Pre-Launch Absolute Spectral Flux Calibration

Introduction

A common approach to pre-launch absolute spectral flux calibration of an instrument is to break the problem into two parts [1]. In the first part, the relative spectral responsivity (RSR) is determined in the laboratory, often by tuning a quasi-monochromatic source across the bandpass of the instrument. The result from this first part is a spectrum (for each pixel and each band) normalized at some convenient wavelength. In the second part, the absolute flux calibration is measured in the laboratory, often by stimulating the instrument using a broadband calibration source of known absolute spectral flux (termed spectral irradiance, having units, for example: $Wm^{-2}nm^{-1}$). The result from this second part is a number (for each pixel and each band) having irradiance responsivity units, for example DN $W^{-1}m^2$ (where DN stands for Digital Number and represents the counts from the detector). These two parts are then combined to determine the absolute spectral responsivity (ASR) of the instrument, resulting in a spectrum (for each pixel and each band) having irradiance responsivity units, for example, DN $W^{-1}m^2$.

The RSR is typically determined by either a multiplying the measured component RSR's or using a system-level measurement approach. As an example of a component approach (for a case where the complete instrument consists of a detector, bandpass filter, and telescope), the quantum efficiency (QE) spectrum of the detector pixels is measured separately from the transmittance of the bandpass filters and the transmittance of the telescope. Then the measured spectra are simply multiplied to determine the RSR. All optics should be included, and so for a realistic instrument the component approach may involve many optical elements. Note that the QE spectrum measurement requires a standard reference detector having a spectrally-known response, whereas the optical component transmittance measurements, being relative measurements (component in / component out), do not.

In the system-level approach for RSR determination, the entire instrument (including detector, bandpass filter, and telescope as in the example considered above) is illuminated during the pre-flight calibration. The quasi-monochromatic source is typically either a lamp-monochromator system or, in the case of the Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) technique described below, a broadly tunable laser system [2]. A key point is that lamp-monochromator systems generally do not fill the pupil (both entrance aperture area and field of view at the same time) of the instrument in the exact way that it is filled on orbit, whereas the SIRCUS technique generally does provide for proper filling of the instrument pupil. An example of the typical difference in RSR determined using the two approaches (component vs. system-level) on the same instrument is discussed later.

As a practical matter, for WFIRST it may be best to use a hybrid approach – call it a subsystem level approach. Here the WFC instrument, for example, involving everything except the 2.4 meter telescope, would be measured at system level. The transmittance of the telescope would then be determined (measured?) separately. Then the RSR of the WFC instrument would be multiplied by the transmittance of the telescope to determine the full RSR.

An example of a broadband calibration source is a type FEL spectral irradiance lamp, calibrated for spectral flux (at 50 cm from the lamp) with traceability to the SI [3]. It can be used with a diffuser, and that diffuser can be at the focus of a collimator for illumination of instruments coupled to a telescope. Alternatively, the FEL/diffuser combination is often replaced by a lamp-illuminated integrating sphere. Usually, rather than attempting to calibrate the throughput of the integrating sphere, diffuser, or collimator, the spectral radiance and irradiance (and hence spectral flux) exiting from the sphere or collimator is measured with a calibrated spectroradiometer, and the SI traceability is then through the spectroradiometer, calibrated for spectral irradiance separately using an FEL lamp. The FEL lamps issued by NIST measurement services are, in turn, calibrated traceable to the NIST Primary Optical Watt Radiometer (POWR), an electrical substitution radiometer [4,5]. POWR also currently serves to provide the scale to SIRCUS, described in detail below. Note that the SIRCUS technique is, in principle, capable of providing an ASR calibration, not just RSR, of the instrument. This is because, as will become clear later, the SIRCUS technique uses standard detectors that carry an absolute scale. This may seem to obviate the need for an absolutely calibrated broadband source. However, most pre-flight calibration programs still follow the prudent practice of including a broadband calibration source in the calibration plan for a variety of good reasons.

SIRCUS Technique

In the SIRCUS facility at NIST, shown in Fig. 1, relatively high-power (typically 100 mW to 1 W), tunable lasers are introduced into an integrating sphere, producing a uniform, quasi-Lambertian, radiant flux source [2]. At each wavelength, both the device under test (representing, for example, the WFC instrument) and a standard detector are exposed, one after the other, to the same radiance emerging from the integrating sphere, and the response of each is recorded on a computer. The purpose is to transfer the flux calibration scale from the standard detector to the device under test. To effect this in an automated manner, either the detectors are moved using a motorized translation stage (as depicted in Fig. 1) or the integrating sphere is moved between fixed detectors (as would be for large detectors). The distance between the source and the detectors can be varied as well along the optical axis, and the entrance apertures of the instruments are generally placed at the same reference plane for flux calibration transfer. A wavemeter uses a Michelson interferometer to measure the wavelength of the tunable-laser radiation, referenced to a precision HeNe laser, with an uncertainty of 0.01 nm or less.

