IMAGING AND FIELD SPECTROMETER DATA’S ROLE IN CALIBRATING CLIMATE-QUALITE SENSORS

Kurtis, J. Thome
NASA/GSFC – Greenbelt, MD

Abstract

The role of hyperspectral data and imaging spectrometry in the calibration of terrestrial remote sensing sensors has been a key to the development of long-term data sets. Most of these data sets are developed from multispectral imagers with tens of spectral bands rather than hundreds to thousands of bands available in spectrometry. Typical lamp-based calibration in the laboratory benefits from including spectrometer characterization of the source output. The advantage of spectrometer-based calibrations is it permits convolution of the data to arbitrary band shapes that mimic the spectral responses of the sensors being calibrated. Lamp-based calibration, while convenient to operate and control, does not simulate the solar spectrum that is the basic energy source for many of the imaging systems. Using the sun as a source for preflight radiometric calibration reduces many of these uncertainties, but introduces its own difficulties caused by the spectrally-varying effects due to the solar spectrum and atmospheric absorption. Spectrometry provides the spectral knowledge necessary to permit calibration of these sensors at a level sufficient to create climate-quality data sets. In-flight calibration has relied on imaging spectrometers on aircraft and satellites for direct comparison to other sensors to removes biases from their preflight calibrations. Similar approaches relying on ground-based, portable spectrometers have also been widely used. The current work describes the typical approaches used for preflight and in-flight calibration of multispectral imagers using spectrometer-based data. Sample results are presented to demonstrate the current state of the art. Such data sets play a critical role in the development of climatic data sets such as those expected from the Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission and application of these approaches to NASA’s upcoming CLARREO mission are discussed including proposed methods for significantly reducing the uncertainties to allow CLARREO data to be used for climate data records.

Introduction

Absolute radiometric calibration of airborne and space borne earth-observing sensors has become increasingly important. The monitoring of change, a main goal of many earth-observing sensors, is highly dependent on an ongoing knowledge of a system’s radiometric calibration. Therefore, the calibration of on-orbit sensors must be monitored starting before flight, and continually monitored throughout their lifetime (Slater et al., 1996; Butler and Barnes, 1998).

Hyperspectral data and imaging spectrometry have played a key role in the calibration of terrestrial remote sensing sensors being used to develop long-term data sets. Most of these data sets are derived from multispectral imagers with tens of spectral bands rather than hundreds to thousands of bands available in spectrometry. The multispectral approach has the advantage of reducing data rates and volumes to a level that permits the global-scale collections on near-daily time scales. The disadvantage is that combining data sets from multiple sensors over time is made more difficult by the fact that spectral bands do not match. Even subtle differences in the spectral bands of “identical’ sensors operating can cause issues with climate records.

The current work describes the prelaunch and post-launch calibration techniques that have been developed that make use of the hyperspectral nature of spectrometry data. Such efforts include typical lamp-based calibrations in a laboratory setting that benefit from inclusion of spectrometer characterization of the source output. More recently, preflight calibration work has included the use of solar-based calibrations that require the use of spectrometry data to characterize the spectral variations in the solar beam due to solar and atmospheric absorption features.

The use of the sun as a source for calibration has led to improvements in instrumentation and techniques for the preflight calibration of imaging sensors with the goal of ensuring consistency between the preflight and in-flight methods, as well as consistency between separate sensors calibrated in different laboratories (Anderson et al., 2007, Sakuma and Ono, 1993). Much of this work has concentrated on a series of transfer radiometers that are used to monitor laboratory sources that are the basis for preflight calibration (Biggar, 1998).

The advantage of the transfer radiometers is their portability allowing them to characterize a variety of sources ensuring that differences in the sources themselves are not causing differences in the results from two imaging systems. The drawback of the transfer radiometers is that they are multispectral in nature to simplify their design leading to more accurate characterization of the radiometer but poorer understanding of the spectral nature of the source. The current work describes results from the solar-based calibration of a recent imaging sensor showing how the multispectral and hyperspectral sensors combine to give an accurate, hyperspectral characterization of a solar-based source.

