the need for improved optical power measurement techniques in their early reports helped NIST identify sources of funding that led to the development and employment of cryogenic radiometers that now operate with very low levels of measurement uncertainty [4]. The cryogenic radiometer's low uncertainty has led to improvement in many of NIST's optical radiation measurement scales including photometry, spectral irradiance and radiance, and radiance temperature. CORM's past proposals for improved colorimetric standards has given NIST direction and incentive for establishing new measurement capabilities for reflected color [5,6].

In the present report, the Optical Technology Division's efforts in addressing the issues raised in the CORM 7th Report are discussed. For simplicity of presentation and to aid the reader in comparing the Division's response to the requests from the CORM 7th Report, the structure of the CORM 7th Report is followed.

2. Radiometry

The CORM 7th Report had eight proposals under the heading of radiometry. Of these, R-1 and R-2 were deemed to be of priority 1 and the rest priority 2.

<u>Proposal Identification</u>	<u>Priority</u>	<u>Proposal Title</u>
R-1	1	New Standards of Luminous Flux
R-2	1	New Standards of Luminous Intensity
R-3	2	New Standards and Definitions for Luminance
R-4	2	New Standards of Spectral Irradiance
R-5	2	New Standards of Spectral Radiant Flux
R-6	2	Improvements to Goniophotometry and Gonioradiometry
R-7	2	Educational Issues of Illuminance
R-8	2	Radiometric and Photometric Issues

R-1 and R-2 address the need for improved standards for light emitting diodes or LEDs, devices expected to furnish the foundation for future solid-state lighting. Priority R-3 is concerned with luminance issues associated with LEDs and liquid-crystal displays (LCDs). The radiometry proposals are discussed in order below.

R-1 New Standards of Luminous Flux

Specifically the CORM report recommended that

- *NIST develop standard methods and evaluate calibration artifacts for their suitability for the determination of the luminous flux from LED sources. This should incorporate internationally accepted definitions related to LED source characteristics. It is necessary to develop methods of measurement for LEDs that result in the measurement of the basic physical quantities associated with light sources so that intercomparison of all sources is facile for specifiers and lighting designers and for federal and state regulators involved in the assurance of energy efficiency claims for light sources.*
- *NIST should continue its involvement in the development of international standards for evaluation of luminous flux for practical light sources of all types. This means primarily involvement in CIE division activities. Presently NIST participation is very active and very productive on behalf of US interests. The level of participation is appropriate and should continue to be supported.*

NIST has been collaborating with a number of organizations to develop and improve methods for measuring the properties of LEDs and other light sources. NIST is working with CIE Technical Committee 2-45, *Measurement of LEDs—Revision of CIE 127*, to improve luminous flux measurements of LED sources. NIST contributed extensively to the latest draft (Draft 4) of CIE

127.2, which expands on the methodology of luminous flux and spectroradiometric measurements of LEDs. In response to requests from industry, the latest draft includes new recommendations on integrating sphere geometries for LED luminous flux measurements and on the definition of partial LED luminous flux (see Figure 1). The draft also discusses the use of spectroradiometers for measuring photometric and colorimetric quantities, a practice that is being widely adopted by industry. The CIE 127.2 draft is still being finalized by the committee.

NIST also participates in the Project 78 *Guide for Measurement of LEDs* being developed by the Testing Procedures Committee of the Illuminating Engineering Society of North America (IESNA). This guide discusses the measurement of LED clusters and fixtures as well as individual LEDs. NIST plans to continue working with industry and national and international standards committees in developing methods and standards to improve LED measurements to help accelerate the development and commercialization of solid state lighting, which promises significant reductions in energy costs and maintenance. Recent advances in LED sources have also motivated NIST to examine their potential as standards for radiometric, photometric, and colorimetric measurements [7-10].

- *NIST should interact with existing laboratories of lamp manufacturers and independent calibration and testing laboratories to review and comment on methods and to make comparisons of methods used to arrive at luminous flux values for non-incandescent, non-LED sources. Participation by NIST in reviewing procedures including evaluating traceability of the luminous flux level transfer is critical to assure the confidence of the marketplace.*

NIST is a participant in the Lamp Testing Engineers Conference (LTEC) that meets semiannually to discuss important issues associated with the measurement of the luminous flux of various types of lamps. NIST has been providing calibrations of fluorescent lamps under Special Test Number 37060S, *Special Tests for Total Luminous Flux of Submitted Incandescent*

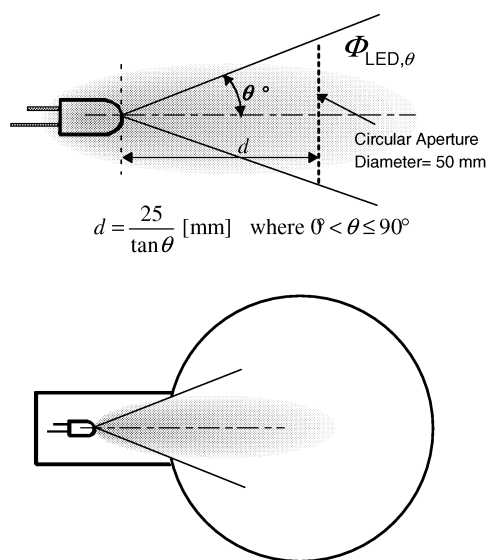


Figure 1. Many applications of LEDs, such as in traffic lighting and in the backlighting of liquid crystal displays, require a specification for the luminous flux in the forward direction, i.e. the partial luminous flux. Currently, the proposed definition of the partial luminous flux is that it is the luminous flux transmitted through a 50 mm diameter aperture positioned at a distance d from the top edge of the LED, thus defining the solid-angle for the measurement. Measurements are performed using an integrating sphere with a 50 mm entrance aperture for sampling the light from the LED, as shown in the lower part of the figure.

Lamps and Fluorescent Lamps, and of discharge lamps, including high-pressure sodium lamps, under Special Test Number 37100S, *Special Photometric Tests*. Unfortunately, it is not possible for NIST to develop capabilities to calibrate the large variety of discharge lamps available commercially. Potential customers are encouraged to explore the availability of measurement services for various discharge lamps from commercial calibration and testing laboratories.

To improve industry measurements on non-incandescent sources, NIST is developing total spectral radiant flux standards [11] to facilitate use of spectroradiometers and thus to avoid the spectral mismatch error which occurs when a photometer is used to measure a non-incandescent light source. NIST is also assisting the National Voluntary Laboratory Accreditation Program (NVLAP) in conducting comparisons of luminous flux measurements of lamp products, including compact fluorescent lamps, through their Energy Efficient Lighting Products program. NIST will continue efforts to improve the accuracy of luminous flux measurements of light sources by industry.

