White Paper on SWIR Camera Test – The New Swux Unit

Austin Richards, FLIR – Chris Durell, Joe Jablonski, Labsphere – Martin Hübner, Hensoldt

Introduction

SWIR imaging technology based on InGaAs sensor products has been a staple of scientific sensing for decades. Large earth observing satellites have used InGaAs imaging sensors for applications that have proven benefits in markets like agriculture, geology, weather prediction and atmospheric science. As is the case with most technology, these very expensive early systems paved the way for much smaller, faster and cheaper imaging products that are proliferating and creating new commercial market opportunities. High-performance cameras for SWIR applications are now available for under $5,000. However, there is not a clear set of test specifications, testing methods or industry language that allows consumers to be able to quickly compare or validate performance of these products. The result of the lack of this clear internal communication on the products is some degree of chaos as companies try to move these products and consumers find the resulting product performance confusing, tough to validate on manufacturer specifications, or, in the worst case, find that the camera will not meet the application requirements. If SWIR sensor testing is going to proliferate, then some basic level of performance needs to be defined, new test methods and units need to be presented to the user community, and SWIR test equipment needs to be uniformly accepted and used.

Discussion

In 1999, a 320x256 pixel InGaAs camera retailed for $30,000, and there were only two companies building commercial cameras. These cameras had a very limited market which was restricted almost entirely to defense and university research laboratories, as well as some telecom companies working with SWIR laser and fiber optics. Today, you can buy a 640x512 pixel InGaAs camera for about $5000 in OEM volumes, and the number of companies worldwide that are building commercial InGaAs cameras now numbers in the dozens. These new cameras have superior performance to the old cameras at a fraction of the size, weight and power consumption. Improvements to sensor yields along with optics and electronics manufacturing economies of scale promise to drive costs even lower. This cost savings is driving global growth of the installed base of InGaAs cameras and pushing these cameras into commercial applications, such as security and surveillance. InGaAs cameras can see through haze and smog much better than visible-light cameras, and they can image in some low-light conditions (like starlight) better than standard silicon sensor cameras.

As these cameras are increasingly used for low-light imaging in outdoor field conditions, there is a need for performance testing that relates to field conditions. Unlike the situation with visible-light and thermal cameras, it is not so easy to predict the performance of an InGaAs camera in outdoor conditions and InGaAs camera performance is specified differently than either visible-light or thermal infrared cameras. Visible-light camera sensitivity performance is typically measured using the lux unit, which is a lumen/m^2, a measure of radiant flux density that is weighted by the spectral response of the “typical” human eye. Lux meters are widely available and are traceably calibrated to internationally agreed-upon National Measurement Institute (NMI) standards of performance, so that different visible-light camera manufacturers can test their visible spectrum products to a standard and units like the lux.

Thermal infrared camera performance is handled differently. Sensitivity is generally characterized by NEdT or noise equivalent delta temperature, or noise equivalent temperature difference. NEdT is a value where the temporal noise is expressed in scene temperature change at a particular scene temperature. This temperature is often chosen to be 25˚C within US standards or 288K in European and NATO standards to simulate laboratory ambient temperatures. NEdT is an easy parameter to measure with standard blackbody sources, since the emitted thermal radiation levels from a blackbody are well understood. NEdT is highly relevant to imaging performance for thermal cameras in field conditions where targets of interest and background scenes can be very close to each other in radiation temperature. A caution should also be noted that NEdT is most effective when used within the same model of camera, but it is of limited use in comparing between different camera manufacturers’ products unless the test parameters are very similar and well defined.

SWIR InGaAs cameras don’t lend themselves to being tested by either of those thermal methods. The spectral response of a typical InGaAs camera has no significant overlap with the human eye spectral response V(lambda) curve, as shown in Figure 1, so it is useless at best, and misleading at worst, to specify InGaAs cameras performance based on lux levels measured by a lux meter. Yet, that is where most customers and specifiers start the conversation today. A SWIR camera does not detect temperature changes in an object unless the object is at a temperature of several hundred degrees C or hotter, which is not the case for a typical scene. Radiance-in-band (aka, integrated energy over a spectral range, 10 W/m^2-sr from 0.9-1.6µm) or spectral radiance (W/m^2-sr-µm), or their irradiance equivalents, are the key parameters for these cameras. Daytime SWIR levels are driven by reflected sunlight, and nighttime levels by reflected man-made SWIR radiation or reflected nightglow. The physical temperature of typical terrestrial objects (between 0-70C) in a scene has no bearing on what an InGaAs camera sees when it looks at them.

