

Development of a Versatile Radiometer-Photometer System

George Eppeldauer¹, Richard Austin², and Charles Lustenberger²

¹National Institute of Standards and Technology

Gaithersburg, Maryland 20899, USA

²Gamma Scientific, San Diego, California 92123, USA

Abstract. A new generation radiometer-photometer system has been developed in a National Institute of Standards and Technology (NIST) and Gamma Scientific (GS) cooperation to satisfy the increased requirements in the dissemination of NIST responsivity scales. The NIST responsivity scales have been extended from the silicon wavelength range to 2500 nm and in addition to the traditional spectral power responsivity calibrations, spectral irradiance and radiance responsivity calibrations are performed as well. The new generation radiometers and photometers can be utilized to maintain the NIST spectral responsivity scales and also to propagate the extended NIST scales to field applications with a minimal increase in the measurement uncertainty.

Mechanical and optical design

The new radiometer-photometer system has a versatile measuring head design. The front geometry of the heads can be simply modified to measure radiant power, irradiance, radiance, or the photometric equivalents, luminous flux, illuminance, and luminance. The different head constructions are made using the combination of apertures, diffusers, filters, filter combinations, and a variety of detectors depending on the head design for a given application. In addition to silicon photodiodes, nitride passivated silicon (for the ultraviolet), InGaAs, and extended-InGaAs photodiodes (for the near-infrared) have been applied. Detectors with large area and spatially uniform responsivity are used for power mode measurements where the detectors are underfilled with the incident radiation (beam). In addition to diffuser-input irradiance meters that can measure different source sizes [1], irradiance meters without diffusers have been developed to measure either “point sources” (where the detector is overfilled with the radiation from a small and distant source) or collimators. In these irradiance meters, the field-of-view is carefully designed and can be determined from goniometrical tests. An ultraviolet (UV) filter radiometer has been designed with interference filter and passivated silicon photodiode. It has a bandwidth of 25 nm with high ultraviolet and infrared blocking and can measure the irradiance produced by the 365 nm Hg line of UV collimators. Also, a versatile photometer has been developed where the attachable input optics can convert the illuminance measuring head into a luminance meter. The aperture plane and the outside surface of the front ring are in the same reference plane of the illuminance meter. With the luminance head attached, measurement field-of-view angles can be changed by choosing one of the six different hole-sizes in the mirror-aperture wheel. A second imaging optics is used in the input optics to produce efficient blocking for radiation outside of the target area and to maintain a constant luminance responsivity throughout the focus range of the

camera lens at the front. This device can also measure radiant power, irradiance, and radiance when the photopic filter is removed.

Design of heating and cooling

For lower measurement uncertainty, both the filters and the detectors can be temperature controlled independently from each other using thermoelectric (TE) coolers/heaters. Usually, detectors are cooled to increase their shunt resistance and filters are heated to avoid condensation.

Thermistor sensors are attached to the temperature controlled components. One stage TE coolers are used for heating and 1 to 4 stage TE coolers can cool the detectors down to -85 degree C. The heat dissipation performance of the measuring heads is matched to the required cooling temperature. The thermal design of extended-InGaAs radiometers is challenging because the coldest possible detector temperature is needed with high temperature stability to produce high detector shunt resistance and low measurement uncertainty. When detectors are applied that have high shunt resistance at room temperature (such as selected silicon photodiodes), both detector and filter(s) can be temperature controlled together. The common (heated) temperature-control is frequently applied in photometers and in other filter-radiometers where the controlled temperature can be slightly higher than the ambient temperature. The spectral responsivity of the detector-filter combinations is optimized for the selected constant temperature [2].

Electronic design

Pre-amplifiers are mounted to the back of the measuring heads that are matched to the detector electrical characteristics to optimize the signal gain, loop gain, and the closed loop voltage gain at the signal frequency [3]. In DC measurements, usually the optimization is simplified for selecting (and/or cooling) the detectors for high shunt resistance. However, only the optimization of these three gain characteristics makes it possible to measure modulated (chopped) radiation with high sensitivity and low measurement uncertainty. Consequently, all three gain characteristics were optimized versus frequency for the radiometers that measure AC radiation. The selected optimum chopping frequency for AC radiation measurements is between 8 Hz and 10 Hz. This is a high enough signal frequency to get rid of the 1/f noise of the applied operational amplifiers. Also, the upper roll-off frequencies of the signal gain characteristics were tuned to 80 Hz (at 10⁹ V/A signal gain selection) or higher using gain switching reed relays of low capacitance instead of the traditionally used rotary switches. For the increased roll-off

frequencies, the chopping frequency is low enough to obtain constant signal gains for all signal gain selections at the chopping frequency.

