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A dual-spectrometer approach to reflectance measurements under sub-optimal sky conditions

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Abstract: This paper presents a practical method for the development of spectral reflectance libraries under sub-optimal sky conditions. Although there are commercially available spectrometers which simultaneously measure both downwelling and upwelling radiance to mitigate the impact of sub-optimal sky conditions, these spectrometers only record in the visible and near infra-red. There are presently no commercially available spectrometers with this capability that can record the visible through shortwave infra-red. This paper presents a practical method of recording and processing data using coordinated measurements from two full-range spectrometers and discusses potential pitfalls and solutions required to achieve accurate reflectance spectra. Results demonstrate that high-quality spectral reflectance libraries can be developed with this approach.

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OCIS codes: (300.0300) Spectroscopy; (120.6200) Spectrometers and spectroscopic instrumentation.

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9 April 2012 / Vol. 20, No. 8 / OPTICS EXPRESS 8959
tropical climates, this poses a significant challenge to obtaining useful spectral reflectance when weather conditions are challenging. In many parts of the world, especially areas with conditions can limit the number of useful spectra that can be collected during field campaigns. The implication of using a single spectrometer to develop spectral libraries is that sub-optimal sky downwelling and upwelling radiance while measuring in a spectral range from the visible and near infra-red (NIR) through short wave infra-red (SWIR). The SWIR is an important spectral region for exploitation of hyperspectral imagery in the very shallow water limit: a case study from the 2007 Virginia Coast Reserve (VCR '07) multi-sensor campaign,” Mar. Geod. 33(1), 53–75 (2010).

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1. Introduction

The measurement of in situ spectral reflectance with portable spectrometers for the development of application-specific spectral libraries has been a key factor in the practical exploitation of hyperspectral imagery [1–5]. Standard methods using a single spectrometer involve the collection of calibrated radiance samples from the specimen of interest (plant, soil, mineral, etc.) and the comparison of these radiance measurements with those obtained from a white reference plaque made of a standard material, such as Spectralon™, to determine reflectance. Although spectrometer systems that measure simultaneous downwelling and upwelling radiance exist for the visible and near infra-red (NIR), there are presently no commercially available portable spectrometer systems that simultaneously record downwelling and upwelling radiance while measuring in a spectral range from the visible and NIR (VNIR) through short wave infra-red (SWIR). The SWIR is an important spectral region for many application domains, such as geology [1], soils [6], and vegetation [1,3,7,8] because of the presence of a large number of spectral absorption features related to these application domains. For coastal applications, the VNIR is critical for retrieval of bathymetry [9–11] and properties of the water column [9,10], while both the VNIR and SWIR can play a critical role in land applications, such as retrieval of geophysical properties of beaches, wetlands, and tidal flats [12,13].

For “full range” spectrometers that record both VNIR and SWIR data, the practical implication of using a single spectrometer to develop spectral libraries is that sub-optimal sky conditions can limit the number of useful spectra that can be collected during field campaigns when weather conditions are challenging. In many parts of the world, especially areas with tropical climates, this poses a significant challenge to obtaining useful spectral reflectance.
libraries given typical weather patterns. More broadly, this is a significant problem for coastal environments, where sky conditions may vary rapidly. The reason for this limitation is that for existing VNIR/SWIR portable spectrometers, the measurement of white reference radiance samples and those from the specimen of interest must be done at different times when a single spectrometer is used. If light levels are changing rapidly, as they may do on days with rapidly varying degrees of cloud or haze, the quantities in the ratios required to compute reflectance (average radiance from the specimen of interest divided by average radiance from white reference) will not have the same scale factors associated with measuring white and specimen samples, and the resulting reflectance spectrum will be erroneous [14].

The collection of spectral libraries remains an important activity [15,16]. To obtain reliable spectral libraries in these environments with a traditional approach means waiting for good weather conditions and therefore a loss of time, significantly raising the cost of spectral library acquisition. One method to allow spectroscopic measurements in challenging conditions is to utilize a dual spectrometer approach [17], which was first demonstrated for multi-spectral systems by [14]. This method has been used with VNIR systems by several authors [18,19]. There have been limited studies with VNIR/SWIR systems [20]. This paper describes our implementation of a method for obtaining reliable full-range spectral reflectance in sub-optimal sky conditions by using two portable spectrometers and covers the implementation details, potential pitfalls, and solutions for practical implementation. While this is similar to the presentations of [14] and [18], we focus on this method as applied to full-range sensors and on the requirements of the relative spectral calibration of the instruments. The remainder of this paper is divided as follows. Background material is first presented on the details of the typical single spectrometer measurement methodology. This is followed by a presentation of our approach using a dual spectrometer measurement paradigm. In the results section, we then show practical examples of high quality spectra obtained using this approach in field measurements at coastal sites where sub-optimal sky conditions are common and compare the single and dual spectrometer measurement methods. Finally, we summarize and draw conclusions.

