NISTIR 5429

Optical Metrology and More

programs and services of the

Radiometric Physics Division

Physics Laboratory

National Institute of Standards and Technology

US Department of Commerce

Technology Administration

Gaithersburg, MD 20899-0001

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Sally Bruce
Editor

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Radiometric Physics Division
Physics Laboratory
Gaithersburg, MD 20899

May 1994

U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

TECHNOLOGY ADMINISTRATION
Mary L. Good, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
Arati Prabhakar, Director

Contents

INTRODUCTION

The Radiometric Physics Division (844) has the responsibility and mission within NIST for promoting accurate and useful optical radiation measurement technology in the ultraviolet, visible, and infrared spectral regions. In addition, the Division has the institutional responsibility for maintaining two SI units: the temperature scale above 1234.96K and the unit of luminous intensity, the candela. The Division's activities are designed to achieve three primary goals:

- to develop, improve, and maintain the national standards and measurement techniques for radiation thermometry, spectroradiometry, photometry, and spectrophotometry,

- to disseminate these standards by providing measurement services to customers requiring calibrations of the highest accuracy,

- to develop the scientific and technical basis for future measurement services by conducting fundamental and applied research.

The Division employs research scientists, engineers, technicians, and calibration specialists, and maintains a balanced mix of research, development, and measurement services. The Division is organized into three groups,

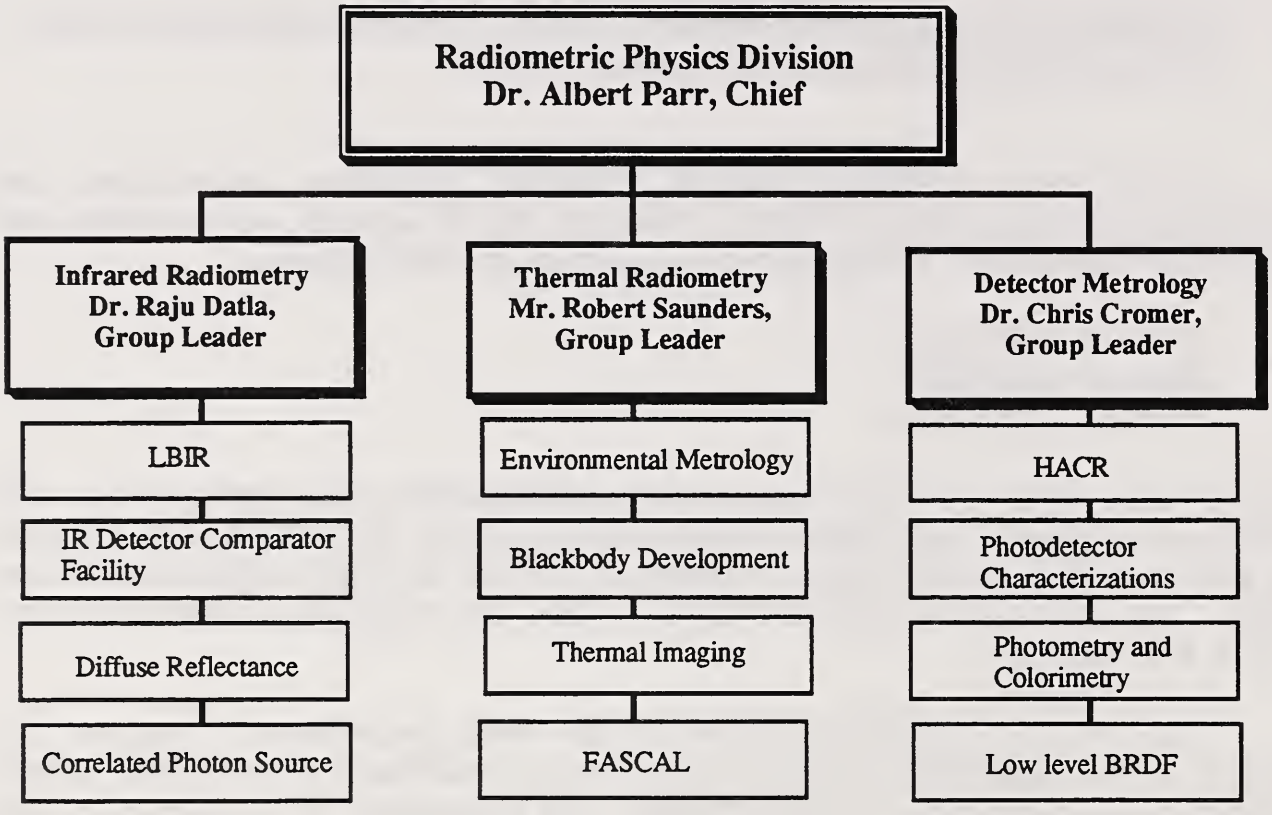
- Infrared Radiometry
- Detector Metrology
- Thermal Radiometry

and operates under a project structure with collaborations across group lines. The calibration programs and related measurement services provided by the Division are documented in a NIST Special Publication, SP-250, the NIST Calibration Services Guide. This publication is revised every two years. Its availability is described at the end of this brochure.

This brochure highlights some of the work performed throughout the Division.. For information on areas of interest not specifically listed, please consult Al Parr, the Division Chief, at 301-975-2316. For information on the content of this brochure, contact the editor, Sally Bruce, at 301-975-2323.

STAFF AND ORGANIZATION

The Division presently employs approximately 30 full time scientists and engineers participating in research and development activities and providing measurement services. The Division is organized into three groups, each managed by a group leader reporting directly to the Division Chief. This organization is largely for administrative purposes with technical activities being carried out under a project structure within the various groups. The project structure allows for well defined technical activities to be accomplished with clear lines of responsibility. The project structure is flexible and can be adjusted to meet timely challenges in the Division's technical activities. The present organization of the Division is shown below.



INTERACTIONS THAT AID GOVERNMENT AND INDUSTRY

In pursuing its goals, the Division is actively engaged in collaborative efforts with industry, other government agencies, universities, professional societies, and standards organizations. Programs are developed in consultation with user groups at national and international levels in order to insure that resources are used to the best advantage to provide services required by our customers.

CORM

The U. S. Council for Optical Radiation Measurements (CORM) is a paramount organization that aims at establishing a consensus on industrial and academic requirements for physical standards, calibration services, and interlaboratory collaborations in the field of optical radiometry. In a 1989 report, CORM identified specific radiometric and spectrophotometric projects that should be undertaken on a priority basis. Many of the projects identified by CORM as a national priority are incorporated into the Division's planning for new program thrusts and initiatives. Other agency support for achieving the objectives is sought when appropriate, and joint programs are created which benefit the radiometric community.

