Techniques and Instruments   Crop Physiology Lab

Spring 5-2003

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Table of Contents

Spectroradiometer	Approximate Cost	Range	# of Units
ASD FieldSpec Pro JR	$40,000	350-2500 nm	1
Apogee/StellarNet SPEC-PAR/NIR	$3,600	350-950 nm	1
StellarNet EPP2000-NIR-InGaAs	$17,000	Vis-1700 nm	2

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Abstract

Spectroradiometers can be used to identify plant stress by measuring crop reflectance. Spectroradiometers can measure nitrogen and water stress, and subsequent adjustments in applications can improve crop yield and reduce over-application. Two portable spectroradiometers and their accompanying software were compared for accuracy and ease of use while conducting experiments to determine water and nitrogen stress in crested wheat grass and soybean plants. The first unit was a higher priced ($40,000) visible/NIR triple diode spectroradiometer (ASD FieldSpec Pro JR) with a range of 350-2500 nm. It uses ASD's FieldSpec Pro RS[3] software. The second was a low-priced ($3600) visible/NIR fixed diode spectroradiometer (Apogee/StellarNet SPEC-PAR/NIR) with a range of 350-950 nm. It comes with StellarNet's SpectraWiz software. The study focused on the software provided by the two manufacturers because the most noticeable differences were software-based. Comparisons were made to determine if the advantages of the ASD spectroradiometer and its software justified their substantially higher cost. The StellarNet SpectraWiz software was much more user-friendly and conveniently designed than the ASD software, which appeared outdated and time consuming to operate. However, results indicate that the ASD hardware is easier to use and simpler to configure than the Apogee/StellarNet model and that the FieldSpec Pro's increased range was advantageous for water stress analysis. However, both spectroradiometers showed similar consistency within the 350-900 nm range.

Introduction

Spectroradiometers have been used to measure plant reflectance and identify plant stress for many years, but only recently have spectroradiometers become economical enough for independent farmers to consider buying one. By using reflectance spectra, crop nitrogen and water levels can be closely monitored in order to maintain appropriate application levels and control costs.

We used the ASD FieldSpec Pro JR, the Apogee/StellarNet model SPEC-PAR/NIR, and the dual-unit StellarNet InGaAs-Vis/NIR unit in our comparison (Figure 1). The ASD spectroradiometer ($40,000) has an overall range of 350-2500 nm and uses three internal diodes

to measure radiation. The first diode is fixed and measures radiation from 350-969 nm. The second and third are scanning diodes and measure incoming radiation from 969-1749 nm (SWIR-1) and 1750-2500 (SWIR-2), respectively. Integration time is set automatically (auto-integrating) for each of the three arrays to optimize incoming radiation

Figure 1: (l-r) ASD FieldSpec Pro JR, Apogee/StellarNet SPEC-PAR/NIR, and StellarNet dual InGaAs-Vis/NIR

levels in all three regions. The Apogee/StellarNet SPEC-PAR/NIR spectroradiometer ($3600) has a single, fixed diode that measures radiation from 350-950 nm. Its integration time must be set manually by the user in order to maximize radiation measurement.

The two software packages provided the most obvious differences and, therefore, will be the focus of this report. ASD provides a program called FieldSpec Pro RS[3]. The Apogee/StellarNet spectroradiometer provides StellarNet's custom software, SpectraWiz. While both software packages function well and are straightforward in operation, they also contain several advantages and disadvantages in comparison to one another. Of the two programs, StellarNet's SpectraWiz was found to be the best overall.

Materials and Methods

The spectroradiometers were used to analyze both single-leaf and whole-canopy reflectance of wheat, soybean and crested wheat grass. To identify nitrogen deficiency, water stress, and strontium contamination, single-leaf reflectance measurements required the additional purchase of a reflectance probe for use with each spectroradiometer. Nitrogen level analysis was

performed on spectra of hydroponic wheat grown at seven different nitrogen levels. Water stress analysis was performed on soybean plant spectra from plants exposed to drought conditions for several days and also on single-leaf soybean spectra from leaves that were scanned regularly over a two hour period after being plucked from their branches. Strontium analysis was performed on mature single-leaf crested wheatgrass spectra of plants grown at three different strontium levels.

