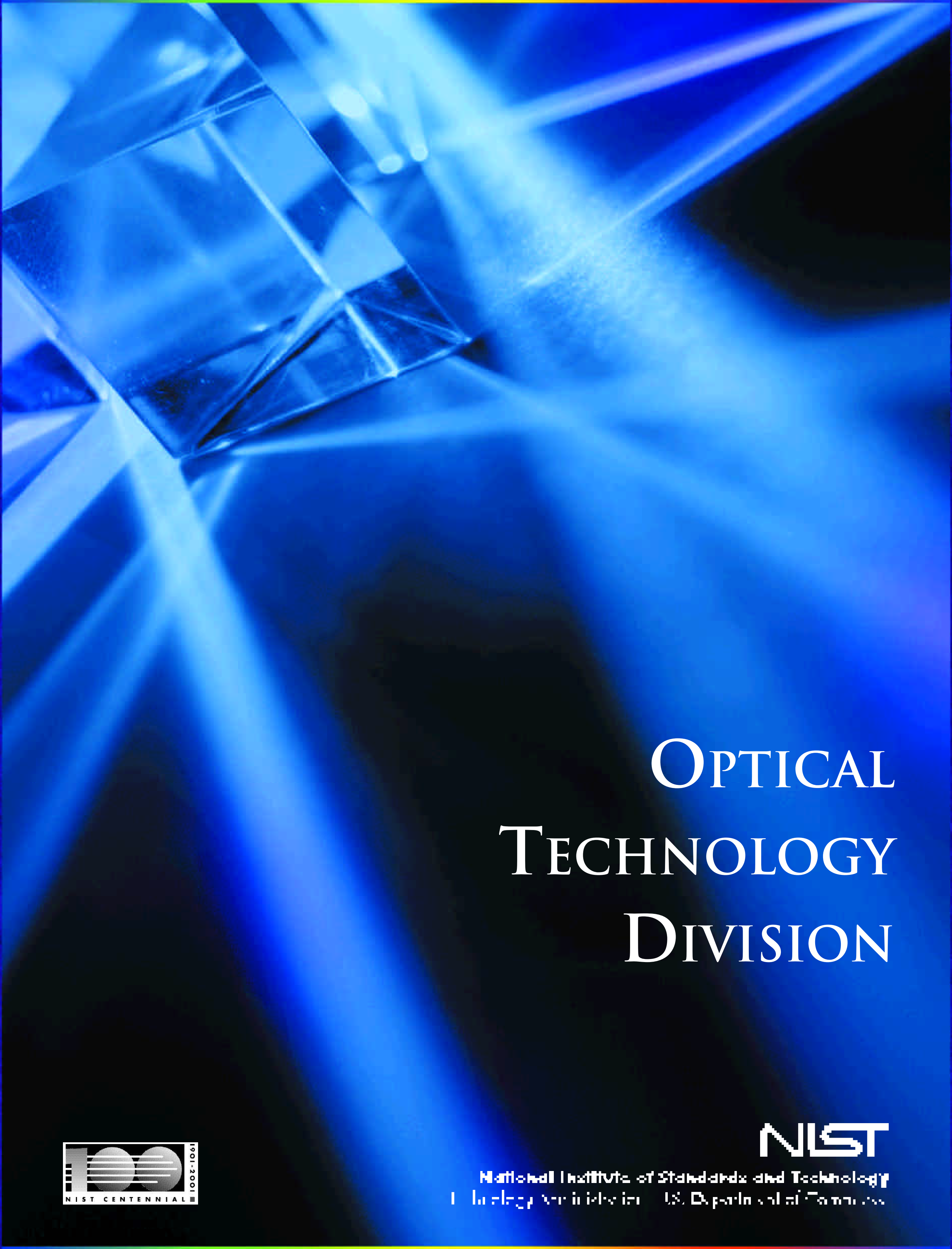


OPTICAL TECHNOLOGY DIVISION

NIST CENTENNIAL 1901-2001

NIST
National Institute of Standards and Technology
Technology Administration • U.S. Department of Commerce

Now celebrating 100 years of service to the nation, the National Institute of Standards and Technology (NIST) is a non-regulatory federal agency within the Commerce Department's Technology Administration. NIST's mission is to promote economic growth by working with industry to develop and apply technology, measurements, and standards. NIST carries out its mission through four interwoven programs: NIST Laboratories, Baldridge National Quality Program, Manufacturing Extension Partnership, and Advanced Technology Program.

NIST has an operating budge of about $720 million and operates primarily in two locations: Gaithersburg, Maryland (headquarters--234 hectare/578 acre campus) and Boulder, Colorado (84 hectare/208 acre campus). NIST employs more than 3,200 scientists, engineers, technicians, business specialists, and administrative personnel. About 1,600 guest researchers complement the staff. In addition, NIST partners with 2,000 manufacturing specialists and staff at affiliated centers around the country.

The Physics Laboratory supports U.S. industry by providing measurement services and research for electronic, optical and radiation technology. Researchers develop new physical standards, measurement methods and data, and collaborate with industry to commercialize inventions and discoveries.

The Optical Technology Division of NIST's Physics Laboratory provides the national measurement infrastructure to support those in industry, government, and academia who rely on optical technologies for their competitiveness and success. The Division has the institutional responsibility for maintaining two SI base units: the unit for temperature, the kelvin, above 1234.96 K and the unit of luminous intensity, the candela.As part of its responsibilities the Division:

- develops, improves, and maintains the national standards for radiation thermometry, spectroradiometry, photometry, colorimetry, and spectrophotometry;

- provides National measurement standards and support services to advance the use and application of optical technologies spanning the ultraviolet through microwave spectral regions for diverse industrial, governmental, and scientific uses;

- disseminates these standards by providing measurement services to customers requiring calibrations of the highest accuracy, and contributes to the intellectual reservoir of technical expertise by publishing descriptions of NIST-developed advances in appropriate scientific journals and books;

- conducts basic, long-term theoretical and experimental research in photophysical and photochemical properties of materials, in radiometric and spectroscopic techniques and instrumentation, and in application of optical technologies in nanotechnology, biotechnology, optoelectronics, and in diverse industries reliant upon optical techniques.

Through these activities, the Division meets the needs of the lighting, photographic, automotive, electronics, and xerographic industries and other sectors dependent upon optical measurements. The Division also provides measurement support for national needs in solar and environmental monitoring, for health and safety concerns, and for the aerospace and defense industries. The Division has advanced programs in applications of laser spectroscopy, terahertz and infrared spectroscopy, near-field scanning microscopy, and synchrotron radiation to provide new insight into physical, chemical, and biological phenomena and to provide new tools for measurement needs in industry and government.The Division has a responsibility to provide measurement support services to other government agencies for the efficient and effective pursuit of their own missions. To this end, the Division develops collaborative projects with appropriate participation from other agencies, and as a result, develops facilities for calibration and other types of measurement support required by the other agencies' particular programs.

Mission: The Optical Technology Division, by advancing knowledge and expertise in targeted areas of optical technology, will provide the highest quality services, technical leadership, and measurement infrastructure to promote the U.S. economy and support the public welfare and the national defense.

This publication provides the reader with an introduction to the Division's programs, major projects, and services. For additional information about the Optical Technology Division, visit our web site at www.physics.nist.gov/otd or call the division office at 301-975-2316

MAINTAINING THE NATION'S REFERENCE POINTS FOR MEASUREMENTS OF LIGHT INTENSITY

The Optical Technology Division Maintains Two SI units:

The Radiation Temperature Scale above 1234.96 K - the freezing point of silver

The International Temperature Scale of 1990 (ITS-90) defines the temperature scale above the freezing point of silver (> 1234.96 K) using one of the fixed-point blackbodies (Silver, Gold or Copper) and the application of the Planck radiation law. At NIST, the Optical Technology Division maintains the temperature scale above the silver freezing point using a gold freezing point blackbody, whose absolute temperature was determined using detector-based radiometry and is in agreement with the ITS-90 assigned value (1337.33 K). The temperature scale from 1073 K to 2800 K is disseminated by the Division through calibration services for pyrometers and other transfer standards.

The Candela: The Unit of luminous intensity

The Division is responsible for the realization of the candela and other photometric units for luminous flux (lumen), illuminance (lux), luminance (cd/m^2), and color temperature (K). Photometric standards are critical to the lighting, optical instruments, visual displays, aircraft, and automobile industries. The photometric units are based on standard photometers, traceable to the Division's High-Accuracy Cryogenic Radiometer (HACR).