Low noise and low input current operational amplifiers with high upper roll-off frequency are used in the current measuring pre-amplifiers. The operational amplifiers and their feedback resistors have not been temperature controlled. Instead, light shutters are applied and the output (voltage) signal is measured with the shutter on and off. The temperature dependent (dark) output (offset) signal is subtracted from the sum of the output signal (to be measured) and the (dark) output signal. The feedback resistors used to have temperature coefficients of 10 ppm/degree C. The resistance uncertainties for the decade nominal values are 0.01 %. Using the low uncertainty feedback resistors and the output (dark) offset subtracting method, the photocurrent-to-voltage conversion uncertainty is 0.01 % without performing any signal gain linearity calibrations or corrections for the pre-amplifiers. The signal gain selections over eight decades can be either manual or remote controlled.

A carefully designed wiring, grounding, and shielding system for the measuring head and the control unit (that includes the power supply, the temperature controller(s), and the remote gain control circuit) minimizes noise and 60 Hz pickup.

Radiometer tests

Photodiode shunt resistances were measured to determine the three fundamental gains of photocurrent measuring detector-preamplifier circuits. A noise floor of 3 fA was measured on the prototype radiometer at 10^{10} V/A signal gain selection when a 20 Gohm shunt resistance silicon photodiode was applied. The electrical bandwidth of this DC measurement was 0.3 Hz. The 6 Mohm shunt-resistance of a 5 mm diameter InGaAs photodiode measured at room-temperature was increased to 42 Mohm when the detector was cooled to 4 degree C. This low temperature decreased the 180 fA (room temperature) noise floor to 25 fA at the 10^{10} V/A signal gain selection of the InGaAs irradiance meter.

The three fundamental gains are always optimized for the signal frequency using partial or full frequency compensations in the current measuring analog control loop of the preamplifier. In order to obtain the best results, photodiodes with the lowest junction capacitance are selected and the external feedback capacitors of the operational amplifier are changed. Because of the variation of the feedback component values (including stray capacitance as well), the 3 dB upper roll-off points of the different gain selections cannot be controlled to the same frequency. This results in significant responsivity differences at decade signal gain switching when the chopping frequency is on the slope of the signal gain versus frequency characteristics. To avoid non-decade signal gain ratios at the

chopping frequency, the responsivity calibration results are usually reported at DC (zero Hz). The solution to obtain exact decade ratios for the different signal gain selections at a given signal frequency is to measure the frequency dependent gain (responsivity) curves first and then to apply correction, based on the measured data.

Operational and performance tests have been worked out for the modular radiometers/photometers to minimize errors and unacceptable performance during fabrication. First, operational DC tests are made where the detector shunt resistance and then the dark output offset voltages are measured at all gain selections. Thereafter, the dark output voltage is measured with an AC measuring digital voltmeter at all gain selections to check for oscillations. After the dark tests, the detector is exposed to different optical radiation levels and it is checked if decade changes are obtained in the output voltages when the signal gains are gradually changed from the maximum to the minimum. These photodiode and preamplifier tests are followed by the cooling tests where the biasing current is selected for the target resistance of the NTC thermistor and the voltage drops on the thermistor are measured at both the ambient and the controlled temperatures. The voltage drop on the thermistor should remain constant during operation indicating that the temperature of the monitored component is stable versus time.

References

- [1] G.Eppeldauer, M. Rácz, and T. Larason, Optical characterization of diffuser-input standard irradiance meters, SPIE Proc. Vol. 3573, pp. 220-224, 1998.
- [2] George P. Eppeldauer and Miklós Rácz, Design and characterization of a photometer-colorimeter standard, Applied Optics, Vol. 43, No. 13, pp. 2621-2631, 2004.
- [3] George P. Eppeldauer, Editor, Optical radiation measurement with selected detectors and matched electronic circuits between 200 nm and 20 μ m, NIST Technical Note 1438, April 2001, U.S. Government Printing Office, Washington, D.C.