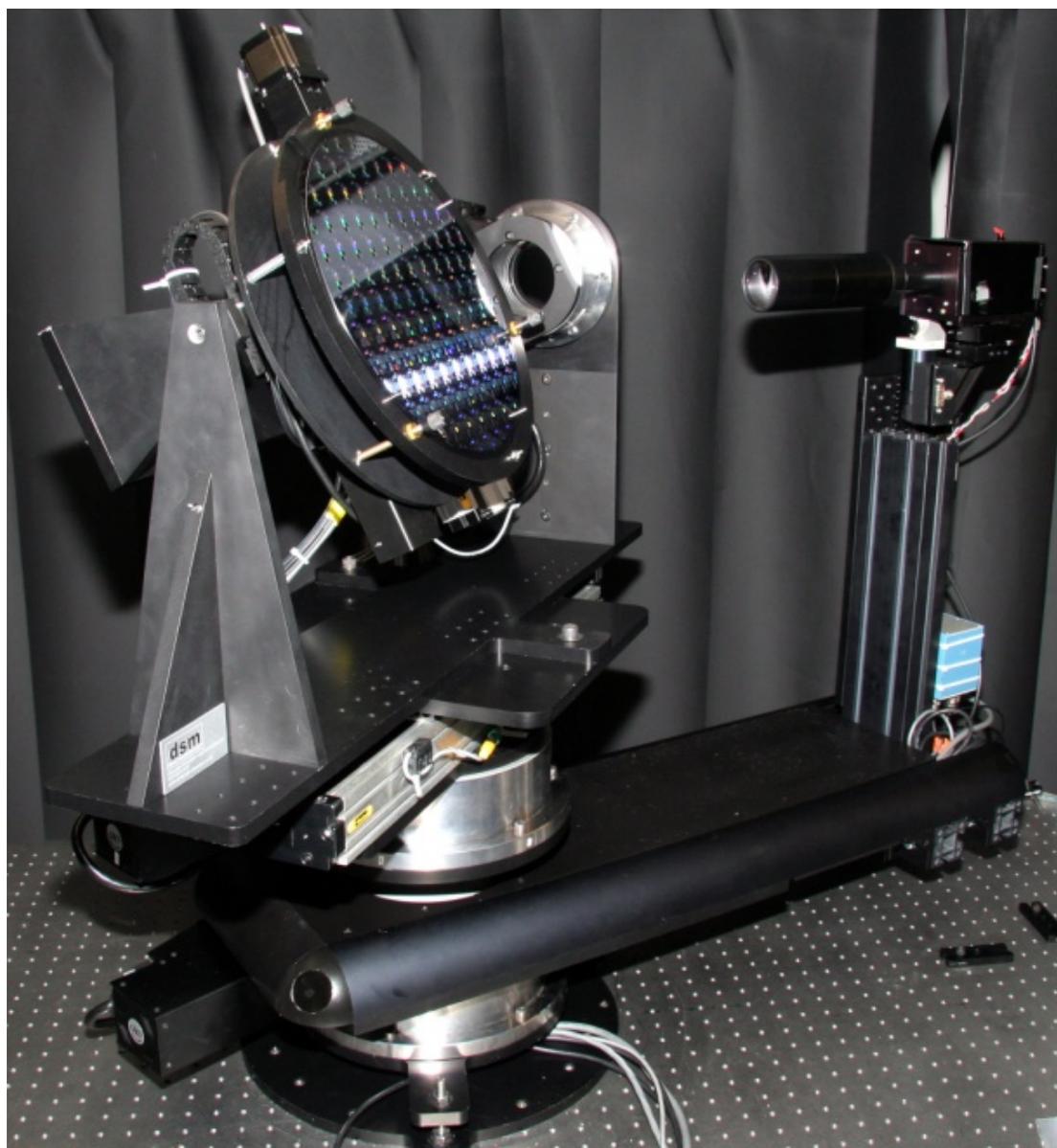


STRATEGIC PLAN 2010

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Physical Measurement Laboratory

OPTICAL TECHNOLOGY DIVISION



Optical Technology Division

Mission, Vision, and Values

Mission: To develop and provide national measurement standards and services to advance optical technologies spanning the terahertz through the infrared, visible, and ultraviolet spectral regions.

Vision: To be the world leader in solving critical optical radiation measurement challenges and promoting equitable standards. Realization of this Vision will stimulate innovation, foster industrial competitiveness, and improve the quality of life.

Values: The Optical Technology Division embraces the NIST core values of People, Integrity, Customer Focus, and Excellence.

Strategic Plan Overview

This Strategic Plan provides the Division staff members and management team a framework for establishing and communicating program priorities, allocating resources, and shaping new research directions to achieve the Mission and Vision of the Division in support of its industry, academic, and government stakeholders and customers reliant on optical radiation measurement, standards, and technology. This Plan has evolved over the last two decades guided by formal and informal input from key stakeholders, including the National Research Council (NRC), Council on Optical Radiation Measurements (CORM), Department of Defense Calibration Coordination Group (CCG), Department of Homeland Security (DHS), Missile Defense Agency (MDA), NASA, NOAA, DoD and their aerospace contractors, SEMATECH, NIST Office of Law Enforcement Standards (OLES), voluntary standards organizations, and calibration service users. The Division plan supports NIST's role in the National Measurement System by helping to ensure that our Nation's optical radiation measurements are tied to national and international standards critical for world-wide acceptance of U.S. commercial products and scientific research.

To achieve its mission, the Division is organized into five groups:

- Optical Thermometry and Spectral Methods Group (03);
- Optical Properties and Infrared Technology Group (04);
- Optical Sensor Group (05);
- Laser Applications Group (06); and
- Biophysics Group (08),

with nearly all major projects involving collaboration between groups. Additionally, the Division maintains a state-of-the-art measurement infrastructure, spanning the ultraviolet through the microwave spectral regions. The Division management, in consultation with the staff members, stakeholders, and customers, constantly assesses the relevance and importance of its programs to ensure resources are directed at the most critical national needs. The outputs from the Division programs are disseminated through scientific and technical peer-reviewed publications, internal

and interagency reports, calibration services, collaborative research, documentary standards, short courses, workshops, and conference presentations.

To ensure the long-term health and success of industries, government programs, and academic research efforts that depend on optical technology, the Division strives to anticipate future U.S. optical radiation measurement needs. The Division management encourages the staff members to work with customers and stakeholders to develop proposals for new optical radiation measurement science and standards research efforts. Staff members are empowered to collaborate with other government agencies and the private sector to obtain the necessary resources to make evolutionary or revolutionary changes in program directions to meet changing national needs. Division staff members participate in and lead workshops and technical road-mapping sessions to help anticipate future optical radiation measurement needs.

Success in the implementation of this strategic plan depends upon the quality of the contributions from the staff members and their projects. Staff member contributions are evaluated in comparison to their peers at NIST and at similar institutions throughout the world. Performance metrics include peer review; number and quality of publications, invited talks, and awards; level of extramural and intramural research funding competitively awarded; strength of collaborations; quality of postdoctoral applicants; and performance of calibration services.

Technical success depends upon the availability of state-of-the-art research facilities. An extensive effort has been undertaken over the last few years to strengthen the facilities supporting our programs. Significant investments have been made in SIRCUS and Traveling SIRCUS, FASCAL 2, AIRI, and LBIR (See the Appendix for a complete list of Acronyms). The Division has been aided in this effort by funding from other government agencies, the NIST Director's Innovations in Measurement Science Program (IMS), and NIST-level budget initiatives. Recent new NIST funding provided to the Division includes the following:

- Optical Medical Imaging for Clinical Applications (2010 IMS)
- Detection of Corrosion in Steel-Reinforced Concrete (2010 IMS)
- Climate Science (Fiscal Year (FY) 2009 Initiative)
- Greenhouse Gas Measurements (FY 2009 Initiative)
- Nano-EHS (FY 2009 Initiative)
- Alternative Energy (FY 2009 Initiative)
- NIST Standard Stars (2008 IMS)
- Redefining Optical Power Traceability: Bridging the Gap from Single Photons to Tera-Photons (2008 IMS)
- Quantum Optical Metrology with N-Photons (2006 IMS)
- Vision Science as a Basis for Optical Metrology (2006 IMS)
- Intrinsic Force Standards Based on Atomic and Molecular Interactions (2006 IMS)
- Fundamental Metrology for Carbon Nanotube Science and Technology (2006 IMS)

Program success also depends heavily upon the Division's continued ability to recruit outstanding scientists and engineers as staff members, postdoctoral fellows, support contractors, and guest scientists. The present quality of our technical staff and facilities aids the Division in recruiting. It is also critical that the Division continues to promote the technical growth of the staff

members by providing resources, opportunities for internal and external recognition, and assistance in seeking funding from internal and external sources.

The Division's Strategic Plan consists of the three overarching strategic elements expanded upon in the paragraphs below:

- Optical Radiation Standards;
- Optical Measurement Methods; and
- Optical Measurement Services,

Overarching Strategic Elements

I. Optical Radiation Standards: Maintain and advance optical radiation standards based on the SI system of units.

The Division is responsible for maintaining, advancing, and disseminating our Nation's primary SI standards for the candela and the kelvin (above the freezing point of silver at 1234.93 K), and related photometric, colorimetric, pyrometric, and radiometric optical radiation quantities. The Division assesses the present and future needs of its customers and stakeholders to ensure that industry, academia, and government have access to the fundamental optical radiation standards necessary for ensuring U.S. economic competitiveness, technological leadership, national and homeland security, and quality of life.