METROLOGY:

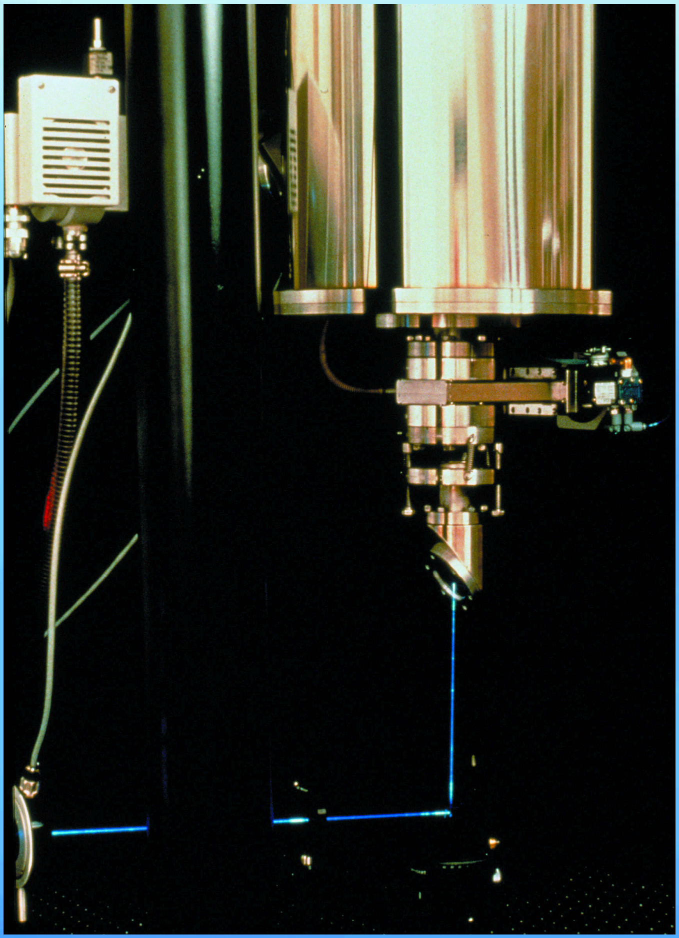
THE CORNERSTONE OF COMPETITIVENESS

The HACR is the Nation's Primary Standard for Optical Power Measurements

The HACR has been developed to serve as the nation's primary standard for optical power measurements. The HACR, with its intrinsic standard uncertainty of better than 0.05%, insures the accuracy of radiometric measurements at NIST. Many calibration services offered by the Division are based on the HACR. It is the foundation of the radiometric measurement chain and is used to maintain the scales of spectral radiance, spectral irradiance, and absolute detector responsivity.

Absolute Detectors and Transfer Detectors

Over the past few decades, absolute detectors have been developed to serve as fundamental radiometric tools to relate, with high accuracy, optical power to the International System of units (SI). To meet the needs of our customers, we are extending this capability to wavelengths from the ultraviolet to the far infrared, for various power levels. In all optical radiation calibration activities offered by the Division, detector-based radiometry has replaced traditional source-based techniques and allows us to provide standards to our customers with significantly improved accuracy, stability, and convenience.



Transfer standards are used to deliver optical power measurements made with the HACR to other instrumentation used for radiometric measurements. Typically, silicon photodiodes in light-trapping configurations are used as high-accuracy transfer detectors in the visible and UV spectral ranges.

Infrared detectors are now available that can provide NIST traceability for the wavelength range of 2.5 µm to 30 µm. Blocked impurity-band (BIB) detectors, also known as impurity-band conductors (IBC), are made of arsenic-doped silicon and are being characterized as transfer standards. Operated at 12 K, these detectors are unique in their spectral range and have a high degree of spatial uniformity and low noise. Such detectors meet the requirements of the aerospace industry and other government agencies for radiometric calibrations of satellite sensors used in a wide range of applications from environmental remote sensing to military.

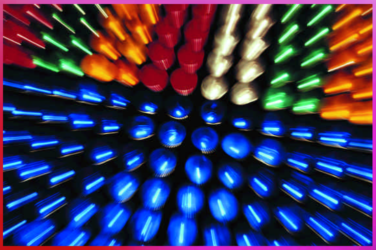
SIRCUS Improves Radiometric Scales

As NIST continues to move from source-based to detector-based radiometry and photometry, reducing the uncertainties in the responsivities of filter radiometers will directly impact NIST's radiometric and photometric scales. A new radiometric source facility has been constructed in the Division with narrowband, widely tuneable lasers for high spectral resolution and high flux levels covering the wavelength range from 200 nm to

12 µm. It also incorporates custom integrating spheres to provide variable source areas with good spatial uniformity. The facility for Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) was developed to reduce the uncertainties in detector power, irradiance, and radiance responsivity measurements. For example, with the new facility we have reduced the uncertainty in irradiance responsivity calibrations from 0.5 % to 0.1 % in the visible wavelength range.

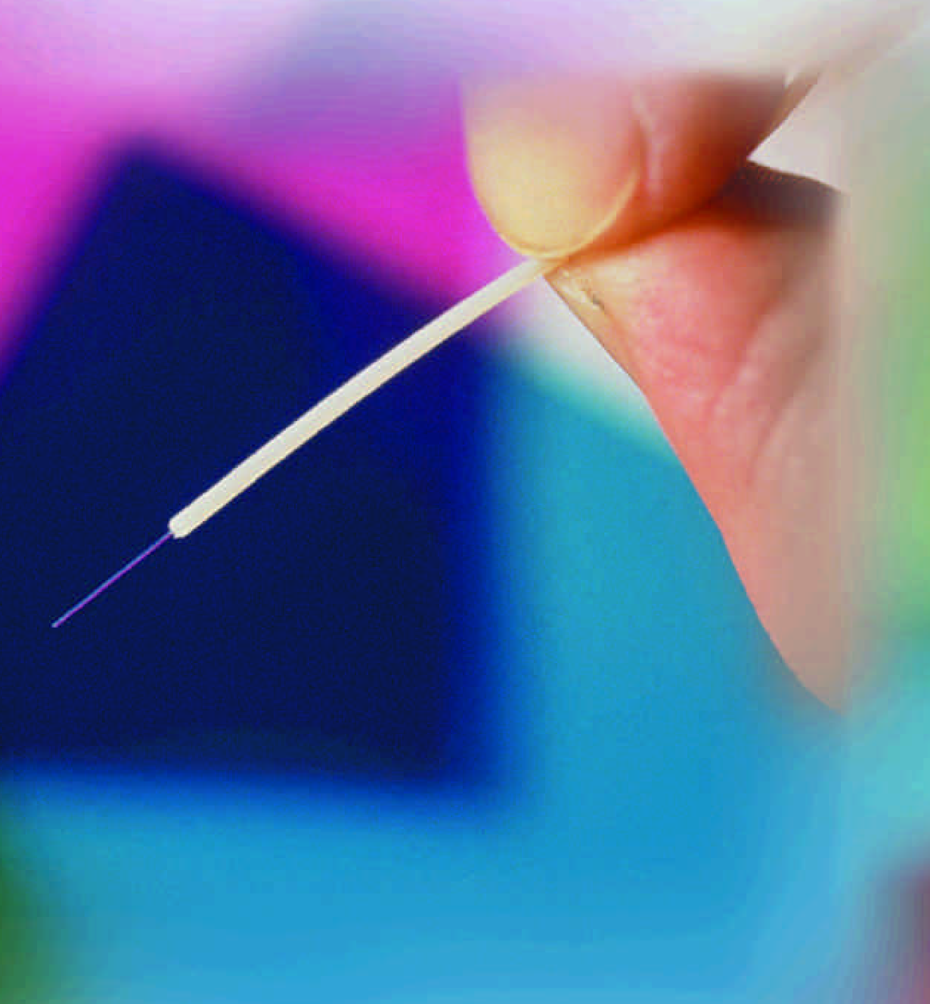
Colorimetry & Appearance

Physical measurements of an object's interaction with or emission of light are used by industry to characterize its color and appearance (gloss, haze, texture, etc.). The primary goals of the NIST Measurement Science for Optical Reflectance and Scattering Project, a multidisciplinary team comprised of scientists from the NIST Measurement and Standards Laboratories, are to develop reference instruments and standards for current appearance measurement technologies and to eventually develop new measurements and standards to more accurately capture visual appearance. This work is part of a joint competence-building project that seeks to relate measured appearance (light scattering) properties with surface microstructure, coating formulations, and advanced photo-realistic computer graphic techniques.



For appearance attributes, a new reference goniophotometer provides specular gloss measurements at the 20°, 60° and 85° geometries required by relevant ASTM and ISO standards. In addition, a new primary standard for specular gloss has been developed, and comparisons with other national metrology institutes are underway.

In the area of colorimetry, we are assembling a new reference instrument for reflectance color with the characteristics necessary for measurements with the lowest possible uncertainty. This instrument will eventually be used to implement a measurement assurance program with industry-standard color tiles.



