

# The Spectral Irradiance and Radiance responsivity Calibrations using Uniform Sources (SIRCUS) facility at NIST

S. W. Brown, J. P. Rice, G. P. Eppeldauer, J. Houston, J. Zhang, and K. R. Lykke  
National Institute of Standards and Technology, Gaithersburg, MD, USA

**Abstract.** We describe the current status of the SIRCUS facility at the National Institute of Standards and Technology (NIST) in the U. S. Recent developments in the facility, including extension to the ultraviolet (UV) and the short-wave infrared (SWIR), are described and future directions of research are outlined.

## Introduction

Detectors have historically been calibrated for spectral power responsivity at the NIST using a lamp-monochromator system to tune the wavelength of the excitation source. Silicon detectors can be calibrated in the visible spectral region with combined standard uncertainties at the 0.1 % level. However, uncertainties increase dramatically when measuring an instrument's spectral responsivity outside the silicon range, or when measuring an instrument's irradiance or radiance responsivity. The SIRCUS facility was developed to provide low uncertainties in such calibrations (Lykke, et al.). Since then the facility has been significantly improved and expanded with added capabilities and lower uncertainties.

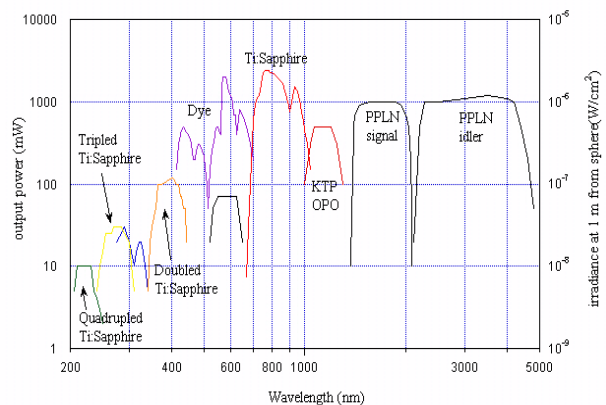
The current SIRCUS facility combines tunable lasers with cryogenic radiometers and stable working standard detectors. Reference standard detectors are calibrated for spectral radiant power responsivity against a cryogenic radiometer directly traceable to the U.S. primary radiometric standard for spectral power responsivity, the Primary Optical Watt Radiometer (POWR) (Houston, et al.). With the development of quasi-cw lasers with extended spectral tunability in the UV and short-wave IR, the spectral radiant power responsivity can be determined in these spectral regions with uncertainties approaching those achievable in the visible, silicon range. Detectors are equipped with apertures measured on the NIST aperture area facility (Fowler and Litorja), and are used to determine the irradiance at a reference plane. Knowing the measurement geometry, the source radiance can be readily determined as well.

In SIRCUS, high-power, tunable lasers are introduced into an integrating sphere using optical fibers, producing uniform, quasi-Lambertian, high radiant flux sources. Instruments can be calibrated directly in irradiance or radiance mode at the system level, with the entrance pupil over-filled. Uncertainties approach or exceed those available for spectral power responsivity calibrations over a wide dynamic range, approaching 10 decades in some applications.

## Extension of spectral coverage

The spectral coverage on SIRCUS depends on the availability of laser sources while the uncertainties achievable are based on the quality of the reference standard detectors (Eppeldauer and Lynch).

Quasi-continuous-wave sources, mode-locked picosecond and femtosecond sources with repetition rates as high as 200 MHz, have been developed to extend the spectral coverage from 350 nm to 210 nm in the ultraviolet and from approximately 1  $\mu\text{m}$  to 5  $\mu\text{m}$  in the infrared. Tunability and power curves for the laser systems currently available in SIRCUS are shown in Fig. 1.



**Figure 1.** Lasers, output power, and spectral coverage on SIRCUS.

Reference standard detectors, UV radiation-resistant Silicon (Si) detectors for the ultraviolet and Indium Gallium Arsenide (InGaAs) detectors for the short-wave infrared, have been calibrated for radiant spectral power responsivity directly against a new cryogenic radiometer (Lorenz). The cryogenic radiometer is on a portable laboratory table, enabling the system to be readily transported to the UV, visible, or IR laser setups to calibrate reference detectors for spectral radiant power responsivity.

## Applications and Future Directions

NIST primary standard radiance and irradiance detectors are transitioning from traditional calibration approaches, often source-based, to the SIRCUS facility. One example is the detector-based thermodynamic temperature scale. As discussed by Yoon et al. (2002), moving from a source-based to a detector-based spectral irradiance and radiance scale can greatly reduce the radiometric uncertainty in the measurement of higher temperature sources. Using SIRCUS to directly calibrate optical pyrometers eliminates the dependence on a blackbody and the ITS-90. Current uncertainties in radiance temperature measurements achievable by optical pyrometers calibrated on SIRCUS approach thermodynamic temperature uncertainties.