Post-launch approaches using spectrometry include vicarious methods, or those methods that rely on sources that are not part of the sensor itself (such as onboard lamps). One of the best known and most trusted vicarious methods is the reflectance-based (Markham et al., 2004). The reflectance-based method used in both direct calibration and as a cross-calibration requires spectrometry in order to simulate the spectral bands of the sensor of interest more accurately.

The above approaches and example results are presented in the following sections. A clear conclusion from the examples presented is that hyperspectral data are vital to an accurate understanding of energy sources in terrestrial remote sensing. Further proof of this is the design and implementation of the reflected solar instrument that is part of the planned Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission. Hyperspectral remote sensing is essential to this mission which as described here has a goal of providing SI-traceable measurements of radiance that are nearly an order of magnitude more accurate than current imaging sensors. The role of spectrometry in calibration of remote sensing instruments has proven itself over the past several decades and with missions such as CLARREO, will be a centerpiece in remote sensing for the coming decades as well.

Laboratory calibration

Common approaches for calibrating imaging sensors rely on a laboratory-based radiance calibration. This method makes use of standard sources of spectral irradiance coupled with a diffusing surface to create an extended source. The output of the source is held constant by actively controlling the current to match the lamp’s calibration current or through a feedback cycle controlled by monitoring the source output at select wavelengths.

As an example, one approach is to place a NIST primary standard of spectral irradiance at 50 cm from a Spectralon® diffuser. The reflectance of the diffuser is known through other measurements (Biggar et al., 1988; Biggar et al., 2007). The illuminated panel is viewed by the transfer radiometer at 45° from the normal. The band-averaged spectral radiance collected by the radiometer being calibrated is given by

$$\hat{L}_\lambda = \frac{\hat{E}_\lambda \hat{\rho}}{\pi} \qquad (1)$$

where $\hat{E}_\lambda$ is the band-averaged lamp spectral irradiance and $\hat{\rho}$ is the band-averaged panel reflectance factor at 45°. The band-averaged lamp spectral irradiance is the result of an interpolation of the calibration data provided by the calibration facility (NIST in this case) with the lamp for the 50-cm distance. The spectral data are generally given in several distinct wavelength increments and as mentioned, are fit with a polynomial-corrected exponential function which is numerically integrated to yield the total spectral irradiance of the lamp in each measurement band (Biggar, 1998).

The laboratory approach has been shown to have absolute uncertainties of approximately ±2% for bands in the VNIR and is slightly dependent on spectral band. Uncertainties are primarily caused by a combination of the uncertainties inherent to the irradiance calibration and its interpolation, lamp distance accuracy and instrument uncertainties.[4] A clear issue with the lamp-based method of calibration is the low output and high variability of the lamp sources at short wavelengths. Another issue is that the spectral shape of the lamp source does not follow the source generally used by most VNIR remote sensing imaging sensors; the solar spectrum.

The smooth spectral nature of the sources used in the laboratory means that minimal improvement is obtained by including spectrometry. In fact, recent work shows that a set of carefully-selected spectral bands providing highly-accurate measurements can reproduce the source spectrum at a level rivaling hyperspectral data (Keef and Thome, 2009).

Solar calibration

Lamp-based calibration, while convenient to operate and control, does not simulate the solar spectrum that is the basic energy source for many of the imaging systems. Using the sun as a source for preflight radiometric calibration reduces many of these uncertainties, but introduces its own difficulties caused by the spectrally-varying effects due to the solar spectrum and atmospheric absorption. Spectrometry provides the spectral knowledge necessary to permit calibration of these sensors at a level sufficient to create climate-quality data sets.