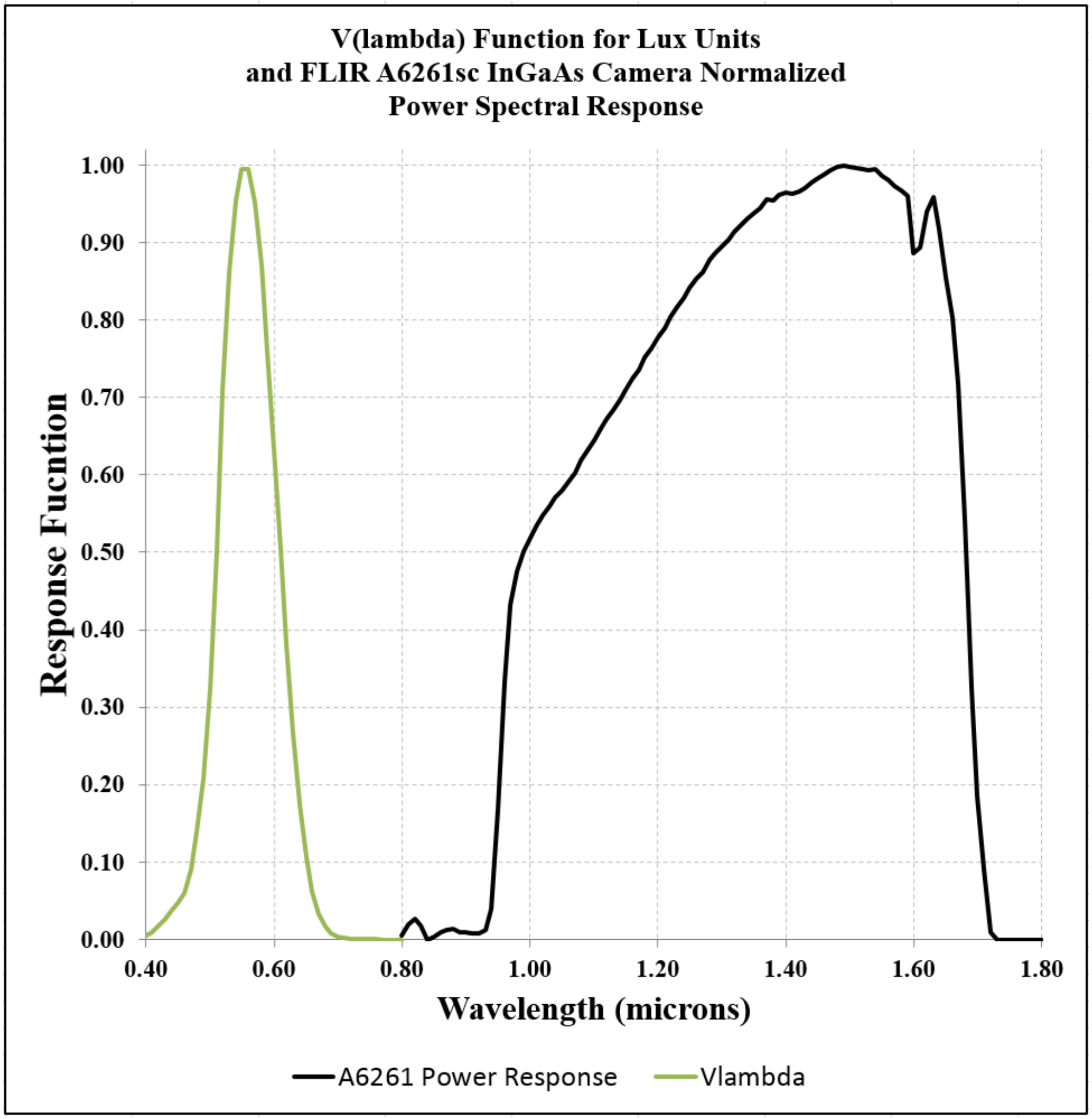

Figure 1. V(lambda) curve used to derive lux units of illuminance and relative power spectral response of a typical high-performance InGaAs camera. Note the complete lack of spectral overlap. Lux meter readings in a field test cannot predict InGaAs camera performance.

