Hyperspectral Imager Characterization and Calibration

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ABSTRACT

Current radiometric calibration standards, specifically blackbody and lamp-based optical radiation sources, produce spatially, spectrally, and temporally simple scenes. Hyperspectral imaging instruments, which in-practice view spatially, spectrally, and temporally complex scenes, would benefit from advanced radiometric artifacts that more closely resemble scenes the sensor will ultimately view. Techniques and artifacts that advance sensor characterization and algorithms that reduce the impact of scattered light on sensor performance are presented in this work. Example applications of the new technologies and algorithms on remote sensing hyperspectral imaging instruments are presented.

Index Terms— Radiometry, Calibration, Image Generation

1. INTRODUCTION

In the past decade great strides have been made in the ability to perform radiometric calibration and characterization of spectrometers. The introduction of detector-based reference standards allows radiometric calibrations at the 0.05% level. The use of monochromatic sources in these systems permits the introduction of stray light correction algorithms to further enhance the characterization of spectrometer performance. These same techniques have been applied to improve the calibration of hyperspectral imaging systems. However, during these calibrations the hyperspectral imager is viewing a ‘scene’ that is both spatially and spectrally uniform. In practice the imager will be viewing scenes that are both spatially and spectrally complex.

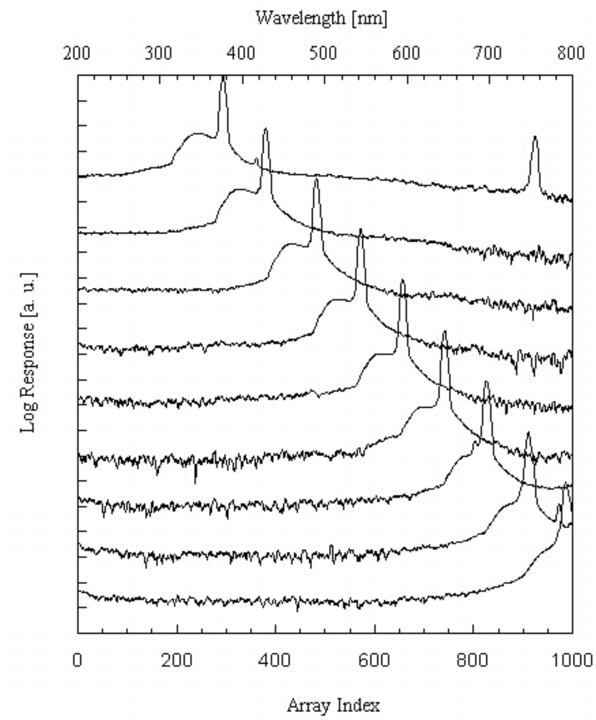
The lack of appropriate artifacts limits the ability of researchers to fully characterize and understand the radiometric performance of hyperspectral imaging sensors in the laboratory, with the result that problems in a sensor’s performance can remain undiagnosed or be first observed when the instrument is in-use. Lacking adequate characterization, it is not possible to develop algorithms that correct a sensor’s output for limitations in performance. Advanced radiometric artifacts that enable more complete instrument characterization in the laboratory can facilitate development of correction algorithms with the resulting potential benefit of improved radiometric performance.

2. RADIOMETRIC CHARACTERIZATION TOOLS

The wavelength accuracy, bandwidth, and available power combine to make tunable lasers powerful tools for characterizing and calibrating larger aperture hyperspectral imaging systems. The National Institute of Standards and Technology, NIST, (USA) has recently expanded on laser-based facilities previously developed at NIST and the National Physical Laboratory, NPL, (UK) and developed a broadly tunable laser-based radiometric calibration facility.[1] The Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) facility has been used to characterize and calibrate spectrographs as well as hyperspectral imaging systems.

The SIRCUS facility contains a suite of tunable lasers that span the wavelength range from 200 nm to 5 µm which can be fiber coupled into an integrating sphere. Transfer detectors that have been calibrated for spectral radiant power responsivity against the Primary Optical Watt Radiometer (POWR), NIST’s primary optical power standard, and equipped with a precision aperture,[2] are used to measure the irradiance of the integrating sphere along with the device under test. This procedure allows for a calibration at the 0.05% (k=2) level from 400 nm to 950 nm.

