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Use of Eutectic Fixed Points to Characterize a Spectrometer for Earth Observations

Saber G. R. Salim · Nigel P. Fox · Emma R. Woolliams · Rainer Winkler · Heather M. Pegrum · Tong Sun · Ken T. V. Grattan

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Abstract A small palm-sized, reference spectrometer, mounted on a remote-controlled model helicopter is being developed and tested by the National Physical Laboratory (NPL) in conjunction with City University, London. The developed system will be used as a key element for field vicarious calibration of optical earth observation systems in the visible-near infrared (VNIR) region. The spectrometer is hand held, low weight, and uses a photodiode array. It has good stray light rejection and wide spectral coverage, allowing simultaneous measurements from 400 to 900 nm. The spectrometer is traceable to NPL's primary standard cryogenic radiometer via a high-temperature metal-carbon eutectic fixed-point blackbody. Once the fixed-point temperature has been determined (using filter radiometry), the eutectic provides a high emissivity and high stability source of known spectral radiance over the emitted spectral range. All wavelength channels of the spectrometer can be calibrated simultaneously using the eutectic transition without the need for additional instrumentation. The spectrometer itself has been characterized for stray light performance and wavelength accuracy. Its long-term and transportation stability has been proven in an experiment that determined the "World's Bluest Sky"—a process that involved 56 flights, covering 100,000 km in 72 days. This vicarious calibration methodology using a eutectic standard is presented alongside the preliminary results of an evaluation study of the spectrometer characteristics.

Keywords Earth observation · Eutectics · Fixed points · Satellites

S. G. R. Salim (✉) · N. P. Fox · E. R. Woolliams · R. Winkler · H. M. Pegrum
National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK
e-mail: saber.salim@npl.co.uk

T. Sun · K. T. V. Grattan
City University, Northampton Square, London, EC1V 0HB, UK

1 Introduction

Earth observation satellites are characterized by their wide spatial coverage, and regular and long-term data collection. This has made them the main source of global data about the Earth. They are currently able to provide data for a wide range of fields such as topography, oceanography, biological distribution, atmospheric conditions, and climate [1]; in this context the accuracy and validity of satellite data is of vital importance. Although considerable effort has been put into improving the accuracy of satellite sensors before launch through a rigorous calibration process, the stress of launch and the harsh environment of space degrade the sensor response and the performance of any onboard calibration equipment, which significantly reduces the accuracy of the measurements they provide. Therefore, it is very important to improve methods for post-launch vicarious calibration and validation of data from satellite sensors and encourage their adoption.

Current techniques for vicarious calibration depend on the accurate characterization of a test site before it can be used as a reference or standard source [2]. Unfortunately, these techniques are limited by several issues. For example, for the ground-based techniques, where small hand-held spectrometers are used to characterize the test site, only a small area is physically sampled. Similarly, when more detailed angular information is required, a larger instrument such as the Gonio RAdiometric Spectrometer System (GRASS) can be used, but due to its size, there are some restrictions to the measurement location [3].

Moreover, in many cases the process is time consuming, and this in turn increases the uncertainty due to the effect of the changing environment and sun angle particularly. By contrast, the use of airborne techniques can cover wide areas in a relatively small time, but the method is very expensive. This makes it largely unaffordable and restricted to very specific campaigns. In addition, regardless of the technique being used, the accuracy and traceability of the optical sensors is still a question, and to ensure the highest accuracy, the detectors should be traceable to an internationally accepted primary standard, which is not the general case for such instrumentation.

In order to increase the accuracy of current earth observation measurements, a novel ground-based calibration and validation technique that avoids many of the previously mentioned limitations is proposed. This incorporates the development of a small size reference spectrometer, with good stray light capabilities and wide spectral coverage. The spectrometer will be mounted on a remote-controlled model helicopter to provide calibrated reference data for optical earth observation systems in the VNIR spectral region. Furthermore, the spectrometer is traceable to the NPL primary standard cryogenic radiometer [4] through a novel high-temperature fixed-point metal-carbon (M-C) eutectic blackbody, which is an ideal source of spectral radiance.