R-2 New Standards of Luminous Intensity

Specifically the CORM 7th Report made the following observations and suggestions:

- ***(NIST should) Develop stable reference LEDs for all types of LEDs presently used.***
- ***NIST should offer a calibration service for these reference LEDs using the CIE recommended (and standardized) measurement conditions.***
- ***New applications are constantly being developed, and new reference standards need to be built and calibrated at NIST as an ongoing project.***

In response to the growing need for LED measurements and standards, NIST developed the facilities and calibration services for LED Averaged Intensity (Conditions A and B) and total luminous flux, available through Special Test Number 37130S, *Special Tests for Luminous Intensity and Luminous Flux of LEDs* (see Figure 2). The technical details of these NIST measurements and uncertainty budgets are reported [12,13]. Through this measurement service, LEDs submitted by customers are calibrated for luminous intensity and luminous flux, with typical uncertainties of 3 %. Calibrations of

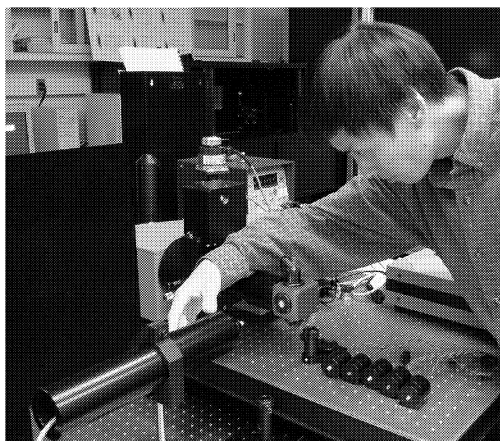


Figure 2. A picture of LED color calibration performed with the LED reference spectroradiometer. The test LED is mounted for the CIE Condition A geometry (baffles around the LED have been removed for the photograph).

LED color and UV radiant flux are being established. NIST is also investigating various LEDs to assess their suitability as transfer standards for radiometric, photometric, and colorimetric measurements. [7-10].

Deleted: ,as illustrated in Figure 3

It is difficult for NIST to prepare standards for all types of LEDs in use, especially when the LED technology is so rapidly changing. The needs for various types of LED standards are fulfilled in part by the current calibration services since they allow users to submit an LED for test. NIST will continue efforts to study new LED sources to ensure the currency of its measurement and calibration programs.

- *Workshops and tutorials need to be organized to introduce the measurement principles and uncertainty evaluation methods to those professionals who are new to this type of optical measurement.*

NIST has been offering a Photometry Short Course since 1998. The course includes lectures on LED measurements with discussion of the measurement uncertainty. We recognize the need for more focused training on uncertainty evaluation, and NIST plans to develop a separate short course on this subject in the near future. See section 4 for further discussion.

R-3 New Standards and Definitions for Luminance

The respondents to the CORM 7th Report outlined three measurement areas of concern in luminance:

- 1. LCD displays are highly polarized. Calibration with relatively unpolarized sources may give significant errors when applied to the displays.*
- 2. A calibration service, offered by NIST, for the calibration of luminance meters and calculation of correction factors was requested.*
- 3. Road signals often utilize discrete devices such as LEDs. Typical characterization of these displays are in terms of luminance vs angle. However, being highly non-uniform in emission, no satisfactory definition of luminance that applies to both near-field and far-field viewing conditions exists.*

To address these concerns the CORM 7th Report provided three recommendations:

- 1. A luminance standard, possibly incorporating an LCD panel, be investigated. This might be part of, or independent from, the current DMATS program. The aim is to allow calibrations to be used directly for LCD or similar displays without the need for compensations for the polarization differences between standard and display.*

Based on earlier recommendations by CORM and knowledge of industry's needs, NIST established calibration service 37120S, *Special Tests for Color Measuring Instruments for*

Displays, to provide state-of-the-art uncertainties for display color measurements [14]. This service allows customers to submit for calibration colorimeters or luminance meters used for measurements on LCD and other displays. Since the instruments are directly calibrated against an LCD display, the effects of polarization are accounted for in the measurements. Surprisingly, this service has had no customers since it was established in 2001, although several price quotations were provided. The quoted fees were only slightly higher than the fees for illuminance meter calibrations. The reason for this apparent lack of interest in the service is not clear, but may be due to poor marketing of the service to potential customers. The related Display Measurement Assessment Transfer Standard (DMATS) program within the Optoelectronics Division is still under development. Related to this, NIST is developing a spectrally-tunable standard source for general radiometric purposes, which can be used for calibration of colorimeters and luminance meters for display applications as well (Figure 3).

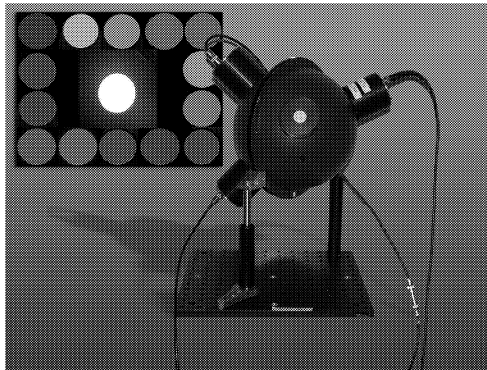


Figure 3. Integrating sphere source instrumented with a number of LEDs with currents individually controlled. Sample outputs from the source are illustrated in the upper left hand corner of the figure. The source is being developed as a spectrally tunable radiance standard [10].

2. ***Communication of NIST services to the measurement community should be increased. The indicated measurement services by NIST already exist. Many respondents in other areas of concern indicated a need for services that are already offered by NIST. It is apparent that information on some services offered are not adequately communicated to those needing them. CORM should aid NIST in making such information more widely available.***

NIST has published a number of papers directed at the display community [14], and has publicized the availability of the service at technical meetings. Additionally, NIST offers an annual Photometry Short Course with approximately 30 attendees, as well as short courses in Radiation Temperature and Spectroradiometry, as discussed in Figure 4, providing attendees with information about NIST's calibration services in photometry, colorimetry, and radiometry. Despite these efforts, NIST and CORM need to work to further improve communication about NIST calibration services to potential industry customers through improved web information and tutorial articles in trade journal and magazines.