ASTM

The Division staff participates in appropriate technical committees of the American Society for Testing and Materials (ASTM) for defining testing procedures in radiation thermometry, spectrophotometry and colorimetry, geometric properties of appearance, scattering, ultraviolet and visible spectroscopy, infrared spectroscopy, and molecular luminescence.

LTEC and IES

The Division participates in the activities of the Lamp Testing Engineers Conference (LTEC). The membership of LTEC is drawn from the lighting manufacturing industry and has as its goal ensuring the quality of lamp testing and providing reliable standards for illuminating sources. The Division staff participates in meetings on photometric testing procedures in the Illuminating Engineering Society (IES). The Division's activities in photometry and spectroradiometry support a wide range of industrial and governmental measurement activities.

CIE and CCPR

The Division is an active participant in international groups such as the International Commission on Illumination (CIE) and the Consultative Committee on Photometry and Radiometry (CCPR). These groups promote international intercomparison of fundamental optical measurements and seek cooperation in devising measurement definition and technology. As an example, the Division has been the lead laboratory in a CCPR-sponsored intercomparison of spectral irradiance

involving 13 national standardizing laboratories. These intercomparisons help ensure that the standards furnished to U. S. customers are consistent with the demands of world trade. The Division's staff maintain an active role in the committees of both the CIE and CCPR and participate in the planning of future intercomparisons and standards maintenance activities.

CCG

The Calibration Coordination Group (CCG) of the Department of Defense maintains primary calibration laboratories for each of its services. A significant portion of the Division's activities is devoted to standards development and measurement support for these agencies. The Department of Defense has funded the development of major measurement facilities in the Division for low–background, infrared radiometry, thermal imaging, UV detector characterization, and bidirectional scattering metrology.

Civilian Agencies

The Division has provided measurement support to NASA and NOAA for space–borne radiometry, and is engaged in collaborations with EPA and NASA on terrestrial and extraterrestrial UV solar–irradiance measurements. The Division is also providing measurement support to the EPA and USDA through the deployment of a solar UV monitoring network.

CRADA

Cooperative Research and Development Agreements (CRADA) provide Federal laboratories and research partners with greater flexibility in accommodating the needs of individual research situations. Depending on the circumstances of the research effort, the non-federal partner may obtain an exclusive license to the patentable research developed in the CRADA. Any organization may enter into a CRADA with NIST. Currently, the Division has CRADAs with a number of U.S. optical manufacturers. These agreements allow NIST staff to work jointly with industrial groups to develop new devices and allow industry to directly benefit from the capabilities available at NIST. Those who are interested in establishing CRADAs with this Division should contact one of the technical staff members.

NCSL

The National Conference of Standard Laboratories is an association of laboratories or organizations that maintain measurement standards and calibration facilities. NIST was the original sponsor of the NCSL. Since its independence in 1985, NIST maintains close working relationships with the NCSL. Representatives from the Radiometric Physics Division attend regional workshops and annual conferences sponsored by NCSL. Most recently, the Division has interacted with the NCSL using their recommended practices as guidelines and references for the ISO documentation of calibration services performed throughout the Division.

PROGRAM HIGHLIGHTS

High Accuracy Detector Metrology

The staff of Detector Metrology group works closely with the other projects throughout the Division to develop appropriate transfer standards with improved accuracy. Figure 1 shows the integration of the improved accuracy afforded by the High Accuracy Cryogenic Radiometer (HACR) into the spectral regions covered by the radiometric services offered by the Division.

The HACR, with its intrinsic uncertainty of 0.01% (one sigma) or better, improves the radiometric accuracy throughout the Division. The HACR forms the basis for many of the calibration services offered by the Division's programs. It is the basis for the radiometric measurement chain and is used to maintain the scales of spectral radiance and irradiance and absolute detector responsivity. A diagram of the absolute cryogenic radiometer is shown in Figure 2. The facility currently operates in the 200 nm to 1000 nm wavelength range and will be modified to operate out to 11 μm in the near future.

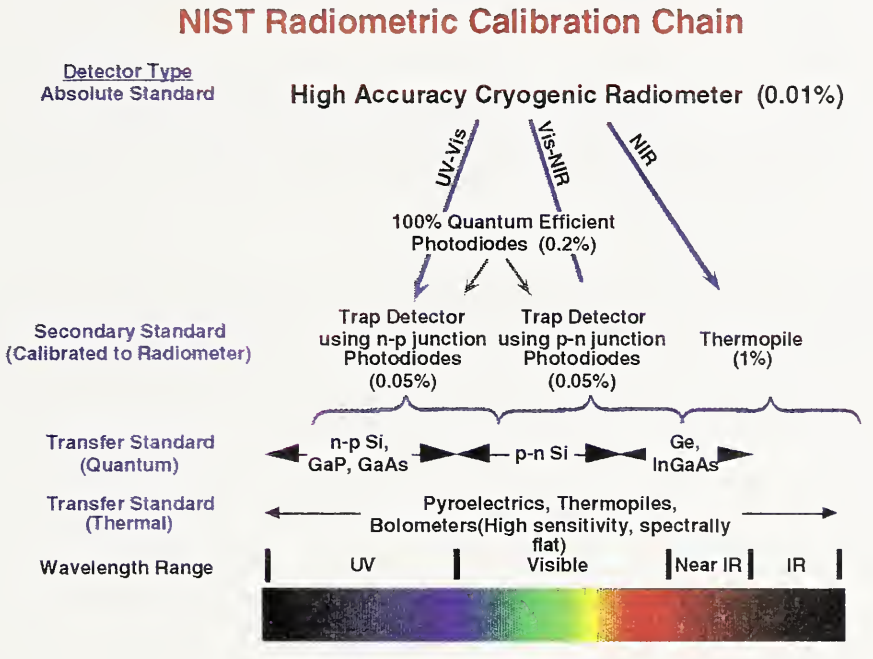


Figure 1. The NIST radiometric calibration chain begins with the measurements from the High Accuracy Cryogenic Radiometer and is disseminated through the detector-based calibrations from the ultraviolet to the infrared spectral regions.

