Lessons learned in the post-processing of field spectroradiometric data covering the 0.4 to 2.5 μm wavelength region

Terrence H. Hemmer
Todd L. Westphal
Spectral Information Technology Applications Center
11781 Lee Jackson Memorial Hwy., Suite 400
Fairfax, VA 22033-3309

ABSTRACT

As the number of recognized applications for and acceptance of spectral imaging increases, the need for field spectral measurements also increases. The goal of this paper is to help ensure the quality and accuracy of field spectral measurements. Unlike laboratory measurements, where everything is controlled to meticulous detail, field measurements tend to suffer from an almost complete lack of control. Hence, assuring data quality of field measurements can be difficult. To help compensate for some of the problems that arise due to this lack of control, collection protocols are established. Even using collection protocols, sensor artifacts are not always apparent. In this paper, some of these sensor artifacts are presented and discussed. While this paper concentrates on a specific spectrometer, many of the issues, protocols and processing procedures should be generally applicable to most field spectrometers operating in this spectral region.

Keywords: field spectrometer, collection protocol, data quality, ground truth, SITAC.

1. BACKGROUND

The Spectral Information Technology Applications Center (SITAC) has been making field measurements since 1996 in a wide variety of backgrounds and environments. These measurements are often taken in support of airborne collection activities. A small number of companies make instruments specifically designed for field use. Each has its own advantages, disadvantages, and unique data format. The differences are less important than the problems associated with field collection. Thus, field protocols were established to ensure the consistency and quality of measurements for all field instruments. SITAC has distributed field measurements to a large number of investigators. Our experiences as well as questions and comments from the investigators have been used to refine field protocols as well as data processing.

As the use of remotely-sensed spectral data increases, so does the use of field spectrometers. Field instruments are often better than laboratory instruments at capturing the properties of fragile or large samples. Tradeoffs in performance have to be made for an instrument to be portable and low power. Every instrument has artifacts that must be corrected during post-collection processing. It is important to characterize each instrument to define and account for these artifacts. Every collection also presents its own challenges. To obtain quality spectra, it is not enough to go into the field, collect spectra, and process the results. The entire procedure must be reviewed and refined. The lessons learned by SITAC can be used to improve the collection and processing of field spectra. An objective of this paper is to dispel some common misconceptions about acceptable field-collection protocols. Lax field measurements yield data that can be neither repeated nor compared to airborne measurements. Data distributed to other researchers should be as free of artifacts as possible. Any processing done by SITAC saves duplication of effort by all of those researches, and increases the likelihood that the data will processed correctly, consistently, and appropriately for that specific instrument.

2. SCOPE

This paper will discuss one instrument – an Analytical Spectral Devices' (ASD) FieldSpec® FR. This instrument was purchased in 1996 and characterized, in a laboratory, in 1996, 1997 and 1998. Hardware upgrades were made to this spectrometer during the fall of 1999, and at least one of the artifacts (sensitivity drift) described below could disappear. Since all instruments have limitations[1], it is not surprising to find some when characterizing any instrument. ASD has been open and responsive to our concerns. The examples provided here are illustrative of typical problems that may arise from using field instruments.

3. LABORATORY VS. FIELD MEASUREMENTS

Laboratory measurements typically use instruments of high spectral resolution and low noise. The size, weight and power consumption of these instruments are not major considerations. Samples are small, uniform and manageable. Illumination and geometry can be carefully controlled to ensure consistent, repeatable, high quality measurements. There are no environmental effects caused by shadows, shading or adjacency. Data is acquired at a steady pace; any noticeable problem with the instrument or the sample can be resolved before taking further data. Since data are collected in-doors, operator comfort and safety may not be driving concerns, and equipment is protected from extremes of temperature and humidity. The equipment is also not at risk to damage.

Field measures tend to have lower resolution. Noise levels tend to be higher because of integration time constraints, and the effects of other error sources. Since the instrument and its power source must be carried to the sample, instrument size, weight and power consumption are all major considerations. Samples can be and often are huge. Illumination may be varying from clouds or the shadow of a nearby tree. Depending on the experiment, shadows, shading and adjacency may all be important. In order to control costs, there are high demands on data quantity and collection rates; and even a minor problem in the field may cause a scheduling disaster. Collecting field spectra under 38°C temperatures and 95% humidity in a tick-infested swamp is just one of many possible environmental conditions that has challenged the comfort of even the most hardy experimenter. Field equipment will be shaken, jolted, soaked, damaged and possibly even dropped 100 feet.

So, why take field spectra? Why not just haul the sample back to a laboratory to make the measurements? Some measurements are difficult or virtually impossible to make in the laboratory: very large samples, large areas on a sample, undisturbed samples, samples under conditions similar to an overflight, and the size and effect of the samples natural environment. For example, a laboratory measurement of a 40-m high tree is rather difficult. Even if a tree could be transported to a laboratory, getting an entire tree into a laboratory is no easy feat. Measuring the spectrum of the tree, rather than the spectra of its components, requires forcing the laboratory instrument to view a large area on the tree. If the tree is cut down or uprooted, the spectra of the component of the tree begin to change. Use of natural light is typically not supported by laboratory instruments. Adequately capturing the influence of nearby trees, the undergrowth, and the ground on the spectrum of the tree is impossible. Similarly, the process of collecting a soil sample cause the moisture level to change, the particles to mix, and the surface texture to change. Rocks in desert environments are often coated with a 'varnish' of neighboring rock dust on their exposed surface. The underside would exhibit different spectral properties.

4. SITAC'S SPECTRORADIOMETER

SITAC's ASD FieldSpec® FR has a spectral response from about 350 nanometers (nm) to 2500 nm. This spectral range is obtained by combining the output of three internal spectrometers. The characteristics of these internal spectrometers are summarized in Table 1.

The VNIR spectrometer is a 512-element silicon photodiode linear array. The resolution is approximately 3 nm, and the sampling internal is 1.4 nm. The SWIR1 and SWIR2 spectrometers are single-element Indium Gallium Arsenide (InGaAs) detectors. The resolution is about 10 nm with a 2-nm sampling interval. A SWIR1 and SWIR2 spectrum are collected in 1/10th second. The VNIR spectrum integration time varies.