Following the re-definition of the candela in 1979,

coupling photometric and radiometric units, many national laboratories, including NIST, derive and maintain the candela and derived photometric units using calibrated standard detectors traceable to cryogenic radiometry rather than standard lamps traceable to primary standard blackbodies and international temperature scales (Ohno). The relative uncertainty for the NIST illuminance unit realized on SIRCUS is expected to be reduced approximately 40 % from the current scale. The current set of 8 NIST reference standard photometers were not calibrated in SIRCUS because large interference fringes were observed. This is a common occurrence due to the use of coherent narrow-band lasers in SIRCUS. As a first step toward the development of a SIRCUS-based photometric scale, two photometers were developed with the SIRCUS calibration in mind. They have been calibrated twice in SIRCUS, with calibrations separated by approximately 2 years. They also measured standard lamps in the photometry calibration facility. The SIRCUS calibration repeated to within 0.1 %, implying that the new photometers are stable enough to hold the photometric scale. These are the first steps toward the development of SIRCUS-derived photometric units.

Stray radiation, or scattered light, within single-grating array spectrometers is often the major source of measurement error with these instruments, limiting their use in applications requiring low measurement uncertainty. Using the tunable lasers available on SIRCUS, the scattered light within array spectrometers has been quantified and correction algorithms have been developed to greatly reduce the errors caused by scattered light in the instrument (Zong et al.). Hyperspectral imaging sensors are often based on single grating array spectrometers. We are extending the stray-light characterization work to include spatial imaging, or an instrument's point-spread function. The first characterization measurements of a hyperspectral imaging sensor, an aircraft ocean color sensor, will be presented and the image correction algorithm discussed.

Ground-based sun photometers and sky radiometers are used to characterize the radiative properties of the atmosphere. Properly characterized and calibrated, they can make key measurements of global concentrations and distributions of atmospheric constituents such as aerosols, ozone, nitrogen dioxide and water vapor. Reductions in the uncertainties using laboratory standards would allow for meaningful comparisons with results from solar-based Langley-Bouger calibration techniques, resulting in independent values of the exo-atmospheric solar irradiance at a set of measurement wavelengths. Previous laboratory comparisons with in-situ measurements showed significant differences between the two approaches (Wehrli, Schmid and Wehrli). Preliminary measurements of the irradiance responsivity of sun photometers on SIRCUS revealed significant differences from standard calibration approaches as well (Souaidia et al.). Further characterization and calibration on SIRCUS with uncertainties of 0.1 % or less approach or exceed the

uncertainties in exo-atmospheric solar irradiance (Thuillier, et al.).

## Summary

The radiometric properties of the SIRCUS source coupled with state-of-the-art transfer standard radiometers whose responsivities are directly traceable to primary national radiometric scales, result in typical combined standard uncertainties in irradiance and radiance responsivity calibrations less than 0.1 %. Extension of the spectral coverage available on SIRCUS to 210 nm in the UV and to 5  $\mu\text{m}$  in the IR will be discussed, the impact of SIRCUS on primary U.S. national radiometric, photometric, and radiance temperature scales will be mentioned; and examples of unique calibrations and future research direction in the facility will be presented.

**Acknowledgments** We would like to acknowledge and thank Albert C. Parr, Chief of the Optical Technology Division at NIST, and John Grangaard, U. S. Air Force (ret.), for consistent and continued support for the SIRCUS facility.

## References

- Eppeldauer, G. P. and D. C. Lynch, Opto-mechanical and electronic design of a tunnel-trap Si radiometer, *J. Res. Nat'l. Inst. Stand. Technol.* 105, 813-828, 2000.
- Fowler, J. and M. Litorja, Geometric area measurements of circular apertures for radiometry at NIST, *Metrologia* 40, S9-S12, 2003.
- Lorenz, S., L-1 Standards and Technology, Inc., Jjamsville, MD, USA.
- Lykke, K. R., et al., Development of a monochromatic, uniform source facility for calibration of radiance and irradiance meters from 0.2 micrometer to 12 micrometer, *Metrologia* 35, 479-484, 1998.
- Ohno, Y., Photometric Calibrations, NIST Spec. Publ. 250-37, U.S. Government Printing Office, Washington, DC, 1997.
- Houston, et al., in preparation.
- Schmid, B. and Ch. Wehrli, Comparison of sun photometer calibration use of the Langley technique and the standard lamp, *Appl. Opt.* 34, 4500-4512, 1995.
- Souaidia, et al., A comparison of laser-based and conventional calibrations of sun photometers, *Proc. SPIE* 4481, 2003.
- Thuillier, G., et al., The solar spectral irradiance from 200 to 2400 nm as measured by the SOLSPEC spectrometer from the ATLAS and EURECA missions, *Solar Physics* 214, 1-22, 2003.
- Wehrli, Ch. Calibrations of filter radiometers for determination of atmospheric optical depth, *Metrologia* 37, 419-422, 2000.
- Yoon, H., et al., The realization and dissemination of the detector-based Kelvin, *Proceedings of Tempmeko 04*, Dubrovnik, Croatia, 2004.
- Yoon, H. W., C. E. Gibson, and P. Y. Barnes, Realization of the National Institute of Standards and Technology detector-based spectral irradiance scale, *Appl. Opt.* 41, 5879-5890, 2002.
- Zong, Y., et al., A simple stray-light correction method for array spectroradiometers, submitted to *Appl. Opt.*