Figure 1. Relative responsivity of a hyperspectral imager for a series of monochromatic inputs measured on SIRCUS. The series of measurements can be used to create a stray light correction



matrix. Application of the matrix to measured spectra can reduce the stray light errors by 1 to 2 orders of magnitude.

3. SCATTERED LIGHT CORRECTION ALGORITHMS[3;4]

In an ideal spectrometer, the entrance slit would be perfectly imaged on the detector array and no input flux would fall on the detector outside of this image. In practice, imperfections in the dispersive elements and scattering from all the optical elements in the spectrometer lead light of a given wavelength to illuminate many, if not all, the elements of the detector array, as seen in Figure 1. Spectral[5] and spatial[5;6] stray light correction algorithms have been developed for spectrographs and imaging systems based on the characterization of the radiometric system using tunable laser sources. These algorithms correct measurements for errors introduced by scattered light by one to two orders of magnitude. The spectral stray light correction algorithm has been successfully used to correct hyperspectral instruments used in the vicarious calibration of ocean color satellite sensors[7] and instruments used to measure Light Emitting Diodes (LEDs).

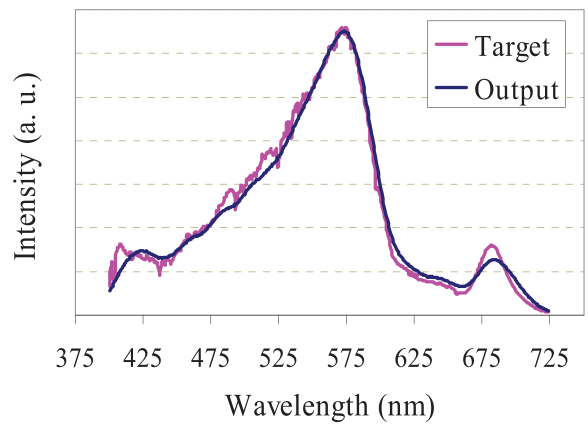


Figure 2. The output of an STS is used to mimic an ocean color spectrum (target).

4. ABSOLUTE DETECTOR-BASED SPECTRALLY TUNABLE SOURCE[8;9]

Spectrally tunable sources (STSs) with user-definable output are based on placing a Digital Micromirror Device (DMD) at the focal plane of a spectrograph, thereby replacing a multi-element detector, such as a charge-coupled device (CCD), with a 2-d array of aluminum mirrors that can be individually addressed, i.e. turned on or off. In an STS, incident radiation is dispersed across the array of mirrors. By turning on different columns of mirrors, different spectral components of the incident radiation are reflected; by turning on individual mirrors within a column, the intensity of the reflected radiation at that particular wavelength can be controlled. Figure 2 shows an example of how the output of a source can be modulated by the DMD to mimic a desired spectral output.

By running the tunable source in ‘monochromator-mode’, so turning on only one (or a few) column(s) at a time, and measuring the resultant output radiant flux with a calibrated photodiode, it is possible to place an absolute spectral radiant power scale on the integrated output of the source, resulting in an absolute detector-based source. The source can be used to directly calibrate an instrument in a manner similar to the tunable laser based approach of SIRCUS. The STS can also be used to validate the performance of an instrument by generating a variety of known source spectral distributions. These distributions can mimic the types of spectra more typically encountered in the field: broadband spectra with relatively narrow emission and/or absorption features.

