New working standards to disseminate NIST radiometric and photometric scales

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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.

1. 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. The computer design of the versatile measuring head is shown in Fig. 1. The filter(s) are heated to a constant temperature to avoid condensation. The filter holder (in the middle of the figure) can be attached to the housing (on the right) of the temperature controlled photodiode. The photocurrent measuring preamplifier is located in the bottom part of the measuring head not shown in the figure. The signal output leads of the detector and the preamplifier inputs are connected using a connector-pair. For radiance or luminance measurements, input optics can be attached to the camera-lens mount on the left side of the figure.

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 radiant power mode measurements where the detectors are underfilled with the incident radiation (beam). In many applications, especially when spatially non-uniform detectors are to be used, the detectors are overfilled with a uniform field of radiation. For these applications, irradiance meters without diffusers have been developed to measure either "point sources" (where the detector is overfilled with the radiation

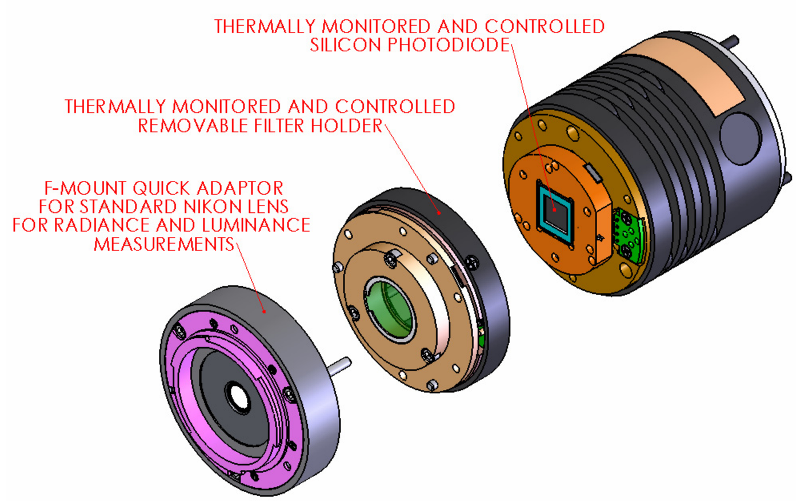

Fig. 1. Design of a versatile photometer measuring head.

from a small and distant source) or collimators. In these irradiance meters, the field-of-view (FOV) is carefully designed. The FOV determination of an illuminance meter (without a diffuser) is illustrated in Fig. 2. This computer designed drawing also shows the cross section of the illuminance measuring photometer head.

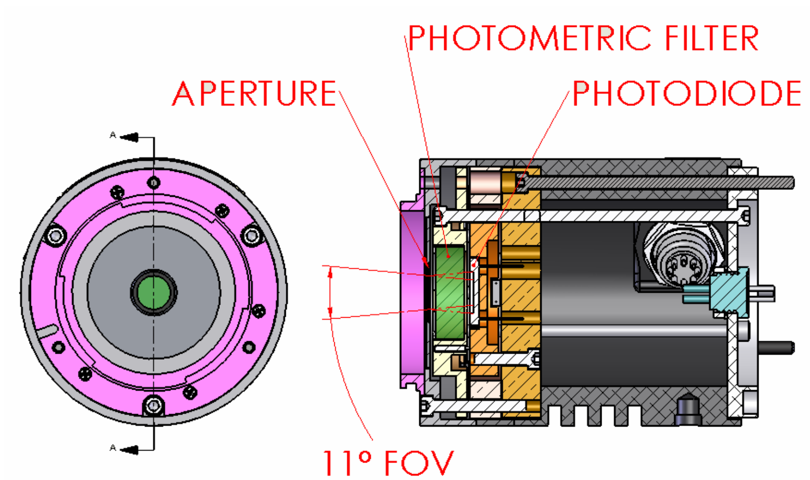

Fig. 2. FOV design and cross-section of an illuminance meter.

With diffuser-input irradiance meters, where a diffuser is located behind the front aperture [1], different-size sources can be measured with small geometrical measurement uncertainties. The angular responsivity of a diffuser-input irradiance meter is shown in Fig. 3 as an example. The diffuser, eliminated the unwanted multiple reflections between the aperture and the detector resulting in an angular responsivity distribution close to the cosine (target) function. Without a diffuser, as shown in the graph, the angular responsivity is different from the cosine function.