II. Optical Measurement Methods: Advance optical radiation measurement science to solve problems in critical and emerging technology areas of national importance.

The Division advances the accuracy and utility of optical radiation measurement science and standards in technological areas critical for US leadership, innovation, homeland and national security, and quality of life. Such areas include semiconductor manufacturing, infrared and optical signatures, biophysics, nanotechnology environmental health and safety, optical medical imaging, quantum information, solid-state lighting, climate research, greenhouse gas mitigation, and missile defense. The Division's efforts are aligned with NIST's Investment Priority Areas in Energy and in Environment, and NIST Fiscal Year 2009 funded initiatives in Climate Science, NanoEHS, Greenhouse Gas Measurement, and Alternative Energy Technologies. The Division's research is also tied to NIST's important infrastructural role within the National Measurement System in the area of optical technology.

III. Optical Measurement Services: Disseminate optical radiation measurement technology and standards to industry, government, and academia.

NIST has a leadership responsibility within the U.S. Measurement System to help ensure that U.S. measurements and associated technical standards are accepted worldwide to enable U.S. companies to favorably compete in the global marketplace. The Division fulfills this responsibility for NIST in the area of optical radiation measurements by actively participating in the Consultative Committees on Photometry and Radiometry (CCPR) and on Thermometry (CCT) under the International Treaty of the Meter. The CCPR and CCT consist of representatives from the national metrology institutes (NMIs) of the participating nations. To assess measurement quality

and comparability worldwide, the CCPR sponsors and NIST participates in measurement comparisons between the NMIs in photometry, radiometry, and optical properties of materials. CCT leads comparisons in pyrometry. NIST also organizes measurement comparisons within the U.S. that includes participation from government and private sector laboratories.

Division staff members collaborate in the development of national and international technical documentary standards to ensure their correctness and alignment with U.S. interests. Division staff members participate in and lead standards development activities within organizations such as the American National Standards Institute (ANSI), Illuminating Engineering Society of North America (IESNA), and the CIE (International Commission on Illumination). International Standards Organization (ISO), Committee on Earth Observation Satellites (CEOS), and DOE/EPA Energy Star Program.

Specific Projects that Implement Overarching Strategic Elements.

On the following pages, key projects are highlighted together with their goals and milestones. The project titles include the number of the strategic element that it supports. Many of the projects are interrelated and even share milestones. The Satellite Calibration Project and Stellar Calibration Project provide one example of the interrelationship of the projects. Both of these projects require the calibration of optical sensors that typically consist of a telescope, spectrometer or optical filters, and a focal plane array. Also, advancements in stellar calibration will improve the ability of satellite sensors to use stars for calibration and tracking of sensor degradation.

Satellite Calibration (Elements II, III)

Goal: Provide the measurement science and standards to ensure that satellite measurements of the Earth's infrared and optical radiation meet the stringent requirements for climate-change science, weather forecasting, and other applications.

Overview: Climate measurements require high accuracy, excellent comparability, and exceptional quality¹ to meet the stringent requirements for detecting small changes in the Earth's climate over decadal and longer time scales. Rigorous traceability to the International System of Units (SI) is essential for meeting these requirements. The Division's leadership role in working with the satellite community to help meet these traceability requirements is well recognized and has been highlighted in the strategic plan for the U.S. Climate Change Science Program:

... Instrument calibration, characterization, and stability become paramount considerations. Instruments must be tied to national and international standards such as those provided by the National Institute of Standards and Technology (NIST)...²

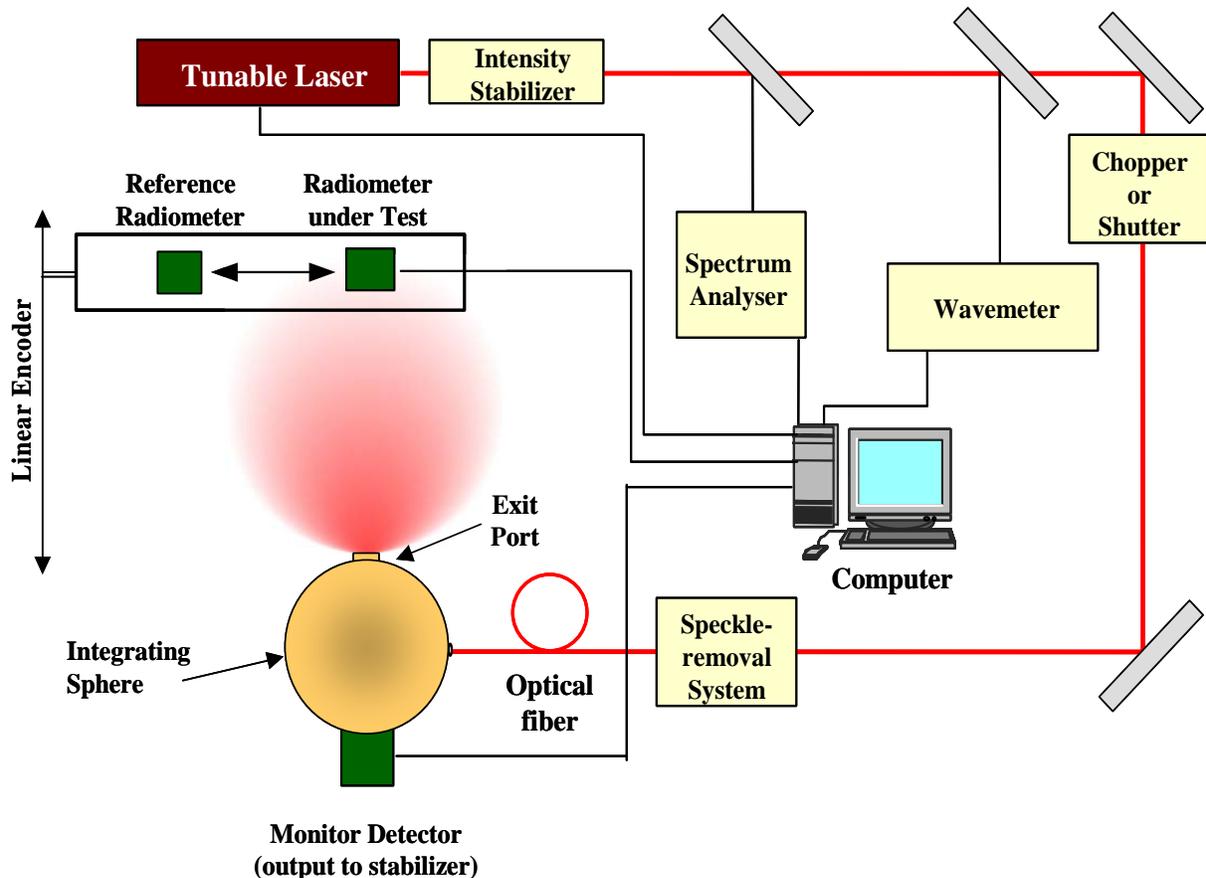


Figure 1. Schematic diagram of the Spectral Irradiance & Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) Facility at NIST

This role is unique among the various government agencies involved in climate change: NASA, NOAA, DOE, USGS, EPA, USDA, and NSF. Moreover, this role is aligned with the Division mission and core

¹ Measurement quality refers to all of the supporting evidence that support measurement accuracy claims.

² Strategic Plan for the U.S. Climate Change Science Program, <http://www.climatechange.gov/Library/stratplan2003/default.htm>.

competencies in infrared and optical radiation measurement science, and is the foundation for the FY 2009 NIST Initiative in Climate Science. Various government agencies and their satellite, air, and ground-based remote-sensing programs partner with NIST to establish the accuracy, comparability, and quality of their measurements. This partnership helps ensure the greatest benefit from our Nation's multi-billion dollar investment in satellite remote sensing by establishing the foundation for measurements which are tied to international standards and are comparable independent of launch organization and time.

Past, present, and future satellite programs that have partnered or are presently partnering with the Division in this area include NPOESS, GOES-R, EOS, LDCM, SeaWiFS, DSCOVR, and CLARREO. Two of these programs, NPOESS and GOES-R, are led by the Department of Commerce and have both weather and climate missions. Within these partnerships, the Division helps establish measurement, calibration, and traceability requirements; participates in instrument reviews; calibrates and characterizes satellite components, sensors, and calibration sources; trouble shoots measurement issues as they arise; and organizes community workshops to address characterization and calibration issues.

The Division develops, maintains, and advances specialized facilities critical to the satellite sensor community to provide component and system-level characterization for satellite sensors. Facilities that serve the satellite sensor community include the Remote Sensing Laboratory (RSL), Spectral Irradiance & Radiance Responsivity Calibrations with Uniform Sources Facility (SIRCUS and Traveling SIRCUS), Aperture Area Measurement Facility (AAM), Facility for Spectroradiometric Calibrations (FASCAL and FASCAL II), Spectral Comparator Facility (SCF), Advanced Infrared Radiometry and Imaging Facility (AIRI), and Fourier Transform Infrared Spectrophotometry Facility (FTIS).