The spectroradiometers' software was tested for the usefulness, simplicity and reliability of the following features; configuration, integration time, dark current, sequential measurement, data management, and attachments and hardware.

Results/Conclusions

Configuration

SpectraWiz software is difficult to configure on a new computer. It requires the user to enter several calibration coefficients specific to the spectroradiometer and synchronize the physical port settings on the spectroradiometer and in the software. As discussed in the appendix, the user might occasionally have to switch between spectroradiometers or use two simultaneously because the ranges of the Apogee/StellarNet units are much narrower than the range of the ASD unit. Configuration and operation when using multiple spectrometers or switching between units proves to be very problematic and time consuming (see Appendix).

The FieldSpec software arrives from ASD configured and ready to use. It comes with its own laptop computer (typically a Compaq Evo N400c) with the software preinstalled and configured for your spectroradiometer.

Integration Time

Integration time in SpectraWiz must be set manually, according to light conditions. While this is a simple task to perform, integration time must be changed frequently as light conditions change. The ASD spectroradiometer uses three internal diodes to measure from 350-2500 nm. There is no need to configure each diode, as the entire unit is calibrated to

Figure 2: Graphs of spectral readings with and without breakpoints.

function as a whole, not three individual parts. The auto-scaling 'optimize' feature automatically adjusts integration time and scaling properties for each diode according to light conditions in order to optimized the amount of radiation received, which results in a decreased signal-to-noise ratio, increased overall accuracy, and a 'seamless' spectrum across the entire range. This process is not perfect, however, and small glitches can occasionally be seen at the switching wavelengths for the three ranges (Figure 2). It is then necessary to modify the data to align the three ranges into a seamless spectrum. However, it is often impossible to correct the changes at the 1750 nm crossover due to high levels of noise from atmospheric water.

Dark Current

The ASD spectroradiometer is equipped with an internal shutter that closes off the light source when taking dark scans. This system, called Driftlock, is helpful in taking accurate dark scans to eliminate background electronic signaling. However, when taking reflectance measurements with FieldSpec, every time a reference scan is taken a dark scan is automatically taken as well. While it is necessary to take dark scans often to decrease the signal to noise ratio and increase the overall accuracy of the measurements, it is not necessary to take a new dark
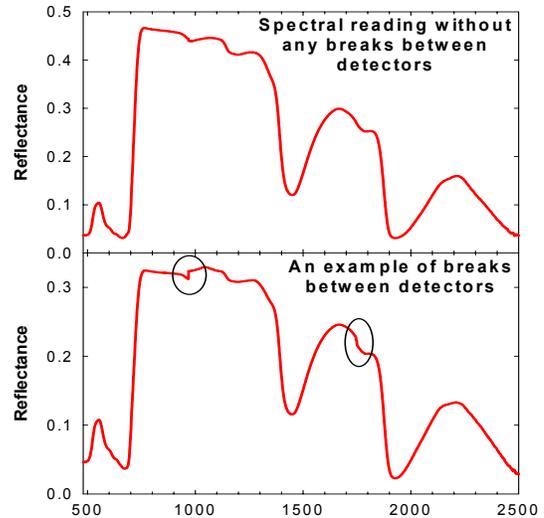
4

scan every time that a reference scan is taken. New reference scans must be taken for almost

every measurement when light conditions are changing rapidly (scattered cloud cover, for

example). It would be better if the user had the option to determine when dark scans are taken.

