Development of a Protocol for Use of a Field Spectroradiometer in Monitoring Lake Water Quality

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Abstract:

Hyperspectral field spectroradiometer sampling can significantly enhance projects that monitor lake water quality through multispectral and hyperspectral satellite remote sensing correlated with water quality 'ground truth' samples. This paper presents the rationale for using field instruments for such projects and describes their potential benefits. The protocol describes the use of the ASD FieldSpec spectroradiometer as an activity integral to the Satellite Lake Observatory Initiative project. The protocol includes instructions and advice needed for effective use of the instrument on a small boat and outlines several techniques for data analysis. Applications discussed include the correlation of field and satellite spectral data as well as a comparison of the spectra with traditional limnological measures of water clarity and chemistry.

1. Introduction

Contemporary research into the monitoring of lake water quality using satellite or aircraft remote sensing (eg. George and Malthus 2001, Giardino et al 2001, Ostlund et al 2001) can be improved through use of a field spectroradiometer. The data from the field instrument, in addition to direct physical measurements of lake water, provides ground truth for the satellite or aircraft data and has several applications. In addition, the versatility of a field instrument allows it to be used on its own as a tool for monitoring lake water quality rather than as a calibration instrument providing ground truth comparison for satellite data.

Many researchers, especially in those Europe, have already used Field spectroradiometers to monitor water quality. Some projects have used spectroradiometers for ground truth to validate data from satellites or aircraft (e.g. Brivio, Giardino, and Zilioli 2001). Others have derived water quality directly from the spectroradiometer (eg. Gons 1999).

This protocol is part of the Satellite Lake Observatory Initiative (SLOI) at the University of Wisconsin, Madison (Lillesand et al 2001). The project currently uses data primarily from the Landsat-7 Enhanced Thematic Mapper (ETM+) to estimate water quality measures for hundreds of the more than 15,000 total lakes distributed throughout Wisconsin. The SLOI project has successfully derived values for water clarity, measured as a Secchi depth, using Landsat-7 imagery. However, the use of a field spectroradiometer is an essential precursor for expanding the project to include data from hyperspectral imagers such as the Hyperion instrument on the EO-1 Satellite. Use of hyperspectral imagery allows more accurate modeling of several water quality parameters

including concentrations of chlorophyll-*a* and dissolved organic carbon (DOC) (Dekker et al 1992).

The instrument currently used by the SLOI project is the Analytical Spectral Devices FieldSpec Hand Held Spectroradiometer. This device is small enough to be transported and deployed effectively even from a small boat or canoe. A portable computer is used to operate the spectroradiometer through a serial connection.   The instrument can be calibrated by pointing at a small white reference panel and measures surface reflectance by pointing an attached foreoptic at the target.   Reflectance data is collected over 512 bands ranging from 325 nm to 1075 nm and typically takes only a few seconds to record.

2. Presentation of the Protocol

The following is the protocol developed for using the ASD FieldSpec Hand Held Spectroradiometer for SLOI. The protocol is unique to the ASD instrument and the goals of the SLOI project. Significant portions of the protocol are adapted from the instrument's instruction manual (2000), which is also included in its case. Refer to this manual for further clarification on the details of operating the device.

I. What to bring

- Everything in the FieldSpec case and laptop case
- GPS unit
- Digital camera
- Tripod (optional)
- Data sheets (with clipboard and pen)
- Simple tools (screwdriver, knife, etc.)
- Always recharge the batteries on all equipment after each day of use; especially the spectroradiometer itself and the laptop. Note that the batteries are removed from the instrument simply by pulling hard. The battery charger is in the FieldSpec case and may take up to 2.5 hours charging time per battery.
- Although one person can operate the instrument alone, the operation is easier with two people. One person then operates the laptop while the other holds the instrument.

II. On-site setup

A. Selecting a location

To minimize the chance of getting the equipment wet, do not set any of it up until the boat reaches the location at which data will be collected. Spectral data should be taken in the same locations as other water quality parameters so that comparisons can be made. Usually, sampling of such properties is done at the deepest point in the lake to minimize the likelihood of 'seeing' the bottom, and to increase the likelihood that the sample represents a well-mixed lake water column. The only non-negotiable requirement for the spectroradiometer sampling location is that the bottom cannot be seen. Reflectance off the bottom of the lake would add significant complications to the data analysis. If the experiment is designed to correlate data with satellites but not directly with water clarity or chemistry, it may be useful to take data at multiple spots on the same lake. This would be practical since radiometer data can be collected much faster than direct analysis of the water.

B. Filling out the data sheet

It is important to gather metadata about the conditions under which a spectrum is taken in order to interpret it properly. Therefore a data sheet (see appendix) should be completed for each set of samples. The data sheet provided includes information about weather conditions, water conditions, location, and how the sample was taken. Not all fields of the data sheet are essential, but information sufficient to interpret the spectrum should be compiled for each lake.

Most of the data sheet can be filled out as data is collected. Even if only a few critical fields are recorded, the GPS point is essential for coordinating with satellite data. Therefore it is important to record GPS coordinates along with the spectroradiometer data. The digital camera also serves as a useful means to record water and weather conditions.

C. Getting started

To physically prepare the spectroradiometer for use:

1. Screw the one-degree foreoptic onto its head but do not over tighten.
2. Optionally, attach the spotting site to the side and tighten the screws.
3. If using the tripod, attach the spectroradiometer firmly to it.
4. Connect to the laptop with the included serial cable.
5. Turn on the power to both the spectroradiometer and the laptop.
6. Click on cancel rather than entering a log-on name to the laptop.