The typical metric used by camera manufacturers for the characterization of SWIR camera performance is noise equivalent irradiance or NEI. This metric is similar to NEdT, but it is expressed in units of irradiance on the sensor, either in watts/m^2 or photons/sec/m^2. The NEI specification is very easily "gamed" by sales and marketing personnel in the industry! For example, the test conditions must be carefully defined if you want to compare two different InGaAs cameras:

1. What is the sensor irradiance? For a camera with a cap on the sensor, the irradiance is virtually zero. This condition will minimize the temporal noise, since there will be no shot noise component to the total noise, which will then be driven by shot noise in the dark current, read noise and electronics noise

2. What is the irradiance spectral distribution? Many manufacturers will measure responsivity at the peak wavelength sensitivity of the camera, typically around 1.3 1.5µm. This maximizes the response and therefore reduces the NEI value for a given noise value.

3. What is the integration time? The longer the integration time, the higher the responsivity and the lower the NEI. Camera manufacturers will typically measure at the longest integration time they can, to reduce the NEI value. But this is a crucial point, because if the InGaAs camera NEI is tested at integration times that are tens of milliseconds, this will impact the frame rate of the camera in those test conditions. A typical InGaAs system is tested at 60Hz frame rates, which restricts the integration time to ~16msec or less.

4. What are the effects of the optics? In the early days, InGaAs cameras all had interchangeable optics. As the market matures, there are going to be low-cost InGaAs camera “cores” with integrated, pre-focused optics. Comparing two of these cameras from different manufacturers will be difficult if their NEI values were measured without the lenses in place.

To ensure that customers can rely on test and performance information provided by manufacturers and to ensure customer success with the SWIR camera products, new objective test methods are needed. How does one address a camera that crosses the thermal and visible boundaries and what analogs can be drawn from well-established testing in the industry today? Part of the answer lies within well-established test fundamentals for silicon sensors, but also the creation of some novel hybrid tests to draw out the capabilities and interesting performance that is driving SWIR applications.

Since InGaAs generally has a well-defined spectral band response and its fundamental semiconductor architecture often has signal response similarities with visible and silicon sensors, SWIR testing can, in part, be based upon analogous silicon-based testing. However, we also must acknowledge that SWIR-band temperature measurement applications do exist and many customers do want to be able to measure temperatures in combination with measurements of in-band radiant energy. The full answer may lie in well characterized radiance and irradiance with the concepts of radiance temperature and in-band radiance.

If we start with spectral radiance, and well-understood broadband sources such as quartz tungsten halogen (QTH) lamps, then we are in a comfortable arena for well-established laboratory standards and metrics. The key may be in language and units rather than changing test methodology. For example, FEL lamps and integrating spheres based on QTH are well understood, stable calibration sources that are used for silicon-based testing of irradiance, radiance and UV-VIS and NIR performance. They are not blackbody sources, but they are close. If one has the spectral radiance measurement of these sources, and that spectral radiance curve is stable over time, then even though they don't match blackbodies, they can still be used in absolute characterization of silicon sensors and cameras. The same sources don't stop in the SWIR region, in fact, they have very useful, regular spectra that can be used for precision measurement and exhibit exceptional stability. With spectral radiance data in W/m^2-sr-µm taken at a decent resolution with a spectrometer, absolute values can be calculated in bands of interest, or equivalence in specific bands can be made to blackbodies with radiance temperatures. Examples of these-sphere radiance equivalencies are given below:

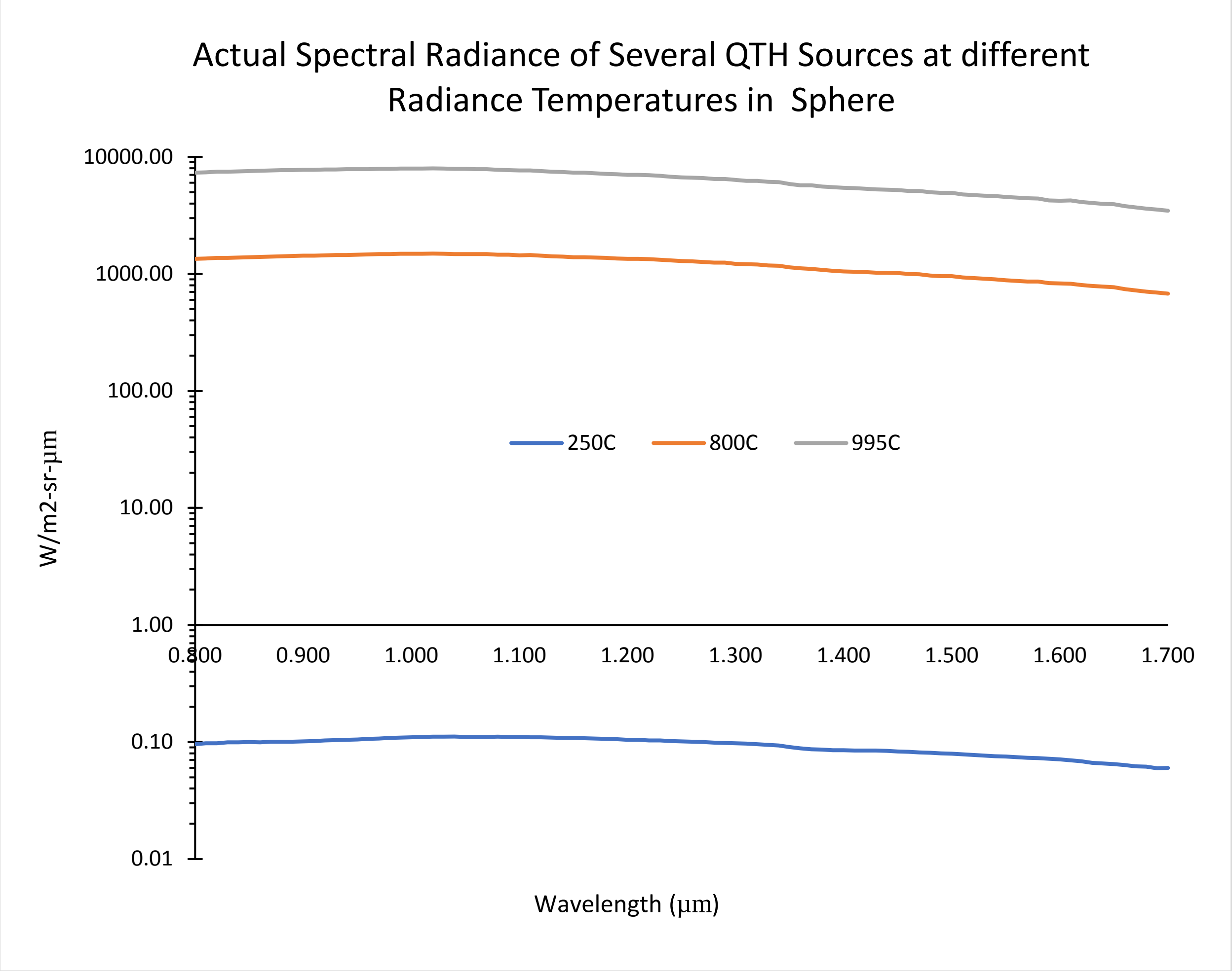

Figure 2. Sphere emulation of Spectral radiance of several sources at different temperatures.

These different radiances were created with an integrating sphere and a standard QTH Lamp at about 3000K as shown below:

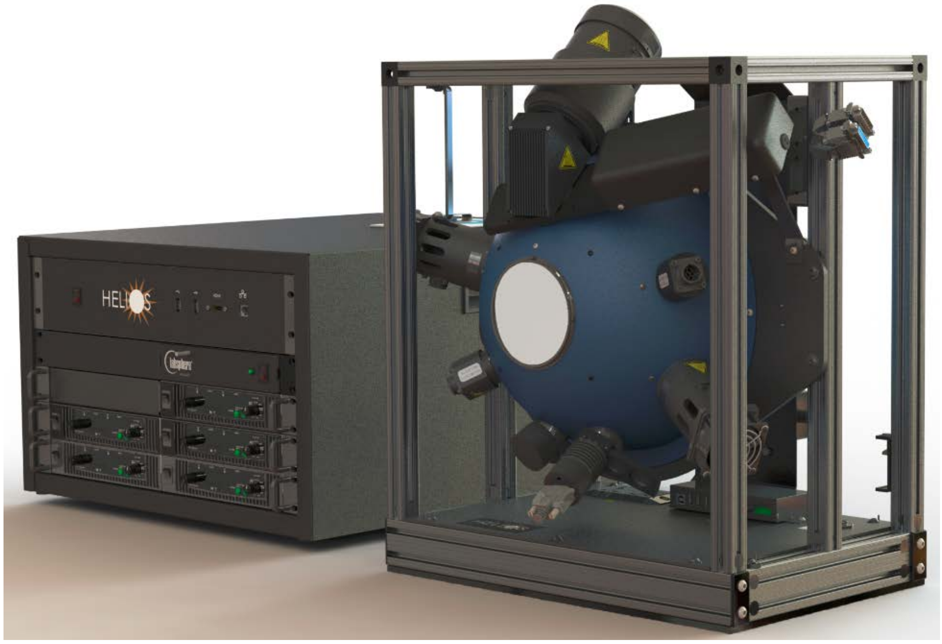

Figure 3. Labsphere Helios Integrating Sphere for SWIR Radiance Emulation

These are regular, relatively featureless, well understood and calibratable spectrums. Radiance or irradiance in band can be well defined and understood with these types of sources. There is also a dramatic dynamic range between these radiance temperatures and what can be used with a SWIR camera to emulate dynamic range tests as well as response of the camera to different radiance temperature sources if the application demands this.

QTH lamps and integrating spheres are staples for a variety of well understood and standardized test and characterization procedures. Many of these tests and standards exist today, and can be borrowed for SWIR characterization. These include Signal-to-Noise Ratio (SNR), Signal Transfer Function (SiTF), Quantum Efficiency (QE), 3D Noise and Non-Uniformity Correction (NUC). These tests are well defined in standards such as EMVA 1288 and NVESD.

So, having shown that radiance, or radiance in-band, or radiance temperature equivalents can be used to create analogous silicon tests with QTH lamps and spheres, we have a well-established set of tests that we can turn towards InGaAs fundamental performance. However, even with a good calibration source, we still have an “alphabet soup” of ways that one can talk about all of these different units and metrics. There is no single unit of measure that can be used for quick inter-comparison of basic InGaAs sensors, and attempts to convey a simple test scale can get caught in the complexities of human language.

In the visible band, for a shorthand reference for test conditions, the lux is used with silicon sensor testing simply because it provides a scale reference that one engineer can relay to another engineer that has grounding in human experience and radiometric validation. Sometimes lux is misleading, as with night vision sensors which lean toward NIR peak responsivity, but it does provide a common reference unit and scale that the start of a proper conversation can based on. In fact, many SWIR camera conversations still try to start with Lux as a reference scale, such as “moonlight-equivalent LUX in the SWIR region”. What does that mean? There are a lot of ways to interpret this optically! There is no similar scale language yet for InGaAs community, so they are borrowing from the ubiquitous power of the lux scale. This borrowing of the Lux leads to confusion since the two spectral regions are often not related with spectral radiance units as a foundation. So, we believe a new unit is needed to discuss SWIR camera performance and scale of light in this region for InGaAs cameras.

This new unit is called the “Swux”, which is an abbreviation of “SWIR-Lux”. The unit was first proposed by two of the authors in April of 2017 at the SPIE DCS conference in Anaheim.[1] The Swux is a measure of SWIR irradiance weighted by a spectral response function S(lambda). This function, shown in Figure 4, is analogous to the V(lambda) function used in the derivation of the Lumen and Lux units, and is the “average” spectral response for many commercially available InGaAs detectors that can be used to fabricate Swux meters. A Swux meter can give an InGaAs camera user a single-number irradiance parameter that is highly correlated with the imaging performance of the InGaAs camera in a variety of different lighting conditions. The Swux unit can also be used to characterize the output of well-established calibration test methods like radiance from a sphere-based uniform source or FEL-based irradiance at an imaging sensor under test.