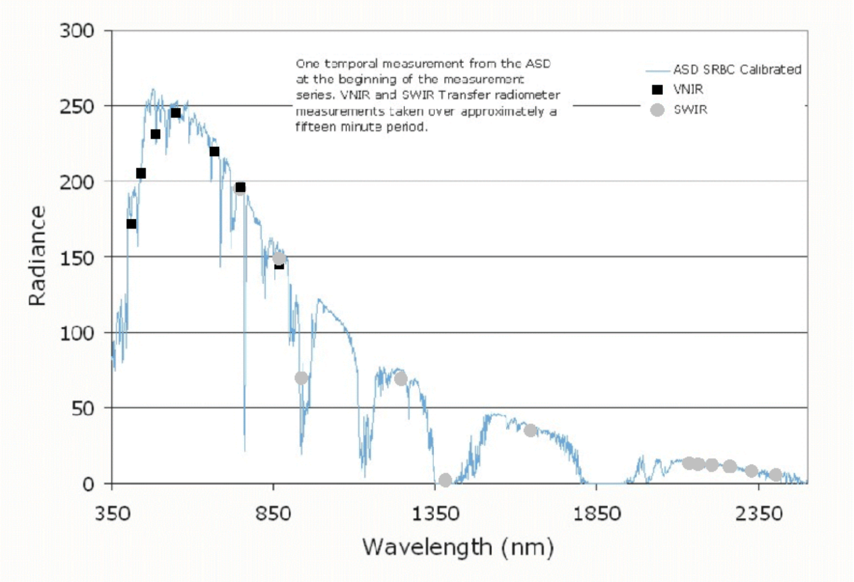
As mentioned, using solar radiation as a source has the obvious advantage of the fact that solar radiation provides the operational illumination for all passive VNIR earth-observing sensors. A lamp approximating 3000K is significantly different than solar illumination. Inherent in this difference is the fact that lamp output in the blue and UV is vastly lower than solar output. In addition, the sun is the “same” at all locations whereas two “identical” sources of spectral irradiance can differ by as much as several percent.

SRBC also has logistical advantages. A calibrated lamp and ancillary equipment can cost tens of thousands of dollars and take a fair amount of time before delivery. A lamp also has the problem that, while it is a small source, it does not simulate the angular spread of the incident solar beam at the required 50-cm distance. The close proximity of the lamp to the panel also leads to the fact that only a small portion of the reference that is on axis with the source is uniformly illuminated while cosine^4 falloff off-axis must be addressed. For sensors with a large field of view, this can be a major complication.

The approach taken combines a preflight calibration relying on the sun as the source and vicarious approaches used after launch. The combination of these methods provides NIST-traceable radiometric calibration with an uncertainty <3% (1-σ absolute) for most spectral bands. These techniques have the added advantage of a unified calibration source, the sun, for both the pre-flight and on-orbit calibrations, and a source that simulates the spectral signal expected when the sensor is in flight (Slater et al., 1996).

The method described here relies on direct measurement of the at-sensor radiance by a well-calibrated transfer radiometer. The multispectral measurements from the radiometer are converted to hyperspectral data via measurements from a field-portable spectrometer. The transfer radiometer has been calibrated by direct reference to a spectral irradiance standard provided by NIST, through direct reference of a radiance standard composed of a reflectance standard illuminated by the NIST irradiance standard, and also by an independent solar-radiation-based calibration.

An example of the results from such a measurement set is shown in Figure 1 which shows the combination of the results from the hyperspectral system and the transfer radiometers. Error analysis of the spectral characterization shows the center wavelength of a hyperspectral imager can be determined to better than 1 nm. The absolute uncertainty of the solar-based radiometric calibration is less than 3% in spectral regions not affected by strong absorption.



One temporal measurement from the ASD at the beginning of the measurement series. VNIR and SWIR Transfer radiometer measurements taken over approximately a fifteen minute period.

Figure 1. Radiance from a solar-illuminated reference panel reported by transfer radiometers and field spectrometer.

Inflight calibration

One method that has been used for calibration and intercomparison of sensors outside of the laboratory is the reflectance-based method of vicarious calibration (Slater et al., 1987). The reflectance-based method has been used for numerous sensors including hyperspectral and multispectral sensors, large and small footprints, and for near-nadir and off-nadir views. The reflectance-based method uses ground-based measurements to characterize the surface of a test site and the atmosphere over that test site. The results of these characterizations are inputs to a radiative transfer code to predict at-sensor radiance. The approach has been used for a wide range of spatial resolutions at sites ranging in size from 100 m in size to over 30 km.

Recent results show that the method can be implemented with precision that is approaching 2% in some bands and precision at the 1% level for sensor cross-comparisons in the NIR. A desire to increase the number of possible reflectance-based calibration opportunities led to develop automated data collection schemes (Thome et al., 2004).