2. Background: typical paradigm for measuring in situ spectral reflectance under favorable skies

Under favorable sky conditions, the typical method for measuring reflectance spectra is to use a single spectrometer to record a number of samples of white reference radiance measurements, using a material such as Spectralon™, and a similar number of samples from the specimen of interest. Spectralon™ is an industry standard material, which is highly reflective across the visible through short-wave infra-red. It is a well-characterized material with highly Lambertian behavior.

By alternating sequences of measurements between reference plaques and the specimen of interest, the underlying assumption is that the illuminating radiance does not vary appreciably during the sampling from plaque and specimen. A sufficient number of samples must usually be taken in order to remove noise, and this is especially true when the spectrometer covers the SWIR in addition to the visible and NIR portion of the spectrum. Samples of white plaque radiance are then divided by samples obtained from the specimen of interest for which a reflectance spectrum is to be determined.

In the field data described in this paper, we used Analytical Spectral Devices (ASD) Fieldspec Pro spectrometers, which cover the full VNIR/SWIR range [21]. The exact strategy for sampling the relevant white plaque and reference spectra may vary according to field conditions, but typically, under nominal sky conditions, we follow a paradigm which calls for an initial optimization of the spectrometer gain and offset for the white plaque followed by a sequence of white plaque and specimen radiance measurements in alternating sets (Fig. 1). We typically collect a minimum of two sets of 30 white reference and 30 specimen radiance samples, in order to ensure that noise in the SWIR, where there is less light available to the
sensor, will not adversely affect the shape of the spectrum in the SWIR. We consider this number of samples to be a minimum; more samples are always better to reduce noise in the SWIR, as averaging $N$ samples of a signal in noise has the effect of reducing the noise power (variance) by a factor of $N$ (assuming uncorrelated noise samples). The purpose of collecting alternating sets of white and specimen radiance samples is to ensure that an adequate sample of both white and specimen samples is computed across the full measurement window in order to minimize the effect of minor variations in light field during the period of measurement. Under these conditions, the fundamental calculation for reflectance for each wavelength $\lambda$ is:

$$R(\lambda) = \frac{C_{\text{plaque}}(\lambda)}{\sum_{t=0}^{m-1} L(t, \lambda)_{\text{specimen}}} \frac{\sum_{t'=0}^{n-1} L(t', \lambda)_{\text{plaque}}}{n}$$

where $R(\lambda)$ is the reflectance, $C_{\text{plaque}}(\lambda)$ is the plaque calibration coefficient determined in the lab, $L(t, \lambda)_{\text{specimen}}$ is the radiance sample of the field specimen at time $t$, and $L(t', \lambda)_{\text{plaque}}$ is the radiance measurement of the plaque at time $t$.

![Image](image-url)

Fig. 1. Two paradigms for measuring reflectance under a clear sky with a portable spectrometer. (Left) mobile measurements with the spectrometer at Waimanalo Bay, HI; (right) fixed position measurements, Hog Island, VA, from tripods in which the white plaque is rotated into the field of view. In each case, white plaque and reference measurements are recorded in alternating sets with target specimen spectral measurements.

### 3. Methods: dual-spectrometer methods for measuring in situ spectral reflectance

When variations in light levels are too large, due to sub-optimal sky conditions, the method summarized in Eq. (1) will not ensure that stable ratios are obtained in reflectance calculations. When sky conditions are not favorable, therefore, it becomes necessary to adopt a different strategy in order to mitigate the effects of the rapidly varying light fields. Similar to the work of [18] and [20], we have developed a strategy that involves in situ cross-calibration of two spectrometers recording simultaneously from white reference plaques, followed by a cycle of simultaneous measurement in which one spectrometer continues to record radiance from a white reference plaque, while the other spectrometer records radiance from the specimen of interest (Figs. 2 and 3). In essence we create a dual-beam spectroradiometer from a matched pair of single beam instruments [19] operating in bi-conical mode [18,22].
Fig. 2. Dual spectrometer measurement paradigm. (Left) Base station spectrometer continuously records from a white Spectralon™ white reference plaque. (Right) The rover spectrometer records in alternating cycles between a Spectralon™ plaque and the land or water specimen of interest.