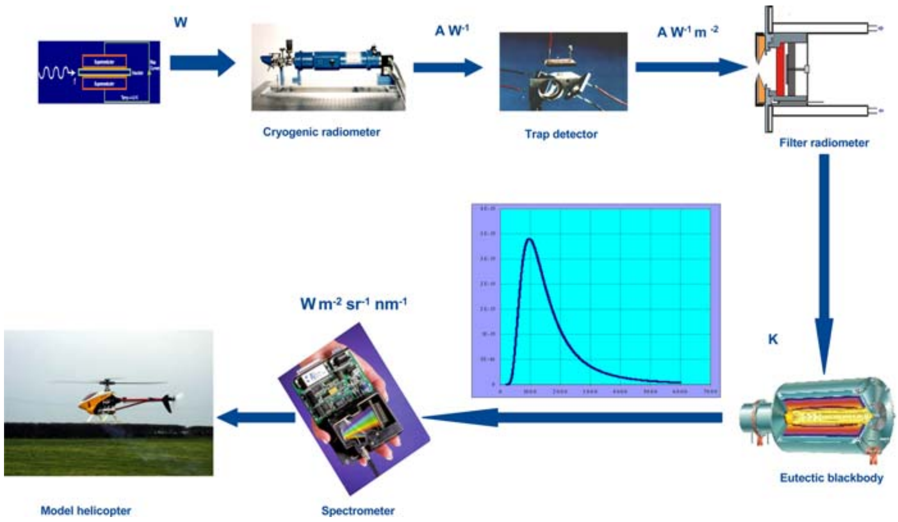

Fig. 1 Traceability chain of the spectrometer

2 The Spectrometer

2.1 Spectrometer Traceability

The spectrometer will be calibrated against an M-C eutectic blackbody. The traceability chain of the spectrometer is shown in Fig. 1. A blackbody is an ideal source of spectral radiance, provided the thermodynamic temperature has been determined. The spectral radiance of the blackbody over the emitted spectral range can then be calculated using Planck's law. Traceability to the SI comes from the determination of the thermodynamic temperature of the blackbody using filter radiometers [5]. The spectral responsivity of the filter radiometer is traceable to the cryogenic radiometers [4] via trap detectors [6].

2.2 Spectrometer Specifications

The calibrated spectrometer (or a group of spectrometers, if possible) will be mounted on a remote-controlled helicopter along with support equipment, such as a viewing camera, a global positioning system (GPS), a compact computer, and a laser source. The weight that a remote-controlled helicopter can carry is limited (~5 kg), so a small and lightweight spectrometer is required. However, the smaller the size of the spectrometer, the larger is the effect of stray light. Although photodiode arrays have a significant advantage in spectrometer design in terms of size and weight, the effect of stray light can be greater when compared to other spectrometer designs.

Stray light can be defined as any undesired signal that is measured simultaneously with the desired signal. There are many sources of stray light, some of which are due to disorders or imperfections in the grating grooves or roughness on the surface of the grating. Other sources may include higher-order diffraction or scattered light from the inside surface of the spectrometer walls, the internal input optics, or the optical mounts. All of these sources can be avoided or corrected in ordinary mechanical spectrometers. However, the problem in photodiode array spectrometers is that they detect all the light diffracted from the grating at the same time, which, in turn, causes each pixel both to detect stray light and also to re-scatter it, thus increasing the effect of the undesired signal.

Stray light errors arise during the calibration of the array spectrometer. Often, a spectrometer is calibrated against a reference source of spectral radiance/irradiance, e.g., a blackbody or an incandescent lamp, where the peak wavelength is usually located in the red or the near-infrared spectral region. When the spectrometer is used to measure the spectral radiance/irradiance of a source that has a completely different spectral distribution, the stray light errors coming from the reference source can no longer assumed to be the same as those of the source under test [7].

Two custom-made spectrometers were chosen for this work, both are characterized by their small size, lightweight, and wide spectral coverage, all are well-suited to the requirements of this application. These are discussed below:

1. The first spectrometer is a Hamamatsu mini-spectrometer TM series C10083MD with 1,024 pixels, where the actual spectral range of the spectrometer is from 250 to 1,025 nm. The dispersive element is a transmission holographic diffraction grating made of quartz, so high throughput and low stray light are expected. The light is guided into the entrance port of the spectrometer through an optical fiber, a collimating mirror directs the beam onto the grating, and the light transmitted by the grating is focused onto a built-in image sensor by a focusing mirror. Data acquisition is via a USB interface, which also provides the power necessary for circuit operation. This means that no external power supply is needed.
2. The second spectrometer is from the Spectroscopic Analytical Developments Company (SAD spectrometer). The spectrometer is attached to a control box that requires an additional power supply, which makes the total weight of the spectrometer relatively large in comparison to the Hamamatsu spectrometer. The SAD spectrometer has 1,024 pixels that cover a spectral range from 350 to 1,150 nm. In order to reduce the stray light signal, modifications have been made to the spectrometer: the internal surface of the spectrometer has been painted with a black coating and a baffle has been added to separate the higher-order diffraction.