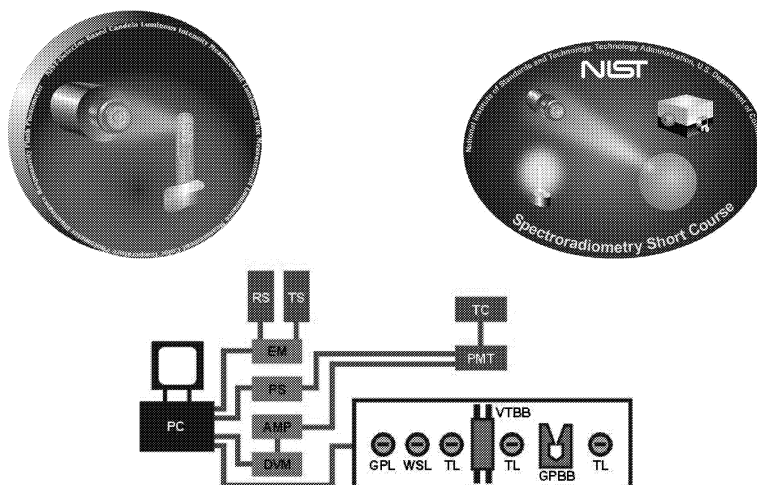


Figure 4. Logos for the Optical Technology Division's Photometry, Spectroradiometry, and Radiation Temperature Short Courses. These week-long short courses typically offered annually, provide attendees with a series of lecture and laboratory sessions which demonstrate fundamental and advanced concepts in photometry, spectroradiometry, or radiation temperature. The courses also provide Division scientists and engineers with opportunities to learn more about the needs of the attendees in the areas of photometric measurements and standards.

3. *NIST and industry should collaborate to provide an adequate definition of luminance, as applied to discrete LED signage. Sources to test and calibrate instruments to this definition would also be needed.*

The definition of luminance for LED signage requires an improved understanding of the human factors involved in assessing the visibility of LED-based signs relative to conventional head-light illuminated signs. NIST currently does not have the resources or expertise to conduct such research. NIST is, however, participating in discussions with standardizing bodies such as the CIE (Technical Committee TC2-50, *Measurement of the Optical Properties of LED Clusters and Arrays*) and the IESNA (*Testing Procedures Committee Project 78*) to develop standards in this area.

R-4 New Standards of Spectral Irradiance

Improved and more reliable spectral irradiance standards from the vacuum ultraviolet to the far infrared have been requested in most of the past CORM reports. While there has been considerable progress in the past decade in this area, the CORM 7th Report makes the following additional suggestions:

- *NIST continues to support and expand its ongoing contacts with critically impacted industries through participation in industry conferences, standards group participation, and technical briefs directed to identifiable segments of the NIST constituency.*
- *NIST promotes the proper use of the recently improved uncertainty of its irradiance scale among its known constituents.*
- *NIST continues to support its aggressive program of development of multiple approaches for realization and maintenance of the spectral irradiance scale. This is a strength that NIST is fully capitalizing on and is the basis of the improved spectral irradiance scale. It is important to continue to support the multiplex approach. This includes continued development of an overall laboratory design and systems automation that facilitate the interaction of complementary methods such as SURF, SIRCUS, LBIR, etc.*

NIST continues to work with industry in the development and dissemination of spectral irradiance measurements and standards. These activities include collaborating with the American Water Works Association Research Foundation (AwwaRF) in developing ultraviolet irradiance calibration standards for water treatment; with heat flux sensor manufacturers and users within the aerospace and fire testing community in improving radiative heat flux (i.e., total irradiance) measurements (see Figure 5); with the U.S. solar U.V. monitoring community to ensure the accuracy of their spectral irradiance standards; with remote sensing researchers to validate spectral radiance scales obtained from NIST spectral irradiance lamp standards; and with the DoD to improve the dissemination of spectral irradiance standards throughout the defense community.

To assist industry and government in improving their use of spectral irradiance measurements and standards, NIST developed a new short course on Spectroradiometry in 2002, modeled after the successful Photometry and Radiance Temperature Short Courses. The Spectroradiometry

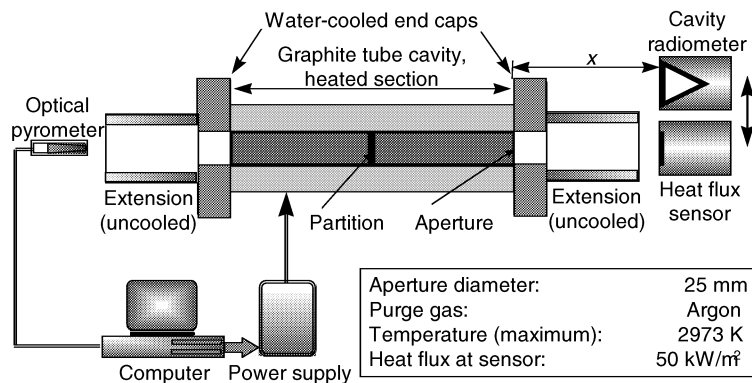


Figure 5. Schematic diagram of the Radiative Heat Flux Calibration Facility [15].

course consists of a week of lectures and laboratories to help educate students in the measurement of optical radiation. In October of 2004 the Division offered a lecture-only short course at the Night Vision and Electronic Sensors Directorate (NVESD) at Fort Belvoir, VA, combining selected topics from the Photometry, Radiance Temperature, and Spectroradiometry Short Courses, with additional topics tailored to the needs of the NVESD. More than 60 contractors and staff members from NVESD attended.

To ensure that NIST customers have access to spectral irradiance standards with the lowest measurement uncertainties, the Optical Technology Division has recently completed the development of a new Facility for Spectroradiometric Calibrations (FASCAL 2) for disseminating spectral irradiance FEL lamp standards [16]. This facility replaces the aging FASCAL facility which has successfully provided NIST customers with spectral irradiance calibrations for some thirty years. This facility will lower the uncertainties of NIST's disseminated scale, particularly in the near infrared, to allow customers to realize the full advantage of NIST's new detector-based spectral irradiance scale traceable to the electrical watt through the cryogenic radiometer.