Fig. 3. Measurement of the transfer function at Freshwater Beach, Queensland, Australia. Two ASD full range spectrometers record from two Spectralon™ white reference plaques simultaneously. In the second stage, one spectrometer continues to record from a white reference, while the second spectrometer records from the specimen of interest. Ideally, both plaques should be leveled on fixed tripods where possible to avoid introducing uncertainties in overall reference radiance levels appearing in the reflectance calculations.

The cross-calibration phase measures a "transfer function" by ensuring that data normalization factors are measured that allow data recorded in one spectrometer to be related to that of the other. Furthermore, the transfer function guarantees that small differences in the wavelength grid and shifts in wavelength accuracy between the two instruments are accounted for and modeled. Wavelength shifts can be detected in an individual ASD spectrometer.
through the use of rare earth plaques or by comparing irradiance data to models [23]. If the data has been collected in the default mode of the ASD instrument, then it has been resampled from the native wavelength grid to a wavelength grid in which data has been interpolated to integer values in nanometers. Without knowing the procedure used for interpolation, which is not provided by the instrument manufacturer, we cannot ensure that the data can be correctly adjusted to account for small wavelength shifts across the whole spectrum. As a further complication, most VNIR/SWIR spectrometers combine multiple sensors, each of which is calibrated separately and therefore each component spectrometer may have shifted different amounts from the laboratory calibration; full-range ASD spectrometers have three separate spectrometers. The manufacturer notes that, for the ASD FR Pro model, wavelength repeatability is ± 0.3 nm within 10°C of the calibration temperature, which for practical purposes means that in many instances, we can expect small scale wavelength shifts to be present in the data due to thermal differences in the field setting compared to calibration.

On the other hand, a small shift \( \lesssim 1\text{nm} \) is not necessarily critical for use in practical applications when using field-derived spectral libraries in analyzing commercial imaging hyperspectral sensors which provide data with native spectral resolution ~3-10 nm throughout much of their spectral range. However, if two high-resolution field spectrometers are operated as shown in Fig. 2 and Fig. 3, the relative shift between the two spectrometers must be modeled and accounted for, or artifacts will be introduced by the relative shifts between the two spectrometers in wavelength.

In the case of wavelength shifts, even a relatively small wavelength shift on the order of a nanometer or less between the two instruments can cause large spike artifacts in the resulting reflectance. Even frequent re-calibration of instruments cannot completely guarantee that this issue will not be present, and as the time since last calibration increases and use of the instrument in a field setting occurs, these differences are likely to become larger as the instruments are shipped and transported to field sites and used in these environments. These small differences in wavelength, which may be \( \lesssim 1-2\text{nm} \), can cause spurious spikes (false maxima and absorption features) in reflectance calculations when the specimen radiance measurements of one spectrometer are divided by the radiance measurements from the white plaque of another. This is most likely to happen near the location of atmospheric absorption features, which, due to the shift in wavelength between the two spectrometers, are no longer properly normalized out of the reflectance calculation, leading to false absorption minima as well as spikes in the spectral reflectance signature. Likewise, any minor variations in shape will be amplified when there is a relative wavelength shift between the two spectrometers, for the reasons just cited.

To understand the spikes and false absorption features that can be generated when there is a relative shift between the two spectrometers, consider the following. Let \( L_{\text{b,s}}(\lambda) \) be the radiance of the base spectrometer recording samples from the white plaque X, and let \( L_{r,s}(\lambda) \) be the rover spectrometer recording from samples from the specimen. Then, if there were no relative shift in the wavelength grid between the two spectrometers, the reflectance would be:

\[
R(\lambda) = C_{\text{plaque}}(\lambda) \frac{L_{r,s}(\lambda)}{L_{\text{b,s}}(\lambda)}
\]