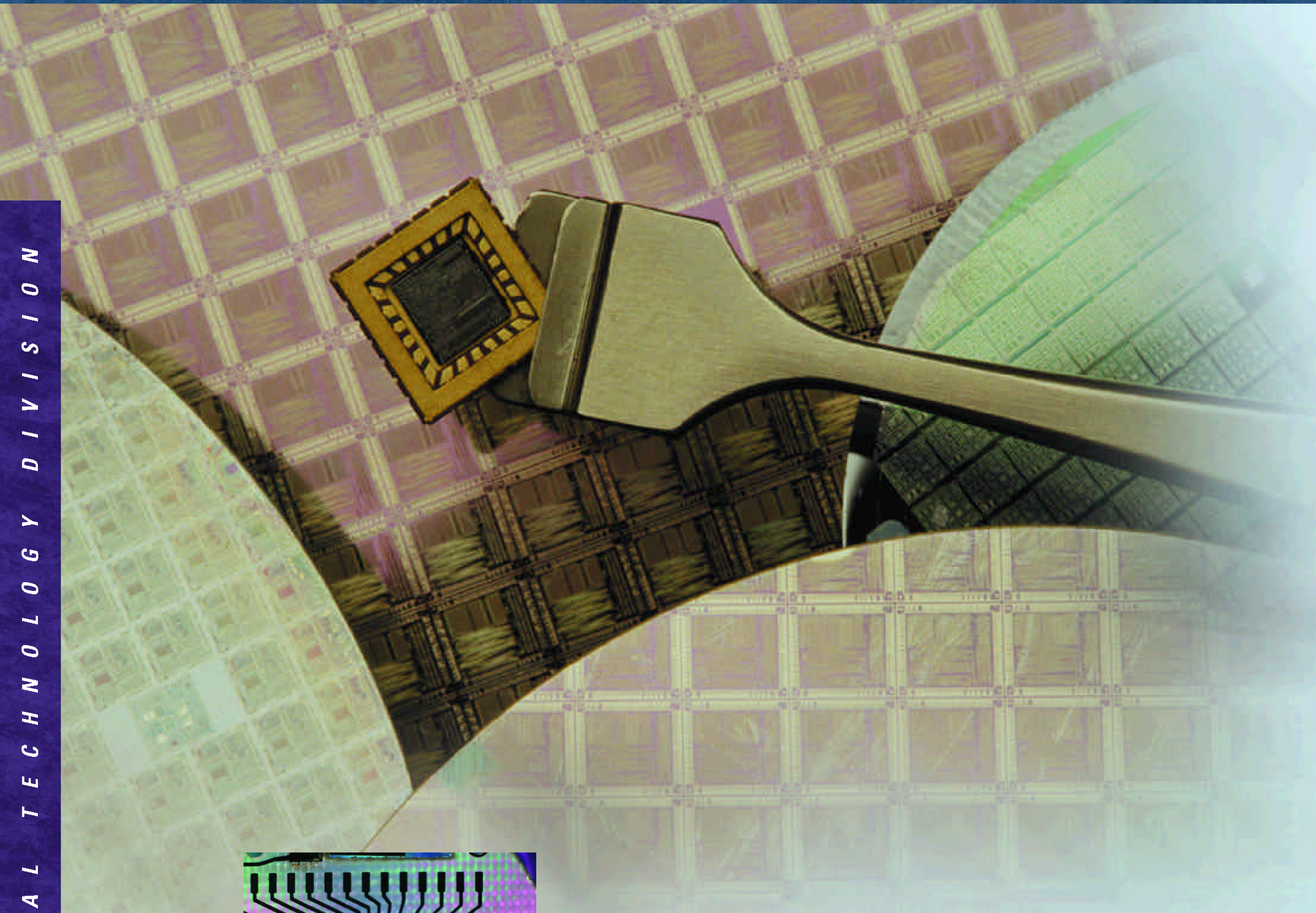
Colorimetrics for the Display Industry

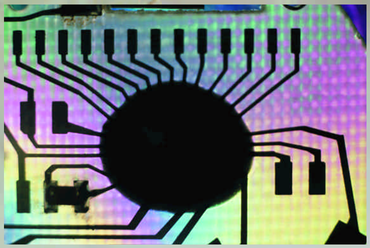
The display industry has requirements for colorimetric characterization of displays both at the pixel and full field levels. The efficiency of the conversion of information from electrical to optical is critical for the development of smaller and more energy-efficient video displays. Increased competition is requiring manufacturers to improve the performance and quality of their products. The Division provides basic colorimetric and photometric standards for the display industry and has engaged in a research and development effort to devise improved standards for industry.

We are also developing capabilities for colorimetric characterization of color displays and other color imaging systems. There is an increasing need for accurate spatially and temporally resolved photometric and colorimetric measurements of color displays, including flat panel displays, and also for precise color reproduction in imaging systems using CCD cameras, scanners, monitors, and color printers, particularly for commercial applications. The Division is developing facilities and standard procedures to meet these needs.

Standard Light Emitting Diodes

The Division has started a new project to investigate and develop measurement methods and standards for photometry and colorimetry of light-emitting diodes (LEDs). Since high-intensity blue LEDs have recently become available, the application of LEDs is expanding rapidly in a wide variety of areas, including color displays, traffic and aviation signals, and signs. Accurate specifications of LED characteristics are therefore becoming increasingly important, however large discrepancies in photometric measurements of LEDs (as much as 50 percent) are being reported by manufacturers and users. To improve this situation, NIST has investigated the technical problems and is developing standard LEDs and recommended measurement methods for luminous intensity, total luminous flux, and color (chromaticity and dominant wavelength). The NIST work is linked to the standardization efforts by CIE (Commission Internationale de l'Éclairage) committees TC2-45 and -46. NIST intends to have LED calibrations and standards available soon.





Temperature Measurement for Rapid Thermal Processing

The Division is participating in a multidisciplinary effort to develop methods to measure silicon wafer temperatures in a rapid thermal processing (RTP) environment to ± 2 °C accuracy to improve metrology practices in the semiconductor industry. The environment for wafer curing is in the 600 °C to 1000 °C range. The major thrust of the project is to establish reliable contact and optical thermometry traceable to NIST national temperature standards in the range used for wafer curing. This is commensurate with the International Technology Roadmap for Semiconductors goals for RTP thermometry (0.18 μm and smaller).

The collaborative NIST RTP project also includes researchers from the Process Measurements Division in the Chemical Sciences and Technology Laboratory and is coordinated by the NIST's Office of Microelectronics Program in the Electronics and Electrical Engineering Laboratory.

Optical Metrology to Support Photolithography

Ultraviolet irradiation alters many materials, including photodetectors meant to measure UV and visible irradiation, making it difficult to obtain detectors that are stable during prolonged UV exposures. This poses a problem, for example, for the metrology of UV radiation at 157 nm and 193 nm, which is a rapidly growing need in such applications as semiconductor lithography and micromachining.

Researchers in the Division have compared the stability of different types of photodetectors subject to irradiation from excimer lasers operating at 157 nm and 193 nm. A purge housing contained a xenon arc lamp and a 0.25-m monochromator that is capable of measuring the spectral responsivity and the reflectivity of the detectors from 180 nm to 500 nm.The simultaneous measurement of the spectral responsivity and the reflectivity yields the internal quantum efficiency of the detectors, which is an important parameter used to characterize their behavior.

Similarly, the transmission of a polymer-based photochromic film was also measured as a function of the dose at 193 nm.The transmission of photochromic film in the visible region changes as a function of the dose that is delivered to the film in the ultraviolet.The material has potential for application in UV metrology as a consumable that is not subject to the long-term degradation of traditional photodetectors.

UV Irradiance Measurements

Researchers in the Division have constructed and characterized a probe that is suitable for accurate measurements of irradiance in the vacuum ultraviolet spectral range. Many industrial applications such as UV curing, photolithography, and semiconductor chip fabrication require accurate measurement of irradiance and would benefit from having such a stable, accurate UV probe. Stability of detectors at short wavelengths has been a major obstacle to being able to measure irradiance accurately. Extensive measurements were made using the continuously-tunable synchrotron radiation from the NIST Synchrotron Ultraviolet Radiation Facility (SURF) III to identify stable detectors in the spectral range from 120 nm to 300 nm.The probe consists of a Platinum Silicon detector behind a precision 5 mm aperture. The probe was characterized at various wavelengths from 157 nm to 325 nm, encompassing many of the wavelengths of importance for industrial applications. The principle of measurement of irradiance is based on scanning the probe in a light field and measuring the spectral responsivity on a grid with regular spacing. Measurement of the spectral responsivity in the center of the probe along with the integrated total responsivity yields the spectral irradiance. This method can alternatively be used to calculate aperture areas as well, by measuring the ratio of the total responsivity and the responsivity in the center.

Ultraviolet Optical Properties of Materials

For various industrial applications, such as semiconductor photolithography and UV laser development, accurate measurement of the optical characteristics of various transmissive materials is essential.The data often are required not only at specific laser wavelengths but also in the neighborhood of those wavelengths in order to design optical systems with a minimum of aberrations and laser-pulse dispersion. We have made preliminary measurements towards a complete characterization of the optical characteristics of calcium fluoride in the UV from 125 nm to 300 nm.This includes regions near 157 nm and 193 nm, which are of particular interest for projection optics in semiconductor lithography. Broadband radiation from SURF is filtered by a 2-m normal-incidence monochromator. The transmittance and the reflectance of samples of different thickness are measured.Additional measurements are made to distinguish surface scatter and surface absorption from bulk scattering and bulk absorption.