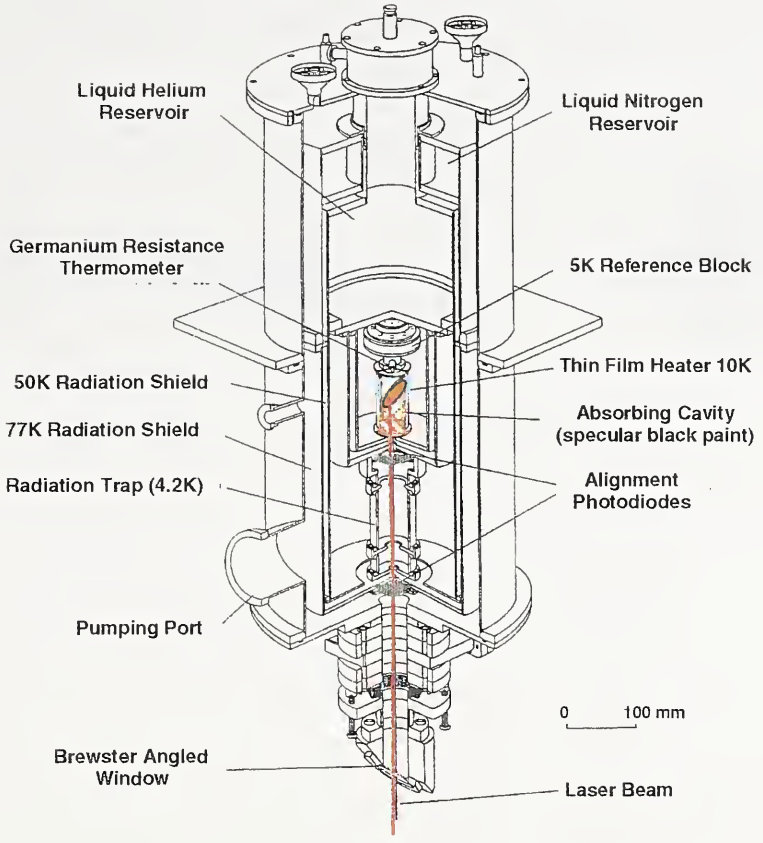


Figure 2. The HACR serves as the basis for the calibrations offered by the Division.

Using a variety of detectors for working standards, the detector metrology calibration program consists of characterizations of absolute spectral response, spatial uniformity, and linearity of photodetectors for use in industrial and government labs. The program also provides calibrated detector package rentals, calibrated silicon detector sales and special calibration on customer supplied detectors. The staff works closely with detector manufacturers and others at NIST to develop new measurement techniques and to formulate requirements for new optical detectors. This development effort will include the development of new transfer standard detectors that can take advantage of the high accuracy inherent in the absolute cryogenic radiometer. A drawing of the spectral comparator, a uniformity map of a detector, and the spectral responsivities of typical diodes are shown in Figure 3. The current facility can measure from 200 nm to 1800 nm. A new measurement facility for characterizing long wavelength infrared detectors from 2 μm to 20 μm is presently under development.

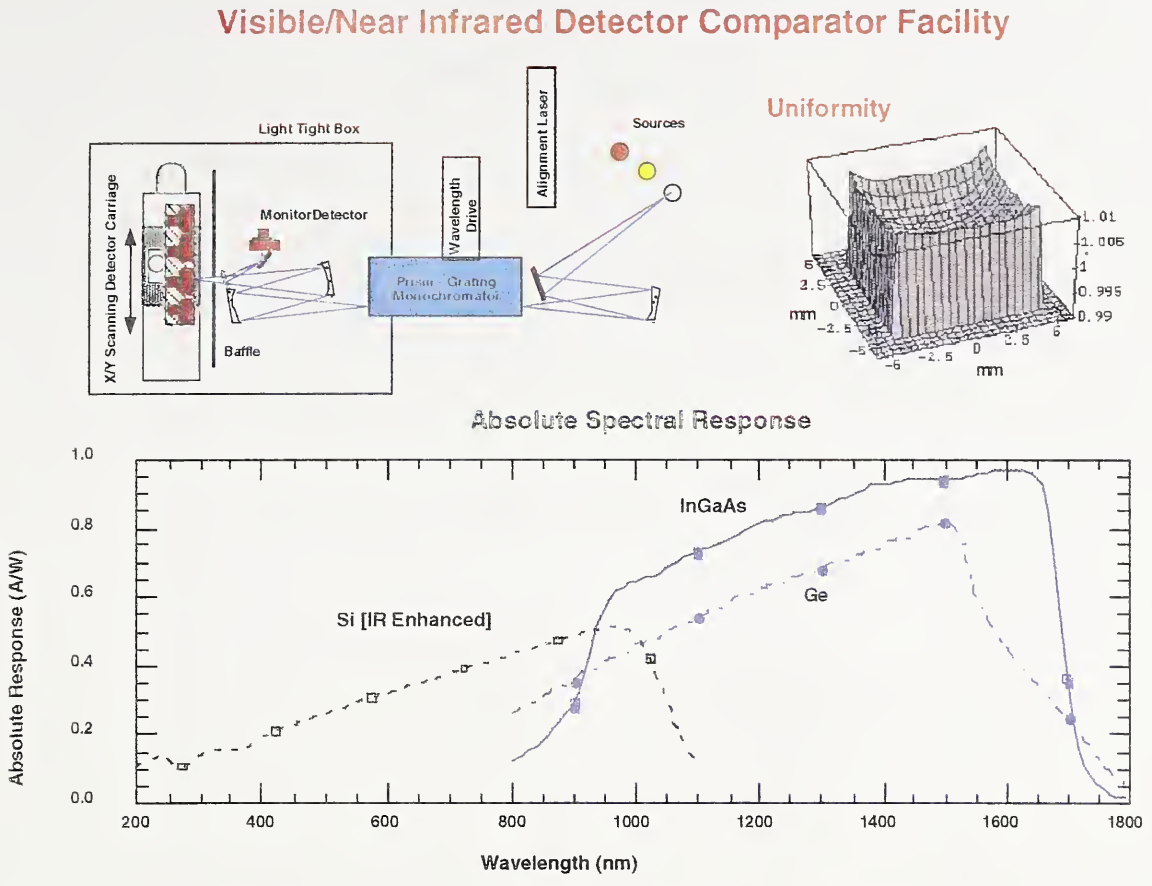


Figure 3. A drawing of the visible to near infrared spectral comparator, a uniformity map of a photodiode's active area, and the spectral responsivities of typical photodiodes are shown.

Photometry

Photometry, the science of measuring light with the response function of an "average" human observer, is an activity that has been made integral to the detector characterization efforts in the Division. The Radiometric Physics Division at NIST is responsible for the realization of the SI base unit, the candela. The candela represents a unit of measure of the apparent brightness of a light source as observed by the human eye. The unit of luminous intensity, the candela, is maintained on a set of well characterized, appropriately filtered detectors. This provides a direct link between the HACR and the SI unit, the candela, and provides an alternate method of transferring this unit to calibration customers. NIST has realized the candela using standard detectors constructed to emulate the CIE spectral luminous efficiency function for photopic vision. The new uncertainty in determining the candela value is 0.4% (2 sigma), an improvement of more than a factor of two over traditional methods. Research is underway to apply the detector-based candela to improve other photometric scales such as luminous flux and luminance. A diagram of the detector based candela measurement scheme and an example of a photometric responsivity curve is shown in Figure 4.