If the base spectrometer is shifted by \( \Delta \lambda_{\text{b},s} \), and the rover spectrometer is shifted by an amount \( \Delta \lambda_{r,s} \), then to first order the expected change in the reflectance is:

\[
\Delta R(\lambda) = C_{\text{rover}}(\lambda) \frac{L_{r,s}(\lambda) - L_{r,s}(\lambda)\Delta \lambda_{r,s} + L_{r,s}(\lambda)\Delta \lambda_{r,s}}{L_{\text{b,s}}(\lambda) - L_{\text{b,s}}(\lambda)\Delta \lambda_{\text{b},s}} - r(\lambda) \left( \frac{L_{r,s}(\lambda)}{L_{\text{b,s}}(\lambda)} \right) \Delta \lambda_{r,s} - r(\lambda) \Delta \lambda_{\text{b},s} \]

\[
\Delta R(\lambda) = C_{\text{rover}}(\lambda) \frac{L_{r,s}(\lambda)\Delta \lambda_{r,s} + L_{r,s}(\lambda)\Delta \lambda_{r,s}}{L_{\text{b,s}}(\lambda) - L_{\text{b,s}}(\lambda)\Delta \lambda_{\text{b},s}} - r(\lambda) \left( \frac{L_{r,s}(\lambda)}{L_{\text{b,s}}(\lambda)} \right) \Delta \lambda_{r,s} - r(\lambda) \Delta \lambda_{\text{b},s} \]

\[
\Delta R(\lambda) = C_{\text{rover}}(\lambda) \frac{L_{r,s}(\lambda)\Delta \lambda_{r,s} + L_{r,s}(\lambda)\Delta \lambda_{r,s}}{L_{\text{b,s}}(\lambda) - L_{\text{b,s}}(\lambda)\Delta \lambda_{\text{b},s}} - r(\lambda) \left( \frac{L_{r,s}(\lambda)}{L_{\text{b,s}}(\lambda)} \right) \Delta \lambda_{r,s} - r(\lambda) \Delta \lambda_{\text{b},s} \]

\[
\Delta R(\lambda) = C_{\text{rover}}(\lambda) \frac{L_{r,s}(\lambda)\Delta \lambda_{r,s} + L_{r,s}(\lambda)\Delta \lambda_{r,s}}{L_{\text{b,s}}(\lambda) - L_{\text{b,s}}(\lambda)\Delta \lambda_{\text{b},s}} - r(\lambda) \left( \frac{L_{r,s}(\lambda)}{L_{\text{b,s}}(\lambda)} \right) \Delta \lambda_{r,s} - r(\lambda) \Delta \lambda_{\text{b},s} \]

\[
\Delta R(\lambda) = C_{\text{rover}}(\lambda) \frac{L_{r,s}(\lambda)\Delta \lambda_{r,s} + L_{r,s}(\lambda)\Delta \lambda_{r,s}}{L_{\text{b,s}}(\lambda) - L_{\text{b,s}}(\lambda)\Delta \lambda_{\text{b},s}} - r(\lambda) \left( \frac{L_{r,s}(\lambda)}{L_{\text{b,s}}(\lambda)} \right) \Delta \lambda_{r,s} - r(\lambda) \Delta \lambda_{\text{b},s} \]

\[
\Delta R(\lambda) = C_{\text{rover}}(\lambda) \frac{L_{r,s}(\lambda)\Delta \lambda_{r,s} + L_{r,s}(\lambda)\Delta \lambda_{r,s}}{L_{\text{b,s}}(\lambda) - L_{\text{b,s}}(\lambda)\Delta \lambda_{\text{b},s}} - r(\lambda) \left( \frac{L_{r,s}(\lambda)}{L_{\text{b,s}}(\lambda)} \right) \Delta \lambda_{r,s} - r(\lambda) \Delta \lambda_{\text{b},s} \]
where radiance factors such as $L_{b,r}$ have two subscripts as before, the first indicating whether the spectrometer is the base or rover (“b” or “r”) and the second whether the plaque used was plaque X or plaque Y, primes indicate a derivative with respect to the wavelength argument, and wavelength shifts such as $\Delta \lambda_p$ are indicated with the same notational convention for base and rover spectrometer.

![Typical Plaque Radiance Sample](image)

**Fig. 4.** A typical radiance measured from white Spectralon™ plaque by an ASD spectrometer. A large number of narrow band atmospheric absorption features are visible. When two spectrometers are used to measure reflectance under adverse skies, these features are the source of spurious spikes and false specimen absorption features because of relative wavelength shift. Use of a transfer function eliminates these artifacts.