The SpectraWiz system estimates the dark current in software by measuring the current

of a small array of optically blackened pixels, but the user must manually remove the light

source by completely covering the fiber optic sensor with black to take a real dark scan. The

advantage that SpectraWiz has is that it allows the user to take dark scans and reference scans

independently of one another, allowing the user to determine how often dark scans are needed.

Sequential Measurements

FieldSpec has a feature that allows the user to take sequential measurements. This

facilitates taking many measurements simultaneously by eliminating the need for the user to

manually save each spectrum. SpectraWiz also has a sequential save option, called episodic data

capture. Episodic data capture allows the user to save a sequence of spectra, but the file has to

be post-processed in a demo program called "SW Demo" to be read in Microsoft Excel.

When saving spectra in the FieldSpec 'spectrum
save' dialogue box (Figure 3), the user is able to specify the
'starting spectrum number,' the 'number of files to save,'
and the 'interval between saves'. The software
automatically increases the spectrum number by one each
time a spectrum is saved. This number is then designated

**Figure 3: Sequential measurement
options for FieldSpec.**

as the file extension on the saved spectrum (i.e. spectrum.001, spectrum.002, etc). However, this

increasing spectrum number cannot be disabled and the user must change the 'starting spectrum

number' value back to 001 every time a spectrum is saved if they wish to take individual scans

and keep the spectral file extensions the same. SpectraWiz saves all measurements as text files. The user must only specify the name of the spectrum to be saved. In summary, saving sequential measurements is facilitated by FieldSpec's design, but this same design makes individual measurements more difficult than in SpectraWiz.

Data Management

When taking spectral measurements with the ASD software, data is stored in a unique file format that is only recognizable by FieldSpec's post-processing program, ViewSpec Pro. The format is not recognizable in Excel and therefore, the operator must first convert the data into ASCII format using ViewSpec (Figure 5).

Figure 5: FieldSpec's post -processing program, ViewSpec, is needed to convert data to ASCII format.
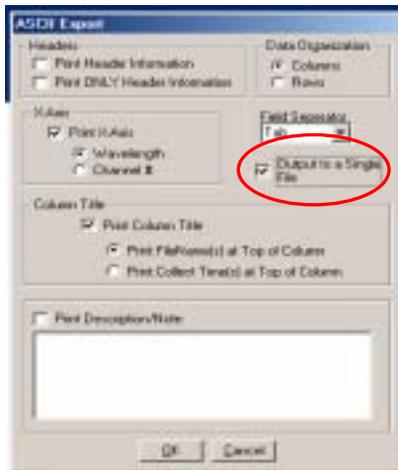

Figure 4: Multiple files from FieldSpec can be saved as one ASCII file using ViewSpec.

There is one advantage to using ViewSpec, however. When transforming the data into ASCII format, the operator is allowed to export the data into a single ASCII file, which can then be opened directly into Excel (Figure 4). Measurements taken using StellarNet's SpectraWiz software are stored as text files, which can be opened directly into Excel, but they must be opened one at a time. This can be extremely time-consuming if many files must be opened at once, unless a short macro is written in Excel to automate the process.

FieldSpec does not have the ability to open previously saved spectra files. You must use the ViewSpec program to do this. This makes it difficult to catch errors in saved data while the erroneous data can still be replaced. If measurements are being taken in the field and saved

spectra are not checked periodically through ViewSpec, errors might not be detected until the user has left the measurement location and can not retake the spectra. SpectraWiz is able to open previously saved spectral files directly in its main window. This is useful not only in double-checking spectra when saving, but in comparing saved spectra to current measurements, as there is a feature to overlay multiple spectra on the same graph.

