

REFERENCE SPECTROMETRY FOR CALIBRATION OF OPTICAL EARTH OBSERVATION SYSTEMS

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ABSTRACT:

A small palm-sized, reference spectrometer, mounted on a remote controlled model helicopter is being developed and tested to provide calibrated reference data for optical Earth Observation systems by the National Physical Laboratory (NPL) in conjunction with City University in London. The spectrometer is traceable to NPL's primary standard cryogenic radiometer. The traceability chain includes the use of a novel high temperature fixed-point metal-carbon eutectic blackbody as an ideal source of spectral radiance, whose thermodynamic temperature is measured using absolute radiation thermometry. The spectrometer is a hand held, low weight, photodiode array, which has good stray light capability and wide spectral coverage, from 400 nm to 900 nm, in a single scan. Combining a calibrated small spectrometer with a remote controlled helicopter is a novel solution for providing efficient low cost remote sensing over relatively large or difficult terrains. This technique minimizes potential damage to a site from human observers and can cover much wider areas in shorter timescales. Data obtained will be used to validate satellite measurements of terrestrial targets and determine its spatial homogeneity. This paper describes this vicarious calibration methodology using a eutectic standard and the preliminary results of an evaluation study of the spectrometer characteristics.

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, in which context the accuracy and validity of satellite data is of vital importance. Although a lot of effort has been put into improving the accuracy of satellite sensors before launch, the stress of launch and the harsh environment of space degrades the sensor response and the performance of any on-board calibration equipment. Therefore, it is very important to improve methods for post-launch calibration and validation of data from satellite sensors and encourage their adoption.

Current techniques that are used to calibrate satellite sensors after launch depend on the accurate characterization of a test site before it can be used as a reference or standard source (Dinguirard, 1999). Unfortunately, these vicarious calibration techniques are limited by several issues. For example, for the ground-based techniques where small hand held spectrometers are used to characterise 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 (Pegrum, 2006). Moreover, in many cases the process is time consuming and this in turn increases the uncertainties 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 performance and wide spectral coverage. The spectrometer will be mounted on a remote-controlled model helicopter to provide a set of reference data in the Visible Near Infra-Red (VNIR) spectral region to calibrate optical Earth Observation systems.

2. THE SPECTROMETER

2.1 Spectrometer Traceability

The spectrometer will be traceable to NPL's primary standard cryogenic radiometer (Fox, 1995) through a novel high temperature fixed-point Metal-Carbon (M-C) eutectic blackbody. The traceability chain of the spectrometer is shown in Figure 1. A cryogenic radiometer is essentially a detector that compares the heating effect of optical radiation to the heating effect of the electric power. It depends on the electrical substitution principle that has been used in radiometry for more than a century. In 1985 Quine and Martin, at NPL, managed to successfully operate a detector at liquid helium temperature (Martin, 1985). A modified version of Quine-Martin cryogenic radiometer was developed by Fox (Fox, 1995), which is able to measure optical power with an uncertainty approaching 10^{-5} (Martin, 1998).

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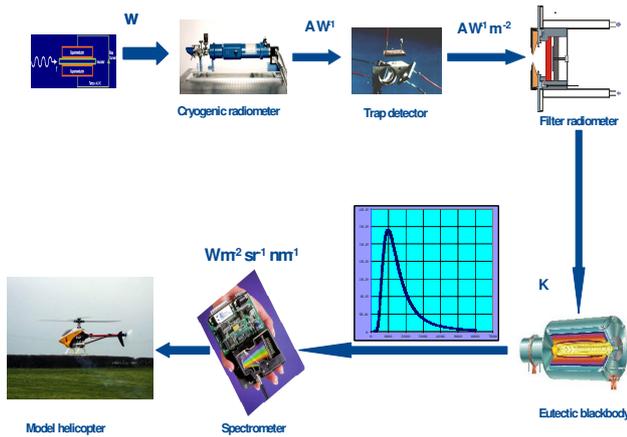


Figure 1: The traceability chain of the spectrometer.

As an absolute detector, the cryogenic radiometer can be used to calibrate the spectral responsivity of a transfer standard detector such as a trap detector (Fox, 1991) by determining the radiant power in high-stabilized laser sources. Due to their high quantum efficiency, low noise to signal ratio, good surface uniformity and predictable relative spectral responsivity, trap detectors are considered ideal transfer standard detectors for spectral radiance.

Using tuneable lasers as light sources, a trap detector- together with a calibrated aperture- can be used to calibrate the spectral response of a narrowband detector that is called filter radiometer. This calibrated filter radiometer is then used to measure the spectral radiance of a reference light source like a blackbody over a narrow spectral range in order to determine its thermodynamic temperature. Then according to Planck's law, the spectral radiance of the blackbody over the whole emitted spectral range can be calculated once the thermodynamic temperature of this blackbody has been determined (Fox, 1991).