In SIRCUS, the laser radiation illuminates an integrating sphere using an optical fiber, as shown in Fig. 1. Speckle in the image from the source, originating from the coherent nature of the laser radiation, is effectively removed by placing a short length of optical fiber in an ultrasonic bath. A monitor detector is located on the sphere to correct for any radiant flux changes in the sphere output between measurements with the reference instrument and the device under test. A laser intensity stabilizer, consisting of a feedback loop between a laser beam attenuator and a monitor detector, holds the light level emerging from the sphere stable to typically within a part in 10^4 or better. A number of different lasers are used to cover the spectral range from about 350 nm to 2500 nm, including continuous-wave (cw) dye lasers, solid-state Ti:sapphire lasers, as well as quasi-cw primary, doubled, tripled, quadrupled systems and optical parametric oscillator systems.

Different integrating spheres are used, depending on the radiometric calibration and the wavelength of calibration. Small diameter integrating spheres – typically diameters of 25 mm to 50 mm – equipped with precision apertures with diameters ranging from 3 mm to 8 mm are typically used for irradiance responsivity (i.e. flux) calibrations. For astronomical instruments, a collimator can be used between the integrating sphere and the detectors to limit the field of view and effectively place the uniform source image at infinity. Larger diameter spheres – 30 cm diameter – with 5 cm to 10 cm diameter exit ports are used for extended-area radiance measurements, typically useful for Earth-observing instruments. The spheres are made of sintered polytetrafluoroethylene-based coating [6] that has high diffuse reflectance from about 250 nm to 2500 nm. Typical flux levels at 1 m from the sphere, using a 25 mm diameter integrating sphere with a 5 mm diameter aperture, range from approximately 1 μW/cm^2 to 10 μW/cm^2. Radiance levels between 1 mW/cm^2/sr and 5 mW/cm^2/sr are standard for a 300 mm diameter sphere with a 75 mm output port. These radiance and irradiance levels can be continuously adjusted down to zero output, allowing for linearity measurements over many orders of magnitude. Note that the exit apertures are normally calibrated at the NIST facility for aperture area measurement [7].

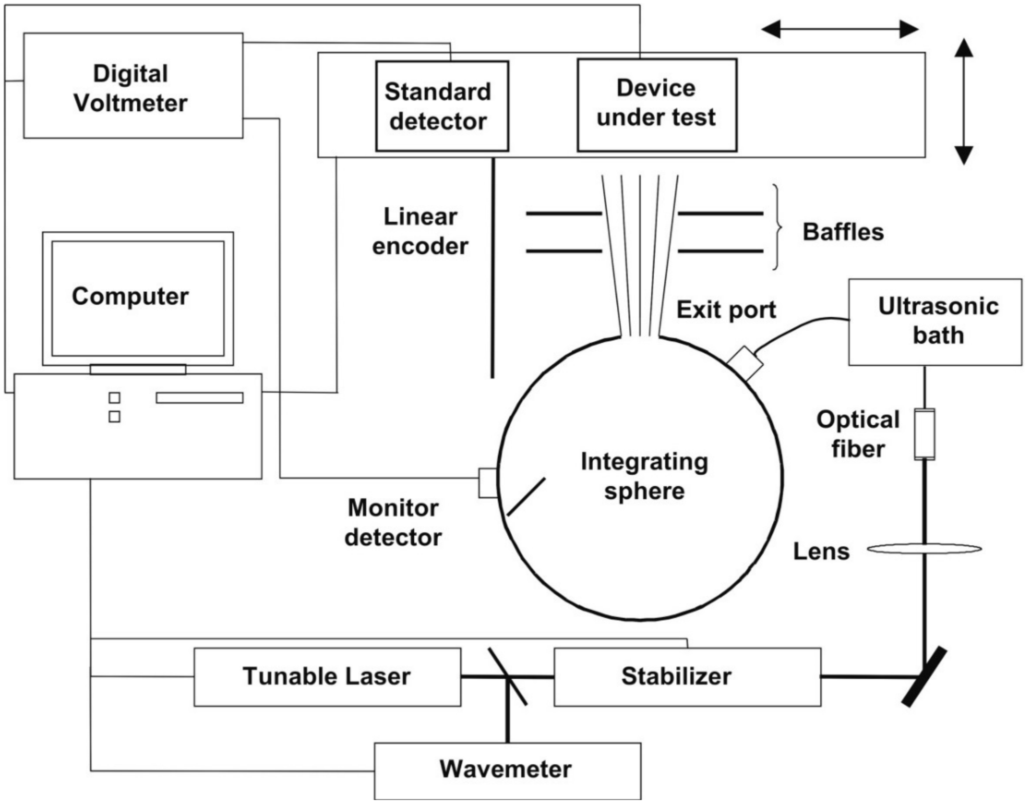

FIG. 1. Schematic diagram of the NIST SIRCUS technique. From Ref. [1].