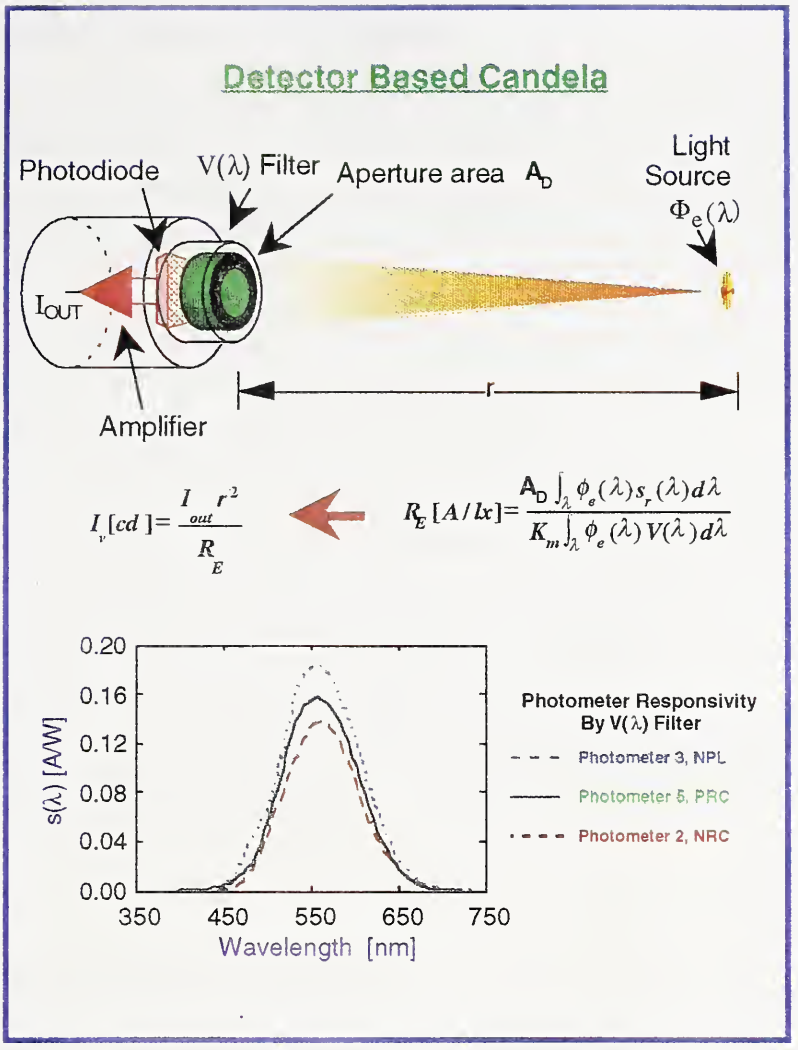


Figure 4. A diagram of the detector based candela measurement scheme, the candela measurement equation, and photometric responsivity curves are shown. The Radiometric Physics Division is responsible for the realization of the SI unit, the candela.

Solar UV Monitoring

The NIST Radiometric Physics Division has developed the procedures necessary to characterize the solar UV instrumentation being deployed in the United States Department of Agriculture (USDA) networks. Instruments have been selected by the instrument advisory panel of USDA for evaluation and subsequent deployment in a status-and-trends network. NIST, with the USDA support, managed a UV-B spectroradiometer intercomparison at the first USDA network and DoE ARM site in the fall of 1993.

Currently, NIST is evaluating six broadband radiometers as well as two USDA research spectroradiometers and a reference spectroradiometer for the EPA. The Radiometric Physics Division is also involved with several NASA/NOAA climatic change satellite projects.

In the future, a high accuracy reference solar measurement site will be established at NIST that will be the EPA's Washington, D.C., UV monitoring site. In addition, Radiometric Physics personnel will assist in setting up a central calibration laboratory at NOAA in Boulder for the US national UV monitoring network.

Metrology Support for NASA's EOS Program

The goal of NASA's Earth Observing System (EOS) science mission is to advance the understanding of the entire earth system by developing a deeper comprehension of the components of that system, the interaction among them, and how the earth system is changing. The Radiometric Physics Division has been advising NASA on the calibration support of several of the instrument packages scheduled to be part of the EOS.

The prime recommendation was that the calibration process must be studied from the fundamental optical physics viewpoint, the sources of error identified, and their effects on the final measurement determined.

SeaWifs is a NASA/NOAA project to study ocean color to provide estimates of bio-optical observations of the upper ocean layers. A satellite instrument will measure upwelling radiances at eight spectral bands in the visible and near infrared regions. The project includes a large number of ground truth measurements with a variety of radiometers and spectroradiometers deployed in the ocean. Radiometric Physics Division personnel are assisting the project by providing calibrated standards and by sponsoring round robin intercomparisons among the participant laboratories. NIST has also developed a portable multichannel radiometer for calibration verification and validation. It will be used on board ships during the deployment of the field instrumentation.

Optical Scattering Properties of Materials

Two absolute spectrophotometric instruments serve as the primary method for maintaining scales of transmittance, reflectance and optical density. They are: the reference transmittance spectrophotometer and the reference reflectance spectrophotometer. These instruments operate in the 200 nm to 2.5 μm wavelength range and provide calibrated samples as references for secondary instruments used for routine service calibrations. The intrinsic uncertainty of the transmittance and reflectance reference instruments is a part per ten thousand and a part per thousand respectively of the appropriate units. In addition to calibration services, SRM materials are prepared for distribution to industrial and scientific customers. These customers include visible and infrared optics industry, aerospace, paint, pharmaceutical, food, and agricultural industries.

New instruments for infrared transmittance from 2 μm to 30 μm, hemispherical reflectance from 2 μm to 20 μm and Bidirectional Reflectance Distribution Function (BRDF) measurements at single wavelengths in the ultraviolet, visible, and infrared are under development. A diagram of the Reflectometer for infrared spectral characterization of diffuse materials is shown in Figure 5.