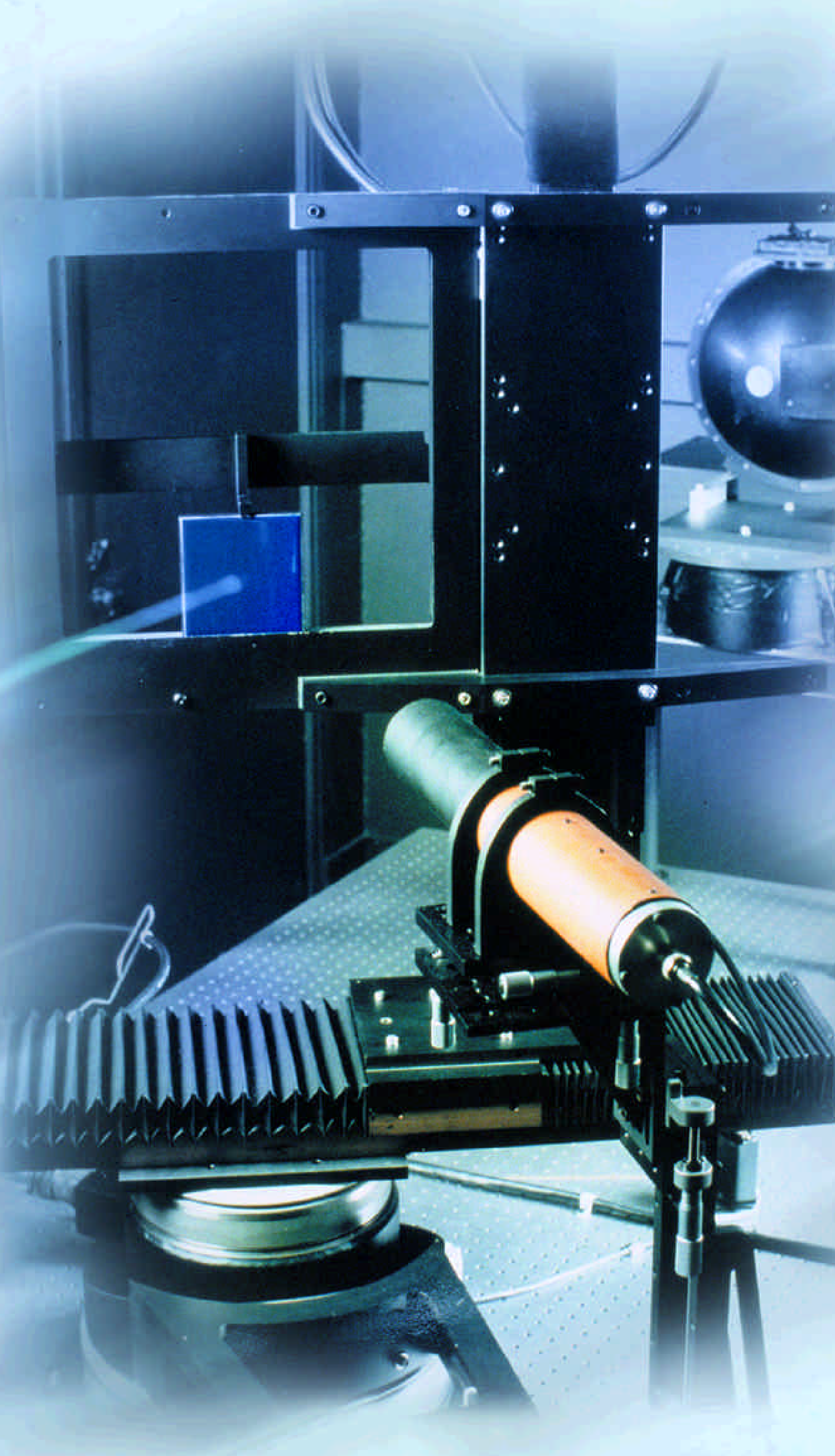
In a collaborative effort with researchers in the NIST Atomic Physics Division, we also have made high-accuracy measurements at 157 nm of the index of refraction and dispersion, and their temperature dependencies, for various grades of calcium fluoride.

OPTICAL PROPERTIES CHARACTERIZATION FACILITIES AND CAPABILITIES

Optical Scatter: STARR

The Division has constructed and operates unique facilities for the measurement of optical scatter. They offer a wide range of measurement capabilities, allowing characterization of materials ranging from paints that are highly diffusive to mirrors that are highly reflective. These facilities measure the bidirectional scatter distribution function (BSDF), defined as the scattered radiance normalized by the incident irradiance as a function of incident and observation angles in reflection or transmission.

The Spectral Tri-function Automated Reference Reflectometer (STARR) facility is optimized for the measurement of BSDF from highly scattering materials, specular reflectance of mirrors, and total integrated scatter. The STARR facility offers greater measurement speed and accuracy, improved mechanical stability, and higher system throughput than earlier versions. The STARR instrument also has raster-scanning capability. The sample holder accommodates artifacts up to 30 cm by 30 cm in size. Measurements of BSDF, spectral reflectance, spectral transmittance, and total integrated scatter are made for wavelengths between 200 nm and 2500 nm.



Optical Scattering from Smooth Surfaces: GOSI

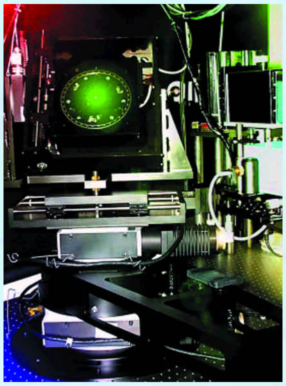
The characterization of optical scatter from surfaces, as a function of wavelength and incident and scattering angles and polarizations, is useful for evaluating elements contained within an optical system. It is also effective for the characterization of materials and surfaces in control and inspection processes in manufacturing. The Division's Goniometric Optical Scatter Instrument (GOSI) employs ultraviolet and visible laser sources, sensitive detection schemes, and polarization control on both the incident and scattered light. Having a dynamic range of about 16 orders of magnitude (in scattered power per solid angle), this instrument is well suited for studying low-scatter surfaces such as silicon wafers and optically smooth mirrors.

Using GOSI, Division researchers found that the polarization of scattered light can be a unique signature of the scattering source. The instrument can detect microroughness, subsurface defects, or particulate contamination. Research is ongoing to evaluate different applications of this finding, including the characterization of small particles and thin films. A second instrument, the Multidetector Hemispherical Polarized Optical Scattering Instrument (MHPOSI), has been built to demonstrate how the polarized light scattering technique can be used to improve the inspection of semiconductor wafers. Optimized for measuring the light scattering properties of localized defects, it employs multiple detection systems to capture the light scattering function over most of the scattering hemisphere at once. Its detection systems are polarization sensitive, enabling a partial mapping of the polarimetric properties of the sample.

Infrared Fourier-Transform Spectrophotometry Laboratory

The Infrared Fourier-Transform (FTIR) Spectrophotometry Laboratory serves as the measurement facility for characterization of the optical properties of materials in the infrared spectral range of 1 µm to 100 µm, with particular emphasis on the 2 µm to 20 µm region.The facility is built around several commercial FTIR Instruments. Custom specialized accessories have been developed to enable transmittance and reflectance measurements of a wide variety of sample types and under the variable control of measurement geometry, beam polarization, and sample temperature. Methodologies and new techniques have been developed for high accuracy measurements. In addition to the directly measured quantities, these have also been implemented for other properties such as refractive index and Mueller matrix elements. New instrumentation for direct emittance measurements at elevated temperatures up to 1000 °C is under construction.

The laboratory serves a wide variety of industries and agencies that (a) require infrared optical property information, including manufacturers of optical components, infrared detectors, and spectrophotometers, materials processing, aerospace, and defense industries, or (b) use optical measurement instrumentation, such as the chemical, pharmaceutical, food, agriculture, and remote sensing industries. Standard reference materials (SRM's) developed in this facility include standards for wavelength/wavenumber calibration (SRM 1921) and a set of neutral density filters for transmittance from 2 µm to 20 µm (SRMs 2053, 2054, 2055 and 2056). Measurement services currently available as special tests include regular reflectance and transmittance over a range of incidence angles and over a range of temperatures from 10 K to 300 K, for the wavelength range of 1 µm to 100 µm. In addition, 8 degree-hemispherical (diffuse) reflectance and transmittance can be measured from 2 µm to 19 µm. The polarimetric dependence of these properties (ellipsometry and polarimetry) can also be measured over the 2 µm to 50 µm range, with complete Mueller matrix information over the 2 µm to 6 µm range.



PUSHING THE LIMITS OF OPTICAL MEASUREMENTS

Modeling of Optical Properties Measurements

Several optical measurements in the Division are currently being modeled including those related to near-field optical microscopy and blackbody calibrations. The Division also has a program devoted to modeling optical properties of materials, including modeling the absorption of visible light and x-rays, x-ray emission, and electron spectra. Extension of modeling is underway to better understanding the absorption of infrared light by matter.