Key Milestones

- Develop and demonstrate system-level, end-to-end and spectral responsivity calibrations for near-infrared to ultraviolet Earth-remote sensing satellite instruments, including VIIRS and TSIS, using Traveling SIRCUS.
- Build a new facility for the accurate and rapid measurement of the reflectance of materials from 200 nm to 2.5 μm as a function of illumination and viewing angles, polarization, and illuminated area to support measurement of the Earth's albedo and for the characterization of optical components used in satellite sensors.
- Establish the Controlled Background Spectroradiometry and Spectrophotometry System (CBS3) Facility for the primary realization of spectral radiance, radiance temperature, spectral hemispherical-directional reflectance, and spectral directional emittance in the far and mid infrared from 2.5 μm to 100 μm for the calibration and characterization of materials and blackbody sources at target temperatures from 180 K to 520 K and radiation background temperatures from 80 K to 320 K relevant for airborne and spaceborne sensors such as CLARREO.
- Realize a full infrared version of Traveling SIRCUS using near-infrared lasers and/or interferometers.
- Demonstrate the application of the Hyperspectral Image Projector to the calibration and characterization of Earth remote sensing instruments.
- Provide calibration support, optical component measurements, and transfer standards to NOAA, NASA, USGS, and DOD satellite programs, including sensors on NPOESS, NPP, LDCM, GOES-R, SBIRS, CLARREO, Glory, DSCOVR, and ACE..

Stellar Calibration—NIST Stars (Elements I, II, III)

Goal: Establish a set of SI-traceable standard stars accurate to better than 0.5 % ($k = 1$) from the near infrared to the ultraviolet for the absolute calibration of ground and space-based optical sensors.

Overview: Present standard stars are too inaccurate (2 % to 5 %) for important defense, civilian, and science applications in Earth sciences; weather, climate, and astronomical satellite calibration; atmospheric monitoring; fundamental physics, astronomy, and cosmology; astronomical surveys; and missile defense. For example, physicists and astronomers attempting to answer one of the most important question in fundamental physics, “What is Dark Energy?”, require photometric measurements of type 1a supernovae from the infrared to the ultraviolet to better than 1 % to allow accurate construction of the Hubble diagrams used to constrain the cosmological constant in the standard model of cosmology.

Present stellar calibrations are all tied to measurements performed on the star Vega in the 1970s. These measurements were calibrated using Cu freezing-point blackbody standards. A telescope-spectrometer combination was first calibrated by viewing the radiation from the blackbody in the far field along a horizontal atmospheric path. The calibrated telescope-spectrometer was then pointed skyward through a vertical atmospheric path to view Vega. Modeling was used to correct for atmospheric extinction differences between the horizontal and vertical atmospheric pathlengths.

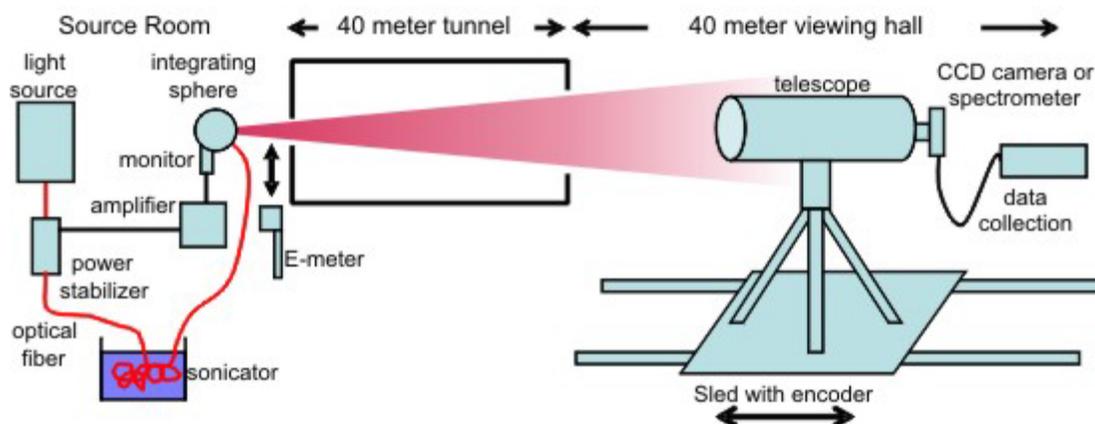


Figure 2. Schematic diagram of the laboratory Telescope Calibration Facility (TCF).

Over the last 30 years significant advances have been made in stellar atmospheric models, Earth atmospheric measurements and models, stray-light analysis, and optical radiation measurements and standards. These improvements are motivating the present effort to improve the calibration of standard stars relative to NIST SI-based standards, with a goal of 0.5 % ($k = 1$) relative uncertainty for top-of-the-atmosphere stellar fluxes from the near-infrared through the visible.

The NIST Stars Program, funded under the Director’s Innovations in Measurement Science Program, will develop methods to calibrate telescope-spectrometer systems using absolutely calibrated optical radiation standards based on tunable and supercontinuum lasers and other light sources. The atmospheric extinction from aerosols and water vapor of the stellar radiation along the line-of-sight between the telescope and the star will be quantified using LIDAR and high-resolution visible-to-infrared spectrophotometry. The results will be validated through comparisons of measurements made from various telescopes, calibrated against different optical radiation standards, and obtained under a variety of atmospheric conditions.

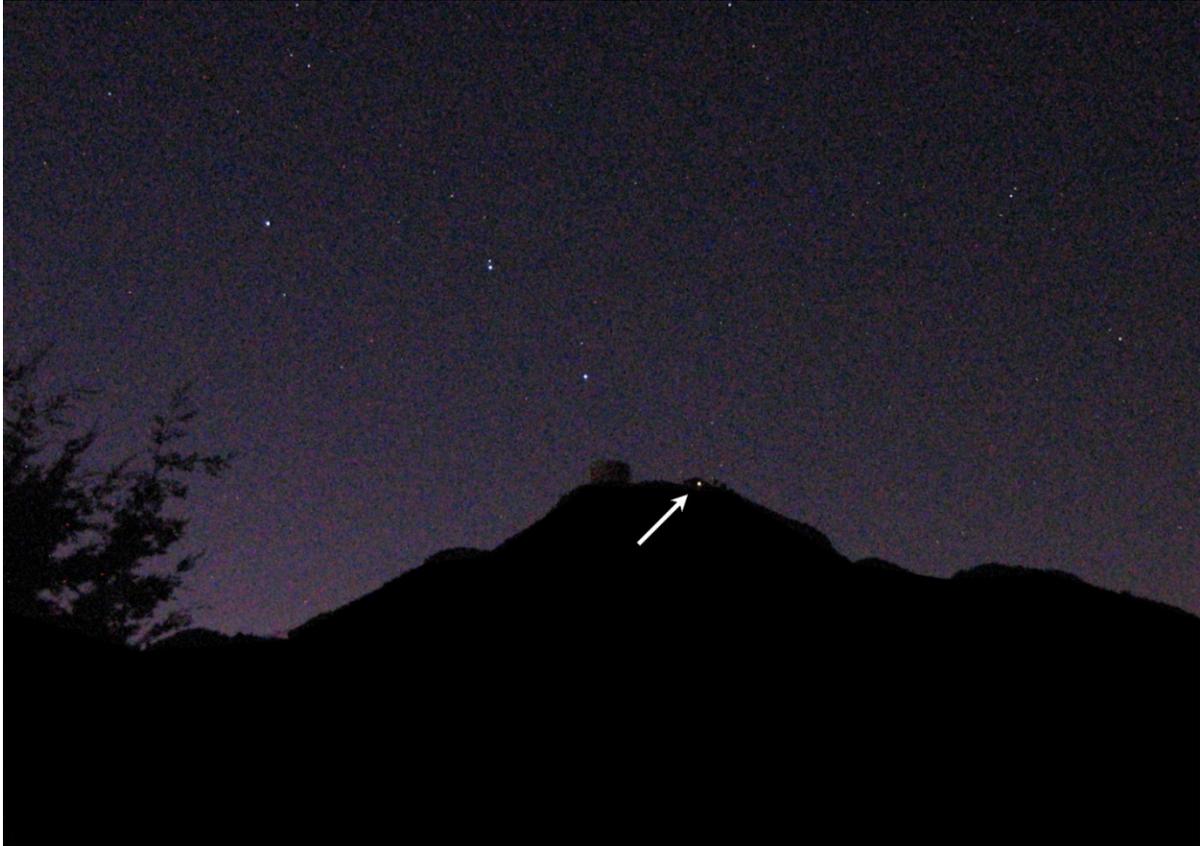


Figure 3. View of the summit of Mt. Hopkins showing the light from a NIST lamp-illuminated integrating sphere radiometric standard that mimics a star with an apparent magnitude of 2.

Key Milestones:

- Develop a Telescope Calibration Facility (TCF) at NIST for laboratory testing and evaluation of telescopes and telescope calibration methods.
- Construct a stable reference telescope-spectrometer system for the spectral flux calibration of standard stars.
- Develop spectral optical radiation standards for the far-field calibration of telescopes capable of near-horizontal lines of sight.
- Deploy a reference telescope-spectrometer system and optical radiation standards at Mt. Hopkins Observatory in Arizona.
- Implement a LIDAR system and a high-resolution near-infrared to ultraviolet spectrometer at Mt. Hopkins Observatory for measurement of atmospheric extinction.
- Demonstrate methods for the accurate at-aperture relative calibration of large observatory telescope systems with demonstration on the Pan-STARRS telescope in Haleakala, Hawaii.
- Develop and implement methods to improve the absolute calibration of rocket, balloon, and space-based telescope systems, include CIBER and ACCESS.
- Leverage the above milestones to realize a set of standard stars referenced to NIST standards to 0.5 % ($k = 1$) accuracy relative to the SI system of units.

Solid-State Lighting (Elements II, III)

Goal: Provide the measurement science and standards to accelerate the development and commercialization of solid-state lighting and realize the promise of improved energy efficiency and reduced greenhouse-gas emissions.