The form of this equation indicates the relative importance of the slope of the atmospheric absorption features in the radiance curves. The slope of these features has a significant role in determining the degree to which the resulting reflectance is altered by the shifts in wavelength in the two spectrometers. Similarly, the second term on the right hand side of Eq. (3) shows that spectral shape in the reference plaque can also have an effect, and that effect depends on the scale of the reflectance. Figure 4 shows a typical radiance file from a white Spectralon™ plaque, illuminated outdoors under typical field conditions and measured by an ASD spectrometer, which highlights the presence of many narrow atmospheric absorption features. The calibration coefficients of the white plaque also show some fine scale structure, although on a broader scale, the plaque is relatively flat spectrally, except in the SWIR, where there is at least one relatively broad absorption feature. It is the fine scale structure in the calibration coefficients that causes the greatest difficulty. Likewise, in the first term on the right hand side of Eq. (3), it is the relative shift of the narrow band atmospheric absorption features in wavelength between the two spectrometers that is the origin of the spurious spikes and false specimen absorption features in the reflectance calculated between the two spectrometers.

To understand this physically, consider the case of a hypothetical atmospheric absorption feature centered at 500 nm. Figure 5 shows a graph of the radiance from two spectrometers, with one recording from a reference surface and the other from a hypothetical specimen of interest. In this hypothetical example, we have assumed for simplicity that the reflectance is flat in this narrow region of spectral space, so that when the two spectrometers are perfectly aligned in their wavelength grid (top row of Fig. 5), the atmospheric absorption feature is divided out in the ratio of the two radiance terms, leaving a flat reflectance curve, plotted on the same graph as the radiance curves. In Fig. 5, we demonstrate the effect of shifting the wavelength grid of each spectrometer in opposite directions away from the true wavelength...
grid in equal amounts, ranging from 0.1 nm to 1 nm. In the first column, the width of the absorption feature is assumed to have a width of $\sigma = 0.5$ nm, while the second and third columns have $\sigma = 1.0$ nm and $\sigma = 4.0$ nm. Figure 4 exhibits many solar and atmospheric absorption features of comparable scale and width. In all three columns of Fig. 5, the hypothetical atmospheric absorption feature is assumed to decrease the true radiance by 20%. Note that when the atmospheric absorption feature is narrower ($\sigma = 0.5$ nm and 1.0 nm cases), even a shift of as little as 0.1 nm of each spectrometer in opposite directions, has a significant impact, producing a spurious peak and absorption feature pair with peak and valley separated by ~0.6 nm. This is the result of the slope factors in Eq. (3). Noting that the ASD spectrometer interpolates to the nearest 1 nm, these false features will be observable in the data, even for this most subtle shift. The size of the spurious features becomes progressively worse up to the maximum point when the absorption features in the two spectrometers are minimally overlapping.

In our dual spectrometer method of measuring spectral reflectance, the expression for the reflectance involves three factors and may be written as

$$R(\lambda) = C_{\text{rover plaques}} (\lambda) \sum_{t} \frac{L_{t,Y}(t')}{L_{t,Y}(t')} \frac{L_{t,Y}(t', \lambda)}{L_{t,Y}(t', \lambda)} \sum_{t} \frac{L_{t,X}(t', \lambda)}{L_{t,X}(t', \lambda)}, \tag{4}$$

In Eq. (4), as before in Eq. (3), $L$ denotes the radiance measured by a particular spectrometer, with the subscripts “r”, “b” denote respectively the rover and base spectrometer, and the subscripts “X” and “Y” refer to white plaques X and Y. The pairs are determined by first sorting the radiance files from the two spectrometers to identify the closest timestamp between the measured radiances from each. Usually, the time difference is a fraction of a second, so a search window of 1 second is usually sufficient.

For a particular wavelength, the first factor is the calibration coefficient of the “rover” spectrometer, which is the instrument that alternates measurement of radiance from a white plaque and the specimen. In some instances, we use the same plaque for both spectrometers during the measurement of the transfer function. In other cases, where it is desirable to move the rover spectrometer around while keeping the “base” spectrometer in the same location, for example, to save time, two plaques might be used, it is important to distinguish between which plaque appears in this first factor. In Eq. (4), it is the rover’s plaque coefficient which appears as the first factor, since ultimately, through the transfer function, we want to refer all measurements to the rover spectrometer.

The second factor is a sum over the ratio of radiance pairs, one measured by the base spectrometer recording continuously from a white reference plaque and the other measured by the rover spectrometer either looking at the same plaque or a second white plaque.