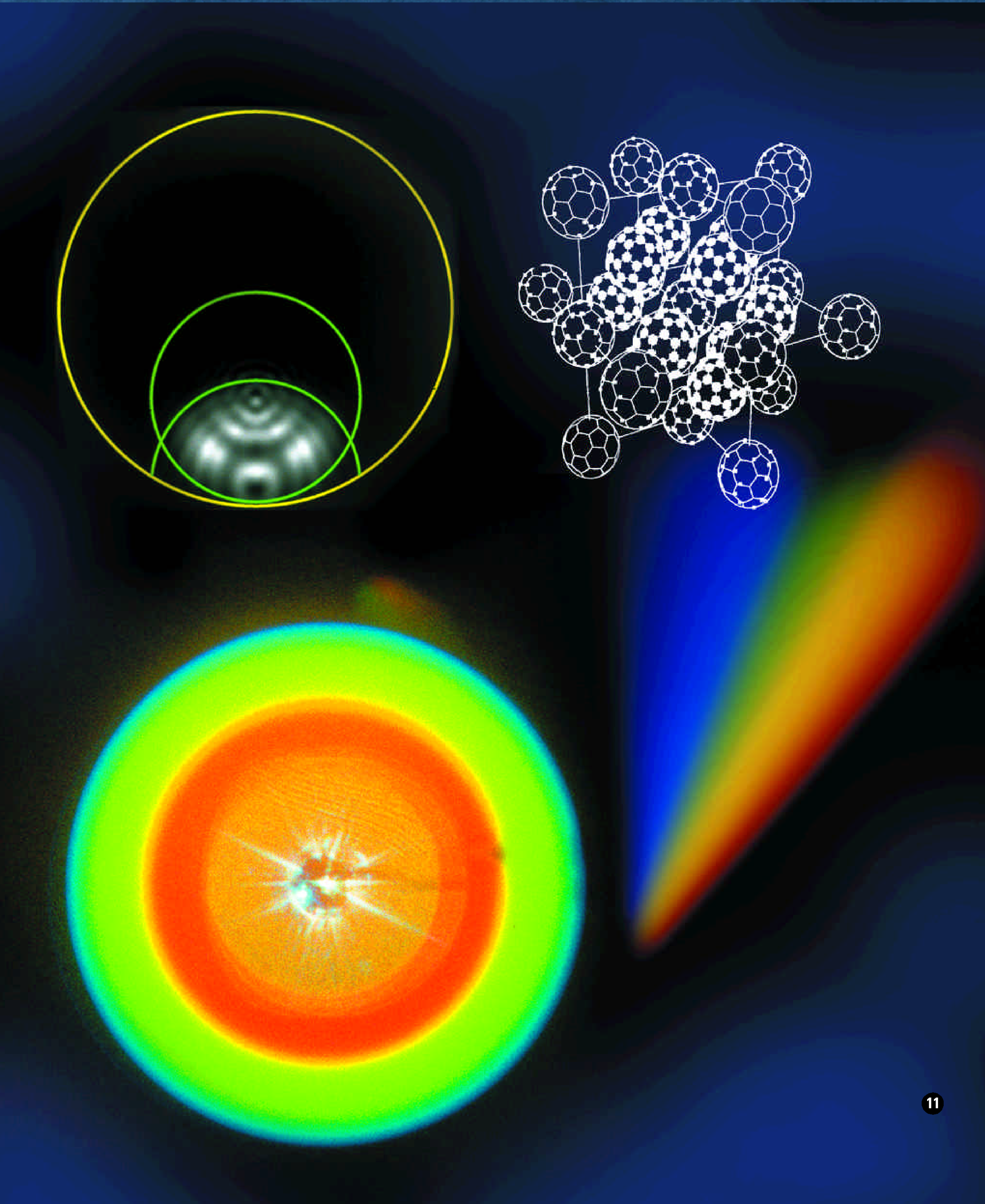
Correlated Photon Metrology

Researchers in the Division are investigating the application of correlated photon techniques to solve metrological problems, including radiometric applications such as detector quantum efficiency, and spectral radiance measurement; and materials applications such as measurement of polarization mode dispersion in optical fibers. Each application of correlated photons has the special property that it is fundamentally absolute, and thus requires no tie to an external primary standard. This feature enables outstanding final accuracy in field applications, by bringing a standard right to the end user. To make this a convenient and practical reality, work is underway to develop robust measurement protocols for these techniques, in combination with inexpensive but robust laser sources of correlated photons. These protocols will be designed to ensure that the measurements are made properly and the results and associated uncertainties can be used with high confidence. In addition to these radiometric applications, correlated photons also have potential applications in the developing areas of quantum computing and data encryption.

Ultrafast Chemistry and Solar Cell Electron Transfer Dynamics

Broadband femtosecond mid-infrared laser probing techniques developed in the Division use multi-element mid-infrared focal plane arrays for detecting time-dependent spectra of ultrafast processes in chemical reactions and solar-cell devices. For example, these advanced optical diagnostics are being used to identify transitory molecular species involved in commercially important catalyzed reactions, such as olefin polymerization. Such studies will lead to new understanding of the mechanism of catalysis. Similar diagnostics may study reactions that serve as the basis for optical switches, molecular memories, and digital communications.

Inexpensive solar-to-electric energy converters using organometallic dyes impregnated on nanoparticle substrates of TiO_2 and related semiconductors are being explored as replacements for silicon-based solar cells. Determining the detailed mechanisms and underlying materials properties of such devices is key to understanding their function and improving solar collection and current generating efficiencies. Division researchers were the first to apply time-resolved infrared spectroscopy to unambiguously reveal that electron injection from excited electronic states of the dye molecules to TiO_2 occurs on the several femtosecond timescale. Groups world-wide have accepted our technique and we find that subtle changes in dye molecular structure affect the electron injection yields and recombination rates. An exciting discovery is that substituting SnO_2 for TiO_2 sufficiently changes the acceptor levels and electronic coupling efficiencies, yielding cells with absorbed photon-to-current efficiencies approaching 40%. These findings suggest that minor modifications to the adsorbed dye and substrate properties could lead to cells with efficiencies approaching theoretical solar-to-electric conversion limits.



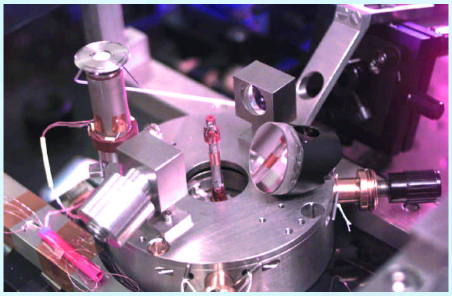
MEASUREMENT TECHNIQUES FOR HIGH TECH MEDICINE

UV Laser Spectroscopy

Many organic compounds exist in two identical chemical structures that are mirror images of each other (a characteristic called chirality). While one structure may have beneficial effects, the other may be inactive or even produce undesirable effects.

Sensitive high-resolution UV laser spectroscopies are being used to test theories relating optical activity to molecular structures and to accurately and sensitively measure the related chiral purity of a material, with potential applications to the pharmaceutical, chemical, and agriculture industries. The pharmaceutical industry, for example, relies on the measurement of optical activity and its theoretical interpretation for assessing the chiral purity of a drug, particularly when the enantiomer (mirror image) of such a drug can have dramatically different physiological effects.

The Division's effort relies on a state-of-the-art UV laser system, based on the efficient frequency doubling of a tunable continuous-wave dye laser. The high resolution and robust frequency control of the spectrometer allows the achievement of a frequency precision of 4 parts in 10^{10} in the UV. Using this laser system, we are characterizing the molecular structure of a chiral prototype, binapthol. We also are developing UV cavity ringdown spectroscopy to allow sensitive optical-activity measurements. The combination of these spectroscopies will provide a rigorous and unprecedented test of current theories that relate optical activity to molecular structure and, in turn, assist efforts toward understanding the biophysics underlying chiral selectivity under physiological conditions.



Raman Spectroscopy of Biomolecules

The Division applies polarized Raman spectroscopy to the determination of the secondary structural elements in membrane proteins and the orientation of the protein in or on the membrane. In these studies, the proteins are bound to synthetic lipid bilayers and aligned in a high magnetic field for study. The alignment, similar to what can be done with liquid crystals with electric or magnetic fields, adds symmetry to the system, which simplifies the Raman analysis and provides additional structural information. We expect this technique to accelerate our knowledge of the structure and function of membrane proteins. This knowledge is presently limited by the difficulty of crystallizing membrane proteins for traditional X-ray crystallography studies and by the fact that Nuclear Magnetic Resonance (NMR) techniques are limited to polypeptides or small proteins. The utility of such studies has been recently demonstrated in NMR measurements, but, no attempt has yet been made to explore the potential of other spectroscopic techniques, such as Raman spectroscopy, which has a throughput advantage over NMR for qualitative structural determinations. Raman spectroscopy is also applicable to the study of large noncrystalline proteins not accessible by NMR.

Near-Field Scanning Optical Microscopy

Near-field scanning optical microscopy (NSOM) is a technique that enables optical imaging on previously inaccessible length scales. The resolution of near-field images is limited not by the wavelength of light, as it is in traditional diffraction-limited microscopes, but by the size of the probe. The probe is a small aperture

(~20 nm) on the end of a tapered aluminum-coated optical fiber that is scanned over a sample a few nanometers above its surface. The position of the NSOM probe with respect to the sample is measured and controlled with sub-nanometer resolution, as in atomic force microscopy (AFM), and our NSOM instruments acquire simultaneously optical (e.g., transmission, fluorescence, or polarization) data and a map of the surface topography of the sample. NSOM is used for non-destructive studies of the small-scale structure of biological, organic, and semiconductor thin films. However, the usefulness of the technique is limited because contrast mechanisms and resolution are poorly understood or ill defined. To develop NSOM as a quantitative measurement tool, Division researchers are working to determine the fundamental mechanisms that generate contrast and determine resolution in different materials. NSOM is already useful in the characterization of organic and biomaterials and organic electronic devices. In addition, near-field techniques have applications in fields as diverse as medicine and optical data storage.