Overview: Solid-state lighting promises increased energy efficiency, reduced greenhouse-gas emissions, flexible spectral and spatial lighting output, smaller fixture size, and near elimination of maintenance costs. A Department of Energy (DOE) study concludes that widespread acceptance of solid-state lighting technology will reduce lighting energy usage by one third, with concomitant reduction in greenhouse gas emissions and annual cost savings of \$30 billion by 2027. The promise of solid-state lighting is now being realized with the recent introduction of general purpose and architectural lighting products.



Figure 4. Examples of some solid-state lighting sources.

The Division, in partnership with DOE, is leading the development of measurement methods, measurement services, and documentary standards for the quantification of the brightness, color quality, and energy efficiency of solid-state lighting components and fixtures. The Division has expanded its measurement capability in the area of light-emitting diodes (LEDs), the primary component of solid-state lighting fixtures. Measurements of LEDs are challenged by their extreme temperature sensitivity and their narrow spectral output, both of which vary with device tested. Industry researchers advancing solid-state lighting devices need accurate and reproducible measurements to assess the small incremental gains in light output realized in LED advances. They also require standard test methods that consider the high temperatures experienced by LEDs during operation in solid-state lighting products. Presently, NIST calibration services for solid-state-lighting products are the primary source of standards for use by industry for assessing lighting performance. NIST is leading the development of standard test methods for solid-state-lighting products (e.g., IESNA LM-79-08), and will be expanding this effort to cover high-power LEDs.

The spectral output of solid-state lighting differs significantly from standard incandescent and discharge lamps and thus many traditional lighting standards are not applicable to solid-state lighting. To aid researchers in the development of appropriate white-light sources using combinations of various LEDs with or without phosphors, the Division has proposed a new color-rendering index for use as an international

standard to more accurately quantify lighting performance. The NIST standard demonstrates that careful consideration of color rendering issues can significantly improve the efficiency of solid-state lighting by leveraging the narrow spectral bandwidths of LEDs to minimize radiation in unnecessary spectral regions. The potential impact for the new NIST standard is large due to the expected market size and promised energy savings for solid-state lighting. NIST has also led the development of a chromaticity standard for solid-state lighting products (ANSI C78.377-2008) and is continuing research in standards related to color quality of solid-state lighting (SSL) products using the new Spectrally Tunable Lighting Facility.



Figure 5. The Division’s Spectrally Tunable Lighting Facility consists of two room-size, furnished cubicles in which observers can be completely immersed in a real-life setting. Each cubicle is lit by 1,800 variable-power LEDs under computer control. The LEDs span the visible spectral range and can be set to simulate the spectra of various types of light sources for testing and optimizing using vision-science methods.

In this facility, vision science experiments are being conducted to better understand the effects of chromaticity, color rendering, and other aspects of spectra on lighting quality and to test and optimize the new NIST color-rendering index. The results of these experiments will provide the measurement foundation for a new international standard for color-rendering index.

Key Milestones:

- Develop expanded calibration services to meet the needs of the LED/SSL industry, including making available new types of spectral standard lamps and high-power standard LEDs.
- Complete a new CIE standard to replace the obsolete Color Rendering Index.
- Propose a revised ANSI chromaticity standard C78.377 based on vision experiments using the NIST Spectrally Tunable Lighting Facility.
- Collaborate with IESNA and CIE to develop new standard test methods for high-power LEDs.
- Conduct round-robin and bilateral proficiency testing for NVLAP applicants seeking accreditation for solid state lighting products.
- Quantify the temporal response of the human visual system to facilitate the development of flickering standards for solid-state lighting products.

Optical Properties of Materials (Elements I, II, III)

Goal: Provide the measurement science, modeling, data, and standards infrastructure to meet the needs for accurate optical properties of materials in the terahertz, infrared, visible, and ultraviolet by industry, government, and academia for research, regulation, defense, and commerce.

Overview: Optics plays a critical role in our lives, as vision is the most far reaching of our senses and attempts to exploit, automate, and improve upon it abound. The optical properties of materials, ranging from reflectance, transmittance, scattering, emissivity, and refractive index, thus govern the choice of materials in a wide range of industries, research, and defense. The design of an optical instrument, whether it is a telescope to peer into the earliest moments of the universe or a digital camera intended to capture family outings, requires knowledge and standards for the optical properties of its component materials. In critical applications, where stray light must be minimized, not only those properties of the image forming mirrors and lenses, but also the supporting and baffling materials, need to be known, and tolerances on contamination levels need to be placed. Optical properties of materials also include color and appearance attributes that play a critical role in a large fraction of consumer purchasing decisions and are important in transportation and occupation safety. Scene modeling, required for simulation, optical signature analysis, or remote sensing, requires knowledge of these properties for the diverse range of materials expected to be encountered. Process control and material inspection in a wide variety of industries is performed optically, because such methods are relatively inexpensive, have high throughput, and do not contact the materials being evaluated, but require advanced understanding of how material properties affect their optical properties. For most of these applications, extending the spectral range beyond the visible further extends optical applications by probing specific physical and chemical properties of interest.



Figure 6. The Goniometric Optical Scatter Instrument is used to measure scattering and diffraction from materials in the visible and ultraviolet, is optimized for using laser sources, small targets, and low scattering levels, and is capable of handling industry-relevant 300 mm diameter wafers.

The Division has established state-of-the-art capabilities to predict, measure, and interpret optical properties of materials in the THz, infrared, visible, and ultraviolet regions of the electromagnetic spectrum. Such measurement and modeling capabilities include the following:

- A surface color measurement laboratory to provide accurate measurements in the $0^\circ/45^\circ$, directional-hemispherical, and bidirectional geometries.
- A variety of instruments to perform bidirectional reflectance measurements using laser and broadband sources, spanning wavelengths from 200 nm to 10.6 μm .
- A variety of instruments to measure spectral reflectance and transmittance covering the range from 200 nm to 50 μm .
- A variety of instruments that measure the diffuse reflectance, covering the range from 200 nm to 18 μm .
- Instruments that measure the spectral emittance (emissivity), covering the range from 1 μm to 20 μm , over temperatures from 20 $^\circ\text{C}$ to 900 $^\circ\text{C}$.
- Terahertz reflectance and transmittance measurements spanning 80 μm to 5 mm.
- A spectroscopic ellipsometer optimized for measuring small nano-grating targets.
- Extensive modeling capability for optical scattering and diffraction, with codes distributed publicly through the SCATMECH library.
- *Ab initio* calculations of the dielectric functions of crystalline materials.

Key Milestones:

- Expand infrared capabilities to include low-spectral-resolution, variable-angle, directional-hemispherical reflectance measurements to 14 μm ; high spectral resolution, temperature-dependent reflectance and emittance measurements to 50 μm ; and out-of-plane BRDF measurements at 10.6 μm .
- Build a new facility for the accurate and rapid measurement of the BRDF of materials in the reflected solar band from 250 nm to 2.5 μm for the calibration of standards used in the measurement of the Earth's albedo and for the characterization of optical components used in satellite sensors.
- Advance terahertz time- and frequency-resolved spectroscopies for the characterization of solar cell photovoltaic thin films, nano-layer metal-oxide insulators, aqueous and crystalline-phase biomolecular samples, and steel-reinforced concrete.
- Expand capabilities for measuring surface color to include a calibration service in the $0/d$ (normal incidence/diffuse reflectance) geometry and measurements of the spectral fluorescence from colored samples, a major contributor to the uncertainty in color measurements for many materials.
- Develop artifact and documentary standards and modeling software³ for improving the characterization of nano-gratings by optical scatterometry, needed by the nanoelectronics industry for process control and monitoring.

³ The software effort refers to extension of the SCATMECH library to include efficient codes for calculating the diffraction from two-dimensional periodic gratings. SCATMECH is described at <http://physics.nist.gov/Divisions/Div844/facilities/scatmech/html/index.htm>.

Optical Medical Imaging (Elements II, III)

Goal: Develop the measurement science infrastructure to improve the utility and comparability of optical medical imaging measurements for surgical and clinical applications.

Overview: The Division is advancing the measurement science and standards infrastructure to accelerate the application of optical medical imaging for surgical and clinical applications. The effort is funded by the NIST Director's Innovations in Measurement Science Program and consists of two overarching technical goals:

- Provide standard, well-calibrated hyperspectral images of normal and diseased tissues to aid the development and demonstration of algorithms for quantifying disease and tissue status
- Develop advanced SI-traceable calibration and characterization technology and standards to assess and improve medical imaging instrument performance

Optical medical imaging could complement and enhance conventional medical imaging modalities, including MRI, CT and PET-CT, which are too expensive for routine use and too complex and slow for surgical applications. By avoiding radiation exposure, optical medical imaging allows continuous monitoring during protracted surgical procedures and long-term monitoring for assessing treatment efficacy and disease progress. Optical medical imaging is of interest for regular clinical examinations as well as surgical, endoscopic, and laparoscopic procedures, and the present state of optical technology makes it both fitting and timely to strive to enlist optical medical imaging into the suite of tools used in medical practice.