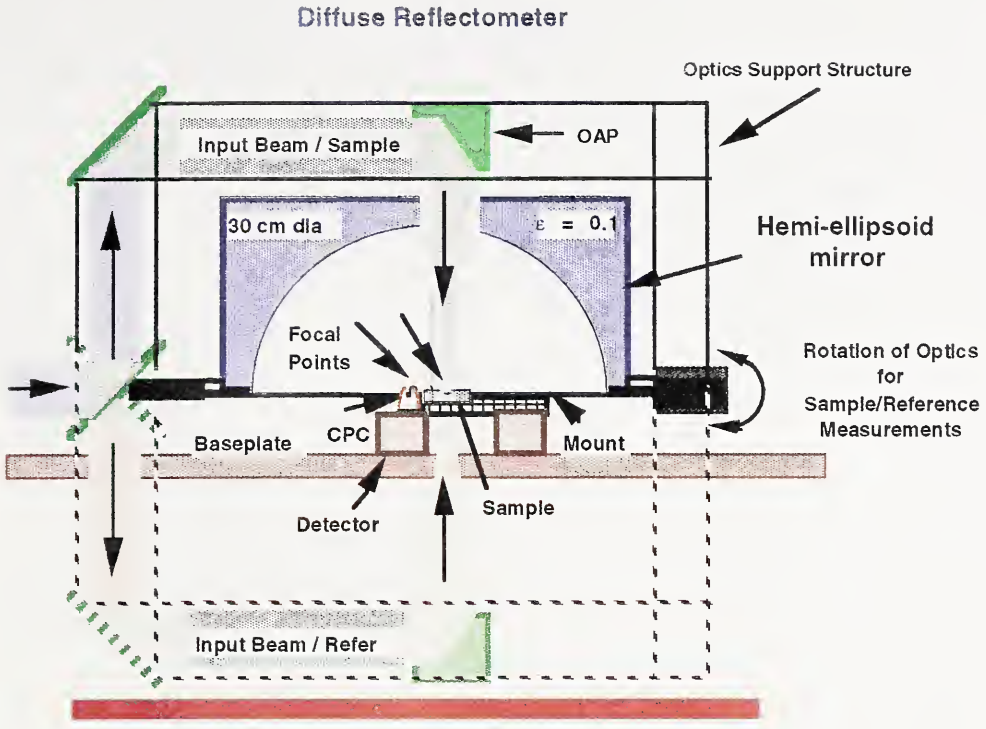


Figure 5. The Diffuse Reflectometer is used for the characterization of diffuse materials.

The BRDF of a surface describes the angular distribution of the radiance reflected by a surface normalized by the incident irradiance on the surface. The bidirectional characterization of optical scatter is a useful diagnostic in evaluating elements contained within large optical systems that require the minimization of scattered light. This information is needed for the development of telescopes, super-polished mirrors, and can be useful in the characterization of materials for use in inspection processes in optical manufacturing. The information is also used for research of near surface structure of materials. The objective of this program is to develop state-of-the-art standard materials and the calibration procedures for BRDF measurements.

Visible BRDF standards are being developed and measured by the Radiometric Physics Division. A diagram of the goniometer used for BRDF measurements is shown in Figure 6.

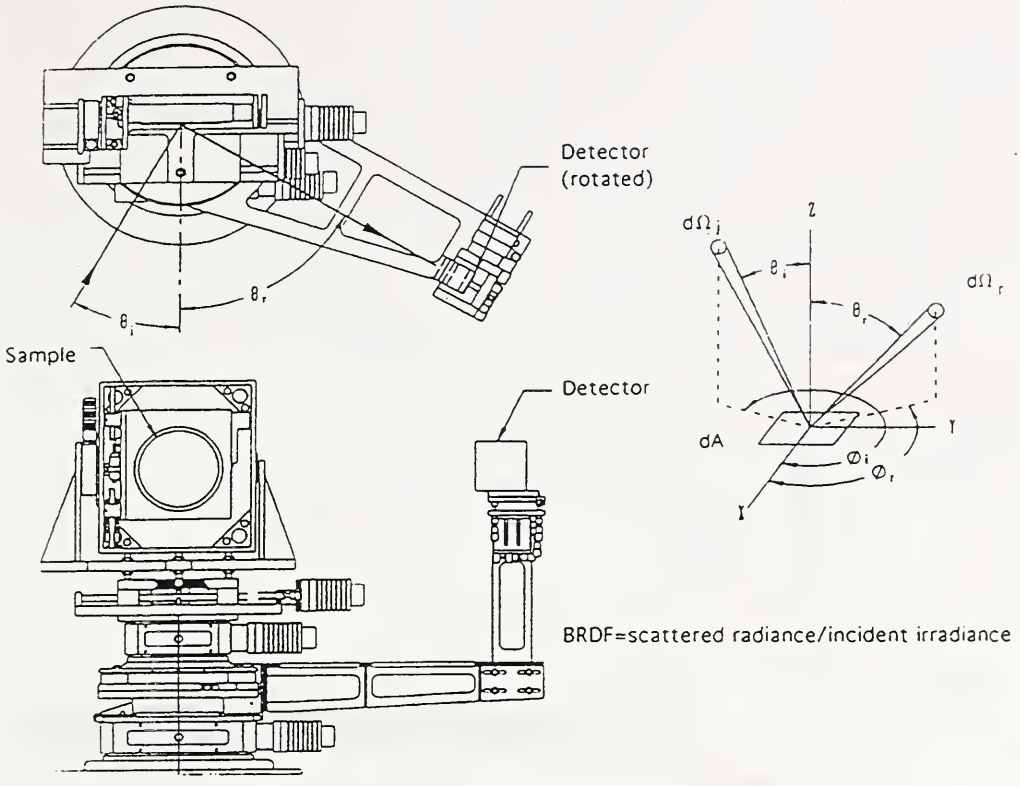


Figure 6. The goniometer used for BRDF measurement. The BRDF is a measure of a sample's reflectance scatter characteristics.

Low Background IR Sources and Detectors

The objectives of the Low Background Infrared (LBIR) Facility are to calibrate user- supplied blackbody sources and to develop the capability to characterize low background IR detectors and attenuators at the LBIR Facility. The LBIR employs its own ACR (Absolute Cryogenic Radiometer) as its primary detector. A low temperature blackbody has been commissioned for use in the LBIR Facility. Capable of functioning in a 20 K environment, the source has an operating range from 100 - 450 K. The instrument has built-in aperture and filter wheels. It is being used for detector calibration, optical materials characterization, and serves as a source for evaluating the ACR performance in the LBIR. The blackbody is housed in a vacuum chamber of the LBIR. A diagram of the LBIR spectral instrument in relation to the blackbody and ACR is shown in Figure 7.