When saving measurements in FieldSpec, the 'spectrum save' dialogue box opens directly on top of the spectrum display and the spectroradiometer continues scanning even after the dialogue box is opened (Figure 6). Therefore, you cannot see the graph of the current spectrum as you specify the 'saving' preferences and the
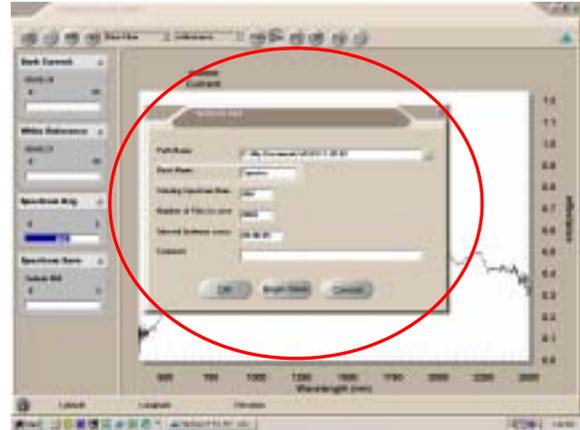

Figure 6: FieldSpec's "spectrum save" window opens right on top of the spectrum graph.

graph you actually save could be different from the graph you intended to save. This is because the software does not actually save the spectrum until the 'Begin Save' button is activated within the dialogue box. To avoid this problem, you have to either manually 'freeze' the graph before opening the dialogue box or drag the dialogue box out of the way in order to see the graph, which adds one more step to the spectrum saving process. This must be done for each spectrum saved, since there is not an option to set the software to do this automatically. SpectraWiz automatically freezes the spectrum that is displayed when the 'save sample spectrum' button is depressed, ensuring that the spectrum seen when the button was pushed is the same one that will be saved. The user then specifies the preferences for saving that spectrum. The spectroradiometer does not continue scanning until after you have completed saving the previous scan. This greatly reduces the amount of time and user interaction necessary to save spectra. It

also increases the accuracy with which measurements can be taken by allowing the user to save the exact spectrum that they selected.

Figure 8: Windows-based browsing in SpectraWiz.

SpectraWiz has a Windows-based file browsing system that allows you to create, delete, rename, cut, copy, or paste files within the SpectraWiz browser windows
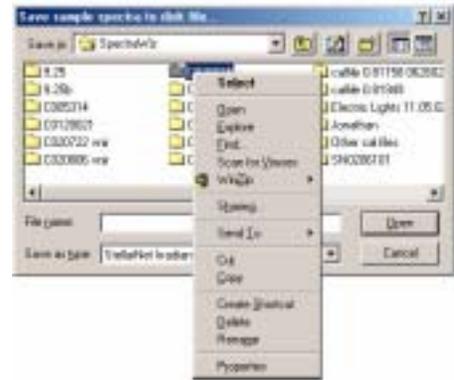

Figure 7: Primitive directory browsing in FieldSpec.

(Figure 8). The FieldSpec 'directory browser' used to navigate Windows directories and specify directory locations is primitive and time consuming to navigate (Figure 7). It is reminiscent of the first versions of Microsoft Windows and increases the difficulty of managing the software. If you want to create a new folder to store new data in, you must leave FieldSpec and create the file through Windows.

Attachments and Hardware

The ASD spectroradiometer uses two-piece plastic cable clamps to connect attachments to the fiber optic cable (Figure 9). This is problematic for four reasons:

1. The removable piece can easily be lost. When changing attachments frequently, and often while in the field, they can easily be dropped or misplaced, which makes it extremely difficult to attach anything to the fiber optic cable.

Figure 9: Cable connectors for ASD pistol grip and Apogee/StellarNet cosine head.

2. The plastic teeth on the attachments must be flared out each time the cable is inserted. When one attachment is removed from the cable, the teeth remain compressed and the opening remains too narrow for the cable to be reinserted. The user must manually spread the teeth out in order to get the cable head past.

Figure 10: StellarNet (top) and ASD reflectance probes.

Figure 11: ASD (l) and Apogee/StellarNet cosine diffusers.

3. The plastic is prone to break and/or stretch out. Plastic is likely to become brittle and can easily be broken as it ages, especially under the conditions experienced in field work.