Table 1. Characteristics of the three internal spectrometers that comprise the ASD FieldSpec® FR[2].

Spectrometer Designation	Spectral Range (nm)	Detector Type	Spectral Resolution (FWHM) (nm)	Sampling Interval (nm)	Number of Samples	Mode of Operation
VNIR	350-1000	Photo-Diode Array	3	1.4	512	Staring
SWIR1	1001-1800	InGaAs	10	2	1060 (combined)	Spinning
SWIR2	1801-2500	InGaAs	10	2		Spinning

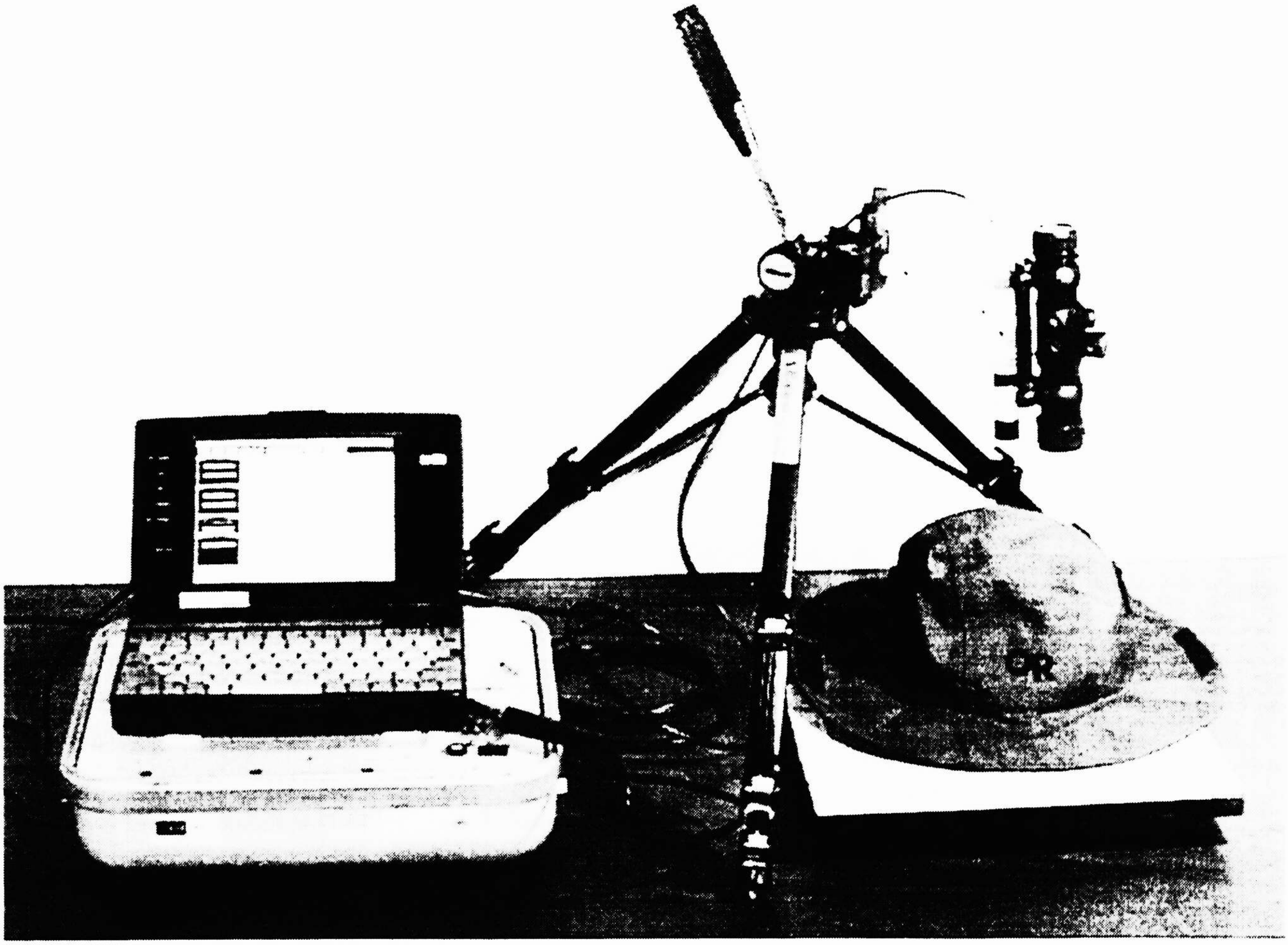


Figure 1. SITAC's Analytic Spectral Devices' FieldSpec® FR before upgrade.

The sample spectrum is collected by pointing a fiber-optic assembly at the sample of interest. Typically, either a 1° or 5° fore-optic is used. The fiber-optic cable carries the signal (photons) into the FieldSpec® FR where the cable is physically split into three parts, one part feeding each of the three internal spectrometers. Hence, a different part of the sample is viewed by each of the three spectrometers[3].

The spectroradiometer was controlled through a ZEOS® 486 Contenda Notebook computer. The software driver was ASD's FR version 1.20. The FieldSpec® FR allows a user specified number of spectra to be internally averaged, while recording only the average. Typically, a large number of spectra are averaged to reduce the noise level. SITAC saves multiple such averages to provide noise estimates and facilitate quality control (QC). The FieldSpec® FR interpolates all measurements to 1 nm using a cubic-convolution algorithm.

The FieldSpec® FR is a single-beam (SB) instrument. Unlike dual-beam instruments that collect radiance data of the sample and of a reflectance standard simultaneously, SB instruments must collect these data sequentially. Hence, in order to obtain a field reflectance spectrum with a SB instrument, such as the ASD, a field measurement of a reflectance standard must be collected. These are materials of know spectral reflectance that are traced to a National Institute of Science and Technology (NIST) standard – note that 1-nm data is needed. SITAC uses a Spectralon® panel, a Lambertian reflector with a nominal 99% reflectance, manufactured by Labsphere, Inc. of North Sutton, NH. Then a field measurement is made of the sample. Since there is a time delay between reference and sample measurements, all SB instruments are subject to scale errors caused by illumination variations occurring between or during measurements. If the spectral form of the irradiance on the sample is changing, there may also be artifacts in the shape of the reflectance spectrum. Spread in the Spectralon® spectra is an indication of changing illumination conditions. There may also be illumination changes (e.g., caused by moving clouds or contrails) on smaller time scales that induce errors into the measurements.