Optical Studies of Single Molecules

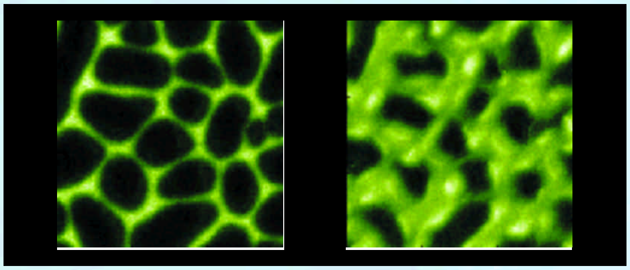
Recent innovations in microscopy have made it possible to observe the position, orientation, and function of single fluorescent molecules embedded in living cells. Single molecule spectroscopy may greatly improve our understanding of how cells respond to disease, how biological tissue is constructed, and how cellular functions are regulated by the action of single protein molecules. Single fluorescent molecules have many optical properties (e.g., lifetime, fluorescence spectrum, polarization) that depend on the local environment of the molecule and can be exploited to better understand that environment. We are determining optical properties of single fluorophores in biologically and technologically relevant environments, and developing better methods to use these probes, e.g., to study the structure and kinetics of organic and biological materials used in drug delivery and tissue engineering.

Mid-IR Imaging Spectroscopy

The Division houses an array-based FTIR-microscope system (1 µm to 12 µm spectral response) useful for assessing the spatial variations and chemical composition of polymeric, biopolymer, tissue, and material films. The approach will benefit chemical processing and medical applications desiring a compact, simple, and fast instrumentation capable of rapid spatial imaging and chemical mapping. This technology is able to identify the location of individual chemical species and provide quantitative concentration information over large (mm^2) sample areas with ~10 µm spatial resolution. It will also provide insight into mechanisms, operating parameters, and yields of products produced by combinatorial chemistry manufacturing techniques.

Nonlinear Spectroscopy at Interfaces

The nonlinear spectroscopy of Sum-Frequency Generation (SFG) is uniquely sensitive to molecular structure at interfaces. We developed a new implementation of SFG that relies on femtosecond lasers and nonlinear optics to generate ultra-fast, spectrally-broad pulses in the infrared (IR) spectral region.These wavelengths probe molecular vibrations and are particularly useful in determining the identity and orientation of chemical bonds. The IR pulses are mixed at the interface of interest with spectrally-narrow visible pulses; and, at IR wavelengths resonant with an interface molecular vibration, a new frequency equal to the sum of the visible and IR frequencies is generated (SFG).The laser-like



The image at the left is a fluorescence NSOM image of an organic electronic material with conducting regions that are shown in green. The image at the right is the corresponding topography (high areas are lighter green). These images are 6.7 microns on a side.

SFG beam is spectrally dispersed by a spectrometer onto a multi-channel array detector. The entire SFG spectrum in the IR region of interest is produced and recorded on every laser shot, rapidly obtaining vibrationally-resonant, SFG spectra with high resolution and high signal-to-noise. Current measurement applications include semiconductors (structure of thin-gate dielectric layers of silicon dioxide on silicon), biomimetic membranes (used for biosensors) in water, and liquid crystal/polymer interfaces used in optoelectronics. This joint research is in collaboration with the Surface and Microanalysis Science Division and Biotechnology Division in the Chemical Sciences and Technology Laboratory, and the Polymers Division in the Materials Science and Engineering Laboratory.

Terahertz Spectroscopy and Imaging

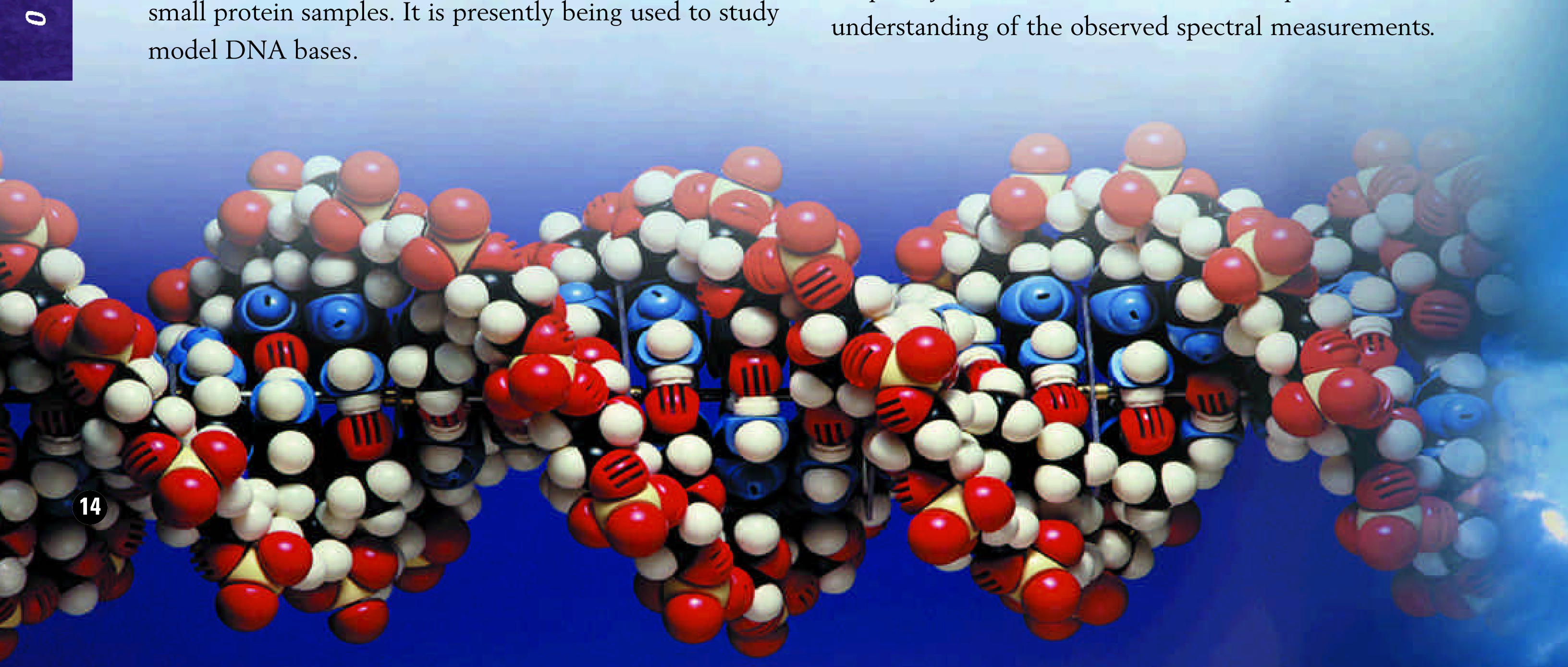
An effort in Terahertz (THz) technology, supported by the NIST Director's Competence Program, is increasing the Division's expertise in long-wavelength, 60 µm to 3 mm (0.1 THz to 5 THz), pulsed and continuous-wave (cw) coherent laser spectroscopy and imaging. The technology is being applied to model biomolecules to understand the complex dynamics involved in such processes as molecular recognition and protein folding.

THz spectra are obtained by using solid-state photon mixers and Fourier-transform methods with a pulsed THz spectrometer. This spectrometer has successfully recorded absorption spectra of pressed DNA pellets and small protein samples. It is presently being used to study model DNA bases.

The cw system spectrometer is being applied to the investigation of the torsional force fields of model biomolecules in vacuum and in the condensed phase. Torsional modes are responsible for the conformational flexibility of biomolecules and have fundamental frequencies in the THz spectral region.

A second pulsed THz instrument has been constructed, using high-power Ti^{+3}:Sapphire pulses at a 1 kHz repetition rate and ZnTe crystals for THz generation and detection.This spectrometer potentially covers a broader frequency range (0.1 THz to >10 THz) than the photon mixer-based systems and is being applied to the study of hydrogen-bonding dynamics and low-frequency biopolymer motions.

The Terahertz competence project includes joint research with the NIST Center for Neutron Research (Materials Science and Engineer-ing Laboratory) to utilize complementary tools to study dynamical processes of proteins and DNA. We are comparing state-of-the-art pulsed and cw THz optical measurements to high-resolution neutron scattering data to explore the microscopic, concerted, nuclear motions associated with molecular conformational changes. Determining the time-dependent variation in torsional motions and biomolecular interactions is crucial for understanding the biological function of enzymes, protein-drug interactions, and DNA helix transitions at a molecular level. We expect to include molecular mechanics vibrational-torsional frequency calculations to aid in the interpretation and understanding of the observed spectral measurements.



SUPPORT FOR THE NATION'S TECHNICAL AND STRATEGIC PROGRAMS

The Division has provided optoelectronic standards to the U.S. Department of Defense (DOD) primary standards laboratories for many decades. The Department of Defense, through its Calibration Coordination Group (CCG), has been a chief supporter for development and upgrades to calibration facilities to keep pace with changing technologies and increased demand for high accuracy primary and secondary standards. Support from the CCG has greatly improved the Low Background Calibration Facility and the infrared spectrophotometry, SIRCUS, HACR, and photometry laboratories.

Calibration Facility Supports Night Vision Technology

Previously available radiometric calibration methods for night vision detectors and goggles were limited to an uncertainty of approximately 10%, which is inadequate for most purposes. This limited accuracy existed because either the calibration chains were too long or the precision of the calibrating equipment was poor. Both DOD laboratories and the night-vision industry needed improved accuracies and calibration techniques.