Improved precision of the reflectance-based approach and inclusion of automated data makes possible the use of these methods for sensor intercomparison in the same fashion as preflight, laboratory calibrations. Behind the success of the reflectance-based method and intercomparison cross-calibration results is the hyperspectral nature of the predicted radiances. The ability to derive band-integrated radiance values for arbitrary bands of a selected sensor is the reason that field spectrometers are the standard approach for determining the surface reflectance. Radiative transfer codes have been developed to incorporate high spectral resolution and the impact of atmospheric scattering and absorption is likewise determined at spectral resolutions on the order of 1-nm intervals.

The same basic method is applied to the case of both with and without automated sensors. The radiometer used in the on-site case is a field-portable spectrometer, as mentioned above. The automated approaches currently rely on multispectral sensors in the green, red, and near-infrared bands. Data are converted to radiance based on an absolute calibration that includes effects for temperature corrections. An iterative approach using atmospheric data and radiative transfer calculations converts the data to surface reflectance. The multi-spectral results are taken to hyperspectral using archived surface reflectance from on-site measurements with the historically-based data from the field spectrometer.

CLARREO application

The well-calibrated data sets such as those described above play a critical role in the development of climatic data sets. A planned sensor as part of NASA's Decadal Survey Missions is the Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission. Hyperspectral remote sensing is essential to this mission. CLARREO addresses the need to observe high-accuracy, long-term climate change trends and to use decadal change observations as the most critical method to determine the accuracy of climate change projections such as those in the IPCC Report. A rigorously known accuracy of both decadal change observations as well as climate projections is necessary to enable sound policy decisions. The CLARREO Project will implement a spaceborne earth observation mission designed to provide rigorous SI traceable observations (i.e., radiance, reflectance, and refractivity) that are sensitive to a wide range of key decadal change variables, including:

- Surface Temperature and Atmospheric Temperature Profile

- Atmospheric Water Vapor Profile
- Far Infrared Water Vapor Greenhouse
- Aerosol Properties and Anthropogenic Aerosol Direct Radiative Forcing
- Total and Spectral Solar Irradiance
- Broadband Reflected and Emitted Radiative Fluxes
- Cloud Properties
- Surface Albedo

There are two methods the CLARREO mission will rely on to achieve these critical decadal change benchmarks: direct and reference inter-calibration. A quantitative analysis of the strengths and weaknesses of the two methods has led to the recommended CLARREO mission approach consisting of two satellites launched into 90-degree, precessing orbits separated by 90 degrees. The instrument suite on each spacecraft includes one emitted infrared spectrometer, three reflected solar (RS) spectrometers: dividing the spectrum from ultraviolet through near infrared, and one global navigation receiver for radio occultation.

The basis of the design of the RS sensor is the retrieval of an at-sensor reflectance over the spectral range from 320 to 2300 nm with 500-m GIFOV and a 100-km swath width. Reflectance is obtained from the ratio of measurements of radiance while viewing the earth's surface to measurements of irradiance while viewing the sun. The need to measure the energy leaving the earth's surface as well as the solar irradiance means that signals vary by factors of 2 to 10 due to multi-dimensionality of the problem caused by:

- Surface reflectance changes
- View/solar geometry (seasonal and geographic)
- Atmospheric effects
- Spectral variation

The RS instrument must be designed to account for these effects as well as include a calibration approach that allows accurate retrieval of the reflectance traceable to SI standards at a level better than 0.2% in the mid-visible. Such a required accuracy provides a data set that when collected globally reduces sampling biases for climatologically significant spatial and temporal averages over annual means.

The calibration approach taken in order to achieve the ambitious 0.2% absolute calibration uncertainty is predicated on a reliance on heritage hardware, reduction of sensor complexity, and adherence to detector-based calibration standards. One design being evaluated currently for the reflected solar instrument is based on an Offner spectrometer which is capable of limiting spectral smile on the focal plane. The design relies on three separate focal planes each with its own entrance aperture and grating to permit the use of single order diffraction gratings. The three separate focal planes cover spectral ranges of 320-640, 600-1200, and 1150-2300 nm implemented as three individual spectrometers.