4. The threaded piece must be screwed down so tightly in order to fix the cable securely in place that it can gouge the plastic sheathing of the fiber optic cable. ASD's attachments include a pistol grip (Figure 9), reflectance probe (Figure 10), cosine diffuser (Figure 11), cuvette holder, and many others for both field and lab work.

StellarNet's fiber optic cables are quickly and easily attached. They are fitted with metal threaded sockets that can be securely fastened to the corresponding threaded male head on the attachments and spectroradiometers (Figure 9). There are no removable parts that can be lost and they are durable. Apogee/StellarNet offers a variety of attachments as well, including: reflectance probes (Figure 10), cosine diffusers (Figure 11), cuvette holders (Figure 12), dip probes, and
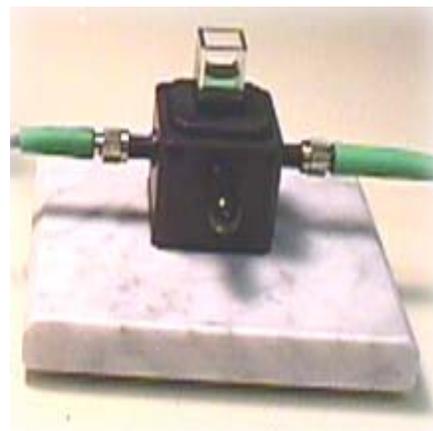

Figure 12: StellarNet cuvette holder.

many other types of fiber optic cables and lenses.

While the ASD spectroradiometer is rather heavy, it is easy to use and almost entirely self-contained. It comes with its own backpack carrying case and internal rechargeable battery. The Apogee/StellarNet spectroradiometer is small and lightweight, but requires that the user find a way to transport the unit and the external power supply because it does not come with a carrying case. It also has a much narrower range than the ASD (350-1000 nm versus 350-2500 nm, respectively). The ASD spectroradiometer costs approximately $40,000. This price includes a lightweight Windows-based Pentium III laptop computer that comes with the software preloaded and configured to run with the spectroradiometer. The Apogee/StellarNet spectroradiometer costs approximately $3,500 and the user must supply the computer and configure the software.

Increasing the Accuracy of the Apogee/StellarNet Spectroradiometer

The Apogee/StellarNet SPEC-PAR/NIR spectroradiometer is accurate between 450-900 nm, and its accuracy beyond these regions can be greatly improved with the use of simple filters. Reflectance measurements are made by first taking a reference scan of a 'perfectly white' reference standard. The software compares subsequent scans to the reference spectrum, and reflectance values are calculated for the subsequent scans. When taking reference scans in sunlight conditions, the spectroradiometer receives much more radiation in the 500-700 nm region than it does in the 350-500 and 700-950 nm regions. This causes the diode to 'saturate' in this visible region before it can receive enough radiation in the other regions to accurately compare reflectance values. This results in a high signal-to-noise ratio and inaccurate readings in the <400 and >800 nm regions. Simple filters that reduce the amount of visible light transmitted to the diodes can be used while taking these measurements. This allows the user to

set a higher integration time, allowing more UV/NIR radiation to be collected, reducing the signal to noise ratio, and increasing accuracy in those regions.

This same effect could potentially be achieved using a software 'fix' by somehow creating an 'auto-scaling' and filtering effect that could divide the 350-1000 nm range up into multiple sections. The software could then take a measurement for each section at an optimized integration time and then patch the data for each section together into a complete spectrum. The spectroradiometer's accuracy could also be extended by physically altering the unit's range. Slit adjustments could increase the accuracy and range of the spectroradiometer. Increases in slit size decreases attenuation, allowing more signal at the far ends of the spectrum to reach the detector. However, increased slit size decreases the wavelength resolution. Adjustments in slit position can change the range of the spectroradiometer, allowing more signal in the NIR region at the expense of the UV/blue region.