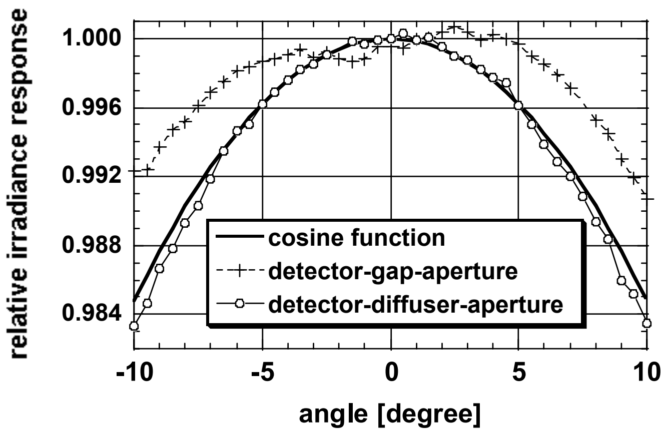

Fig. 3. Angular responsivities of an irradiance meter with and without input-diffuser.

The attachable input optics can convert the versatile measuring head from an illuminance meter into a luminance meter. The aperture plane and the outside surface of the front ring (of the measuring head) are in the same reference plane of the illuminance meter. With the luminance head attached, the measurement field-of-view angles can be changed by choosing one of the six different hole-sizes in the mirror-aperture wheel. The design of the attachable input optics is shown in Fig. 4. A second imaging optics is used in this input optics to produce efficient blocking for radiation coming from 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.

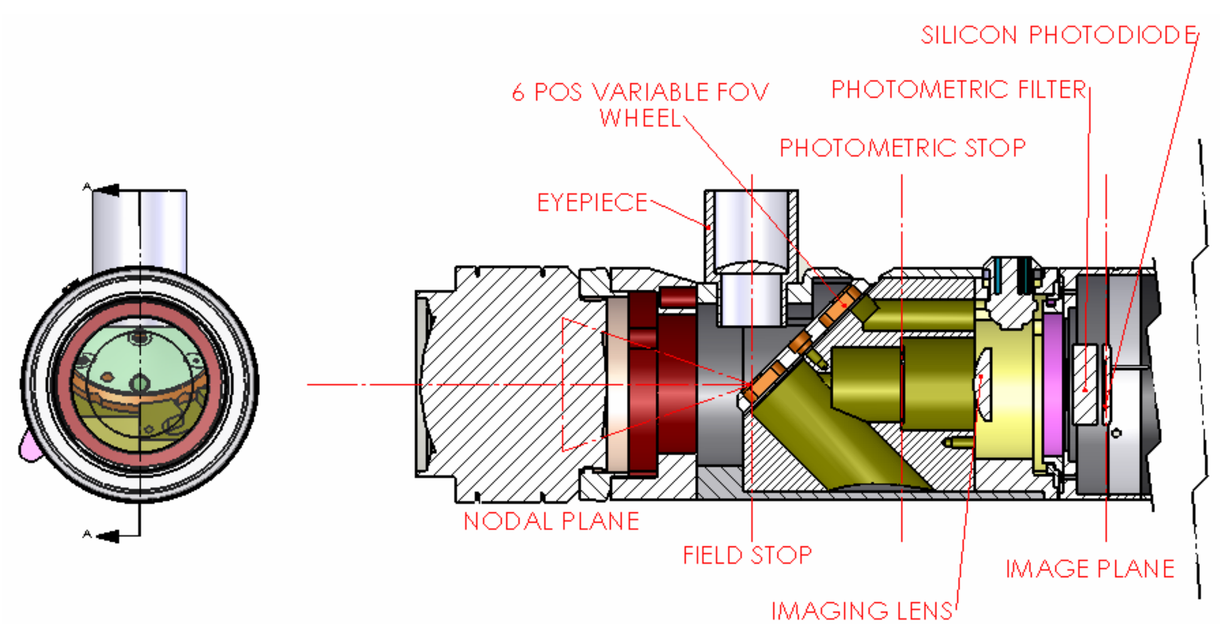

Fig. 4. Radiance (luminance) measuring input optics.