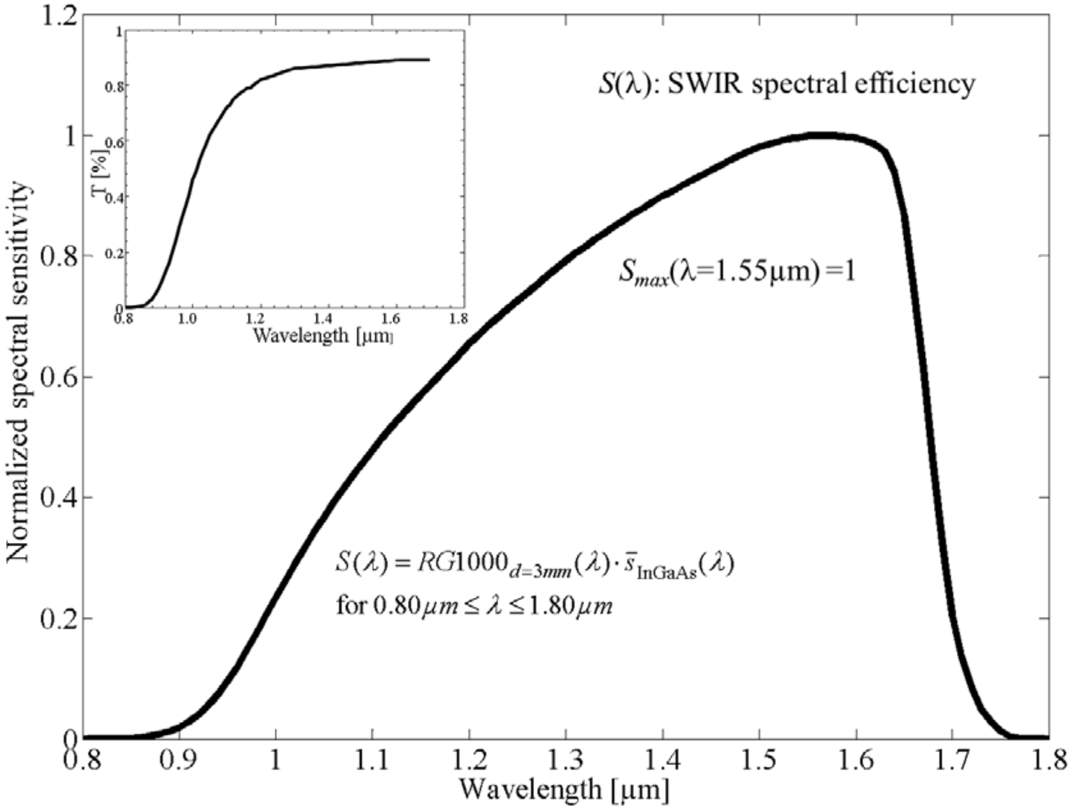

Figure 4. S(lambda) function for the derivation of the Swux unit

The Swux unit is a much-needed method of characterizing SWIR irradiance with a single-number measurement that traces back to an agreed-upon standard for spectral shape and absolute magnitude. The Swux meter is particularly useful to characterize irradiance conditions where the irradiance spectra are not precisely known or controlled. Traditionally, workers in the SWIR band have had to determine the spectral irradiance for a scene in the field using a spectroradiometer to be able to then derive a spectrally-weighted irradiance for their particular camera system. Commercially available spectroradiometers in the SWIR band are expensive and bulky instruments, and, generally, do not have the sensitivity to measure spectral irradiance under nightglow conditions. An alternative method that has more sensitivity than the spectral method, would be to use a single-element InGaAs detector with a large active area as a SWIR meter to measure relative light levels. This ad-hoc approach is useful, and much more relevant to observed camera performance than a lux measurement, but it still does not give an absolute in-band irradiance value, or any measurement that holds to an agreed-upon standard. The spectral response of the single-element InGaAs detectors is different from InGaAs camera pixels, so there is no effective way to draw an equivalence between the measured irradiance for a given InGaAs detector and the performance of an InGaAs camera.

The Swux unit remedies this problem, because the unit is built on a defined spectral shape, just like the lux unit. A single-element InGaAs detector is combined with a Schott RG1000 filter to make a stack that can be calibrated in the laboratory as a Swux meter by using a source with a known absolute output as a function of wavelength. A correction factor is applied to account for variations between the detector/RG1000 stack and the S(lambda) function. We have found that the correction factors for several as-built Swux meters are very close to unity for a variety of lighting conditions, so the error introduced even if the correction factor is not used is still fairly small. Swux meters based on different InGaAs detectors still read out the same Swux values, especially if the correction factor is applied.

The Swux meter is particularly useful in a low-light field test situation where a number of cameras from different vendors are being compared to each other. The Swux meter can characterize the InGaAs spectrally-weighted irradiance from downwelling nightglow and light pollution while cameras are imaging and recording the ambient scene. Thus, all the camera images can be correlated later with an absolute measurement of SWIR irradiance at the time of image capture.

Conclusions

It is the authors' hope that this discussion on SWIR units will spur the industry to talk to itself and take action to form working groups on these topics. Armed with better language, new units, spectral radiance and testing analogs to silicon sensors, a new generation of InGaAs sensors can proliferate further in current applications and realize their full market potential. Using common unit language, silicon-based testing metric analogs and objective baseline testing will promote customer confidence that the SWIR camera they acquire will meet their intended solution. The Swux unit and standard definition is needed for SWIR cameras.