Image Decomposition - Visible

Classification according to components spectra

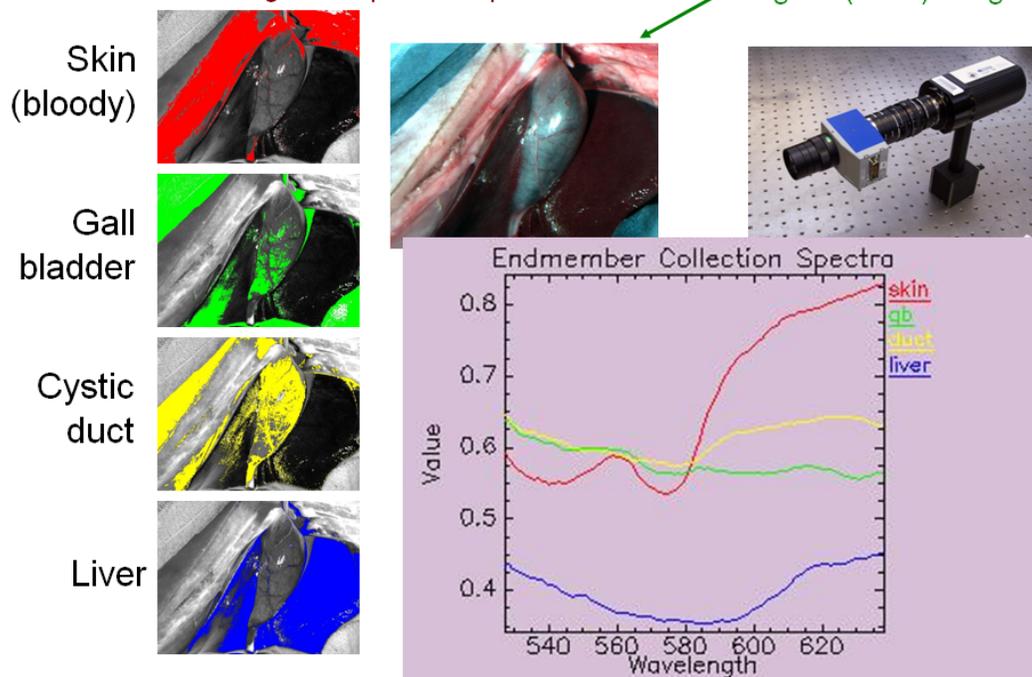


Figure 7. Application of hyperspectral imaging to the identification of different tissue types during a cholecystectomy (gallbladder surgery). During such surgery it is essential to avoid damage to the cystic duct, which resembles nearby tissues under ordinary visual inspection. (Original RGB image courtesy of Karel Zuzak, University of Texas at Arlington.)

The Division program in optical medical imaging is initially concentrating on hyperspectral imaging, which shows great promise due to its broad spectral coverage and high spectral resolution. Hyperspectral imaging has successfully demonstrated robust instrument designs and data-processing algorithms in environmental and defense remote sensing. Hyperspectral optical medical imaging could potentially measure tissue status in the early stages of disease progression, because of its high spatial and spectral resolutions. Hyperspectral imaging passively measures infrared and optical light reflected or emitted from tissue, expanding the three-component palette native to human vision to hundreds of contiguous wavelength bands, significantly enhancing the potential for medical diagnosis and treatment.

In collaboration with clinical partners, the Division will acquire high-fidelity images of tissues in surgical and endoscopic procedures. Of particular interest are images of chronic wounds to quantify oxygenation levels, of esophaguses for diagnosis of precancerous dysplasia, of kidneys prior to transplant to assess viability, of skin burns to grade severity, of skin lesions for cancer detection, of cancer margins during surgery, and of retinal images for diagnosis of histoplasmosis. Initial images will be of animal tissues, such as porcine kidneys, gallbladders, and would. These images would be available by leveraging ongoing preclinical animal trials at NIH and elsewhere. This approach will help establish measurement protocols prior to clinical trials.

The SI-traceable datacubes that are collected would aid the establishment of the SI-traceability of OMI instrumentation by using hyperspectral image projector (HIP) technology already under development in the OTD for remote-sensing work. A HIP-rendered datacube would be a type of digital tissue phantom. Whether it is used for instrument calibration or for examination on a computer screen by a medical practitioner prior to a procedure, the datacube can be accurately rendered by accounting for the anticipated illumination conditions. Such examination of a medical scene could conversely be used to optimally plan the tuning of the illumination source in advance of a procedure.

As of now, we have already demonstrated the viability of HIP projection and recollection of hyperspectral datacubes in the context of aerial images of coral reefs. Furthermore, the full spectral content of datacubes allows their subsequent examination to be used in combination with tissue assays and chemical analyses to correlate what can be observed optically with the disease state of tissue. While the SI-based calibration and characterization strategy will be based on synthetic, radiometrically accurate scenes projected by the HIP, we naturally anticipate that the virtual tissue phantoms will still be complemented by artifact phantoms that realistically mimic tissue optical properties.

Key Milestones:

- Realize an absolute scale for *in vivo* oximetry of serum and tissue based on statistical correlation of hyperspectral datacubes with *in vitro* chemical assays in a controlled environment that is transferrable to the clinic because of the richness of hyperspectral data.
- Collect hyperspectral datacubes of medical images from a myriad of laboratory and clinical environments to permit optimization of tunable light sources to achieve the best feasible illumination conditions in the corresponding settings.
- Ensure robust scientific practice in the analysis of optical medical images by establishing the baseline for natural inter-patient variability and deducing the thresholds of contrast in signals in data that are statistically significant.

Radiometric and Photometric Fundamental Standards (Elements I, III)

Goal: Maintain, disseminate, and advance fundamental radiometric and photometric standards with the lowest uncertainties relative to the SI system of units to support research, development, regulatory requirements, manufacturing, and trade.

Overview: The Division has developed state-of-the-art capabilities to maintain and disseminate fundamental standards for the measurement of optical radiation, including for two of the seven base SI units, the kelvin above the freezing point of silver at 1234.93 K and the candela. The Division's optical radiation measurements are primarily tied to the cryogenic radiometer, an electrical substitution radiometer which compares the electrical watt to the optical watt. The Division's primary cryogenic radiometer is called POWR for Primary Optical Watt Radiometer. The state of the art of cryogenic radiometer presently limits the accuracy of optical-power related measurements such as irradiance (W m^{-2}) and radiance ($\text{W m}^{-2} \text{sr}^{-1}$) to approximately 0.01 % ($k = 1$) and of temperature at the silver freezing point (1234.93 K) and above to approximately 25 mK. ($k = 1$) Measurements of the areas of optical apertures that define the distance and angular units in irradiance and radiance quantities have uncertainties of approximately 0.005 % ($k = 1$). The Division also provides ultraviolet radiation standards tied to absolute ultraviolet radiation levels provided by the NIST Synchrotron Ultraviolet Radiation Facility, denoted by SURF III.

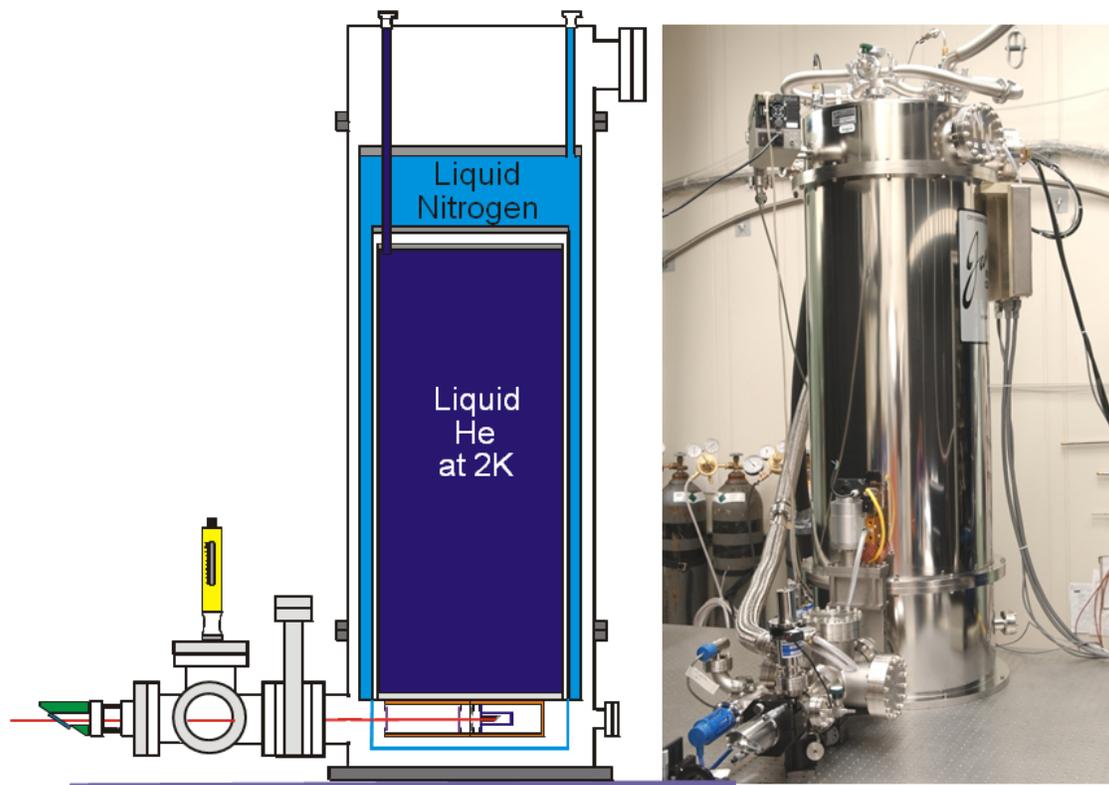


Figure 8. Schematic diagram and photograph of the NIST Primary Optical Watt Radiometer (POWR), the National standard for optical power responsivity.