2. 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 ^{o}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. The housing design of a 4-stage cooled extended-InGaAs radiometer is shown in Fig. 5. The hot side of the detector is mounted to a copper plate attached to a heat sink. The air flow from an outside fan is utilized to remove the heat from the heat sink

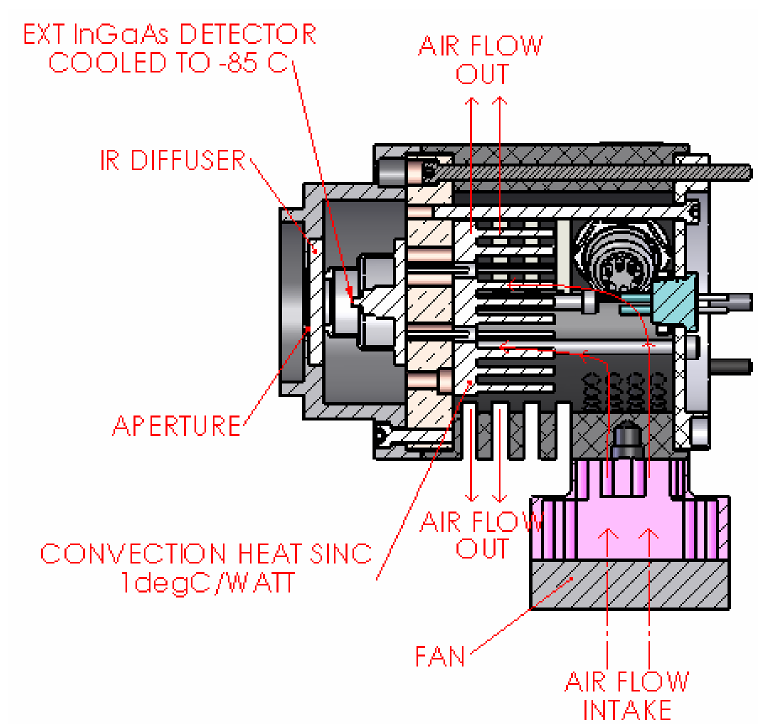

Fig. 5. Housing-design of a fan cooled extended-InGaAs detector.

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].

3. Electronic design

The pre-amplifiers mounted to the back of the measuring heads 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 10^9 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 are not 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 applied feedback resistors have temperature coefficients of 10 ppm/^{o}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 % (k=1) 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 signal-gain control circuit) minimizes noise and 60 Hz pickup.

4. Radiometer tests

Photodiode shunt resistances were measured at different temperatures to determine the three fundamental gains of the photocurrent measuring detector-preamplifier circuits.

The noise equivalent currents (NEC) measured on Si and InGaAs radiometers are shown in Table 1. When the InGaAs detector was cooled from 23 ^{o}C to 4 ^{o}C its shunt resistance increased by a factor of seven. This resulted in a noise floor decrease of a factor of seven as well.
The results of the spectral irradiance responsivity measurements are shown in Fig. 6. The relative spectral responsivity curves were determined against an InGaAs reference irradiance meter using the detector substitution method on the NIST Spectral Comparator Facility (SCF).

The absolute irradiance responsivity (tie) points were made at three wavelengths using stabilized lasers. The tie point calibrations were made on the NIST Facility for Infrared Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (IR-SIRCUS). The InGaAs detectors for the two irradiance meters were selected from the same batch. The curve shapes are different because of the different spectral transmittances of the applied diffusers.

Table 1. NEC measured in dark at a signal gain of 10^{10} V/A.
The electrical bandwidth of the DC measurement was 0.3 Hz.

Hamamatsu [4] photodiodes	R_S	23°C NEC (Δf=0.3 Hz)	R_S	4°C NEC (Δf=0.3 Hz)
Si S1226	20 GΩ	3 fA	-	-
InGaAs G5832-25	6 MΩ	180 fA	42 MΩ	25 fA

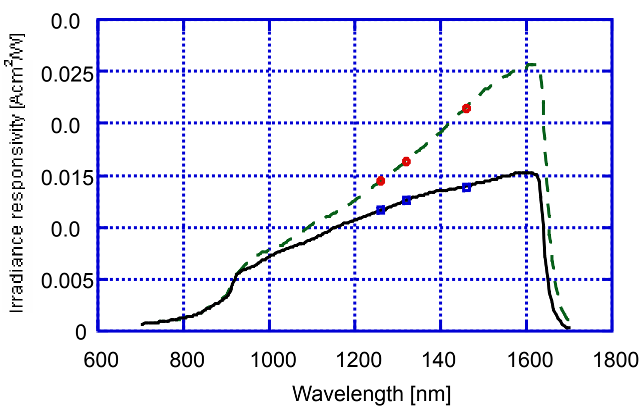

Fig. 6. Spectral irradiance responsivities of two InGaAs irradiance meters.

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 a 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 with the different signal-gain settings. 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. These frequency variations result in responsivity differences at decade signal-gain switching if 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 results of the responsivity calibrations 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 signal-gain (responsivity) curves and then to apply responsivity corrections, based on the measured data.

Operational and performance tests have been worked out for the modular radiometer/photometer system 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 signal-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 maximum to 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

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