The third factor is a sum over ratios of radiance pairs from the “rover” spectrometer recording from the specimen of interest, while the “base” spectrometer is recording from its associated white plaque.

We refer to the first sum in Eq. (4) as the plaque-to-plaque transfer function, when both rover and base units are measuring radiance simultaneously or nearly simultaneously at times $t'$, while each spectrometer unit is recording radiance from different Spectralon$^{TM}$ reference plaques, X and Y (see Fig. 3) or from the same plaque in the case where only a single plaque is used. The second sum is over simultaneous or nearly simultaneous measurements when the rover spectrometer is recording radiance measurements from the specimen of interest, while the base spectrometer is recording radiance from plaque X. The term “nearly simultaneous” refers to the fact that the two spectrometer measurements are not triggered simultaneously but only recording measurements over the same period. In practice, we find that the actual sample-to-sample time correspondence between the two ASD spectrometers may differ by a small time interval, $\Delta t \leq 1$ second, after time differences between the clocks on individual data recording laptops are accounted for.
Fig. 5. Spurious reflectance minima and maxima resulting from shifts in the wavelength grid of the two spectrometers used in the dual mode method in the vicinity of a hypothetical atmospheric absorption feature centered at 500 nm. (Left column) $\sigma = 0.5$; (middle column) $\sigma = 1.0$ nm; (right column) $\sigma = 4.0$ nm. Rows, top to bottom, are shifts of the two spectrometers from the true wavelength grid in opposite directions in amounts: 0.0 nm, 0.1 nm, 0.25 nm, 0.5 nm, 0.75 nm, and 1.0 nm.

$C_{\text{rover,plaque}}(\lambda)$ is the calibration coefficient for panel Y as measured for the rover unit in the calibration facility for panel Y at wavelength $\lambda$, prior to use in the field. The overall effect of the transfer function is to estimate the equivalent reflectance as if the rover unit were simultaneously measuring the radiance from the specimen and the plaque Y. As noted earlier this will also alleviate the problem of spurious spikes and false absorption features produced
by slight misalignments in wavelength between the two spectrometers, and takes advantage of the fact that there is a high degree of correlation between bands that are shifted by \( \lesssim 1-2 \) nm.

Over time, white Spectralon\textsuperscript{TM} plaques used in field conditions are exposed to many environmental factors, which means that the true calibration coefficients of these plaques will drift from those originally measured at the factory. To overcome this, recalibration in the lab may be necessary. In a practical field setting, some plaques may have drifted further from their original calibration. In Eq. (5) and Eq. (6), we assume that the plaque used by the rover spectrometer has drifted significantly from its last calibration, while the plaque used by the base spectrometer has not. Under this scenario, the cross-calibration in the field still can be used. The reflectance can be calculated as:

\[
R(\lambda) = C_{\text{base, plaque}}(\lambda) \sum_{i=0}^{n} L_{i, y} (t', \lambda') \sum_{i=0}^{n} L_{i, y} (t, \lambda) \sum_{i=0}^{n} L_{i, t} (t, \lambda)
\]

which uses the assumed transformation:

\[
C_{\text{rover, plaque}}(\lambda) = C_{\text{base, plaque}}(\lambda) \sum_{i=0}^{n} L_{i, y} (t', \lambda') \sum_{i=0}^{n} L_{i, y} (t', \lambda)
\]

4. Results

The role of the plaque-to-plaque transfer function plays a critical role in producing a physically reliable result. Shifts in wavelength as small as 1nm or less between the two spectrometers used in dual mode can lead to spurious results if no transfer function is calculated (plaque-to-plaque normalization) as shown in a real field measurement shown in Fig. 6 and in the earlier hypothetical example in Fig. 5. In Fig. 6, we compare the resulting reflectance in two cases, one with and the other without the plaque-to-plaque transfer function described in the calculations in Eq. (4). Note the presence of unphysical spikes and false absorption features resulting from small wavelength shifts between the two spectrometers when the transfer function is removed vs. when the transfer function is included. The use of the plaque-to-plaque transfer function removes these spurious spikes, while preserving true absorption features such as the one observed in this sand sample near 2.206 \( \mu \)m. This particular absorption feature is likely one of several carbonate features (aragonite) seen in the short-wave infra-red portion of the spectrum. We expect to see absorption features such as this in this sand reflectance measurement, which was taken at a Freshwater Beach in Queensland, Australia on May 20, 2009. For coastal applications, reliably identifying the type of sand or soil is one of several factors that play a critical role in the retrieval of geophysical properties of beaches, wetlands, and tidal flats [12,13].