The Division disseminates radiometric and photometric standards through a variety of Measurement Services that include the following:

- Luminous Intensity and Color Temperature Standard Lamps
- Spectroradiometric Source Measurements
- Spectral Radiance or Spectral Irradiance Lamps
- Spectral Radiance Integrating Sphere Sources
- Silicon Photodiode Detectors
- Pyrometers/Radiation Thermometers
- Tungsten Strip Lamps
- Blackbody Sources
- Radiative Heat-Flux Sensors

The Division has also developed state-of-the-art techniques to extend its radiometric measurement capabilities to levels appropriate for photon counting detectors and sources. Photon counting methods are growing in importance due to the burgeoning fields of quantum information and quantum communication, which rely on single-photon generation and detection. While typical radiometric standards operate best in the milliwatt or fraction of the milliwatt level, photon counting detectors typically saturate at a few to 10 million photons/s, which corresponds to pW or smaller power levels in the visible spectral region. Recently, measurements in this low-power regime were made in the Division with uncertainties at the 0.2 % ($k = 1$) level or better, the lowest uncertainty yet achieved with photon-counting methods.

Milestones

- Develop a formal measurement service with a quality system for aperture area, a measurement critical to the accurate development of radiance and irradiance measurement instruments.
- Develop a new Radiance and Radiance Temperature facility to improve the dissemination of NIST radiometric scales for spectral radiance and radiance temperature from the near infrared to the ultraviolet.
- Develop and disseminate standards for use in the photon counting regime that give the user community direct access to measurements with 0.5 % ($k = 1$) uncertainties or better.
- Research alternative radiometric standards beyond FEL lamps and integrating spheres to reduce the uncertainty in NIST spectral radiance and spectral irradiance Measurement Services by an order of magnitude.
- Advance the state-of-the-art of transfer and working standard radiometers in the near infrared and short-wave infrared to achieve performance levels similar to the performance of silicon detectors in the visible.
- Development new detector/radiometer calibration facilities to disseminate near-infrared and short-wave infrared detectors at the above performance levels.
- Extend the spectral range of the NIST Spectral Comparator Facility to 100 μm to meet the requirements for climate remote sensing, defense, and other applications.

Optical Standards for Defense and Homeland Security (Elements II, III)

Goal: To develop and disseminate the critical measurement science and standards required for our Nation's defense and homeland security.

Overview: The Division provides standards, calibrations, and expertise in optical radiation measurement to support our Nation's defense and homeland security. The Division also develops specialized measurement facilities in response to National needs in defense and homeland security. Such facilities include the Low-Background Infrared (LBIR) Facility, the premiere facility for the measurement of low-levels of infrared radiation from a blackbody source against low-levels of thermal background radiation intended to mimic the thermal background level of space. The LBIR facility was developed and expanded over a period of some 15 years in a partnership with the Missile Defense Agency (MDA) and the Calibration Coordination Group (CCG) of the Department of Defense.

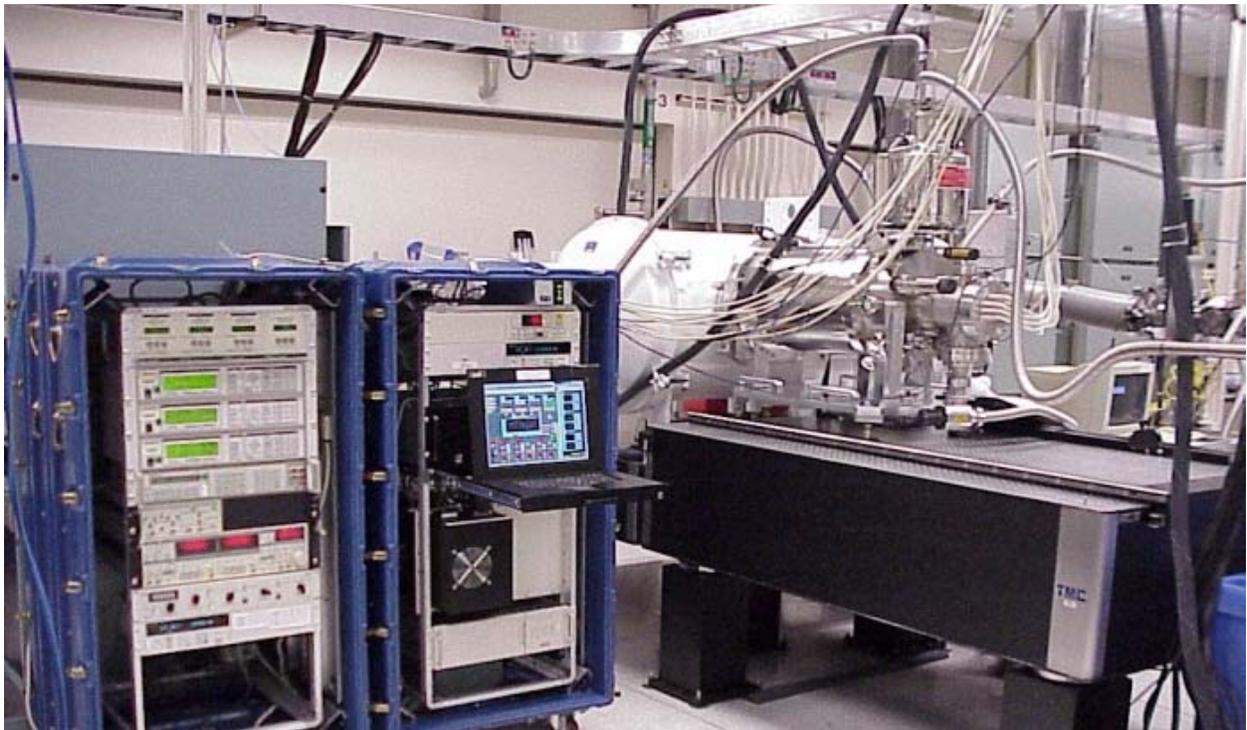


Figure 9. The BXR (BMDO Transfer Radiometer), an asset of the LBIR Facility, pictured during a deployment at Raytheon.

The range of optical measurement and standards needs within the defense and homeland security communities are broad, with recent Division efforts including the following:

- Leadership of an infrared reflectance intercomparison within the DOD community that included 21 participants with a goal to assess and improve the quality and accuracy of infrared measurements in support of signature measurement and modeling.
- Development of a draft government standard for the certification of the performance of directed infrared countermeasure systems (DIRCM) for the protection of civilian aircraft against heat-seeking shoulder-fired missiles called MANPADS for man-portable air-defense system.

- Measurement of the optical properties of standard fabrics over the spectral range extending from the far-infrared/THz to the ultraviolet to support the development and assessment of technology to detect improvised explosive devices (IEDs) hidden on individuals.
- Development of standard measurements for characterizing coatings with fluorescent additives used by the Navy in corrosion prevention programs.
- Advancement of the Hyperspectral Image Projector into the infrared for application to the calibration and characterization of hyperspectral imagers.
- Development of the Missile Defense Transfer Radiometer (MDXR) a cryogenic Fourier-transform absolute radiometer, to provide spectral calibrations to the Missile Defense Agency (MDA) through the LBIR Facility.



Figure 10. Set of reflectance standards used in a NIST-led intercomparison involving DoD and its contractors.

Key Milestones:

- Development of in-house and transfer calibration standards for the measurement of femtowatt levels of infrared radiation.
- Deployment of the Missile Defense Transfer Radiometer (MDXR) to government and contractor sites supporting the Missile Defense Agency (MDA)
- Determination of the microwave electro-optical properties of missile radome materials (i.e., radar viewing window) from terahertz measurements and models.
- Development of broad-band ultraviolet calibration methods and standards for non-destructive tests in military applications.
- Development of SI traceable calibrations for night-vision goggles.
- Transfer of the Hyperspectral Image Projector (HIP) technology to the DoD
- Development of measurement methods and standards to quantify the body coverage factor for whole-body imagers.

Greenhouse Gas Measurements (Element II)

Goal: Develop the optical measurement technology, standards, and testbeds for the accurate quantification of greenhouse-gas emissions from natural and anthropogenic sources and sinks to meet the requirements for local, national, and international mitigation efforts.

Overview: Methods to accurately quantify the emission and absorption of greenhouse gases from natural and anthropogenic sources are required to ensure accurate and complete greenhouse gas inventories and consistency of bottom-up inventory approaches with top-down atmospheric concentration measurements. The need for such methods for climate research and greenhouse gas mitigation is generally recognized, leading to new Division funding for optical measurement and standards in this area through the NIST FY 2009 and FY 2010 initiative process. The Division effort is collaborative with several of the NIST Laboratories.

The measurements are challenged by the need to measure fluxes of greenhouse gases from or to the source or sink. Sources and sinks cover a range of spatial and temporal scales and include factories, landfills, farms, forests, wetlands, and oceans. Ideally, such measurements would be standoff, i.e., made without actually requiring placing instruments on the site since the terrain might not be easily or safely navigated. Such standoff systems are also important for the validation/verification of claimed emissions levels by factories. A standoff system would allow interrogation of a plume from beyond a factory fence lines, or outside of a country's border if satellite based.