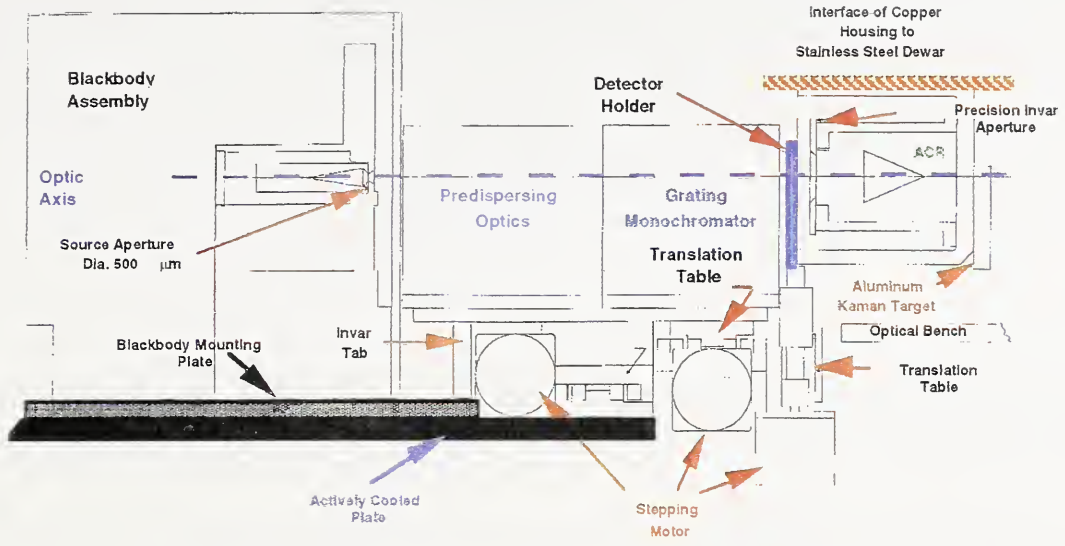


Figure 7. A cross-sectional view of the LBIR, its blackbody, and its Absolute Cryogenic Radiometer. The LBIR facility serves as the foundation for research and development for technology applications in space and other areas where sensitive infrared sensors are used.

The LBIR Facility performs calibrations and serves as the foundation for research and development for technology applications in space and other areas where high sensitive infrared sensors are used. The ACR in the LBIR has been characterized to measure the irradiance at its aperture in the range from a few nW/cm^2 to 10 $\mu W/cm^2$ with less than 1% (2 sigma) uncertainty. A cross-section view of the ACR is shown in Figure 8.

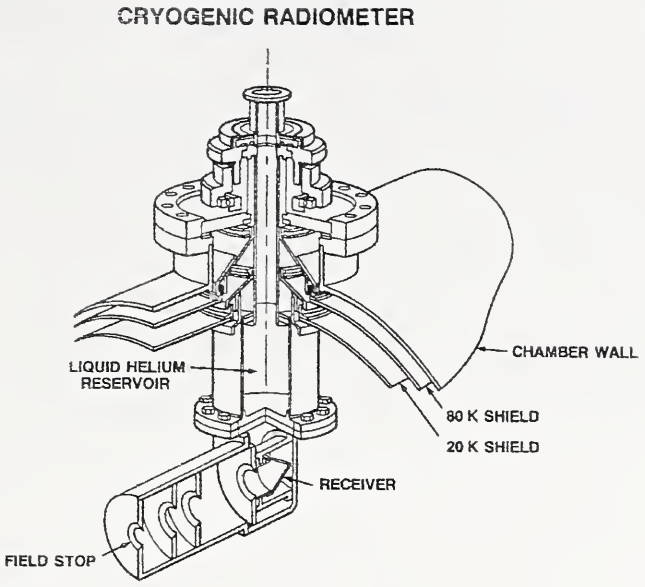


Figure 8. A cross-section of the Absolute Cryogenic Radiometer of the LBIR is shown. The ACR is the LBIR's primary detector and has been characterized to measure irradiance at its aperture from a few nW/cm^2 to 10 $\mu W/cm^2$.

Presently NIST has the capability to measure detector responsivity in the 200 nm to 1.8 μm spectral range. To meet the needs of the IR user community, the Radiometric Physics Division is working to extend this capability to 25 μm. An ambient background facility is currently under construction. A schematic diagram of the IR detector spectral calibration facility is shown in Figure 9.

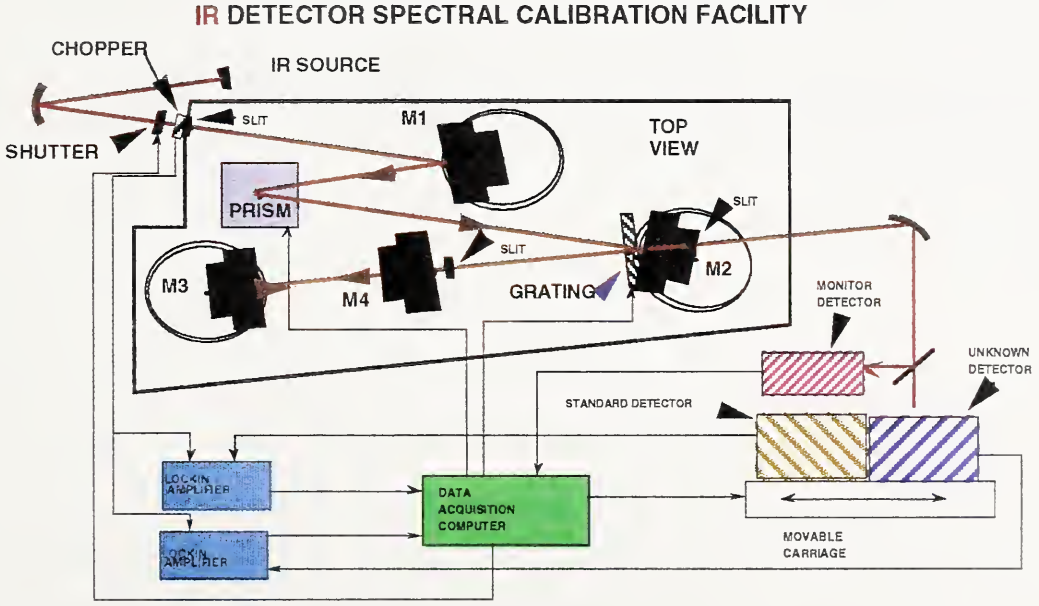


Figure 9. A schematic diagram of the IR detector spectral calibration facility shows its major components. The facility is under construction and once on-line will expand the Division's infrared detector calibrations out to 25 μm.

Optical Radiation Temperature Measurements

The Radiometric Physics Division is responsible for maintaining the International Temperature Scales above the freezing point of silver (1234.96 K) utilizing techniques of optical pyrometry. Efforts in the radiance temperature field have been expanded at NIST through the development of a low-temperature graphite blackbody. Using this instrument, the NIST Radiance Temperature Scale has been extended over the range of 0 °C to 3200 °C in order to meet most of the major needs of developing technologies and these blackbodies will be the basis for work in imaging radiometry. NIST researchers are investigating the use of thermal imaging cameras as a temperature measuring tool. Figure 10 is a diagram of a high temperature blackbody.