The reflectance can be calculated from

$$\text{Field Reflectance}(\lambda) = \frac{\text{Field Sample Measurement}(\lambda)}{\text{Field Spectralon® Measurement}(\lambda)} \cdot \text{Lab Spectralon® Measurement}(\lambda) \quad . \tag{1}$$

Note that in some cases, the multiplication by the lab Spectralon® measurement is skipped. The result, called a reflectance factor, is often what is reported as " reflectance". While this liberty yields a small spectrally-benign error in the VNIR and the lower-wavelength portion of the SWIR, the error increases to up to 7% and has spectral structure further out in the SWIR. Since Spectralon® is not exactly Lambertian for low-elevation illumination or viewing angles, another error is introduced in these cases. To properly process data collected with low solar-elevation angles, the Spectralon® must be characterized in the laboratory.

5. SENSOR ARTIFACTS

Suppose that a field collection is scheduled soon after the spectrometer arrives. It would be tempting to think that an expensive piece of equipment could be deployed immediately, and that soon after returning from the field all the data could be processed and distributed. It would be tempting, but it would also be wrong.

Figure 2a shows a subset of the measurements of a White Sage plant collected early last year. Note the discontinuities in two of the three spectra between 1000 and 1001 nm. There are also discontinuities between 1800 and 1801 nm. Discontinuities occur at the "seams" between the VNIR and SWIR1 spectrometers, and between the SWIR1 and SWIR2 spectrometers. What causes these discontinuities? Atmospheric absorption causes a low signal level in specific spectral regions, for example, around 1900 nm. These low-signal levels cause the erratic behavior in the reflectance spectrum in these regions. Also, note that one of the measurements (14Feb99a.006) is substantially noisier than the others. In fact, the noise level is so high that there is an apparent spectral feature at about 2000 nm. Is this feature a material property or a sensor artifact? Actually, the reflectance spectrum labeled 14Feb99a.006 is the mean of 12 measurements made of the same area of the plant and with the same geometry – no measurement parameters were changed! Figure 2b shows the mean, minimum, maximum and standard deviation of the radiance measurements that were used to produce the spectrum labeled 14Feb99a.006 of Figure 2a. Note that for radiance spectra, even uniform samples can have discontinuities at the spectrometer seems. Are there any other artifacts in the data? This section presents some of the results obtained by SITAC in our attempts to answer some of these questions.

The FieldSpec® FR, like all instruments, has artifacts that adversely affect the quality of the collected spectra. These artifacts fall into two classes: those that affect all spectra (i.e., artifacts that do not cancel in ratio or reflectance spectra computation), and those that primarily affect radiance spectra. The essential point here is that all instruments have artifacts. So when a new instrument is purchased, that instrument should be characterized in the laboratory before deployment to the field, and must be characterized before processing field data. The SITAC undertook a series of characterization measurements beginning in 1996 and continuing into 1998[4-5]. The results of two of these characterization measurements, FOV and spectral sensitivity, are presented below. The FOV of an instrument can affect all spectra, while the spectral sensitivity usually affects only radiance spectra.

5.1. Field of view

Since each of the internal spectrometers of a FieldSpec® FR is fed by dedicated optical fibers, the FOV of each of the spectrometers views a different part of the sample[3]. If the sample is not spectrally homogenous, then the combined spectrum is composed of partial spectra (one from each of the internal spectrometers) of up to three different materials. If the FOV's are tightly intertwined, then the effect should be minimized. If the three FOV's are relatively distinct, then the effect will be more pronounced.

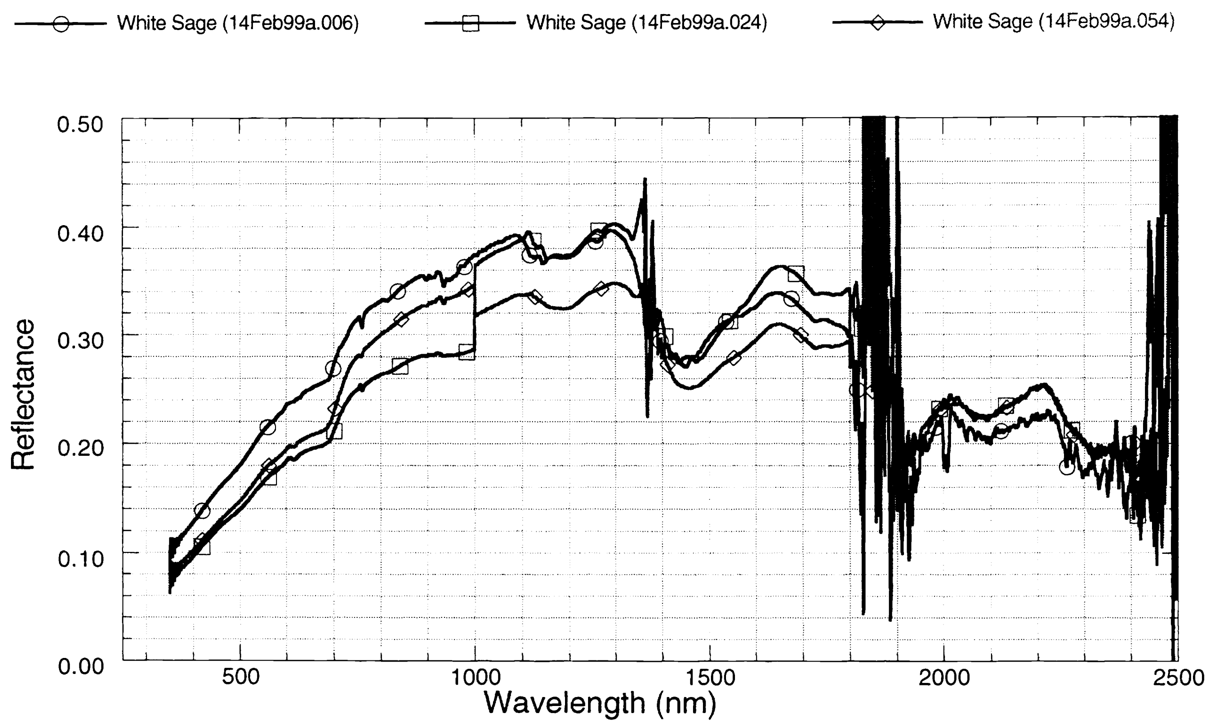


Figure 2a. Field reflectance spectra of White Sage. These are a subset of the mean spectra of the measurements