Ultimately, lasers determine the spectral coverage available in laser-based calibration facilities while the quality and characteristics of the reference standard detectors determine the achievable uncertainty. The standard detectors used at SIRCUS are trapped silicon photodiodes for the spectral range 350 nm to 950 nm, and InGaAs and Extended InGaAs detectors for the spectral range 950 nm to 2500 nm [1]. They are fitted with precision apertures calibrated by the NIST aperture area measurement facility [7] and are calibrated for spectral power responsivity directly against the NIST Primary Optical Watt Radiometer (POWR) [5]. The latter is an absolute cryogenic radiometer that operates on the principle of electrical substitution, whereby optical power is measured in terms of the equivalent electrical power required to hold a black absorbing cavity at a fixed temperature difference above a heat sink near 5 kelvin in vacuum. This technique is in common use to establish radiometric scales in the visible-near infrared at national measurement institutes [4], and is a cryogenic version of the technique used to measure solar irradiance in what are commonly called active cavity radiometers [8].

Calibration scientists at NASA Goddard Space Flight Center have recently developed a version of SIRCUS called the Goddard Laser for Absolute Measurement of Radiance (GLAMR) that has been used for pre-flight calibration of Earth-observing instruments [9]. The radiance reference standards in the GLAMR facility operate across the 320 nm to 2500 nm spectral range. They have been periodically calibrated for spectral radiance responsivity against the NIST SIRCUS facility over parts of this spectral range. For example, within the 400 nm to 870 nm region a standard uncertainty below 0.3 % has been achieved, and in the 870 to 1100 nm region a standard uncertainty ranging from 1 % to 1.5 % has been achieved. With a dedicated effort at NIST, the uncertainty could be improved and the spectral range increased. Plans are in place during 2017-2019 to improve the SIRCUS transfer calibration techniques to enable standard uncertainty of the GLAMR radiance standards to drop below 0.3 % from 320 nm to 1620 nm and below 1 % from 1600 nm to 2300 nm. With further dedicated effort and the use of newer transfer detector technologies, it is conceivable that uncertainties below 0.3 % in the 1620 nm to 2300 nm range could be achieved.

Component vs. System-level RSR

Differences between the component approach and system-level measurements can occur because of different measurement geometries – if optical elements and detectors are illuminated differently during component measurement than when in the system - and also because the former doesn't take into account inter-reflections between optical elements that are present in the complete system. For example, Fig. 2 shows the calculated (by component) and measured relative spectral responsivity of 3 channels of a telescope, the Robotic Lunar Observatory (ROLO), that was a ground based system used for lunar irradiance measurements [1]. Spectral shifts, changes in the spectral shape and width are readily observable. The out-of-band response (not shown here) also differs significantly between the two approaches.

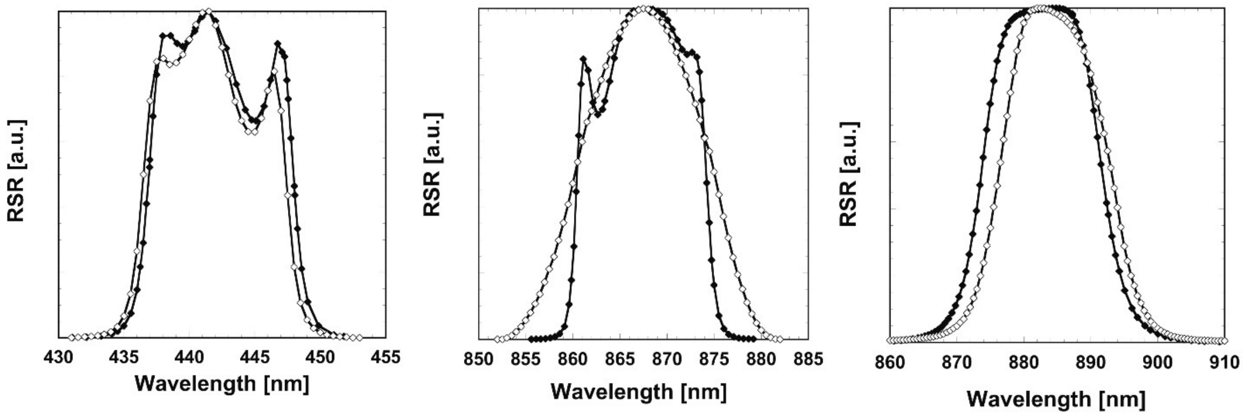

FIG. 2. Comparison between component (open diamonds) and system-level (closed diamonds) relative spectral responsivity of three ROLO filter channels. From Ref. [1].

References

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