In addition to improving its scale dissemination, NIST is continually advancing its spectral irradiance and radiance scales. Recent activities include the following:

- The implementation at the Synchrotron Ultraviolet Radiation Facility (SURF III) of new capabilities for calibrating the spectral irradiance of deuterium arc lamps between 200 nm and 400 nm using SURF as an absolute source [17] (see Figure 6).
- The development of new absolute pyrometers calibrated at SIRCUS for improving the determination of the thermodynamic temperature of high-temperature fixed-points important in the realization of the ITS-90 temperature scale. Such pyrometers will allow NIST to make the move from source-based to detector-based scales for spectral radiance and radiance temperature [18].
- The move of the SIRCUS, Aperture Area Measurement, and High Accuracy Cryogenic Radiometer 2 facilities to the new Advanced Measurement Laboratory to improve the quality of the measurement environment through lower particulates, better temperature and humidity control, and reduced vibration necessary to ensure the most accurate realization of the Division's radiometric and photometric scales which are ultimately all dependent on these three facilities.

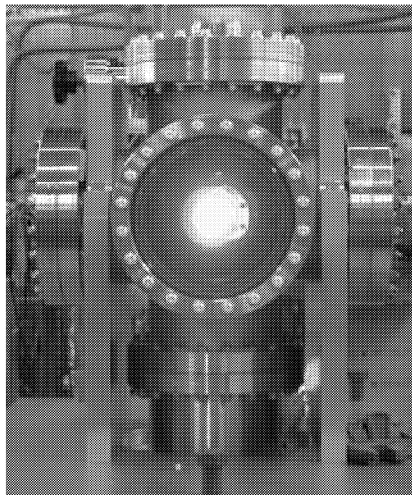


Figure 6. Synchrotron radiation from SURF III viewed through a glass viewport at the end-station of the beamline 3. This beamline is used to realize a spectral irradiance scale from 200 nm to 400 nm for the calibration of deuterium arc lamps [17].

- Near completion of the IR-SIRCUS facility, which will allow the infrared radiometry community to realize the benefit of absolute tunable-laser-illuminated integrating sphere sources for spectroradiometric calibrations [19] (see Figure 7).

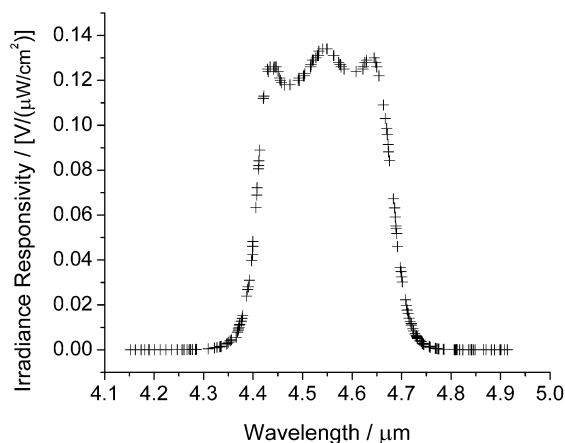


Figure 7. Absolute irradiance responsivity measurement of an infrared radiometer performed on the IR-SIRCUS facility. The relative measurement uncertainty is 1.5% ($k = 2$).

R-5 New Standards of Spectral Radiant Flux

Spectral radiant flux measurements provide the spatially-integrated spectral distribution of light sources such as incandescent, fluorescent and discharge lamps used in a variety of applications, particularly for lighting. Advances in LED and other solid-state lighting sources are generating new interest in spectral radiant flux measurements. The CORM 7th Report identified the following two needs for spectral radiant flux measurements:

- *NIST develops methods for calibration of spectral radiant flux of light sources. Combined standard uncertainties should be 1% or better over the wavelength range from 360 nm to 800 nm. Uncertainty due to source instability should be separately listed in the uncertainty budgets to allow for reduction of uncertainty by repeated measurements by the end user.*
- *NIST should work with industry organizations to develop artifacts capable of achieving the target uncertainties.*

The Division has nearly completed the realization of the total spectral radiant flux scale to be disseminated by FEL lamps. The availability of total flux measurements as a function of wavelength will eliminate problems associated with the spectral mismatch of photometers when used to measure non-incandescent light sources, such as single-color LEDs. Total spectral

radiant flux standards are also required for color measurements of light sources placed in integrating spheres.

The total spectral radiant flux scale is being realized at NIST from 360 nm to 800 nm region with a target uncertainty of 1 % ($k=2$). Two independent methods are under development, a goniospectroradiometric method and an absolute integrating sphere method. The scales realized from the two methods will be used to verify the scale uncertainties. The NIST goniospectroradiometer is illustrated in Figure 8. Total spectral radiant flux standards based upon 1000 W FEL tungsten halogen lamps (mounted on a screw base) will be available in 2005, and for lower power lamps for use in smaller integrating spheres (e.g., for LED measurements) somewhat later. Future plans include expanding the scale into the ultraviolet and infrared. Further details are available in reference [11].

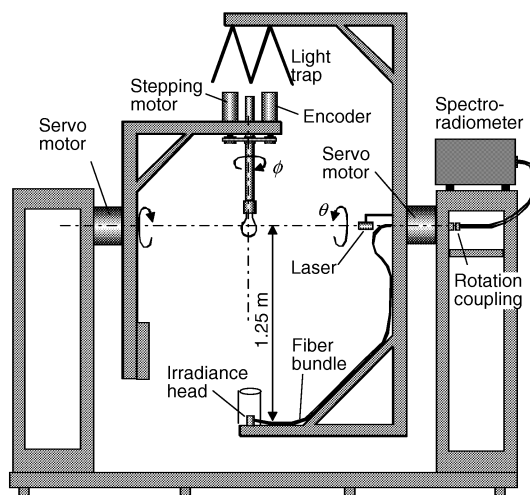


Figure 8. Design of the NIST goniospectroradiometer.

R-6 Improvements to Goniophotometry and Goniometri

CORM has also identified needs in characterizing the angular distribution of radiation from illumination and other types of light sources such as lamps, LEDs, and electronic displays. In particular, the CORM 7th Report identifies the following needs:

- *Develop new or improved standard procedures for measuring extended sources. These could positively impact the measurement uncertainty.*
- *Provide better analysis and simulation tools to model a given measurement. Software simulation tools could serve as a possible alternative to developing and maintaining expensive standards or as a tool to calculate measurement uncertainty.*

The Optical Technology Division has not addressed the goniometric characterization of general light sources, although goniometric measurements are performed on standard lamps and LEDs used at NIST. Goniophotometry measurements of luminaries has been well established through standards developed by IESNA and by calibration services provided by commercial testing laboratories. Measurements on electronic displays are available from the Optoelectronics Division. Procedures for the goniophotometric measurement of extended sources are highly application dependent, and better addressed by industry laboratories knowledgeable about the

specific application. CORM and NIST can aid these industry laboratories by working with standards organizations to initiate the development of appropriate technical standards for the measurement procedures.