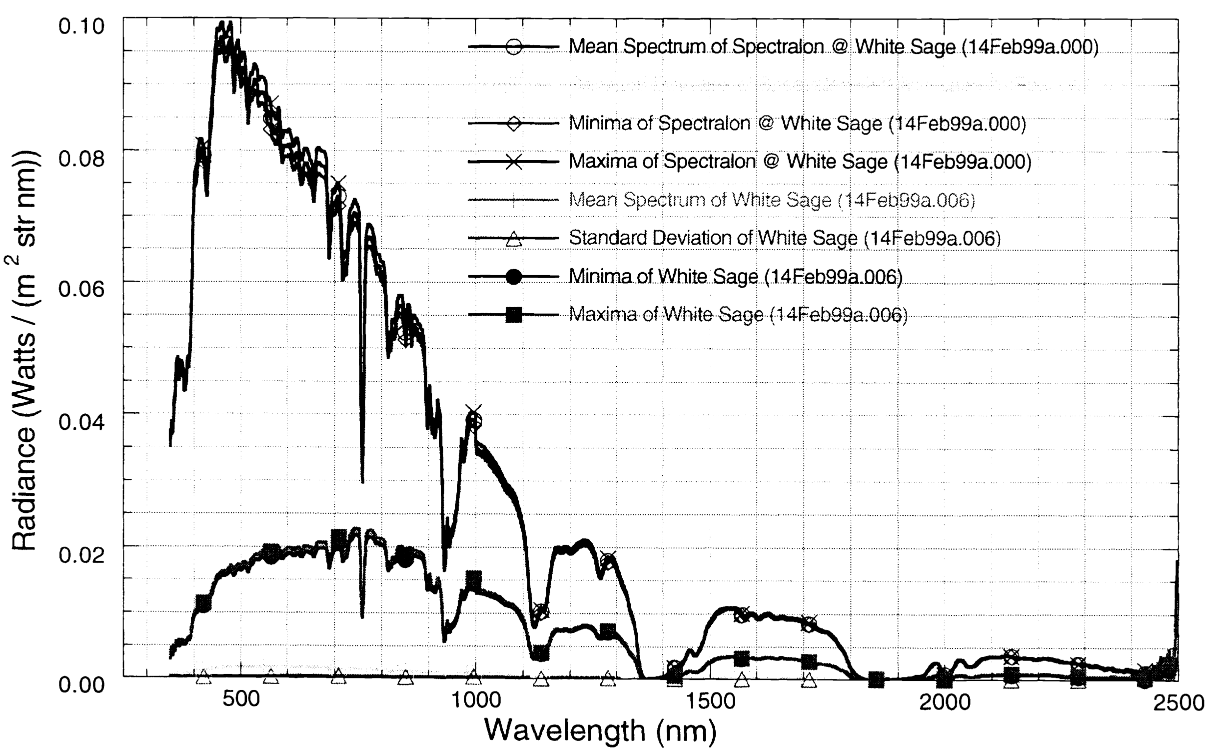
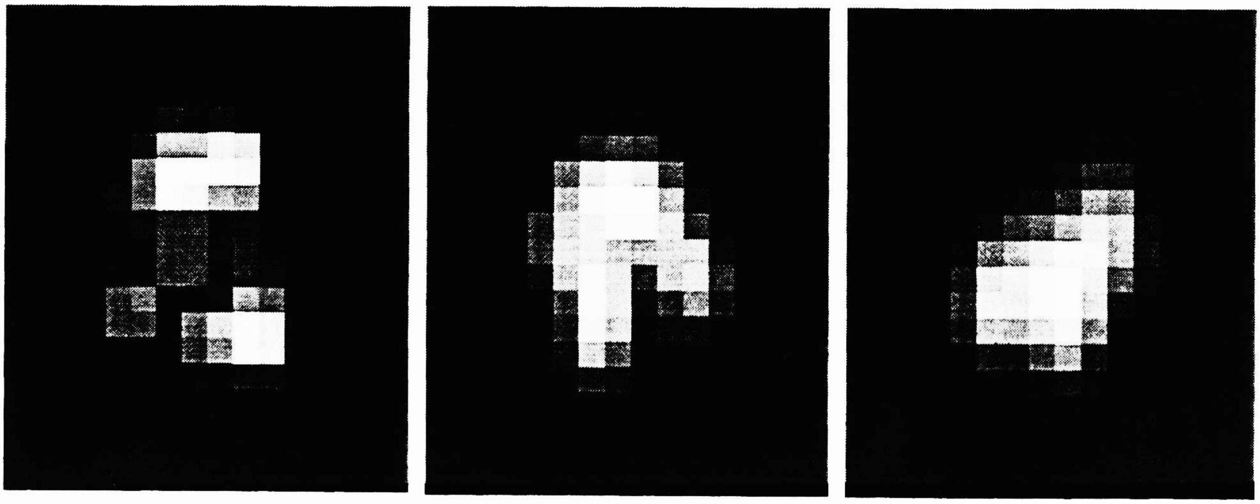


Figure 2b. Field radiance spectra of White Sage. These are a subset of the mean spectra of the measurements

In order to characterize the relative FOV's of the internal spectrometers, a two-dimensional array, 17 columns (horizontal) and 19 rows (vertical), of "pin-hole" measurements were made with the 5°-FOV fore-optic attached. These measurements were converted to radiance using the ASD supplied calibration procedures and data, and then combined into an "image" format: a 2-D FOV sensitivity "image" for each of the 2151 bands (from 350 to 2500 nm in 1 nm intervals). Each band was normalized to the maximum value in that band. The result for each of the three internal spectrometers is the pixel-by-pixel average of all the normalized bands measured by that spectrometer. The results are presented in Figure 3. Since the irradiance source used for this experiment was a calibration sphere, essentially all of the variation can be attributed to the FOV's. Unfortunately, no light source of sufficient brightness for a pinhole experiment was available for the experiment, so a larger aperture was used. Consequently, reality is worse than the data suggest.