In Fig. 6, note that the spectrometer reflectance in the vicinity of the broad atmospheric absorption windows, centered \( \sim 1.39 \) \( \mu \)m and \( \sim 1.89 \) \( \mu \)m, is unreliable in these spectral regions. Even on relatively clear sky days using a single spectrometer, this is quite often observed because the number of available counts in these bands is very small, making the ratio between the white plaque and specimen samples numerically unstable. Typically, these bands are removed in analysis.

Figure 7 shows a second example obtained for a water reflectance spectrum using the dual-spectrometer approach on the same day as the beach example (Fig. 6). When the transfer function is not used, note the presence of the spurious peak and minimum around 762 nm, a known atmospheric absorption feature due to oxygen. However, when the transfer function is used, the reflectance spectrum remains free of spurious absorption features and peaks, even for this lower albedo water spectrum. The resulting spectrum is free of spurious features that would otherwise limit the utility of the spectrum in matching and retrieval of water column properties such as bathymetry [11], bottom type, and water column properties [9,10].
Fig. 6. Sand spectral reflectance measured by the dual spectrometer method under sub-optimal sky conditions: with (black) and without (red) the use of the plaque-to-plaque transfer function. Small wavelength shifts between the two spectrometers require the use of the transfer function to avoid the appearance of unphysical spikes (seen in the red curve but not in the black). (Inset) Photo showing the site where the spectral data was collected (photo shows a geotechnical measurement being taken at the same location).

The ability to track temporal changes in the light field is limited by the ability to match clocks (in the field without GPS units attached to the clocks, to ~1s), the start time of the scan on the physically separate units, and the amount of time each scan takes (newer generations of field spectrometers are typically faster; likewise brighter targets also allow faster acquisition), and the fact that the time recorded in the files is recorded to the nearest second. Consideration of all these factors tends to limit our ability to obtain quality data to times when the light field does not vary significantly at time scales $\lesssim 5$ s.

In addition to temporal changes in the light field, there can also be spatial changes in the illumination field that are caused by the complex geometry of the surrounding scene, i.e., the fact that each plaque (as well as the target) is rarely illuminated by a full $2\pi$ steradians of the sky. The ratios in Eq. (4) ensure that each location (the location of the rover and the base station) appears in the numerator and the dominator of the equation. In practice, close proximity of the rover and base station can minimize this effect.

We obtained results similar to those of [18] in regards to the usefulness of laboratory calibration of the sensors compared to the field calibration. The solar and atmospheric spectral features are much different than those found in the laboratory and, given even a slight spectral mis-registration, are what need to be corrected in the data. Laboratory calibrations using integrating spheres allow us to track changes in the instrument sensitivity over time, but are not useful in the field since they cannot remove the effects of spectral mis-registration.
The importance of using the dual spectrometer approach over the traditional single spectrometer methodology is illustrated in the following two Figures. In Fig. 8, we consider a set of measurement cycles taken on the same transect as the data portrayed in Fig. 6. During the cycle the dual spectrometer methodology was also followed. However, even though sky conditions were sub-optimal, because the base spectrometer continuously monitors the radiance from a white Spectralon™ plaque during the measurement cycle, we can identify relatively short periods during which the radiance level is approximately the same for both rover spectrometer specimen and plaque measurement cycles. If these are used, the traditional method should be approximately the same as the dual spectrometer method. However, if all of the data is used, the two will differ and indeed, by examining Fig. 8, we see that outside these relatively short periods when the radiance was stable and consistent between the two rover measurement cycles, the rover specimen samples not in the windows tended to have lower radiance, while the rover plaque measurements were typically higher than in the stable windows, due to the overall temporal fall-off in the radiance that occurred as time increased and the relative timing of the rover specimen and plaque measurement periods. The result is that when the traditional single spectrometer is used with all of the data samples taken, it will
underestimate the true reflectance. Figure 9 shows that, as expected the single spectrometer method processed using the relatively stable periods differs from the dual-spectrometer method by less than $\lesssim 5.6\%$, while the same method using all of the data underestimates the reflectance and differs from the dual-spectrometer method by as much as 20% for the reasons cited.