- ***Play a role in reducing measurement uncertainty by education of users. CORM workshops and/or NIST short courses can be a means to ensure that industry really understands the techniques for measurement and for uncertainty analysis. NIST should look at the possibility of using computer based/web-based training media to meet basic educational needs.***

NIST recognizes the need for improved education on the treatment of measurement uncertainty. The Division's three short courses offer lectures on measurement uncertainty. We also plan on working with CORM to develop a full short course, workshop, or web-based training materials on the evaluation of uncertainty (see section 4).

R-7 Educational Issues of Illuminance

This request was concerned with the special measurement problems that occur with some modern illumination sources such as LEDs. Specifically the CORM 7th Report suggested the following:

- ***CORM recommends that a workshop or short course on the measurement of LEDs and LED lighting should be arranged. Development of a computer-based or web-based primer or tutorial would be helpful as well.***

A lecture on LED measurements has been added to the Photometry Short Course offered annually at NIST. In addition, NIST has collaborated with other organizations such as CIE to provide opportunities for discussion of LED measurements. For example, NIST hosted the CIE 2nd Expert Symposium on LED Measurement, May 10-12, 2001 in Gaithersburg, MD, which included a one day tutorial on LED measurements. NIST also contributed to organizing the CIE Expert Symposium on LED Light Sources, June 2004 in Japan, which included a number of papers on LED measurements. We will continue our efforts in providing opportunities for improved education on LED measurements by working with CORM and other organizations.

R-8 Radiometric and Photometric Issues

This proposal dealt with the changing needs in radiometry and photometry driven by the new types of light sources being developed and deployed in a wide range of applications. In addition to LEDs, the widespread use of high-intensity discharge lamps poses new types of design, application and measurement problems for their effective use. In other applications, researchers in a wide range of fields from photobiology to remote sensing are using radiometric and photometric techniques for which standard measurement procedures do not exist. The CORM 7th Report suggests the following for NIST and the community:

- ***NIST participates and actively contributes to the effective standardization of methods and procedures used in measurements related to these emerging technologies.***

Currently, the level of active participation in international discussions on standardization is appropriate, and this should continue to be the policy of NIST.

- *NIST establishes measurement service capabilities in line with such standard methods and procedures.*
- *NIST pro-actively seeks to establish standard sources and other artifacts appropriate to these emerging technologies.*
- *NIST, CORM and industry provide education and training to users and manufacturers on appropriate measurement procedures.*

NIST is participating in international standards activities on measurements on new types of light sources, including LEDs, as described above through CIE Technical Committees 2-45, 2-46, and 2-50 and on the photometry of flashing light sources through CIE Technical Committee 2-49 and ASTM Committee E12.11. NIST also consults with the Optoelectronics Industry Development Association (OIDA) to better understand measurement and standards needs associated with LED and organic LED (OLED) source development and commercialization. OLED sources are typically large flat-area light sources which require unique measurement methods. NIST also recently started a collaboration with the American Water Works Association Research Foundation (AwwaRF) to develop standard methods for characterizing and calibrating UV sensors used to monitor the ultraviolet irradiance (produced by medium pressure mercury lamps) for disinfecting drinking water in treatment facilities. NIST will continue to keep close contact with various industrial groups and standards organization to learn about measurement needs associated with emerging technologies.

3. Optical Properties of Materials

The CORM 7th Report made six proposals for action in the area of optical properties of materials. There were three priority 1 proposals and three priority 2 proposals that included the traditional areas of reflectance and transmittance, as well as color and appearance. The proposals are listed below:

<u>Proposal Identification</u>	<u>Priority</u>	<u>Proposal Title</u>
O-1	1	New Standards for Reflected Color
O-2	1	New Standards for BRDF/BRTF
O-3	1	New Standards for Fluorescence
O-4	2	New Standards for Regular Transmittance
O-5	2	Measurement and Standards for Retroreflection
O-6	2	Measurement and Standards for Appearance

There has been increased interest in the last decade in the measurement of color and appearance of products. The CORM 6th Report issued in 1995 had some of the same proposals and NIST has been able to make progress on some of these areas identified by the CORM reports. We will discuss the specifics of each proposal in the following sections.

O-1 *New Standards for Reflected Color*

Color standards is the area that elicited the most response in the optical properties of materials category. This interest is being driven by the increased attention to color quality in consumer products, to color discrimination in various tests, including for the presence of chemical and biological agents, and to color reproduction on computer screens and printers for electronic commerce. To meet the needs in these areas as well as others, the CORM 7th Report recommends the following:

- ***Improve the referee capability to measure spectrally using total hemispherical and bi-directional (45/0 or 0/45) reflectance factor measurements in order to correspond to the 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.***
- ***Plan and initiate a measurement assurance program suitable for verification of the measurement capabilities of calibration and testing laboratories.***
- ***Provide, singly and in cooperation with CIE, CORM and other organizations, educational programs to industrial users emphasizing the SRMs, measurements available at NIST and the uncertainties involved in the measurement process.***
- ***Facilitates measurements at multiple angle combinations for gonioapparent materials, with uncertainties of less than 0.5 CIELAB color difference unit.***

In response to needs articulated by members of CORM, the Inter-Society Color Council (ISCC), the ASTM International Committee E-12 on Color and Appearance, and other industry groups, NIST has developed a new reference instrument for measuring reflectance color [5,6], as pictured in Figure 9. The NIST Reference Reflectance Colorimeter presently has capabilities for determining the bidirectional reflectance factor in the standard 0°/45° or 45°/0° geometry. Efforts are presently underway to develop capabilities for measuring the reflectance factor for the total hemispherical geometry and for arbitrary input and output angles.

The 0°/45° or 45°/0° measurements are available to NIST customers through the NIST Calibration Services under Special Tests of Spectral Reflectance and Surface Color, number 38060S. The typical submitted test item is a set of twelve to fourteen standard 10 cm square BCRA glossy color tiles. Measurements of the reflectance factor are performed from 380 nm to 780 nm in 5 nm steps for both parallel and perpendicular polarizations of the incident radiation. The results for the two polarizations are averaged. The reflectance factors are referenced to the reflectance of a Spectralon[†] polytetrafluoroethylene standard as determined using the NIST Spectral Tri-function Automated Reference Reflectometer or STARR. Although the measurement uncertainty on the reflectance factor varies with wavelength and color of the tile, typical values are less than 0.0003 ($k = 2$), the stated requirement in the CORM 7th Report.