Extent of the Quantitative GHG Emission Reduction and Verification Challenge

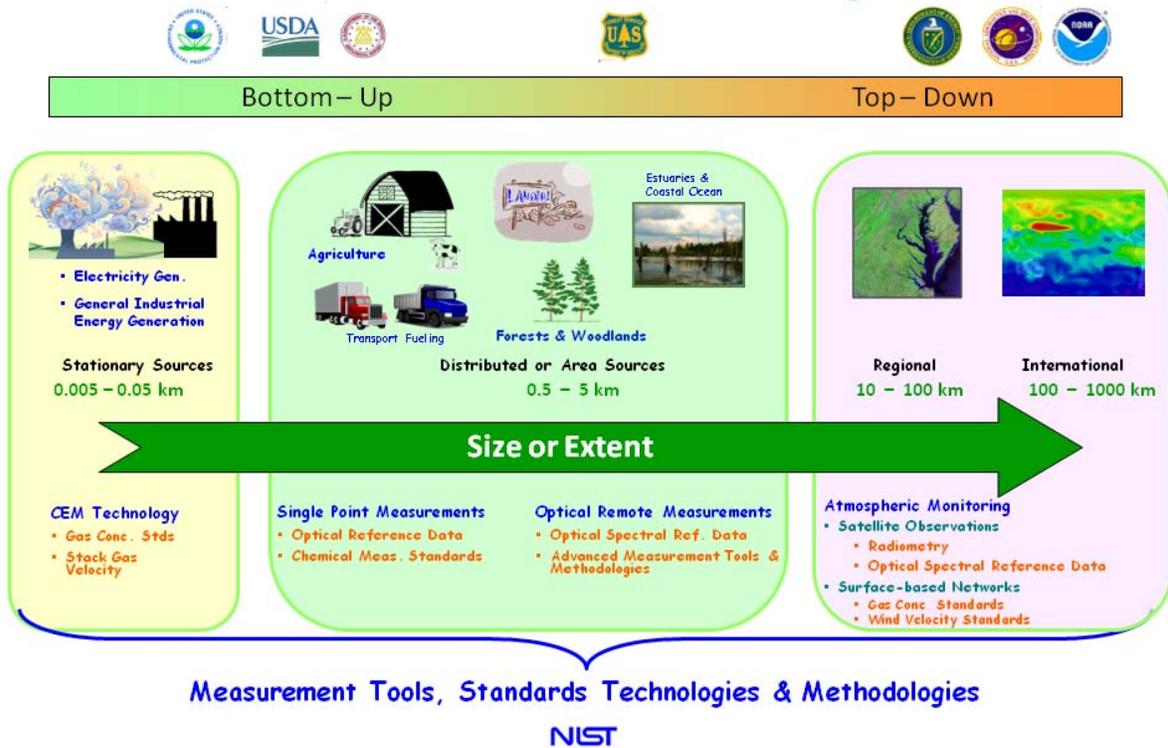


Figure 11. Range of scales for Greenhouse Gas Measurements.

Within the larger NIST Greenhouse Gas Program, the Division is exploring laser and hyperspectral imaging methods for standoff detection from point and large area sources.

Key Milestones:

- Determination of the strategy and requirements and selection of partners for the development of an accurate, field-deployable Differential Absorption LIDAR (DIAL) system for simultaneous GHG velocity and concentration measurements for spatial scales of 1 km² to 9 km².
- Demonstration of prototype DIAL instrument using a long-pathlength indoor test range.
- Assessment of mathematical models to invert DIAL, long-pathlength absorption, and multiple point measurements together with meteorological measurements for the determination of GHG fluxes. Effort includes a NIST-led intercomparison of models and measurement methods within the community.
- Development of indoor and outdoor test ranges for validating and establishing traceability of emissions measurements, retrieval algorithms, and uncertainties.
- Spectroscopic measurements of discrete and continuum absorption of water vapor to improve the quantification of greenhouse gases from ground and satellite based optical sensors.
- Benchmark atmospheric measurements with well characterized atmospheric pathlength to assess standard atmospheric models used by the community for horizontal columns.
- Development and assessment of hyperspectral imaging for the standoff quantification of emissions from smokestacks and other point sources to validate claimed emissions levels.

Single-Photon Metrology tools for Quantum Information and Quantum Measurement (Element II)

Goal: Develop advanced single-photon metrology (single-photon sources, detectors, and processors) to enable quantum-information applications and quantum-enabled measurement.

Overview: Single-photon metrology is important for the advancement of quantum information science, including quantum computing, quantum communication, and quantum enhanced sensing. These subfields of quantum information are expected to revolutionize science and technology:

- Quantum computing has the potential to extend the Moore's law progress in computation beyond the physical limits set by conventional semiconductor technology that will soon be reached as feature sizes approach atomic scales. Additionally, quantum computing promises an exponential increase in computing power over current classical computers, enabling solutions of new classes of problems presently intractable.
- Quantum communication has the potential to advance communication security by making it impossible to eavesdrop without being detected. Quantum communication offers security based on physical principles rather than on computational difficulty so that information protected by encryption will not be susceptible to any future advances in computational capabilities.
- Quantum sensing by the direct counting of photons that may be in non-classical states has the potential to improve measurement sensitivity and resolution. For example, the phase sensitivity of an interferometer can be made to vary as the photon number times the wavelength rather than as the wavelength, leading to significant increase in sensitivity even for detected states consisting of only a few photons.

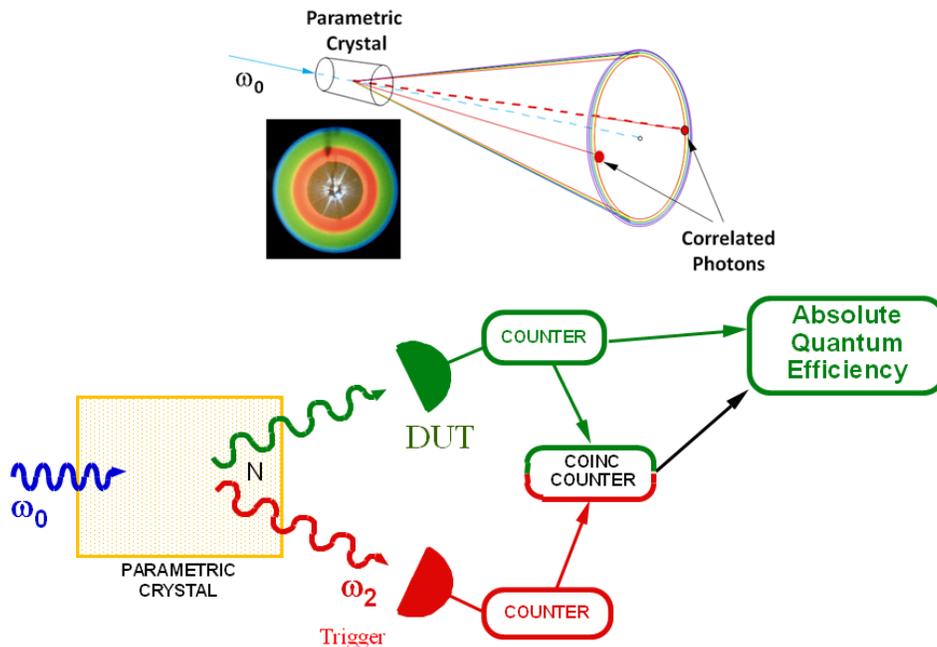


Figure 12. Correlated photons produced using parametric down conversion and their application to determining the absolute response of a detector under test (DUT).

The Division's effort in single-photon metrology is based on extensive research using nonclassical light sources to produce correlated photons: parametric downconversion in nonlinear crystals, as shown in the figure above, and four-wave-mixing in optical fibers. These sources produce correlated photon pairs for application in heralded single-photon sources and in entangled photon-state sources. Efforts at improving these sources include optimizing the pumping geometry, engineering the crystal by periodically poling the crystal's nonlinear coefficient, using crystal waveguides, and exploring the effects of fiber structure. These efforts have allowed the demonstration of the highest accuracy measurement to date for a detector response characterized using correlated photons (see figure). Additionally, they have led to a fiber-based source that was used to rule out a nonlocal hidden variable theory alternative to quantum mechanics.

The Optical Technology Division in collaboration with the Atomic Physics Division is using two-photon sources and high-efficiency, photon-number-resolving detectors to produce "Schrödinger-cat states," where the entanglement is in macroscopic rather than single-photon states. Because of their macroscopic nature, these states offer potential advantages in certain measurement situations where enhanced sensitivity to external fields is desired and in quantum encryption for improved detection of an eavesdropper.

Milestones

- Develop methods based on multiple detector schemes, transition-edge detectors (TES), and minimization of the duration of photo-induced avalanches in infrared avalanche photodiodes to improve the counting rate for photon events presently limited by detector recovery times, which can be as long as 10 μs for infrared avalanche photodiodes.
- Develop quantum memory and single-photon-on-demand devices based on the storage of quantum states in long-lived hyperfine levels of Pr^+ ions doped in optical crystals for applications in quantum communication and quantum computation.
- Advance the ability to couple optical and material qubits necessary for transferring quantum information between transmission and storage devices by mating a spectrally broad optical parametric down-conversion system producing photon pairs with a spectrally narrow quantum-dot system.

Biophysics, Nanobiotechnology, and Biophotonics (Element II)

Goal: Establish the optical measurement science to enable applications of nanomaterials in biological environments.

Overview: New optical measurement science, modeling, and simulation tools are being developed to enable the characterization and control of the interactions of nanomaterials with biological molecules. The ability to measure and quantify the assembly, aggregation, and transformations of nanomaterials and biomolecules is critical to realizing nanomaterials applications in medicine, energy, and the environment.

The research effort focuses on the development of the following:

- Spectroscopy and microscopy methods for studying nanoparticles and nanoparticle-biomolecule complexes to enable new nanomaterials applications and to assess the environmental, health, and safety risk associated with these applications.
- Computational tools to investigate the structure, properties, and interactions of biomolecules and nanomaterials.
- New biosensors and bioassays based on nanomaterials such as quantum dots and carbon nanotubes.