![Base station spectrometer shows relatively stable and consistent periods](image1)

![Rover specimen samples Stable period](image2)

![Rover plaque samples Stable period](image3)

Fig. 8. (Top) Time history of radiance measurements taken by the base station spectrometer, continuously monitoring a white plaque (shown only the periods when the two spectrometers overlapped). Brackets show time periods of relative radiometric stability at levels consistent between two base spectrometer cycles that corresponded to distinct sets of rover spectrometer plaque and specimen measurements. These periods for the rover spectrometer were used to compare against the dual spectrometer approach for consistency.
Fig. 9. Comparison of dual and single spectrometer reflectance calculations for sand under suboptimal sky conditions, corresponding to the same example used in Fig. 8. Relatively stable and radiometrically consistent small subsets were chosen by inspecting the base station spectrometer time history of plaque radiance values seen in Fig. 8. These were used to calculate the reflectance by the single spectrometer method, which as expected, produces a result similar to the dual spectrometer approach (differing by \( \lesssim 5-6\% \)) using the whole data set. Using the full data with the single spectrometer approach, however, underestimates the true reflectance by as much as 20\% because of variation and trends in the plaque and specimen radiances over the whole measurement cycle.

5. Conclusions and summary

Collection of spectra under sub-optimal sky conditions can be a limiting factor for full range spectrometer systems. Although dual-sensor spectrometers can overcome this limitation by simultaneously measuring downwelling and upwelling radiance, commercially-available systems only cover the VNIR (350 – 1000 nm). No full-range (VNIR/SWIR) portable spectrometers with this capability are commercially available at this time. This paper presented a practical approach to measuring reflectance spectra using two portable spectrometers sampling radiance at the same time. The method consists of comparing the radiance when both instruments measure a white reference plaque and when one continues to measure the plaque while the other measures radiance from the specimen of interest. The plaque-to-plaque transfer function was shown to be particularly important in order to avoid the introduction of spurious features caused by small misalignments in the wavelength grid of the two spectrometers. Hypothetical cases were first examined to show that even subtle shifts can lead to artifacts (false minima and peaks) caused by this misalignment which are
especially prominent near atmospheric absorption features. These are the result of the fact that the atmospheric features are no longer factored out when ratios are taken between plaque and specimen radiances when the two wavelength grids are not perfectly aligned. Use of the transfer function effectively models the relationship between the two spectrometer wavelength grids, and produces high quality spectra. For coastal sites, where sub-optimal sky conditions may be prevalent, following this approach allows the development of high quality, representative spectral libraries, but the method is by no means limited to just coastal environments, as these conditions may exist anywhere.

The last example illustrated the importance of using nearly coincident data in time to estimate reflectance. The traditional method of estimating reflectance cannot accommodate the kinds of radiometric variations that exist when sky conditions vary considerably. Our example showed that when down-welling radiance was temporarily stable and at a consistent level, then the original method and dual method produced similar results as expected. However, under the sky conditions described in this paper, periods of stable and consistent downwelling radiance were limited, which otherwise would have limited our ability to collect any useful data. The problems inherent in these variations were apparent when the traditional single spectrometer approach was attempted with the data from a full measurement cycle over which significant variation and trending occurred. When this was attempted, the single spectrometer method made a poor estimate of the true reflectance differing by as much as 20% from our best estimate of the true reflectance. The dual spectrometer method not only allows one to monitor the changing light levels, but it permits the use of nearly coincident data in time to make a better estimate of reflectance.

The method developed here addresses primarily improved measurement practices for measurement of spectral reflectance at nadir. Measurement of bi-directional reflectance functions and the significance of the three-dimensional distribution of irradiance are beyond the scope of this paper, however, it is important to consider the potential impact that these effects can have on the measurement process: even at nadir the three-dimensional irradiance distribution can influence the result of measurement, especially for a highly structured surface with anisotropic characteristics [24–27]. On less structured surfaces such as beaches or tidal flats, these factors will be less of an issue than they might be over a vegetated surface, but they are still present. For the method of measurement described here, which relates to simple reflectance measurements at nadir, there are steps that can be taken to diminish the impact of this on the results. To that end, it is important to ensure that the base and rover spectrometers remain in close proximity to the greatest extent possible under field conditions. When this is done, as long as the surface is relatively uniform, then the ratios taken between plaque radiances and the specimen radiances taken at approximately the same time will tend to mitigate this effect.