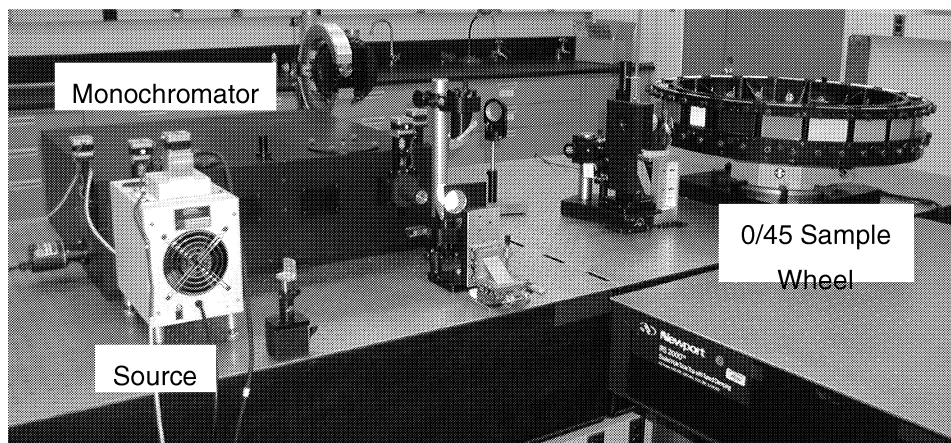


Figure 9. Picture of the new NIST Reference Colorimeter with sample wheel for 0/45 measurements of reflected color.

NIST is working to ensure the quality of color measurements by calibration and testing laboratories and instrument manufacturers by participating in proficiency testing programs offered by independent testing services. This approach allows NIST to leverage the extensive measurement comparison infrastructure developed by independent testing services to effectively assess the performance of industry laboratories in making measurements comparable nationally and internationally against national and international standards. Measurement comparisons with other National Metrology Institutes (NMIs) have also been undertaken to aid calibration and testing laboratories and instrument manufacturers in ensuring that their measurements are comparable internationally.

As part of its development of measurements methods and standards for reflected color, NIST has undertaken an analysis of uncertainties in the measurement of 0/45 reflected color. In an effort to communicate this work to color measurement practitioners, NIST staff members have presented the results at meetings of CORM, ISCC, and ASTM and have published a paper on the subject [20].

Finally, as part of its color measurement research, NIST is developing the capability for full goniometric measurements of reflected color at arbitrary input and output angles. This capability is expected to be fully implemented in the near future and will allow full characterization of gonioapparent materials.

O-2 New Standards for BRDF/BTDF

Standards for BRDF/BTDF (bidirectional reflectance/transmittance distribution function) measurements were requested in the CORM 6th Report and have been of interest to NIST's customers for many years. While NIST has measurement programs and calibration services in

this area and provides calibration services, there is a continual new demand for reference materials. This is reflected in the CORM 7th Report which 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 different spectral reflectivity, should be considered) in the area of interest. In the absence of SRM's, a measurement service to allow customers to obtain NIST-certified values for customer supplied materials would be an acceptable alternative.*
- *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). Again, in the absence of SRM's, measurement services on customer-supplied samples would be an acceptable alternative.*
- *NIST work with U.S. industry, military and NASA to develop and maintain SRM's for these measurement techniques.*

NIST has extensive capabilities for measuring the BRDF and BRTF of materials, including STARR shown in Figure 10. These capabilities extend from the infrared to the ultraviolet and are available to NIST customers through NIST Calibration Service Special Tests 38060S and 38061S. Because of the varied needs of NIST customers for specific measurement wavelengths and angles and material size and composition, the Division has not made these capabilities available through Standard Reference Materials (SRMs). NIST is willing to work with U.S. industry, military, and NASA to improve BRDF and BRTF measurements and standards. Indeed, NIST has had ongoing collaborations in BRDF measurements with the semiconductor industry for wafer inspection and with the remote-sensing community for realizing a spectral radiance scale from illumination of a Spectralon plaque with an FEL lamp spectral irradiance source. Partners in other areas of remote sensing, defense, and homeland security are welcome.

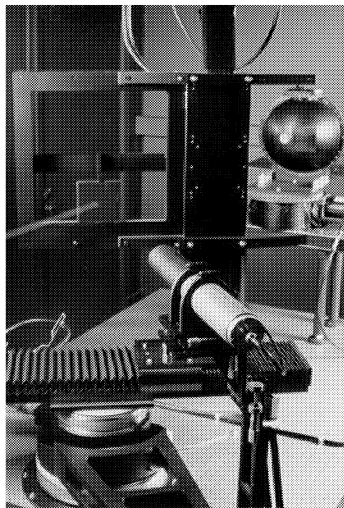


Figure 10. A picture of STARR, the Spectral Tri-function Automated Reference Reflectometer, used to measure in-plane BRDF.

O-3 New Standards for Fluorescence

Fluorescence plays an important role in the appearance of an object upon illumination, and is critical in many biophysical measurements, including in single molecule microscopy performed within the Optical Technology Division and absolute flow cytometry performed within the Chemical Science and Technology Laboratory (CSTL). The CORM report indicates that there is an increased need for reference materials in this area and specifically recommends that NIST undertake the following:

- *provide at the national level, a referee measurement service using an accurate two-monochromator system and including goniometric capability for measurement of the total radiance and fluorescence of materials. This should include an appropriate procedure for the calculation of color appearance.*
- *initiate a measurement assurance program for calibration and testing laboratories to establish their traceability to NIST 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 Optical Technology Division does not presently have a program in fluorescence standards. With the addition of a second monochromator, the recently developed reflectance colorimeter will have the capabilities to measure fluorescent color. Funding for such an effort is presently being sought. The Division has also collaborated with the CSTL in developing improved absolute fluorescence measurements for flow cytometry to better assess the number of fluorescently labeled antibodies bound to a target antigen [21].