Summary

The biggest difference between hardware and software problems is that problems with software are often easier and less expensive to fix. The majority of the problems with these two spectroradiometers could be fixed with changes in the software programming.

The ASD FieldSpec Pro JR has excellent hardware design. Its triple diode scanning design far exceeds the single diode Apogee/StellarNet SPEC-PAR/NIR. It arrives from the manufacturer pre-calibrated and ready to use in its own carrying case/backpack. Its all-in-one design eliminates the clutter and hassle of multiple units, external battery packs, and excess wiring. Its range allows increased ability to measure water stress, which is indicated by several major water bands above 1100 nm. However, it costs approximately ten times that of the Apogee/StellarNet model. The software (FieldSpec Pro RS[3]) is poorly designed and difficult to

navigate. The only software feature in FieldSpec that is better than SpectraWiz is the sequential

measurement option, and even that needs to have a 'disable' option. Its directory browsing, data

saving process, inability to manually disable dark scan measurements, and post-processing

convenience are all inferior compared to SpectraWiz. All of these software problems could be

remedied quite simply with programming changes. Its hardware, however, is excellent if you

have the budget to invest in one.

For comparing light between 350 and 950 nm, the Apogee/StellarNet SPEC-PAR/NIR

spectroradiometer is an economical and reliable alternative. While it involves more user-input

and configuration, the measurement accuracy is equal to the ASD unit. Its resolution is even a

little bit more precise than that of the ASD spectroradiometer. The hardware is small and

lightweight, but requires an external power supply and does not have its own carrying case. If

Apogee/StellarNet offered a package that included a laptop with pre-loaded software that was

configured to the spectroradiometer in the spectroradiometer package, the problems with

configuration would be simplified. The SpectraWiz software is convenient and much more user-

friendly than the ASD FieldSpec software, once it is properly configured. It simplifies and

quickens the processes of taking and saving measurements, reviewing saved data, and analyzing

spectra.

Appendix: Multi-Unit Spectroradiometers

Limited testing was also performed on a mid-priced ($17,000) dual-unit

spectroradiometer (StellarNet's InGaAs unit coupled with an EPP2000 Vis/NIR unit) which has

a range of 580-1700nm (Figure 13). It also uses StellarNet's SpectraWiz software. The dual-

unit spectroradiometer (InGaAs-Vis/NIR) was tested primarily to evaluate the ease of using

multi-unit spectroradiometers and to illustrate the advantages and disadvantages of linking

multiple units together to increase the overall range of measurement. It is difficult to configure, but provides accurate measurements once configuration is completed.

The StellarNet dual InGaAs-Vis/NIR has a variable lower range, depending on the Vis/NIR unit used, and an upper limit of 1700

Figure 13: (l-r) ASD FieldSpec Pro JR, Apogee/StellarNet SPEC-PAR/NIR, and StellarNet dual InGaAs-Vis/NIR

nm. The unit tested in this experiment measures from 580-1700 nm (Vis/NIR=580-1000 nm, InGaAs=900-1700 nm). The two units must be linked together and operate at the same integration time, which is set manually by the user. A custom "Y-cable" is also necessary to allow concurrent measurements with both units.

When using multiple units or switching between different spectroradiometers, you must re-enter the coefficients for the new spectroradiometers and readjust their port settings. When using two spectroradiometers simultaneously, as with the InGaAs spectroradiometer, each unit must be configured separately and connected sequentially to the computer via a daisy chain ISE cable, which is time consuming and complicated. Several bugs within SpectraWiz must be worked out in order for the range and scaling to function properly while the two spectroradiometers run simultaneously.

When using two spectroradiometers simultaneously in SpectraWiz, only one integration time may be used for both units, which creates another problem. One of the spectroradiometers may be saturated with light while the other may not be receiving enough light to produce an accurate spectrum.

While using multiple units together or frequently switching between different units may increase the overall measurable wavelength range, it also creates several configuration and operational problems that are not experienced when using a single-unit spectroradiometer.