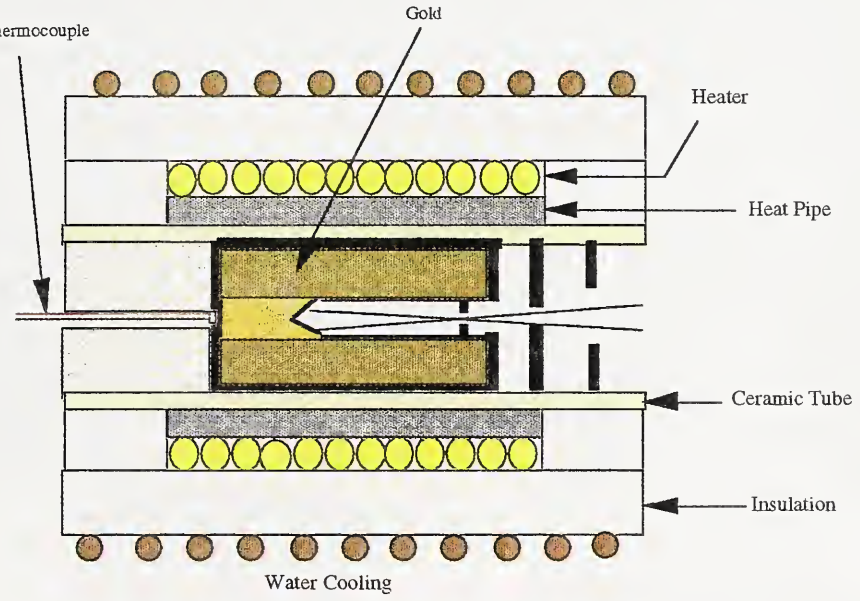


Figure 10. A cross-section view of a high temperature blackbody. The Radiometric Physics Division is responsible for maintaining the International Temperature Scale above the freezing point of silver.

The rapidly evolving technology of large scale arrays of infrared detectors is leading to the development of practical and accurate imaging radiometers. Such instruments make video quality images of the thermal radiation emitted by (or reflected from) objects with spatial resolution approaching 10 mK in some systems. With proper detector calibration, imaging radiometers with high accuracy and excellent spatial resolution can be used for real-time remote temperature measurement. Activities in the Division related to thermal imaging include: fundamental investigations into the spatial and thermal resolution limits of thermal imaging systems and investigation of new technologies such as large scale arrays of thermal emitters for imaging radiometer studies and calibrations. Other activities in thermal radiometry include the development of large aperture blackbodies of high thermal and spatial uniformity for imaging radiometer calibrations in the 0 to 400 °C range using fluid bath blackbodies and 400 to 1100 °C range using pressure controlled heat pipe blackbodies.

Calibrations of optical pyrometers are performed in the temperature range of 800 °C to 4200 °C. A special test is also available to calibrate infrared pyrometers from 800 °C to 2700 °C. Ribbon filament lamps are calibrated using the NIST photoelectric pyrometer. Reports of radiance temperature at 655 nm verses direct current are issued.

Facility for Automated Spectral Calibration (FASCAL)

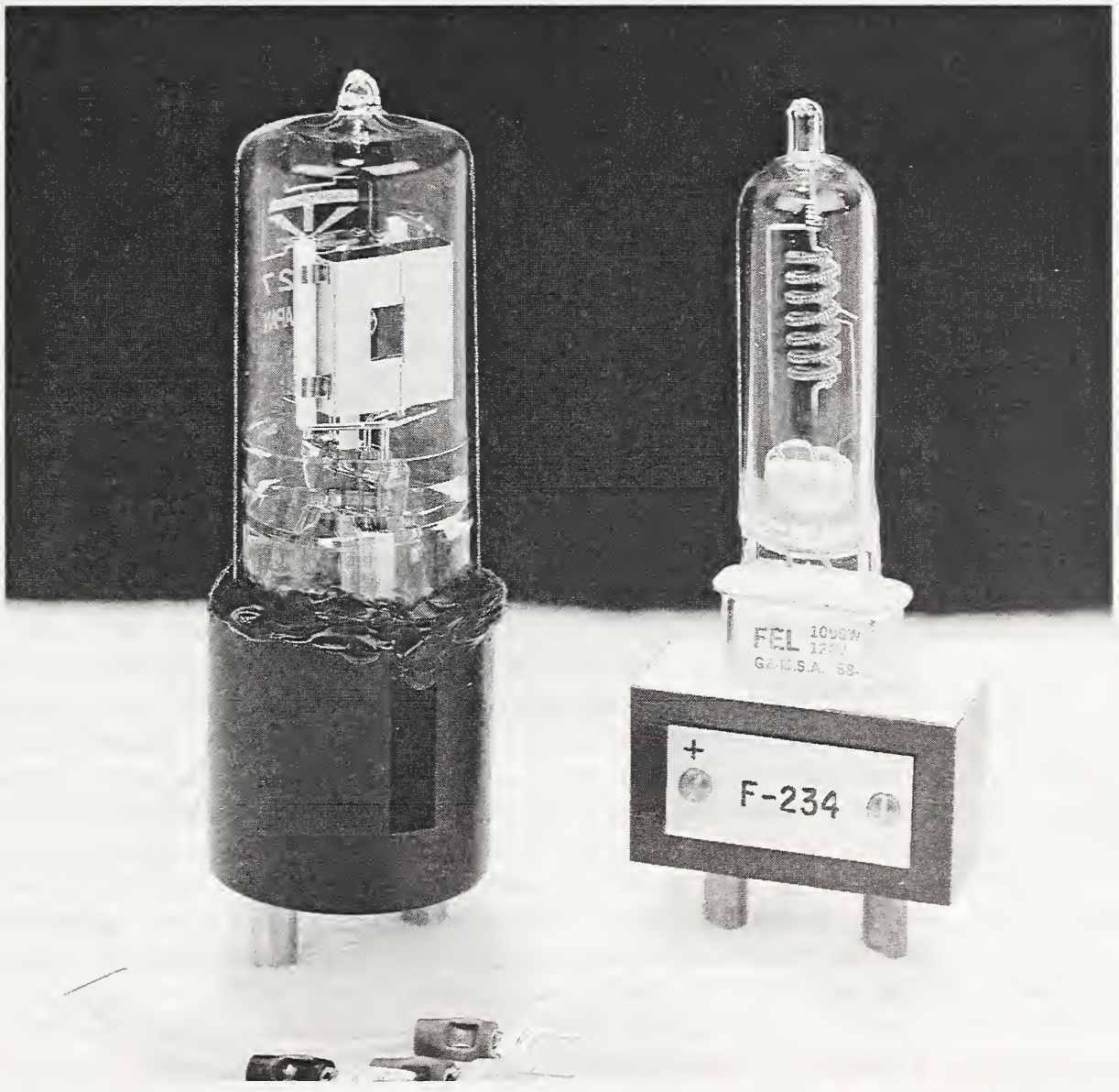


Figure 11. A photograph of the lamps used in FASCAL. On the left is a deuterium lamp used as a source from 200 nm to 400 nm and on the right is a FEL lamp used as a source for 250 nm out to 2400 nm.