The system design currently being evaluated relies on a direct solar view as the primary calibration approach. The data from a solar view are coupled with the earth view data and knowledge of the sensor optical geometry to retrieve at-sensor reflectance. The method is similar in concept to past sensors that rely on solar diffuser data to derive reflectance. One reason for adopting a reflectance philosophy is it reduces the need for elaborate onboard calibration sources. Conversion of the reflectance to an absolute radiance will rely on access to an appropriately accurate solar irradiance.

The goals of CLARREO including the reflected solar instrument are daunting but achievable. Characterization of the reflected solar instrument relies on improvements to currently-available calibration approaches. Careful sensor design to limit stray light and polarization sensitivity also is critical to achieving the needed accuracy. In the end, adherence to these basic design and characterization principles will provide data at the accuracy required to provide the basis for a set of data records needed to understand the earth’s climate.

Conclusions

The success of a mission such as CLARREO requires data at high spectral resolution. The sensor design is strongly based on heritage designs of past sensors. Further, the calibration techniques that will be used for CLARREO and future projects with similarly climate-level requirements have been a direct result of the imaging spectrometry and hyperspectral remote sensing work over the past 30 years. Clearly, hyperspectral data are vital to our understanding of the earth and its climate. The role of spectrometry in the design of remote sensing instruments has proven itself over the past several decades and with missions such as CLARREO, will be a centerpiece in remote sensing for the coming decades as well.

References

Anderson, N., S. Biggar, K. Thome, and N. Leisso, (2007), “Solar radiation-based calibration of laboratory grade radiometers,” *Proc. SPIE Vol. 6677*, San Diego, Calif.

Biggar, S. F. (1998), “Calibration of a visible and near-infrared portable transfer radiometer,” *Metrologia*, Vol. 35, 701-706.

Biggar, S. F., J. Labed, R.P. Santer, P.N. Slater, R.D. Jackson, and M.S. Moran, (1988), “Laboratory calibration of field reflectance panels,” *Proceedings SPIE Conf #924*, pp. 232-240, Orlando, Florida.

Biggar, S. F., K.J. Thome, R.B. Lockwood, and S. Miller, (2007), “VNIR transfer radiometer for validation of calibration sources for hyperspectral sensors,” *Proceedings SPIE*, San Diego, CA.

Butler, J.J and R.A. Barnes, (1998), “Calibration Strategy for the Earth Observing System (EOS)-AMI platform,” *IEEE Trans. On Geoscience and Remote Sensing*, Vol. 36, pp. 1056-1061.

Keef, J. and K. Thome, (2009), “Hyperspectral source prediction based on an optimal selection of multispectral data,” *J. Appl. Remote Sens*., 033518.

Markham, B. L., K.J. Thome, J.A. Barsi, E. Kaita, D.L. Helder, J.L. Barker, and P.L. Scaramuzza, (2004), “Landsat-7 ETM+ On-Orbit Reflective-Band Radiometric Stability and Absolute Calibration,” *IEEE Trans. On Geoscience and Remote Sensing*, Vol. 42, No. 12.

Sakuma, F. and A. Ono, (1993), “Radiometric Calibration of the EOS ASTER Instrument,” *Metrologia*, Vol. 30, pp. 231-241.

Slater, P., S. Biggar, R. Holm, R. Jackson, Y. Mao, M. Moran, J. Palmer, and B. Yuan, (1987), "Reflectance- and radiance-based methods for the in-flight absolute calibration of multispectral sensors," *Rem. Sens. Env*., Vol. 22, pp 11-37.

Slater, P. N., S. F. Biggar, K. J. Thome, D. I. Gellman, and P. R. Spyak, (1996), "Vicarious Radiometric Calibration of EOS Sensors." *J. of Atmospheric and Oceanic Technology*, **13**, 349 – 359.

Thome, K. J., J. Czapla-Myers, and S. Biggar, (2004), "Ground-monitor radiometer system for vicarious calibration," *Proc. SPIE Conf. #5546*, pp. 223-232, Denver, Colo.