In response to this need, NIST developed a facility to calibrate night vision detectors in spectral radiance and irradiance response modes against NIST detector-based

radiometric scales. A large output area monochromatic sphere was developed for the visible and near infrared wavelength ranges using the integrating sphere technique. A detector-based spectral radiance and irradiance response calibration system is now available for accurate and uniform calibration of night-vision transfer-standard radiometers with an expanded uncertainty of approximately 1.5%.

Flashing Light Standards to Improve Aircraft Safety

The photometric measurement of flashing light is essential in the evaluation of flashing-light sources used in such applications as photography and transportation signaling. A White House Commission on Aviation Safety and Security addressed the need for higher aviation safety and security standards; the Federal Aviation Administration (FAA) requested accurate measurements of aircraft anticollision lights. The FAA specified requirements for the intensity of anticollision lights and enforces the maintenance of the anticollision lights on all commercial airplanes. However, large variations in measurement results ascribed to the absence of standardized measurement procedures and calibration standards for flashing lights have been a problem.Thus, the Division established flashing-light photometric standards, while the measurement procedures for anticollision lights are being developed by the ARP5029 committee in the Society for Automotive Engineers (SAE).

To achieve state-of-the-art accuracy in flashing-light measurements, a flashing-light photometric unit (lx·s) has been realized at NIST using the detector-based method previously employed in the realization of the candela. Four flashing-light standard photometers equipped with current integrators were built and calibrated against the NIST illuminance standard photometers. Two different approaches have been taken to calibrate these standard photometers; one based on electrical calibration of the current integrator, and the other based on electronic pulsing of a steady-state photometric standard.The units realized using the two independent methods were intercompared, and the uncertainty of the unit realization was evaluated. A procedure for calibration of flashing-light photometers for anticollision lights has also been established.

The Low-Background Infrared Facility for Space-Based Technologies

The Division's Low-Background Infrared (LBIR) Facility is designed to calibrate user-supplied blackbody sources and to characterize low-background IR detectors and attenuators. The LBIR facility employs an 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 K to 450 K. With a built-in aperture and filter wheels, it is being used for detector calibration and optical materials characterization.The instrument, housed in a vacuum chamber, also serves as a source for evaluating

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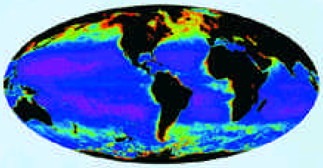
the ACR performance in the LBIR facility. The LBIR Facility is available to service the user community to characterize infrared radiometric sources, detectors and optical components in a low background environment. The facility has calibration capability and serves as the foundation for research and development for technology applications in space and other areas where highly sensitive infrared sensors are used. The ACR in the LBIR facility has been calibrated to measure the irradiance at its aperture in the range from a few nW/cm^2 to 10 mW/cm^2 with less than 1% uncertainty.

NISTAR (NIST Advanced Radiometer)

Researchers from the Optical Technology Division and Ball Aerospace and Technology Corporation partnered to design NISTAR for the NASA Triana mission that is being undertaken by the Scripps Institute of Oceanography. The Scripps-NISTAR instrument package is composed of three cavity radiometers and one photodiode channel designed to take advantage of Triana's location at the Lagrange-1 point orbit (the Lagrange-1 is the neutral gravity point between the Earth and the Sun -- 1.6 million km from Earth). Triana provides a unique vantage point from which to measure both the reflected solar energy and the radiant power emitted by the sunlit Earth.

NISTAR is being characterized using the LBIR Facility. Once deployed from the Space Shuttle, NISTAR will measure the energy emitted and reflected by Earth, providing information for global climate models.

OUR ROLE IN THE MISSION TO PLANET EARTH



As policy makers worldwide wrangle with strategies to mitigate the effects of global climate change, scientists must ensure that the data collected by a variety of instruments show real trends and not just differences in instrument performance. NASA's Earth Observing System (EOS) relies on NIST calibrations to ensure the accuracy of global climate change measurements and data collected over many years. At the Division's Facility for Advanced Radiometric Calibration (FARCAL), scientists calibrate radiometers that measure temperature changes on Earth from satellites in space. FARCAL will boost the accuracy of remote sensing instruments used in climate research. A part of the FARCAL facility consists of a 1.2-m diameter x 1.8-m long high-vacuum liquid-nitrogen-cooled chamber that has a rollout optical bench. The thermal environment of the chamber simulates the thermal environment in which EOS instruments are commonly used.

NASA’s EOS is an international, multi-instrument, multi-platform satellite remote sensing program designed to produce long-term data on global climate change. EOS constitutes the major component of NASA’s Mission to Planet Earth (MTPE), and data from EOS will be used as a guide for the implementation of international environmental policies. NIST’s role in the EOS project is to identify EOS instrumentation that requires the transfer of NIST metrology scales and develop measurement methods and instrumentation to transfer the NIST absolute scales to the EOS instrumentation. The ultimate goal of this program is to establish and maintain a radiometric and metrologic calibration capability that will enable NASA to calibrate and characterize EOS, MTPE, and international instruments at required levels of accuracy. It is anticipated that participation by NIST in the EOS calibration program will enable long-time-scale global-change data sets that are accurate and on the same calibration scales as instruments on the same and successive platforms.

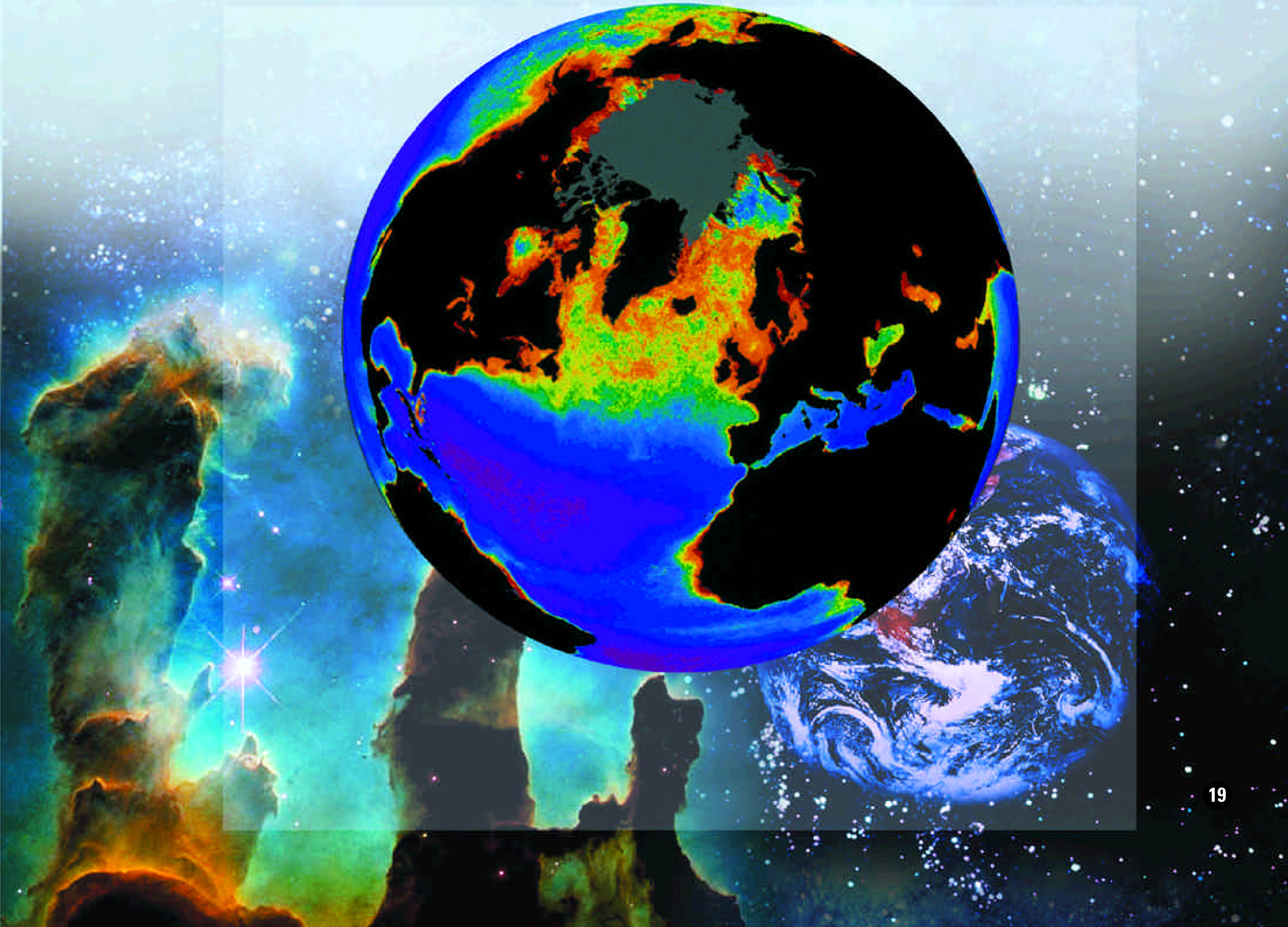
NASA's Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) Project uses satellite observations to measure the spectral radiance reflected from the oceans. From these observations, scientists are able to map the concentrations of chlorophyll and phytoplankton in the oceans. These microorganisms are essential to the process of reclaiming carbon dioxide from the atmosphere, an important process in the modeling of global warming. Phytoplankton are sensitive to the temperature, salinity, and chemical makeup of their ocean environment, and measurements of their distribution from space can be used to document the patterns of ocean currents and the temperature changes in the water.