Spectral radiometric measurements of radiance and irradiance standards in the spectral region of 200 to 2500 nm are performed in the Facility for Automated Spectral Calibration (FASCAL). Approximately 40 calibrations are requested for FASCAL in a given year. Figure 11 shows a Deuterium and a FEL lamp used in FASCAL.

RESEARCH AND DEVELOPMENT

Luminescence Spectral Radiometry

Luminescence techniques have broad applications in virtually every scientific field, including radiation measurement, remote sensing, quantitation of biomolecules by intrinsic luminescence and immunoassay techniques, and characterization of laser, semiconductor, and superconductor materials. Luminescent phenomena under investigation at NIST are photo-, chemi-, thermo-, electro-, and bioluminescences. Researchers from the Radiometric Physics Division are conducting luminescence radiometric research in the near-ultraviolet, visible, and near-infrared spectral regions and are developing accurate standards and measurement procedures for these regions.

High T_c Superconductors for Radiometry

A cooperative research program with the University of Maryland to investigate optical and thermal properties of high T_c superconductors to build absolute radiometers at liquid nitrogen temperatures has been established. Absolute cryogenic radiometers have been constructed that operate at liquid helium temperatures. Absolute cryogenic radiometers having a flat response in the visible to far infrared regions have become the absolute standard detectors for radiometric calibrations at NIST, and similar radiometers are used in the measurements of solar irradiance, the earth's radiation budget, and laser power calibrations.

Correlated Photon Methods

The Radiometric Physics Division has begun a program to develop correlated photon methods for radiometric applications. This method allows photon counting detectors to be absolutely calibrated without reference to an externally calibrated standard detector. Correlated photons are produced by the process of parametric down conversion where a photon decays within an appropriate nonlinear material into a pair of photons under the restrictions of energy and momentum conservation. An apparatus to produce correlated photons and detect coincidences has been set up. Tests are underway to calibrate the efficiencies of avalanche photodiodes and photomultiplier tubes.

Colorimetry for Displays

The display industry has requirements for colorimetric characterization of both pixel level and complete devices. The efficiency of the conversion of the electrical to optical information is critical to the drive for smaller and more energy efficient computers and video displays. Increased demand is requiring manufacturers to be competitive regarding performance and price. The Radiometric Physics Division is providing basic colorimetric and photometric standards for this industry and has engaged in a research and development effort to devise appropriate standards for industrial use.

FUTURE OPPORTUNITIES

Optical Properties of Materials

Knowledge of optical properties of materials under a variety of temperature conditions, and to improved precision, is required for a variety of scientific and technical applications. Space-based systems have new and more demanding requirements for spectral emittance and transmittance data. Details of the scattering of light from optical surfaces are important for characterizing a number of sophisticated optical and electronic manufacturing processes. Detailed characterization required by industry dictates the development of new and enhanced measurement techniques. The rapidly evolving photonics industry has generated new requirements for accurate information on materials used in a variety of devices that underpin new technologies. The Radiometric Physics Division will meet these challenges by developing technical expertise and furnishing calibration and measurement support.

Focal Plane Arrays

Electronic rendition and storage of images offer exciting new opportunities for radiometric characterization of light sources and for temperature determination of spatially resolved objects. This field is undergoing a fundamental change, from the silver chemistry of conventional image storage and recording, to electronic and magnetic media. To accommodate this revolutionary change, radiometric procedures must be developed to characterize and standardize the measuring processes for images and to provide a national measurement basis for image analysis related to the spectroradiometric output of imaged objects.

Need for Improved Radiometry and Radiometric Standards

Environmental and health concerns about the penetration of UV radiation into the biosphere due to ozone depletion has renewed emphasis on the necessity for accurate and reliable UV radiometry. The role of "greenhouse" gases in determining the global radiation balance is studied in part by careful monitoring of solar radiation from space-based and ground based sensor systems. NIST is in a unique position within the scientific community to offer long term measurement support for USDA, NASA, NOAA, EPA, DOE, universities, and industrial laboratories studying the long term consequences of UV on the biosphere. Requirements for defining health effects and determining energy efficiency of building and outdoor lighting also drive the need for improved radiometry in the UV and visible.

American industry has expressed the need for improved radiometric standards for a variety of technical, competitive, and production quality reasons. These needs have been documented in the CORM 5th report, and projects designed to answer some of the issues have served as an impetus for several NIST Director reserve proposals. The challenge remains to implement the necessary methodology and instrumentation to meet the needs of our customers.

CALIBRATION SERVICES

The Division staff performs calibrations to support a wide range of radiometric, pyrometric, spectrophotometric, and photometric needs. These services and the staff members responsible for them are listed below. Information on the availability of service should be obtained from the associated staff member directly.

Photodetector Characterizations
Contact: Tom Larason, 301-975-2334, e-mail larason@garnet.nist.gov

Photometric Measurements
Contact: Yoshi Ohno, 301-975-2321, e-mail ohno@garnet.nist.gov

Low Background Infrared Measurements
Contact: Raju Datla, 301-975-2131, e-mail rudatla@vax844.phy.nist.gov

Spectrophotometric Measurements
Contact: P. Yvonne Barnes, 301-975-2345, e-mail yvbarnes@enh.nist.gov

Pyrometry Calibrations
Contact: Charles Gibson, 301-975-2329, e-mail gibson@enh.nist.gov

Spectral Radiance and Irradiance Source Calibrations
Contact: Charles Gibson, 301-975-2329, e-mail gibson@enh.nist.gov

(Government staff may dial FTS-879- rather than commercial 301-975-)

Mail correspondence should be addressed to the appropriate staff member at the following address.

Staff Member
NIST
Radiometric Physics Division
Metrology A305
Gaithersburg, Maryland 20899

CALIBRATION PUBLICATIONS

The following publications are available which describe the calibration activities of the Division:

NBS SP 250-1, Spectral Radiance Calibrations

NBS SP 250-6, Regular Spectral Transmittance

NBS SP 250-7, Radiance Temperature Calibrations

NBS SP 250-8, Spectral Reflectance

NBS SP 250-15, Photometric Calibrations

NBS SP 250-17, The NBS Photodetector Spectral Response Calibration Transfer Program

NBS SP 250-20, Spectral Irradiance Calibrations

NIST SP 250, NIST Calibration Service Users Guide 1991

NIST SP 260, NIST Standard Reference Materials Catalog 1992-93

To obtain these publications, contact either:

Superintendent of Documents
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