2.2 Spectrometer Specifications

The calibrated spectrometer or a group of spectrometers, if possible, will be mounted on a remote controlled helicopter together with support equipment such as a viewing camera, a Global Positioning System (GPS), a mini-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. One draw back to this, however, is that the smaller the size of the spectrometer, the larger the effect of stray light on it. Although photodiode arrays have the significant advantage in spectrometer design in terms of size and weight, the effect of stray light on them can increase 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 disorder or imperfections in the grating grooves or roughness on the surface of the grating. Other sources may be due to higher order diffraction or attributed to 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 re-scatter it, thus increasing the effect of the undesired signal.

Stray light errors arise during the calibration process 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 be assumed to be the same as those of the source under test (Yuqin, 2006).

Two custom-made spectrometers have been chosen for this work, both of which are characterized by their small size, light weight and wide spectral coverage, all of which best suit the requirements of this application. These are discussed below:

- The first spectrometer is a Hamamatsu mini-spectrometer TM series C10083MD with 1024 pixels, where the actual spectral range of the spectrometer is from 250 nm to 1025 nm. The dispersive element is a transmission holographic diffraction grating made of quartz, so a high throughput and low stray light signal is expected. The light is guided into the entrance port of the spectrometer through an optical fibre, 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.
- The second spectrometer is from the Spectroscopic Analytical Company. The spectrometer is attached to a control box that requires an additional power supply, which makes the total weight of the spectrometer relatively high in comparison to the Hamamatsu spectrometer. The spectrometer has 1024 pixels that cover a spectral range from 350 nm to 1150 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 1kw 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 in comparing stray light rejection for different spectrometers.

Typical relative spectral stray light values for array spectrometers using a broad-band source is on the order of 10^{-1} to 10^{-3} of the source signal, but this does depend on the quality of the array spectrometer (Yuqin, 2006). The stray light

measurements for the Hamamatsu spectrometer showed that it is reasonably good in comparison to the other array spectrometer as it is well below the 1.0 % of the FEL lamp signal over the spectral range from 400 nm to 900 nm as it is illustrated by Figure 2. 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 (Yuqin, 2006).

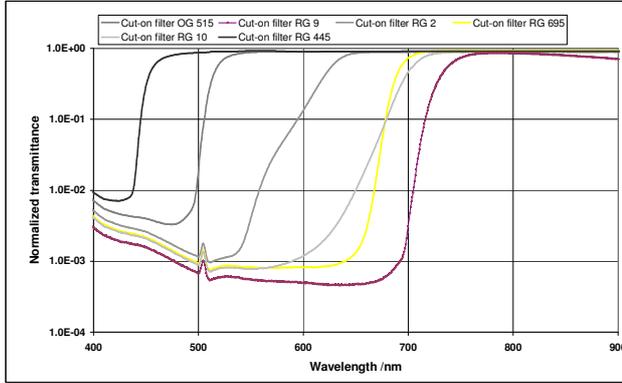


Figure 2: Filter signal to the lamp signal using different cut-on filters for the Hamamatsu spectrometer.

The wavelength accuracy of the 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 has been 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 under went a total of 56 flights, covering 100 000 km in 72 days (Pegrum, 2006). The results showed no significant changes in the wavelength accuracy or the spectrometer readings before and after the series of flights that was undertaken.

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 blackbodies to establish their spectral radiance and irradiance scales (Woolliams, 2005). Variable temperature blackbodies can operate at very high temperatures (up to 3500 K), which is an advantage in terms of output power, especially at shorter wavelengths. On the other hand, variable temperature blackbodies are only stable to ~ 0.2 % in the IR and even worse in the UV region. Moreover, the spectral radiance of these blackbodies must be determined using filter radiometers. These filter radiometers are prone to drift which means that they should be recalibrated periodically through a long and relatively expensive calibration chain, which, in turn, adds some restrictions on using variable temperature blackbodies as reference sources.

Fixed-point blackbodies can provide some significant advantages, as they have high temperature uniformity and better

emissivity and stability (Woolliams, 2006). The melting and freezing point of pure metals is an intrinsic property of the metal, which occurs at a fixed thermodynamic temperature. This intrinsic property means that a calibrated filter radiometer need only to be used once to determine the thermodynamic temperature of the blackbody, therefore avoiding costly periodical calibration of the filter radiometers.

Until recently, having a high temperature fixed-point blackbody was a problem, as the crucible that is used to hold the fixed point blackbody inside the furnace, usually made of Carbon, contaminates the pure metal during the heating process. Although Tungsten and Ceramic have high melting points, they are not the ideal substitutions for the Graphite crucible due to their low emissivity, this is why the highest fixed-point on the International Temperature Scale (ITS 90) is the copper point (1357.77 K) (Preston, 1990).