In support of SeaWiFS, Division researchers have developed a prototype large-area field calibration light source, the SeaWiFS Quality Monitor (SQM).The SQM, designed to be rugged and economical for field use, monitors the changes in the sensitivity of marine radiometers during a long cruise. Until now, it has not been possible to assess marine radiometers, known to be unstable during a cruise. These radiometers are operated for weeks under the harsh sea environment.The SQM will be used to assure the reliability of the ocean data necessary to meet the stringent requirements of the SeaWiFS project.

OUR PARTICIPATION IN THE U.S. GLOBAL CHANGE RESEARCH PROGRAM

The Environmental Metrology Project at NIST is a response to the critical needs of the U.S. Global Climate Change Research Program for accurate radiometric calibration of optical sensors. From the ultraviolet to the thermal infrared, quantitative measurements of the radiant flux incident, emitted, scattered, and reflected from the Earth and its environment can be used to determine physical parameters required for scientific research, global warning models, and ultimately, environmental policy decisions. The Division, with the support of NASA, NOAA, USDA, and EPA, is assisting in verifying these measurements by direct interaction with the various programs. Specialized transfer radiometers, field-deployable sources, round-robin activities, and measurement intercomparisons have been developed.

Laboratory measurements are also being undertaken with support from the NASA Upper Atmosphere Research Program to provide quantitative spectroscopic data on atmospheric molecules, with a particular emphasis on broad absorption features made possible through molecular collisions in the atmosphere. Collision-induced absorptions in and by such gases as nitrogen, oxygen, water, and carbon dioxide are important contributors to the atmospheric opacity and are often neglected in atmospheric modeling due to the lack of reliable quantitative data on these broad continua features. The spectra are measured using a Fourier-transform infrared (FTIR) spectrometer and a long optical path length of 84-m, achieved by crossing the infrared beam through a cooled 2-m-long White cell 42 times. Data are acquired at high pressures, between 5 and 10 times that found in the atmosphere, to mimic the kilometer path lengths possible in the atmosphere. As part of this effort, a second mid-infrared spectrometer is being developed based on cavity ring-down spectroscopy with a tunable CO_2 laser radiation source. This spectrometer has an optical path length approximately three times greater than the FTIR-based system.



OUTREACH TO INDUSTRY

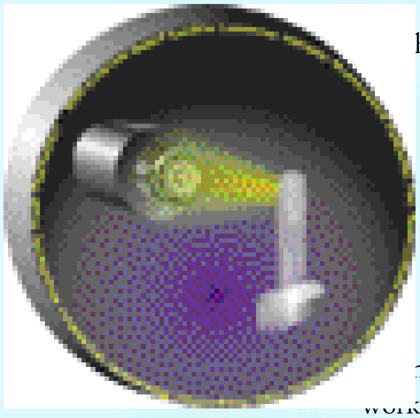
The Optical Properties of Materials Consortium

The Optical Properties of Materials Consortium was established to provide NIST with direct input from industry concerning its critical needs for optical properties of materials and related data, standards, calibration services, materials research, measurement, and methodologies. Representative industries include manufacturers and processors of optical materials; optics; ultraviolet, visible and infrared measurement instrumentation, such as spectrometers, optical filtering/scattering devices, and remote sensing instruments; lasers; pharmaceuticals; consumer health products; food and beverages; cosmetics; paper; textiles; and, chemicals.

The R&D staff of each industrial partner in the Consortium will have the opportunity to interact with every NIST Measurement and Standards Laboratory. They can schedule collaborative projects, and request NIST measurements of materials of choice. Investigations of Standard Reference Materials suitable for use in the wavelength of 193 nm to 30 µm in accordance with U.S. regulatory protocols and acceptable standard protocols is an integral part of the mission of the NIST/industry consortium. Examples of recent Consortium activities include: the measurement of index of refraction of lens material for ultraviolet photolithography; the development of color standards for color film and printer paper production; the characterization of low-level absorption in infrared sensor windows; and assistance to the US Pharmacopoeia in the establishment of a guide to the practice of near infrared spectroscopy.

The Optical Properties of Materials Consortium was established as a Cooperative Research and Development Agreement (CRADA) through the NIST Office of Technology Partnerships.

Photometry Short Course



The need for education and training for photometry engineers and technicians has been stressed by the Council for Optical Radiation Measurements (CORM), Lamp Testing Engineer's Conference (LTEC), and other metrology groups within industry. In response to this need, the Photometry Short Course was developed by he Division and made available to participants beginning in 1998.The course is aimed mainly at the customers of NIST photometric calibrations, and more widely, engineers and high-level technicians ngaged in photometric work in industry. The course covers fundamentals in photometry, radiometry, colorimetry, optical properties of materials, and practical aspects of measurements of luminous flux, luminous intensity, illuminance, luminance, color temperature, and chromaticity of light sources. In addition to lectures, the course also features hands-on experiments at the NIST photometry laboratory using the 4-m bench, the 2.5-m integrating sphere, and the color temperature facility. Course participants, divided into three groups, perform actual measurements of luminous flux, luminous intensity and illuminance, and color temperature. Participants gain experience in the calibration of lamps, photometers, and colorimeters.

Short Course on Temperature Measurement by Radiation Thermometry

This course consists of both lectures and laboratory experiments. The lectures cover the fundamentals of radiometric physics and instrumentation associated with determining temperature from observations of thermal radiation from materials. The exercises provide participants with experience in performing radiometric analyses, and serve as preparatory work for the experiments. The American Society for Testing and Materials (ASTM) voluntary industry standard test method (E1256-95) is discussed. Scientists, engineers, and technicians who need to make reliable temperature measurements using radiation thermometers will benefit from this experience.

The Division is the official sponsor of this short course. The laboratory experiments use radiometers and blackbody sources that were borrowed from several equipment manufacturers. NIST is grateful to the ASTM Subcommittee E20.02 on Radiation Thermometry for their support in facilitating the organization of this effort.

OPTICAL TECHNOLOGY DIVISION

Calibration and Measurement Services

To inquire about or to procure these services, contact
the NIST Calibration Program office at 301-975-2002.

PHOTODETECTOR MEASUREMENTS

This service provides characterized silicon detectors and special tests of customer-supplied detectors. Measurements of spectral responsivity and spectral response uniformity are made on photodiodes, detectors, and radiometers from 190 nm to 1800 nm.Additional spectral response measurements are available for infrared detectors from 2 µm to 18 µm. For further information, visit our website, http://physics.nist.gov/photodetector or contact Tom Larason at 301-975-2334 or Sally Bruce at 301-975-2323.

PHOTOMETRIC MEASUREMENTS

The Optical Technology Division is responsible for the realization of the SI base unit, the candela.The detector-based candela is the basis of other photometric units. The luminous flux scale and luminance scale have been realized based on the candela. Various calibration services are available for luminous intensity, total luminous flux, illuminance, luminance coefficient, and color temperature for a variety of artifacts and standards including lamps, opal glass, luminance meters, illuminance meters, and flashing light photometers. For further information, visit our website, http://physics.nist.gov/photometry or contact Yoshi Ohno at 301-975-2321.

OPTICAL PROPERTIES OF MATERIALS MEASUREMENTS

Measurements are made on customer-supplied artifacts over the spectral wavelength range 230 nm to 2500 nm. Measurement services include: transmittance: regular and diffuse; and reflectance: specular and diffuse, using hemispherical and bidirectional geometries. Standard Reference Materials (SRM), such as filters, mirrors, and density tablets, are developed for wavelength and photometric scale calibrations.

A new specular gloss measurement service is available for standards at the specular geometries of 20 °, 60 °, and 85 ° in compliance with ISO 2813 and ASTM D523. For further information, visit our website, http://physics.nist.gov/spectrophotometry or contact Ted Early at 301-975-2343 or Maria Nadal at 301-975-4632.

RADIANCE TEMPERATURE MEASUREMENTS

These calibration services provide access to the International Temperature Scale of 1990 (ITS-90) as realized by NIST for the temperature range 800 °C to 4200 °C. NIST disseminates the radiance temperature scale by issuing ribbon filament lamp standards of radiance temperature and by calibrating customer-supplied pyrometers and radiation thermometers. For further information, visit our website, http://physics.nist.gov/pyrometry or contact Charles Gibson at 301-975-2329.

SPECTRAL RADIANCE AND IRRADIANCE SOURCE MEASUREMENTS

Tungsten ribbon-filament lamps are supplied by NIST as lamp standards of spectral radiance. Spectral radiometric measurements of radiance and irradiance standards in the spectral region of 200 nm to 2400 nm are performed. Spectral irradiance standards are supplied by NIST in two forms: tungsten filament lamps and deuterium-arc lamps. Special tests are available. For further information, visit our website, http://physics.nist.gov/fascal or contact Charles Gibson at 301-975-2329.

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Albert C. Parr, Chief
Sally S. Bruce, Editor

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U.S. DEPARTMENT OF COMMERCE
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