O-4 New Standards for Regular Transmittance

The CORM 7th Report requests additional reference materials for an expanded wavelength region and over a wider range of absorbance. While NIST has a program in this area, the CORM report asks for it to be expanded through the following recommendations:

- *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).*
- *The overall wavelength range of the standards of high absorbance should be 190 - 850 nm and 850-2,500 nm, respectively. Ideally, standards for transmittance as low as 100 nm should be eventually developed.*

Presently, NIST provides measurements of regular transmittance beyond 100 μm in the far-infrared to 250 nm into the ultraviolet. These capabilities are available to NIST customers through Calibration Service 38061S, *Special Test of Spectral Transmittance*. Offering these capabilities through a Calibration Service rather than through a Standard Reference Material allows the customer to furnish an optical artifact of a material and size appropriate to their needs. Additionally, the customer is free to specify the wavelength region of interest to minimize costs. Measurements further into the ultraviolet, to 130 nm, are available using a ultraviolet spectrometer installed at the Synchrotron Ultraviolet Radiation Facility (SURF III).

O-5 *Measurement and Standards for Retroreflection*

The old NIST retroreflectance facility became dysfunctional over 15 years ago and could not be used for the measurement assurance program or for calibrations. CORM and others have requested for many years that NIST reestablish this capability to support the highway marking industry and others that use retroreflective materials. The U. S. Department of Transportation has identified correct characterization of highway marking materials to be a critical element of highway safety and is working with the various states to develop appropriate measurement assurance programs. The CORM 7th report recommends that NIST;

- *Reestablish state of the art, retroreflectance measurement instrumentation for the calibration of transfer materials and to conduct measurements. This should emphasize testing of retroreflective road marking materials as well as the geometric aspects of newer micropismatic signing materials. Measurements of pavement markings at 1.05 degrees observation angle and 88.76 degrees entrance angle is needed. Measurement of sign sheeting at a variety angles, including 0.2 degrees observation and -4 degrees entrance angle, is needed.*
- *Provide a spectral retroreflectance measurement service. This includes the capability to measure spectral retroreflectance of all types of retroreflective materials and devices. Spectral measurements form the basis for color control and classification.*
- *Re-establish the NIST retroreflectance Measurement Assurance Program and the associated SRM's necessary to allow secondary laboratories and testing laboratories to confirm the accuracy of their retroreflectance measurements.*

NIST has recently completed a state-of-the-art facility for retroreflectance measurement with funding from the National Cooperative Highway Research Program (NCHRP) through project 05-16, *National Calibration Facility for Retroreflective Traffic Control Materials*. NIST completed this project and the development of the facility in 2004; an official calibration service for retroreflective materials will be launched in



Figure 11. A STOP sign be mounted in the new NIST retroreflectance measurement facility.

2005. The facility consists of a six-axis goniophotometer mounted on 35-m long rails, a uniform beam projection system with lighting provided by a tungsten strip lamp, and a photometric detector system. A “STOP” sign mounted on the goniometer is shown in Figure 11. The facility is designed to measure both signing materials and road marking materials, and meets all the geometrical requirements requested by CORM and specified in CIE and ASTM standards. The details of the NIST measurement facility and uncertainty budget were presented at CORM 2004, and are described in the final project report submitted to NCHRP [22]. NIST is also leading efforts in the international standardization of retroreflection measurements through CIE Technical Committee 2-56, *CIE/ISO Standard on Retroreflection Measurements*, chaired by C. Miller of NIST.

The capability for spectral measurement of retroreflectance was not included in the NCHRP project mentioned above. However, NIST plans to expand the facility to enable spectral and color measurements of retroreflective materials excluding fluorescent material. The equipment required for this capability has been purchased with NCHRP support.

As part of the NCHRP project, NIST is re-establishing the retroreflectance Measurement Assurance Program. NIST is in the process of obtaining the standard materials required for this program and assessing their temporal stability. The Measurement Assurance Program provides a mechanism for testing laboratories to participate in bi-lateral comparisons with NIST using NIST provided materials. NIST is also working with the National Voluntary Laboratory Accreditation Program (NVLAP) to develop an accreditation program for calibration laboratories.

O-6 Measurement and Standards for Appearance

The development of new paints and coatings with complex angular-dependent visual effects, such as metallic and pearlescent coatings whose appearance depends upon both viewing and illumination angles, is challenging the ability of industry to characterize and quantify product appearance. The increased globalization of manufacturing and its supply chain requires improved international standards for color and appearance to ensure that product appearance can be correctly specified and realized independent of locale. The importance of product appearance in nearly all commercial transactions motivates NIST and other national metrology institutes efforts to develop standards in this area. The CORM 7th Report likewise recognizes the importance of appearance metrology, recommending that NIST do the following:

- ***Continue and complete the “Optical Reflectance and Scattering of Materials Project”.***

The Division’s Color and Appearance Program was initiated by the successful NIST Director’s Competence Program in *Measurement Science for Optical Reflectance and Scattering*. This program led to the development of calibration services for specular gloss using the instrument shown in Figure 12 and for reflected color in the 0/45° geometry using the instrument shown in Figure 9. A calibration service for diffuse reflected color is also under development. The expertise developed through this competence program spawned new research, funded by the NIST Advanced Technology Program, into the colorimetric characterization of special-effect coatings, particularly pearlescent coatings. This research determined a subset of optimal measurement angles for accurately characterizing the coatings.

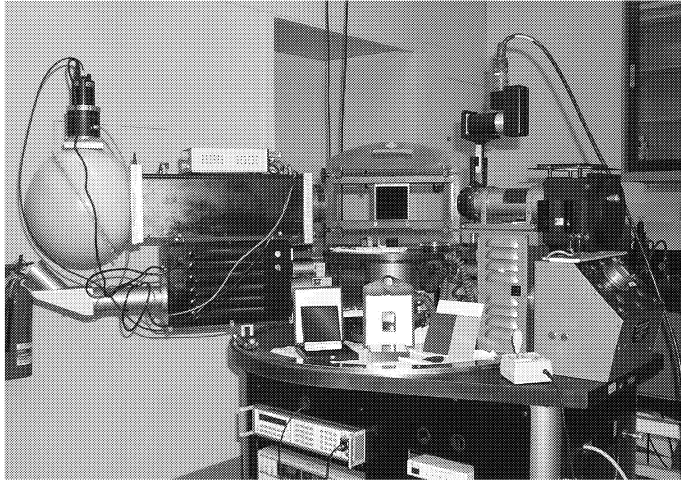


Figure 12. The NIST Specular Gloss instrument. Specular gloss standards are available from the Optical Technology Division through a calibration service.

- *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.*

Due to a lack of expertise in psychophysical research, NIST has not addressed the issue of human factors in appearance attributes. The Optical Technology Division is willing to partner with universities, government, or industry in research into such human factors by furnishing the appropriate physical measurements.