VNIR FOV SWIR1 FOV SWIR2 FOV

Figure 3. Normalized field-of-view for the 5° fore-optic for the three internal spectrometers that compose the FieldSpec® FR. The y-axis exaggeration is 1.26.

5.2 Spectral-sensitivity drift

The FOV's are not the only cause of the spectral discontinuities at the spectrometer seams. The spectral sensitivities of the silicon and InGaAs detectors are temperature dependent. As the instrument warms or cools, the spectral sensitivities of the detectors change; thus, measurements of a sample under identical illumination at two different times will be different. For reflectance measurements, this effect cancels if sample and reference measurements are collected sufficiently close in time. For radiance measurements, this effect must be quantitatively characterized.

To characterize the sensitivity drift, our FieldSpec® FR was taken to a calibration laboratory. The 5° fore-optic was mounted on an optical table and aimed at a calibration sphere. After the calibration sphere stabilized, our FieldSpec® FR was turned on and set to save one averaged spectrum every minute for two hours. The spectrum saved was an internal (to the FieldSpec® FR) average of 100 spectra. Since each spectrum requires only $1/10^{th}$ second to collect, each averaged spectrum required 10 seconds to acquire. This experiment was performed on two days. The results from the second day are presented in Figure 4. Figure 4 shows ratios of the spectra collected at various times to the spectrum collected at 120 minutes.

Since the light source was stabilized and monitored, any deviation from a ratio of one in Figure 4 is due to a change in the sensitivity (response) of the spectrometer: a spectral sensitivity drift. The low end of the SWIR2 spectrometer is seen to drift by up to 20% over the two-hour period; and the high end of the VNIR spectrometer is seen to drift by 7.5%. In the newer models of the FieldSpec® FR, this drift is ameliorated by cooling the VNIR focal plane. For older instruments, ASD proposed a correction[6] for the spectral drift problem based on the assumptions that the response of the cooled SWIR1 spectrometer is stable, the drift eventually stops, and the sample is uniform – so there are no FOV effects. An examination of Figure 4 suggests that the SWIR1 spectrometer does stabilize, but the drifts of the VNIR and SWIR2 detectors did not stop in two hours. If the sample is not uniform over the FOV's of the detectors, then the spectral discontinuity is real, and this approach should not be used. If the temperatures of the detectors were available, then laboratory measurements like these could be used to correct for the drift. Without detector temperatures, measurement of Spectralon®– a normal part of the collection protocol – can still be used to chose one of the VNIR curves to correct for the drift. Since the low-wavelength end of the SWIR2 range in our instrument is very close to an atmospheric band, drift correction is less reliable in the SWIR2 region.

In an uncontrolled environment (i.e., in the field), the effect of the drift should be exacerbated. In addition to the instruments internal heating, changing the outside temperature and solar loading will also affect the temperature of the detectors. Temperature changes from turning the instrument off (to save battery power), entry or egress from a building, movement in or out of shade, and even the wind will cause the detector response to change in uncooled instruments.

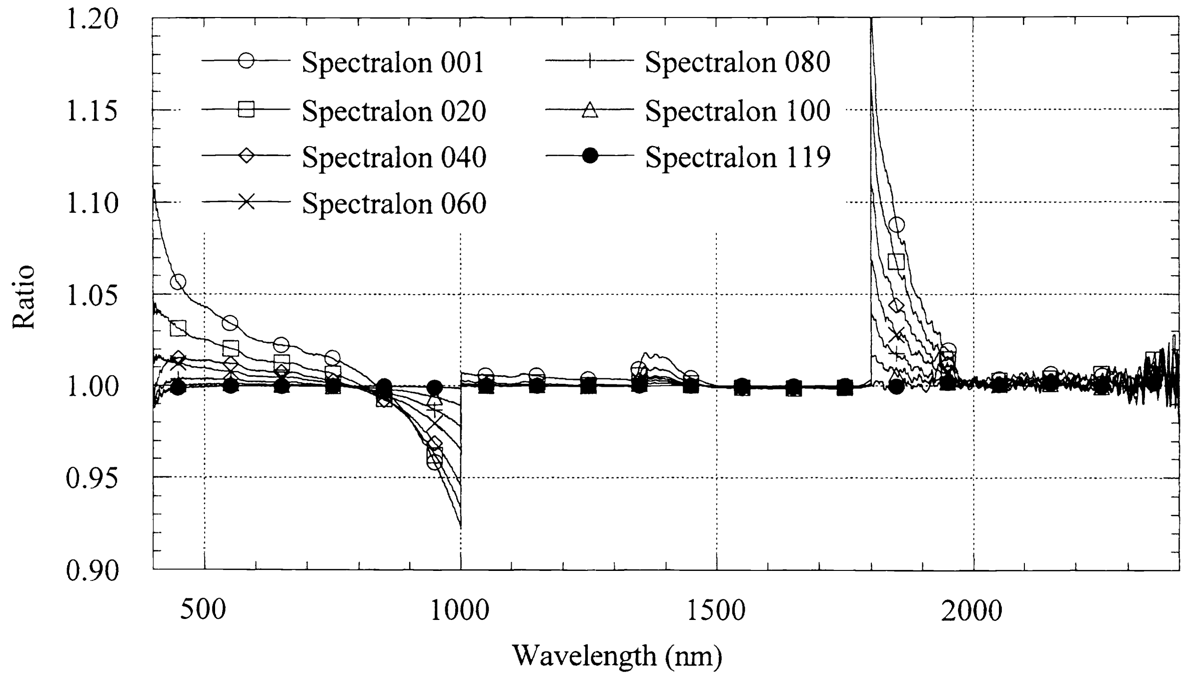


Figure 4. Ratio of spectrometer response at various times to the response at 120 minutes. Times are relative to the start of the experiment, rather than the FieldSpec® FR power-up time.