It was not until 1999, when Yamada et al (Yamada, 1999) showed that the contamination problem disappeared if M-C binary eutectic alloys were used instead of pure metals inside the graphite crucible. Since the carbon is an integral part of the eutectic alloys, a graphite crucible could be used safely. Subsequent research has shown the possibility to use a series of M-C and Metal (Carbide)- Carbon (MC-C) eutectics as fixed-points in the range from 1426 K to 3453 K (Woolliams, 2006).

In our application a high temperature M-C eutectic fixed-point blackbody will be adopted as a reference source to calibrate the spectrometer rather than using a variable temperature blackbody. As a preparation for adopting such a source, the thermodynamic temperature of Re-C, Ru-C, Pt-C and Co-C eutectic blackbody cells, which were produced at NPL, were measured by the NPL Absolute Radiation Thermometer (ART) (Salim, 2007) that has been thoroughly investigated and calibrated (Winkler, 2007).

The spectral radiance of a blackbody radiator in vacuum can be determined by Planck’s law as follows:

$$L(\lambda, T) = \frac{c_{1L}}{\lambda^5 (\exp[c_2 / \lambda T] - 1)} \quad (1)$$

Where c_{1L} is the first radiation constant for spectral radiance and c_2 is the second radiation, λ is the wavelength, and T is the temperature of the blackbody.

According to Planck’s law, the thermodynamic temperature of the blackbody can be determined if the radiance of this blackbody at a specific wavelength or over a specific wavelength band is measured. Once the thermodynamic temperature has been determined, the spectral radiance of the blackbody over the whole spectral range can be calculated.

As the temperature of the Re-C eutectic cell increases through the heating process, the spectral output increases. This can be monitored over time with a filter radiometer as shown in Figure 3. The plateaus occur at the melting (C) and freezing (E) points of the Re-C cell. The melting point of a eutectic blackbody has been defined in all publications as the minimum of the first differential of the melting process with respect to time (Woolliams, 2006), and the spectrometer will be calibrated at this minimum point.

The spectral changes in the Re-C eutectic over time were simultaneously recorded by the spectrometer at equal time intervals over the melting phase, see Figure 4. As the blackbody reaches the melting point, the rate of change in the optical output decreases and the spectral response curves move closer together. The spectral output starts to increase again after the melt, as the temperature of the blackbody increases.

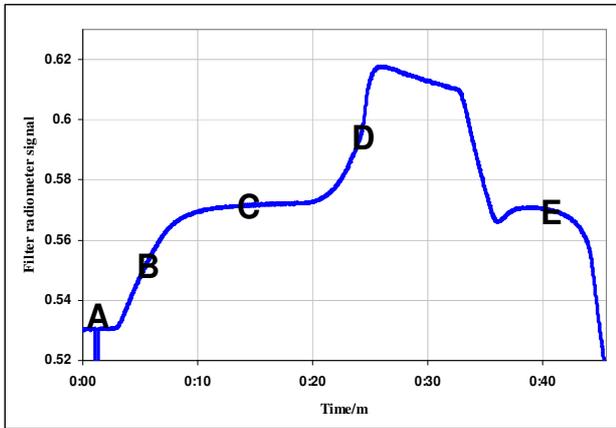


Figure 3: Melt and freeze plateaus of the eutectic cell

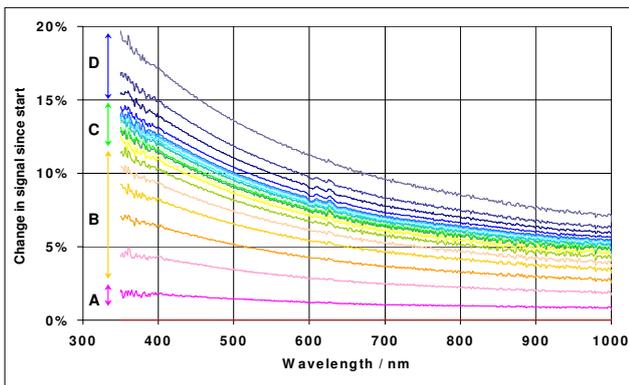


Figure 4: The spectral response of the spectrometer to the Re-C cell with time.

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 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) (Nicodemus, 1977).

For this application two model helicopters have been 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, which allows a spatial coverage of nearly $2.9 \times 10^5 \text{ m}^2$.

4. ADVANTAGES OF THE TECHNIQUE

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 any damage to 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 control 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.

5. CONCLUSIONS

A new technique that provides accurate Earth Observation measurements is being developed and tested at the National Physical Laboratory (NPL) and in conjunction with City University in London. The optical sensors will be traceable to a new reference source 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 instrument, 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 in a short period of time, the data will be used to calibrate and validate satellite information.

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