The spectrometers have been characterized for stray light performance using a set of cut-on filters and an FEL-type tungsten halogen 1 kW lamp. Assuming a zero transmittance below the cut-on wavelength, the cut-on filter prevents the direct light from the source below the cut-on wavelength from entering the spectrometer. Ideally, the pixels positioned to normally detect this light should give a zero signal, which is not the actual case because of the presence of stray light. Although evaluating the effect of stray light using cut-on filters is not ideal, as the value depends on the source used in the evaluations, it does give an understanding of how much stray light is inside the spectrometer, and it is also a good and fast way to compare stray light rejection for different spectrometers.

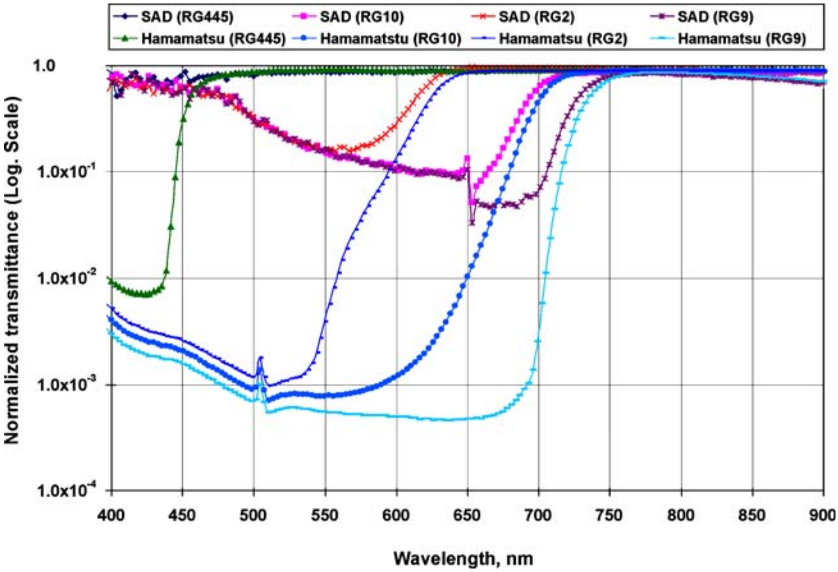

Fig. 2 Ratio of the stray light signal to the lamp signal using different cut-on filters for both spectrometers

Typical relative spectral stray light values for array spectrometers using a broadband source are of the order of 10^{-1}–10^{-3} of the source signal, but this depends on the quality of the array spectrometer [7]. The stray light rejection for both spectrometers is shown in Fig. 2. The figure shows that the stray light performance of the Hamamatsu spectrometer is considerably better than that of the SAD spectrometer, as it is well below 1.0% of the FEL lamp signal. However, further evaluation of the stray light performance will be adopted in the future by using monochromatic light, in order to apply a correction before using the spectrometer in the field. A method similar to that described elsewhere will be used [7].

The wavelength accuracy of the Hamamatsu spectrometer was determined using spectral lamps, which showed an error in the wavelength of the order of ± 1 nm. The full width at half maximum (FWHM) was also checked using the He-Ne laser line and it was found to be around 4.5 nm, which is sufficient for this application.

The long-term and transportation stability of the Hamamatsu spectrometer was evaluated in another experiment in collaboration with the travel company Expedia. In their "Blue Sky Explorer," which was designed to determine the "World's Bluest Sky," the instrument underwent a total of 56 flights, covering 100,000 km in 72 days [8]. The results showed no significant changes in the wavelength accuracy or the spectrometer readings before and after the series of flights.

2.3 Spectrometer Calibration

To calibrate the spectrometer, an ideal source of spectral radiance is required. Currently, many national metrology institutes (NMIs) use variable high-temperature blackbod-

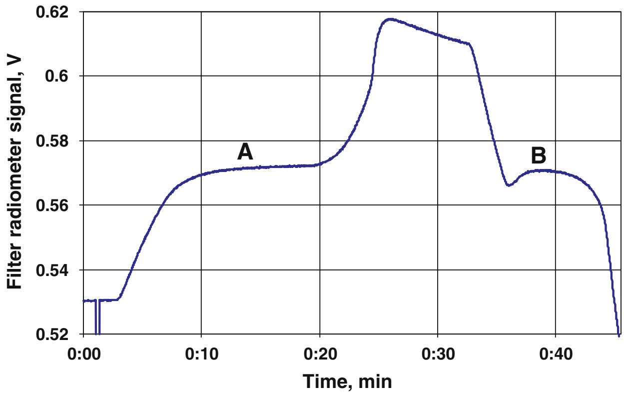

Fig. 3 Melt and freeze plateaux of the eutectic cell

ies to establish their spectral radiance and irradiance scales [9]. Variable temperature blackbodies can operate at very high temperatures (up to 3,500 K), which is an advantage in terms of output power, especially at shorter wavelengths. The spectral radiance of these blackbodies must be determined using filter radiometers. These filter radiometers are prone to drift, which means that they need frequent recalibration through a long and relatively expensive calibration chain.