6. FIELD MEASUREMENTS

The goal of field work is to collect the best data, of as many materials as possible, in the time available. This goal is constrained by personnel, schedule, equipment, and logistics. Several spectra should be taken of each sample to characterize the natural variability of the sample. Making multiple careful measurements takes time, and that limits the amount of data that can be taken. Measurements must also be repeatable to be of value in comparisons to other sensors.

Field spectroscopy is subject to more varied errors than laboratory spectroscopy. Weather plays a major role due to its variability and effects on the sample. Clouds, some of which are subvisual, can change the illumination conditions continuously. Some instrument settings, such as integration time and saturation level, are related to illumination and may require frequent resetting. A material's signature may be affected by dust, debris, moisture, adjacency, shadowing or shading, all of which can change with the wind. The geometry of the measurement can also affect the results. Many aspects of a field collect cannot be controlled, but they must be measured well and controlled to the extent possible if repeatable measurements are to be made.

6.1. Measurement Constraints

If data is collected to compare with a specific airborne sensor, then field spectra should be adjusted to match that sensor's characteristics. This includes the perspective, spot size, and time of overflight used by the airborne sensor. A similar field of view should be used if possible. Not all of these parameters can be matched for both the airborne and the ground instruments.

Using a perspective similar to that of the intended sensor is important. For example, consider a large oak tree. While taking a field measurement by pointing up through the branches may be useful for ground based sensors, such measurements will not match those collected by any airborne sensor. A ground-based sensor would see the bottom of more leaves, a higher proportion of bark, and the sky. An airborne sensor would mostly view the tops of leaves, a little bark, any undergrowth, and the ground. Since, the spectra of most leaves' top and bottom surfaces differ, the component percentages differ, and the sky has few spectral similarities to soil, the wrong perspective would produce spectra of little value. For example, Figure 5 shows the same tree from two different perspectives: one low looking up, and the other just above the tree looking down.

In order to collect spectra comparable to aircraft measurements, the size of the sample measured is important. Collecting spectra with a smaller spot size will yield more variable results than will measurements with a larger spot size. The larger spot size will average over more materials, while a smaller spot size may isolate a component material, for example, a hole in the canopy, bark, or a leaf. However, in cases where measurements matching airborne sensor characteristics are prohibitive, then spectra of all of the individual components, and their mixing ratios, should be measured. For trees, component measurements should include leaf top reflectance, leaf bottom reflectance, leaf transmittance, bark reflectance, and local undergrowth or soil.

Similarly, the FOV of the field instrument should not exceed the total FOV of the airborne instrument. Larger FOV's will sample other parts of the bi-directional reflectance distribution function (BRDF) of the sample, and may also include other materials. If the sample is non-Lambertian, then the measured spectrum may not compare well with that from the aircraft.

In order to match or characterize illumination, shadowing, shading and adjacency effects on a sample, the measurement should be made as close to the time of the overflight as possible without contaminating the overflight measurement.

Matching perspective, FOV and spot size may require some fairly-innovative approaches. If large targets are to be measured, expect to secure the use of a lift.

If data are collected for incorporation into a spectral library, then well established and documented measurement protocols must be used. Component spectra (e.g., leaf top and bottom reflectances, leaf transmittance, and bark reflectance) should also be measured.

6.2. Approach to Field Measurements

Since there is no control over the environment, and little control over any thing else, how can useful data ever be collected? One approach is to: develop protocols to reduce errors, increase repeatability, and aid in planning; plan everything; detect and characterize errors; and allow for weather days – there are some days that collecting data is a waste of time.

Many organizations have developed protocols to improve the quality of the data[2,7-8]. These protocols are especially important if multiple teams with different types of instruments are deployed.

6.2.1. Collection Planning

To meet collection goals given these constraints, advance planning is required for: the collection and processing of the data; deployment of personnel and equipment to and from the field; safety of personnel during the collect; care of the materials deployed; and coordination between the air and ground teams. In addition to the collection issues already discussed, prioritization of samples should be determined in case of bad weather or instrument failure. The plan must identify who is responsible for processing, and how long it will take to process all the field data.

Figure 5. Views of the same tree from two different perspectives: one low looking up, and the other just above the tree looking down.

Communication between all personnel is often difficult in the field. Cellular telephones, pagers and radios do not work in all locations. Routing messages between teams through team leaders reduces the number of communication devices needed and keeps the team leaders better informed. Ground personnel should work in pairs and be aware of local temperature extremes, and hazardous weather, animals and plants in the area. Coordination between ground and air crews is needed to ensure a successful collection, and daily meetings are needed to help prevent problems.

Equipment limitations must be included in the planning process. Battery life and power availability limits the amount of data that can be collected. The time required for the instrument to stabilize sufficiently further reduces the time available for acquiring data. Temperature and humidity limitations can easily cause equipment failure and possible loss of data. Many laptop screens are unreadable in direct sunlight; this should be tested and solved before deploying. Managing available disk space and performing nightly backups, data QC and battery recharging are also necessary. A quick look at the data may be sufficient to detect problems, so that, schedule permitting, the data can be re-taken the next day. If a problem is not discovered until after the collect, then little can be done.

7. POST PROCESSING

A common misconception is that the field work is the most time-consuming part of a field collection. In many ways, post processing can require substantially more time. Post-processing tasks include quality control, data processing, report generation, and distribution. Post processing must be completed soon after the collect to guarantee the quality and utility of the results. Hastily written log entries may be inaccurate, incomplete, or simply illegible, and result in unusable data and a wasted collection effort. Discrepancies should be identified and fixed while the events are fresh in the minds of those involved. The process of reducing the data should include consistency checks and be as automated as possible. This will speed up the process, reduce the chance of human error, and allow the process to be resumed if it fails. Data formats common to the intended community should be used – avoid propriety formats. Platform variations must be accounted for – even a simple ASCII text file differs between Unix, Macintosh, and DOS platforms.