Deleted: psychology

- *Develop a system of SRM's on gloss, haze, 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.*

Instrumentation development efforts for color and appearance measurements have continued since the completion of the *Measurement Science for Optical Reflectance and Scattering* Competence Program. Implementation of full goniometric capabilities on the NIST Colorimeter now in progress will allow reflected color measurements as a function of illumination and detection angles, a critical capability for characterizing special-effect pigment coatings. It is anticipated that such research capabilities will lead to new NIST standards for haze, contrast, texture, translucency, and other appearance attributes to be distributed through Calibration Services rather than through SRMs to provide flexibility to meet specific customer needs.

4. Measurement Uncertainty

There was only one proposal in the category of measurement uncertainty:

A significant number of CORM Seventh Report surveys (72%) noted that a need exists to “reduce the measurement uncertainty” of optical radiation measurement parameters and a “better understanding of the concept of measurement uncertainty” is needed.

The report recommends that NIST strive to lower the uncertainties of the calibration artifacts used for disseminating spectral irradiance, spectral radiance, and other radiometric and photometric scales. In response, NIST is working to reduce the uncertainties of the fundamental photometric and radiometric scales disseminated to U.S. industry and government by leveraging recent advances in laser technology, cryogenic radiometry, and detector-based radiometry, as illustrated by HACR II (the Division’s new High-Accuracy Cryogenic Radiometer shown in Figure 13), and SIRCUS, a tunable-laser based facility for spectral irradiance and radiance responsivity calibrations of detectors and radiometers [23]. SIRCUS will significantly reduce the uncertainties of all of NIST’s fundamental radiometric and photometric scales. SIRCUS is also being applied to the direct calibration of various radiometers for applications in defense, remote sensing, and health and safety. SIRCUS will be a critical tool for the remote sensing community to realize the small measurement uncertainties required for climate-change research [24].

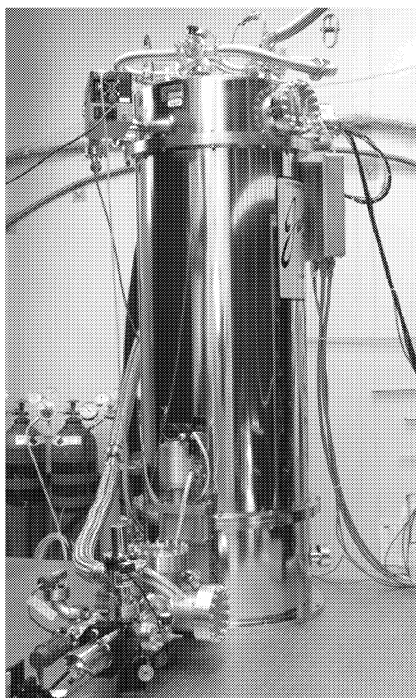


Figure 13. The Optical Technology Division’s second generation High-Accuracy Cryogenic Radiometer (HACR 2). HACR measures the absolute power of a laser beam used to calibrate silicon trap transfer standard detectors by comparing thermalized optical power to thermalized electrical power.

It is also requested that NIST provide leadership in educating the community on determining the uncertainties of their measurements. This request is a consequence of ISO 17025 quality standards which require that calibration laboratories state their measurement uncertainty and how it is derived. The Report suggests that CORM and NIST collaborate in the development of improved training tools to facilitate the implementation of ISO 17025 by calibration laboratories. The community has found that the primary reference document, the *ISO Guide to the Expression of Uncertainty in Measurement* (GUM), provides insufficient information to enable calibration scientists and engineers to address the uncertainties in their measurements [25].

NIST recognizes that there is significant demand for training in the area of uncertainty evaluation. In response, NIST has helped organize several recent meetings such as CORM Measurement Uncertainty Workshop, May, 2002, in St. Louis; CIE-USA Workshop on

Uncertainty in Lighting Measurements, November, 2001, in Niagara Falls; and CIE Expert Symposium on Uncertainty Evaluation, January, 2001, in Austria to provide improved training and discussion opportunities. NIST also provides a lecture on uncertainty evaluation coupled with a laboratory session in the NIST Photometry Short Course since 1998. While these meetings and courses have been successful, the CORM 7th report suggests growing demand for education on this subject. NIST will work together with CORM to explore the possibility of offering a tutorial workshop or short course on uncertainty evaluation directed towards scientists and engineers striving to implement ISO17025. The possibility of disseminating such training electronically will also be explored.

5. Conclusions

Over the past four years, the Optical Technology Division has successfully addressed many of the high-priority recommendations in the CORM 7th report. This success has been aided by improvements in the accuracy of NIST's radiometric and photometric measurements made possible by SIRCUS. SIRCUS has improved the Division's ability to replace its source-based radiometric scales with detector-based scales directly tied to the cryogenic radiometer. In addition, SIRCUS, its infrared implementation, IR-SIRCUS, and its transportable version, Traveling SIRCUS, have improved the Division's ability to respond to DoD, NOAA, and NASA's needs for improved instrument characterization and calibration in support of national priorities in climate-change research and missile defense.

The CORM reports have also aided the Division in ensuring that its programs are current with changing industry needs. Examples include CORM requests for improved measurements and standards for LEDs and for color and appearance. Both of these requests have led to significant NIST efforts in developing new measurement facilities directly addressing needs in these areas. Measurements and standards provided by these facilities are accelerating the development and commercialization of solid-state lighting and aiding electronic commerce and global manufacturing.

The CORM 8th report is due to be released in the near future and we look forward to studying its recommendations to gain guidance on future opportunities for NIST programs. We view this response to a CORM 7th 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 response 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.

6. Acronyms

Below is a list of common acronyms used in the radiometric and photometric literature, including this report:

ANSI	American National Standards Institute
BIPM	Bureau International des Poids et Mesures

BRDF	Bi-directional Reflectance Distribution Function
BTDF	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
DHS	Department of Homeland Security
DoD	Department of Defense
EOS	Earth Observing System
HACR	High Accuracy Cryogenic Radiometer
IEC	International Electrotechnical Commission
IESNA	Illuminating Engineering Society of North America
ILAC	International Laboratory Accreditation Council
IR	Infrared
ISO	International Standards Organization
JCRB	Joint Committee of the Regional Metrology Organizations and the BIPM
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
NMI	National Measurement Institute
NOAA	National Oceanic and Atmospheric Administration
NVLAP	National Voluntary Laboratory Accreditation Program
OIDA	Optoelectronics Industry Development Association
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

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