An alternative approach would come from using fixed-point blackbodies. Once the temperature of a fixed point has been determined and defined, no further filter radiometer measurements would be required and the blackbody spectral radiance would be known directly. M-C eutectic fixed-point blackbodies [10] have high melting temperatures and, therefore, provide measurable spectra into the ultraviolet.

As well as the convenience of not needing a recently calibrated filter radiometer, these fixed points are expected to have reproducibilities of the order of 100 mK ($k = 2$), 2–3 times better than the short-term stability of a variable temperature blackbody. An internationally defined temperature, based on a combination of the best temperature measurements, will also always be superior to a day-to-day measurement of a variable temperature blackbody's temperature. Furthermore, the eutectic blackbody has high uniformity and better emissivity than that of a variable temperature blackbody.

During our recent measurements [11] to determine the thermodynamic temperature of eutectic blackbody cells, we used the Re-C blackbody as a reference source to calibrate the photodiode array spectrometer. Other higher temperature metal carbide-carbon (MC-C) blackbodies such as TiC-C or HfC-C may be adopted in the future.

As the temperature of the Re-C eutectic cell increases during the heating process, the spectral output increases. This can be monitored over time with a filter radiometer, as shown in Fig. 3. The plateaux occur at the melting (A) and freezing (B) points of the Re-C cell. It is widely accepted that the melting point is more repeatable than the freezing point [12]. The melting point of a eutectic blackbody has been defined as the minimum of the first differential of the melting process with respect to time [10], and the spectrometer will be calibrated at this minimum point.

The light from the blackbody was focused into the diode array spectrometer using two off-axis parabolic mirrors, the first focusing on the cavity of the eutectic cell and the second on the fiber optic feeding the spectrometer. The eutectic was heated to 20 K below the melting temperature while being monitored with a filter radiometer. The normal current step was applied to the furnace to heat the eutectic to 20 K above the melting temperature and the melt was observed with the spectrometer on a 1 s integration time. This setup gave a strong, low-noise signal on all channels of the spectrometer. The melt was clear as the spectral curves became closer together and then overlapped—with each wavelength simultaneously following a curve similar to that shown in Fig. 3.

3 The Model Helicopter

A remote-controlled model helicopter is an efficient, low cost, remote sensing device for earth observation applications. It can fly over relatively large areas and capture data more rapidly than ground-based techniques. When fitted with a spectrometer or a group of spectrometers, the helicopter will make relatively large-scale measurements at a number of detection angles in order to determine the surface bi-directional reflectance distribution function (BRDF) [13].

For this application, two model helicopters were acquired; a small helicopter to learn the handling techniques and a larger one that is able to carry ~5 kg of equipment, on which the spectrometer (or group of spectrometers) and the other equipment will be mounted. The helicopter has a controllable flying range of more than 600 m diameter at height up to 300 m (depending on wind and load), which allows a spatial coverage of nearly $2.9 \times 10^5\,\mathrm{m}^2$.

4 Summary

A novel technique that provides accurate earth observation measurements is being developed and tested at the National Physical Laboratory (NPL) in conjunction with City University, London. The optical sensors used are traceable to a new reference source of spectral radiance based on high-temperature M-C eutectic fixed-point blackbodies that are characterized by their high temperature uniformity, high emissivity, robustness, and reproducibility. A remote-controlled helicopter, which is an efficient and low-cost device, will be used to carry the spectrometer. The proposed technique has the potential to provide accurate and low-cost surface measurements for large and difficult terrains over a short period of time, where the data will be used to vicariously calibrate and validate satellite-derived information.

5 Conclusions

There are many advantages in combining a calibrated reference spectrometer (with its enhanced traceability) with a remote controlled helicopter as a new technique for earth observation measurements and these advantages include:

- Reducing the uncertainty in the current earth observation measurements through traceability to an ideal standard source of known spectral radiance, and providing a set of reference data to vicariously calibrate and validate satellite measurements.
- Covering wider areas compared to other ground-based techniques.
- The ability to fly over difficult terrains without damaging the test site.
- The ability to provide surface measurements at different angles.
- Reducing the time of data collection, which in turn reduces the uncertainties due to the effects of the changing environment.
- A remote-controlled helicopter is not large in size or heavy in weight, and this makes it very easy to transport without incurring restrictions on the measurement location.
- The field-of-view could easily be changed to adapt to the experimental requirements by changing the helicopter's altitude.
- A single person could run the experiment in the field.
- It is an accurate, fast, and cheap technique, which has potential applications for use in a variety of measurements.

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