Data of unknown quality is worse than no data at all. Hence, insuring and verifying data quality is of paramount importance. Data quality checks that are typically performed on field data include detection of "overt" and "covert" saturation, data drop-outs, illumination variations, sample movement, pointing errors, log and data mismatches, anomalous spectra, and low quality data. Other tasks can include correction of the sensitivity drift, FOV issues, cross calibration with other sensors, and comparison of field spectra with aircraft data. Most of these tasks are required for every instrument – they are not specific to the FieldSpec® FR.

Detection of overt saturation in data from a FieldSpec® is relatively easy in the VNIR range since the instrument saturates at 64K. In the SWIR1 and SWIR2 range, the saturation level is not readily apparent; the saturation level depends on the gain and offset that are set dynamically by the software. In either case, the effect on the data is a flat top at the highest data levels. This typically occurs during morning collections. As the sun's elevation angle increases, the irradiance on the Spectralon® also increases, and saturation will occur if the user does not reset the detector gains frequently.

"Covert" saturation can occur if the illumination is varying wildly. In the FieldSpec®, a user-specified number of spectra can be averaged. The average spectrum is then saved to disk. If the illumination varies, saturation may be reached on one or more the spectra that are averaged. If not all of the spectra saturate, then the flat tops normally caused by saturation get rounded. Hopefully, if the illumination is varying that wildly, the user can wait for more stable illumination.

Our FieldSpec® FR was subject to data dropouts. Usually, these appear to be 1 or 2 bit errors that occurred during the transfer of a spectrum from the spectrometer to the controlling computer. With the ASD's 1-nm posting and wider band-passes, these are fairly easy to identify and correct.

Despite their deleterious effects on collected spectra, illumination variations often cannot be avoided due to field scheduling constraints. The most common causes of illumination variations are clouds – both visual and subvisual. With dispersive instruments like the FieldSpec® FR, the effects of clouds are most pronounced near atmospheric absorption bands and in the 2000-2500 nm region.

Vegetation samples will move under windy conditions. If the wind is strong enough, the bottom side of leaves and more stems will be in the instrument FOV. Since the spectra of the bottom side of leaves are often different from the top side and stems, this can have a significant effect on the measured spectrum. Accurately recording the wind conditions and their effect on the sample at the time of measurement is important.

The FieldSpec® FR is marketed as a hand-held device. If the fore-optic is not mounted (e.g., on a tripod), there are three more error sources: pointing error, jitter, and perspective. All of these error sources reduce the repeatability of the measurements. Use of a tripod or other fixed mounting device will reduce the likelihood of missing the intended sample (pointing error), jitter, or missing the intended view angles. While tripod use is strongly recommended, its use increases measurement times.

A recurring problem with our pre-update FieldSpec® FR was the unintentional collection of spectra, caused by an unfortunate choice of a trigger key – the space bar. These unintentional spectra often caused a mismatch between the field spectral-measurement logs and the data actually collected. If sufficient care is taken in the field, the extent of the mismatch can be restricted. After the trigger key is pressed, the FieldSpec® FR saved the next completed spectrum. However, depending on the number of spectra used in averaging, collection of a spectrum may have started before the user intended. This type of error is very difficult to detect unless multiple spectra are recorded for each measurement. If only a single spectrum is recorded (saved in a disk file) for any given measurement, quality assessment is very difficult.

"Cross calibration" with other sensors and comparison of field spectra with aircraft data are invaluable in identifying problem areas. The challenge here is determining which data source, if any, is the most reliable.

When our pre-updated FieldSpec® FR was used in the field. A small number, typically six, spectra were recorded instead of just one. That is, without moving the fore-optic or changing the location on the sample, six of more spectra were recorded. These multiple measurements were in addition to measurements of multiple locations on each sample, and measurements on multiple samples. These multiple measurements make QC orders-of-magnitude easier, and allow for better QC. On the downside, all of these measurements must be processed and analyzed. Figure 6 shows the data-flow diagram for processing these multiple measurements. Note that the essential point here is that even post-QC processing is not trivial, so time must be budgeted into the collection effort.