5. HYPERSPECTRAL IMAGE PROJECTOR[10]

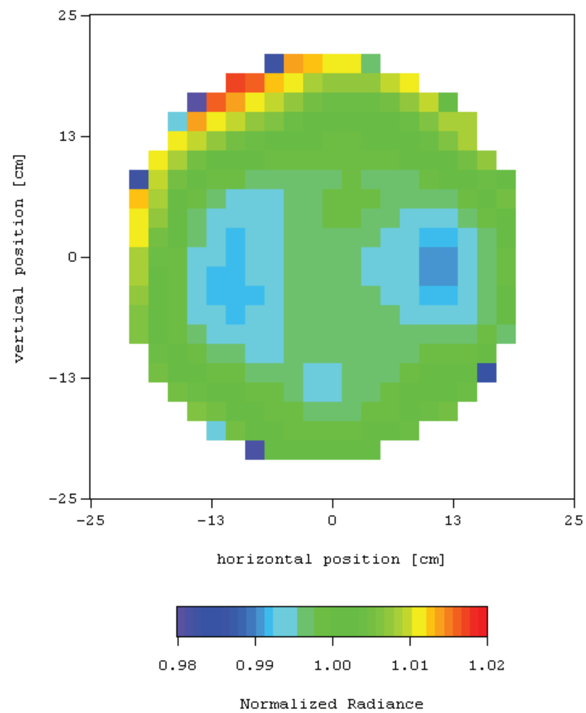
The techniques discussed so far have focused on the hyperspectral nature of the instruments but have ignored the imaging component. The calibration and validation sources discussed above are by design highly spatially uniform as shown in Figure 3. This is beneficial for calibration, but just as a spectrally uniform source can not provide a realistic spectrum for validating the performance of a spectrometer, a spatially uniform source can not provide a realistic validation scene for an imaging system. Commonly available tools for generating complex scenes, such as color photography, color printing, color television displays, and DMD based projectors, use a three or four color system (e.g. red, green, blue (RGB) or cyan, magenta, yellow, key (CMYK)) to approximate true color in the display for human vision. So, while these systems are capable of creating spatially complex scenes, they have very limited spectral capabilities.

A Hyperspectral Image Projector (HIP) is a system designed to project a user-definable, high-resolution spectral distribution into each pixel in a projected scene. A HIP consists of an STS coupled with a spatially programmable projection system. Thus a unique spectrum can be programmed for each pixel in the display. A hyperspectral imager can then view the HIP display and see a scene that is both spatially and spectrally complex and fully calibrated. The HIP serves as a radiometric platform for the development of application-specific metrics to quantify the performance of sensors and systems in terms of the accuracy of measurements of standardized sets of spatially, spectrally and temporally complex source distributions. In essence, the HIP will be a radiometric platform for laboratory validation of a hyperspectral imager calibration. The same platform can also serve as a basis for algorithm testing and instrument comparison. The HIP can also be applied to multi-band sensors that do not have contiguous bands. Indeed, since the HIP supplies spectral radiance even between the bands, as the sensor will be exposed to in the real world; out-of-band stray light problems can potentially be discovered in these sensors as well.

6. CONCLUSIONS

The technologies and algorithms discussed serve to improve the characterization, calibration and ultimately the performance of radiometric hyperspectral imaging systems, instruments that play a key role in areas ranging from Earth remote sensing, medical imaging and law enforcement. The ability to provide calibrations with low uncertainties and validate the performance of instruments under test conditions similar to their intended use will require the continued development of validation systems. Work continues at NIST on exploration of new technologies and algorithms to aid in the characterization and calibration of radiometric instrumentation.

(a)



(b)

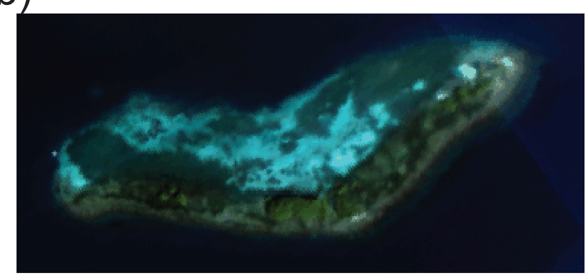


Figure 3. The integrating spheres used in calibrations are designed to have a highly uniform spatial distribution (a). A hyperspectral image of Enrique reef (Puerto Rico) taken with an AISA Eagle airborne sensor shows the spatial and spectral complexity of typical scene data (b). The instrument has 3 nm spectral bans from 400 nm to 995 nm. Channels at 649 nm, 550 nm, and 459 nm for red, green, and blue respectively were used to create this image.[11] Validation tools need to be able to mimic this level of spatial complexity with the full spectral complexity.

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