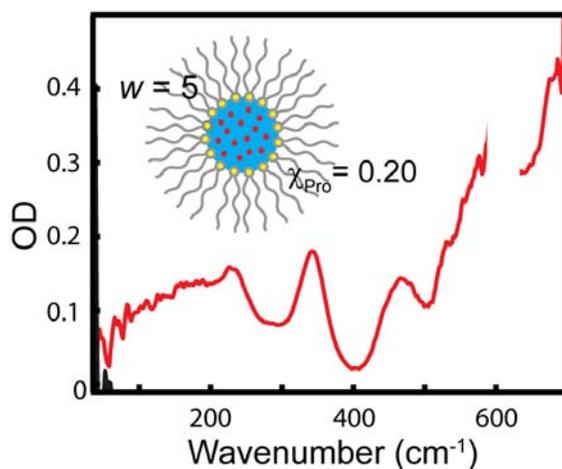


Figure 13. The far-infrared/THz spectrum of L-proline in water encapsulated in a surfactant-based reverse micelle in heptane.

The program leverages the Division's advanced capabilities in spectroscopy, microscopy, nanomaterials, imaging, and modeling, including the following:

- Expertise in the synthesis of novel monodispersed metallic nanoparticles of various sizes, shapes, and compositions.
- Tip-enhanced Raman Atomic Force Microscope (AFM) for nanoscale mapping of vibrational motions and Raman chromophores.
- Continuous-wave and pulsed THz spectrometers and imaging systems with waveguide-enhanced and aqueous inverse micelle sampling systems for studies of large-amplitude biomolecular motions.
- Time-correlated, confocal nano-spectroscopic microscopy of single and clustered nanomaterials and biomolecules
- Microscopy of photo-excited nanoparticles and related processes

- Optical tweezers and single-molecule microscopy of biomolecular interactions
- Multimodal optical microscopy of molecular dynamics and cellular processes
- Vibrationally resonant, sum-frequency spectroscopy (VR-SFS) of biomolecular structure and dynamics at interfaces.

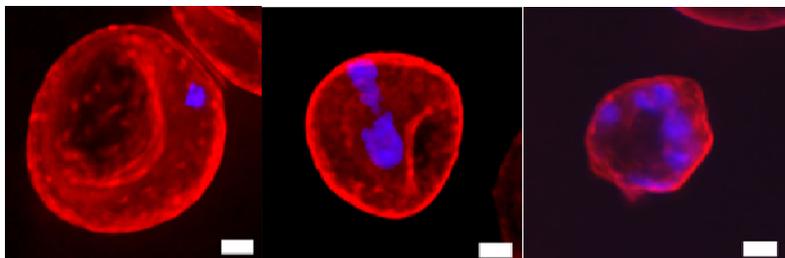


Figure 14. Membrane proteins on the surface of human red blood cells are targeted and labeled with quantum dot (QD) nanocrystal probes, revealing clustering of the proteins. The number of purple features, which are the nuclei of malaria parasites, increases as the malaria developmental stage progresses.

Milestones

- Develop time-correlated confocal hyperspectral microscopy of single and clustered nanocrystal probes for quantitative molecular imaging.
- Develop standardized quantitative methods to improve bacterial colony counting for assessing the performance of vaccines.
- Establish the essential measurement science to quantify the extent and rates of *transformation processes* of key nanomaterials in biologically relevant media through combining AFM and Raman spectroscopic measurements.
- Develop THz spectroscopy methods, peptide nanotube systems, and quantum mechanical models for investigating channel formations in cellular membranes from renegade amyloid peptides that have been hypothesized to cause cellular leakage implicated in neural degenerative diseases.
- Advance THz spectroscopic methods for investigating static and dynamic structures and interactions of amino acids, peptides, small proteins, and DNA in water using aqueous reverse micelles.
- Release well-characterized carbon nanotubes as NIST reference materials.
- Advance the application of biomolecules as molecular force standards.
- Develop techniques for rapidly acquiring high spatial resolution cell or tissue images (without sample motion) based on novel 3-D wide-field microscopic imaging using two-photon fluorescence probe microscopy coupled with holography and super-resolution techniques.

Appendix—List of Acronyms

ACCESS	Absolute Color Calibration Experiment for Standard Stars
ACE	Aerosol-Cloud-Ecosystems satellite
AFM	Atomic Force Microscopy
AIRI	NIST Ambient Infrared Radiometry and Imaging Laboratory
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit on the operational polar-orbiting satellites
ANSI	American National Standards Institute
Aqua	Also called EOS-PM1 is one of three major NASA-EOS satellites
ARM	Atmospheric Radiation Measurement (ARM) Program at the Department of Energy
AVHRR	Advanced Very High Resolution Radiometer on NOAA's POES satellites
ATMS	Advanced Technology Microwave Sounder on NPP/NPOESS
Aura	Also called EOS-CH1 is one of three major NASA-EOS satellites
BMDO	Ballistic Missile Defense Organization, renamed as the Missile Defense Agency (MDA)
BXR	BMDO Transfer Radiometer
CBS3	Controlled Background Spectroradiometry and Spectrophotometry System
CCG	DoD Calibration Coordination Group
CCPM	International Committee on Weights and Measures
CCPR	Consultative Committee on Photometry and Radiometry
CCT	Consultative Committee on Thermometry
CEOS	Committee on Earth Observation Satellites
CERES	Clouds and the Earth's Radiant Energy System on NPP/NPOESS
CIBER	Cosmic Infrared Background Experiment
CIE	International Commission on Illumination
CLARREO	Climate Absolute Radiance and Refractivity Observatory satellite under development at NASA
CrIS	Cross-track Infrared Sounder on NPP/NPOESS
CORM	Council on Optical Radiation Measurements
CT	CAT Scan, i.e., Computed Axial Tomography Scan
DIRCM	Directed Infrared Countermeasure system
DoD	Department of Defense
EDR	Environmental Data Records
EEEL	Electronics and Electrical Engineering Laboratory at NIST
EOS	Earth Observing System of satellite sensors NASA program
EPA	Environmental Protection Agency
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FASCAL	NIST Facility for Automated Spectroradiometric Calibrations
FTIS	Fourier Transform Infrared Spectrophotometry Facility
FY	Fiscal Year
GAO	General Accounting Office
GCOS	Global Climate Observing System
GHG	Greenhouse Gas
Glory	NASA satellite waiting launch which includes a sensor for total solar irradiance
GOES-R	Geostationary Operational Environmental Satellite Version R
GSICS	Global Space-based Intercalibration System
HIP	Hyperspectral Image Projector
IASI	Infrared Atmospheric Sounding Interferometer on the European MeTop satellites
IED	Improvised Explosive Device
IESNA	Illuminating Engineering Society of North America
IORD	Integrated Operational Requirements Document
IR	Infrared
ISO	International Standards Organization
ITL	Information Technology Laboratory at NIST
LBIR	NIST Low Background Infrared Facility
LIDAR	Light Detection and Ranging instrument used for measuring atmospheric aerosols

LDCM	Landsat Data Continuity Mission satellite under development
LUSI	Lunar Spectral Irradiance proposal for measuring the Moon
MANPADS	Man-portable air defense system
MDA	Missile Defense Agency
MERIS	Medium Resolution Imaging Spectrometer of the European Space Agency
METOP	Refers to the European polar-orbiting operational satellite system
MIS	Microwave Imager/Sounder on NPOESS
MOBY	Marine Optical Buoy for calibrating ocean-color satellites
MOBY-C	Next generation MOBY
MODIS	Moderate-resolution Imaging Spectroradiometer deployed on EOS-Terra and EOS-Aqua
MRI	Magnetic Resonance Imaging
MSU	Microwave Sounding Unit on the operational polar-orbiting satellites
Nano-EHS	Nanotechnology Environmental Health and Safety
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center at NOAA
NESDIS	National Environmental Satellite, Data, and Information Service at NOAA
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NIST STARS	A program to improve the absolute spectral calibration of stars.
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NVLAP	National Voluntary Laboratory Accreditation Program
OIG	Office of the Inspector General of the Department of Commerce
OLES	NIST Office of Law Enforcement Standards
OMI	Optical Medical Imaging
OMPS	Ozone Mapping and Profiler Suite on NPP/NPOESS
ORCA	Ocean Radiometer for Carbon Assessment
PML	Physical Measurement Laboratory at NIST
POES	Polar-Orbiting Environmental Systems
PPBES	Planning, Programming, Budgeting and Execution System
ROLO	Robotic Lunar Observatory ground-based observatory
RSL	Remote Sensing Laboratory
SCF	NIST Spectral Comparator Facility
SeaWiFS	Sea-viewing Wide Field-of-view Sensor ocean-color sensor
SEMATECH	Semiconductor Manufacturing Technology research consortium
SI	International System of Units
SIM	Solar Irradiance Monitor on TSIS
SIRCUS	Spectral Irradiance & Radiance Responsivity Calibrations using Uniform Sources Facility
SNO	Simultaneous Nadir Overpass used for intercalibrating satellite sensors.
SSL	Solid-State Lighting
STAR	Center for Satellite Applications and Research at NOAA/NESDIS
SURF III	NIST Synchrotron Ultraviolet Radiation Facility
Terra	Also called EOS-AM1 is one of three major NASA-EOS satellites
TIM	Total Irradiance Monitor on TSIS
TSIS	Total Solar Irradiance Sensor on NPOESS-C1
VIIRS	Visible/Infrared Imager/Radiometer Suite on NPP/NPOESS
WGCV	Working Group for Calibration and Validation under CEOS
WMO	World Meteorology Organization