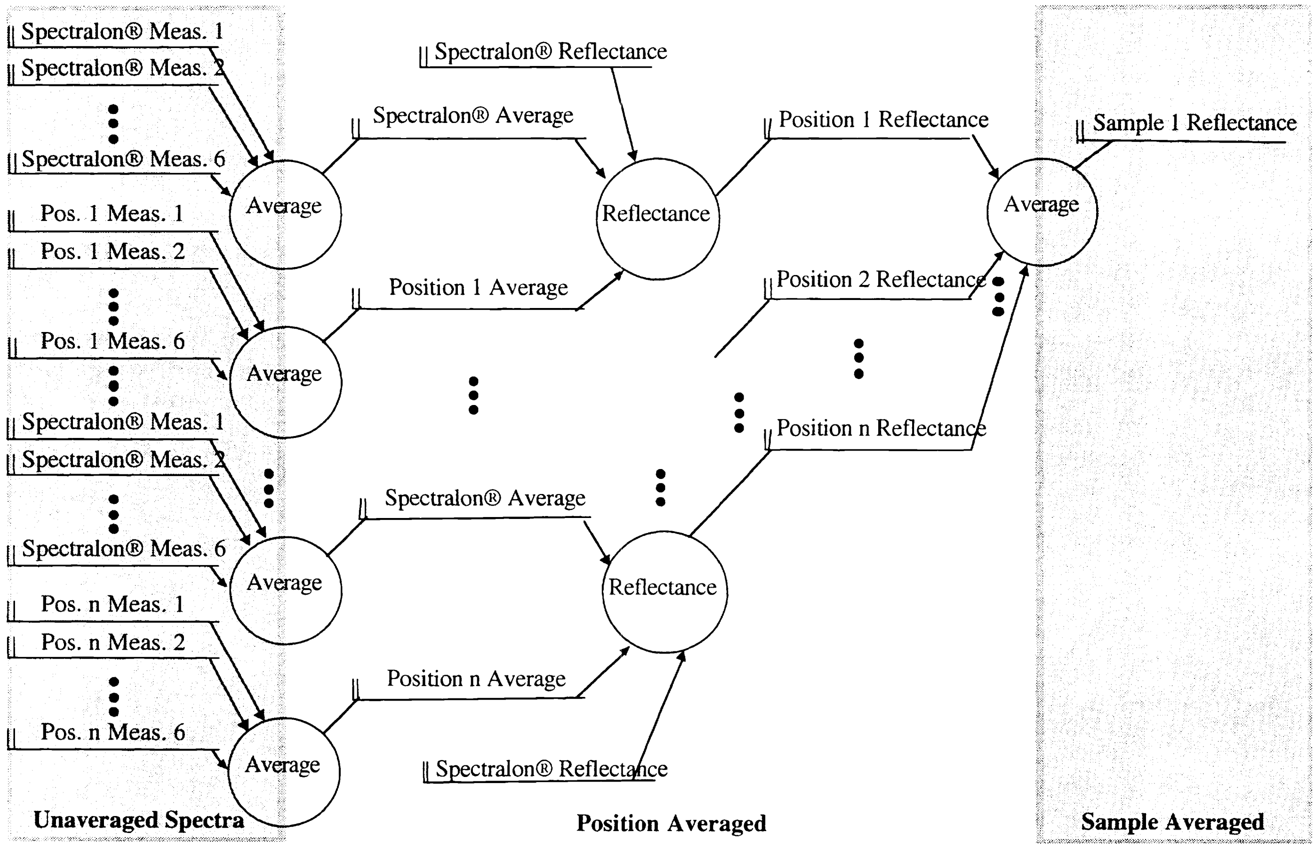


Figure 6. Data-flow diagram for processing of FieldSpec® FR field data. Quality-control processing occurs earlier.

Quality of reporting can vary as much as the quality of the data. At the very least, a number of relevant notes (a "README" file), a description of the instrument, a description of data formats, a spectral collection log, a photography log, and scans of photographs are needed even for quick turnaround projects. More formal reporting is encouraged, including spectral plots, detailed descriptions of samples, measurement procedures, and experimental goals.

SITAC data sets have been distributed to a large number of organizations. Hence, a little time spent in on our side can save an enormous amount of redundant effort by the data users. Users also tend to vary on preferred data formats and the amount of processing desired. To this end, a data distribution includes all the intermediate results. At many intermediate stages, data are provided in the following formats: a binary spectral-data file with an ENVI® style header file (a commonly requested data format), including nominal band centers and bandwidths; individual ASCII files (2 column tab-delimited files with a fixed number of significant figures); tabulated ASCII files (under 200 columns including a wavelength column); and, if time permits, spectral plots.

8. CONCLUSIONS

The high cost of a field spectrometer can belie the necessity for characterization of the instrument before and after field use. Cross calibration with other instruments also reduces the chance of anomalous or low quality data.

Data of unknown quality is worse than no data at all. Recording six or more spectra for every field measurement greatly facilitates QC of field data. These multiple measurements are of the same spot on the sample using the same geometry – nothing under the users control changes. These measurements facilitate identification of "covert" saturation, illumination variations, sample movement, pointing jitter, log-data mismatches, anomalous spectra, and low quality data. Measurements of multiple locations on a sample and of multiple samples are still required.

Common problems that occur in field spectroscopy that are in control of the user include: incomplete or no documentation of sample characteristics; failure to allow time for post processing and quality control checks; log-data mismatches, collection geometry mismatches (especially between ground and airborne collections); non-flat Spectralon® or other "reference panel" measurements; sample transparency; too few sample measurements and insufficient log entries (especially, sky condition entries). If the reference standard is not kept clean or is damaged, the resulting spectral measurements will be adversely affected. Failure to follow maintenance procedures may result in loss of NIST traceability.

Typically, most samples are assumed to be Lambertian reflectors. Since this is often not the case for off-nadir measurements, changes in viewing and illumination angles will cause a change in the measured reflectance. For materials with non-Lambertian BRDF's, the changes will be more pronounced. Some means of consistently controlling the collection geometry must be used to prevent this source of variation. Non-standard collection geometries should always be logged. As long as established protocols are used, the results will at least be consistent. An interesting effect, of measuring non-Lambertian samples when a Lambertian reflectance standard (e.g., Spectralon®) is used, is that the calculated reflectance can be greater than one.

Lastly, the fact that a spectrometer is a field instrument does not mean that one person can efficiently or safely operate the instrument, or do all of the other required tasks. It takes more than two hands to perform the required tasks. These tasks include recording data filename, sample description, and its surroundings, hold and level the Spectralon®, operate the spectrometer, take photographs, keep a photo log, and watch for snakes, muggers and other health and safety threats.

ACKNOWLEDGEMENTS

The authors would like to thank Paul Lewis for encouraging and facilitating this paper; Darryl Wilson and Herb Mitchell for their reviews; Mark Czarnaski and William Graver for their assistance in the laboratory.

BIBLIOGRAPHY

1. J. W. Salisbury, *Spectral Measurements Field Guide*, SITAC, Fairfax, VA, Report, 25 March 1998.
2. ASD, *FieldSpec Full Range Spectrometer: Procedures Reference*, Boulder CO, 1993.
3. J. Mustard, Private Communication, 1996.
4. R. Buntzen, *Analytical Spectral Devices FieldSpec Radiometric Calibration from TOWER I*, SITAC, Fairfax, VA, Internal Report, 3 December 1996.
5. T. Hemmer, Unpublished.
6. D. Beal, and M. Eamon, "Preliminary Results of Testing and a Proposal for Radiometric Error Correction Using Dynamic, Parabolic Linear Transformations of "Stepped" Data (RCALCX.EXE)", Analytical Spectral Devices, Boulder CO, (No Date).
7. SITAC, *HYMSMO Program: Ground Truth Protocol*, SITAC, Fairfax, VA, Internal Report, 30 April 1997
8. J. L. Mueller, and R. W. Austin, *Volume 5, Ocean Optics Protocols for SeaWiFS Validation*, NASA Technical Memorandum 104566, Vol. 5, July 1992.