7. Begin running the control software by double clicking on the "collect spectra" icon on the desktop or entering the DOS command **c:\hh\hh.exe 1154 1**.

Once the software is started there are certain options that must be selected before proceeding:

1. Change the menu that reads "bare head" to 1 degree.
2. Select an appropriate integration time for the lighting conditions. 68 ms is a good value to start with for bright sunlight, but this value should be changed later before taking a white reference measurement.
3. Under the control menu, select "adjust configuration".
4. On the configuration screen change each of the three values under "number of samples" to the 15 to 50 range. If a higher integration time is needed, these values should be lower.

In general, on a cloudy day the typical numbers should be 272 ms integration time and 15 or 20 samples. On a sunny day, with a lower integration time, try at least 40-50 samples. In general, the integration time should always be based entirely on the lighting conditions, but the number of samples can be changed (although recalibration would be required). The more samples are taken the less noisy the spectra will be. Since the signal to noise ratio is particularly poor on water, it is always best to set this as high as possible. Note that the amount of time a sampling cycle takes is a product of integration time and the number of samples.

III. Calibration

The spectroradiometer must be calibrated for current lighting conditions before taking data at each individual sampling point. Also recalibrate any time lighting conditions change, and at least after every ten minutes of sampling. Before beginning this process, make sure that the lighting on the white reference disk is the same as that on the water to be analyzed.

A. Handling the white reference

It is very important that the Spectralon™ white reference disk remain as clean as possible. Always handle the reference wearing clean gloves to prevent oils from damaging it. Never leave it where it is at risk of becoming dirty.

Before beginning the calibration process:

1. Open the case connecting the reference disk to the frame, placing it in a position that is secure from the wind and exposed to direct sunlight.

2. The frame has a cross of tape on which the spotting site can center in order to ensure that the foreoptic is pointing directly at the reference. The specroradiometer should remain steady, pointing downwards up to a meter above the Spectralon.

3. If boat movement is a problem, put the instrument closer to the reference disk.

The exact distance shouldn't matter as long as the entire field of view contains only the reference disk. The tripod may be useful at this stage if holding the spectroradiometer is a problem. Also, it is important to avoid casting a shadow on the reference disk because it must have identical lighting to the water.

B. Testing the integration time

Once the spectroradiometer is pointing directly at the white reference, the laptop will begin displaying raw digital numbers (DN) representing the radiance off of the reference disk. If the highest-DN point on the graph is off the top of the graph, it is over saturated and the integration time is too high – lower it until the entire spectrum is visible on the screen. If the magnitude of the peak of the spectrum is less than half of the maximum value, try increasing the integration time to increase the accuracy of the reflectance measurements.

C. Taking a white reference measurement

To calibrate the spectroradiometer using the white reference:

1. Press F4 or select "take white reference measurement" on the control menu.
2. The computer will prompt the user to press a key to continue at certain points. It begins by measuring dark current and then proceeds to collect actual data from the white reference.
3. Make sure (using the spotting site if necessary) the foreoptic is pointing directly at the white reference for the entire time that it is recording.
4. After calibration is complete the program should automatically enter reflectance mode (if it doesn't do this, change the "raw DN" to read "reflectance).

D. Testing the calibration

Before proceeding with data collection, it is important to test whether the instrument is calibrated correctly. If anything other than the white reference has been in the field of view for any of the integration time, there will be a problem. To test this:

1. Place the head of the instrument extremely close to the reference disk so that there is no doubt that it covers the entire field of view.

2. After the instrument has pointed at the disk for an entire cycle of measurement, the computer should display a straight line with a reflectance of about 1.0 at all wavelengths if the calibration was performed correctly.
3. If the line is lower, curved, or off the screen, the entire calibration process must be repeated until it passes this test.
4. Once calibration is complete, put the white reference back in the box to keep it safe.

IV. Data collection

A. Setting up the computer to save data

It may be useful to set up a folder for each lake on the computer using windows explorer before starting. Note that the software requires DOS filenames. A good example is c:\spectra\Mendota\.

1. Tell the software the name of the file in which data will be saved before acquiring the spectrum:
2. Click on "spectrum save" to enter the appropriate dialog and enter the path name set up for this lake.
3. Enter a base name and comments descriptive of the site (8 characters or less for the base name).
4. Write the filename, along with as much other relevant information as possible, onto the data sheet in order to later identify the measurement.

B. Acquiring the spectra

Once the computer has a filename to store the spectral data, pressing the spacebar will cause it to save a new file. Pressing the space bar again causes another file with the same base name to be saved. Thus multiple files will acquire names like Mendota.000, Mendota.001, and Mendota.002. In order to acquire accurate spectra, consider the following advice:

- Make sure to press the spacebar only during data collection cycles in which the instrument is pointing only at the water the entire time.
- Watch the graph – reading from the water should have very low reflectance
- Make sure the boat is anchored and relatively stationary if possible
- Make sure that there are no shadows from the boat or the instrument on the target water.
- Although exact distance from the water is not important, the spectroradiometer should point directly downwards to best approximate a satellite.

- Waves and other surface movement on the water will cause unusual reflectance readings. The effect is difficult to avoid but can be minimized by taking more data.
- If lighting conditions change, adjust integration time and recalibrate before taking more readings. Even if light appears constant, recalibrate at least every ten minutes.
- Take a large number of readings if time permits. At least three readings from each side of the boat is an absolute minimum at each location sampled.
- After every few samples, test the calibration again to make sure it's still consistent. If it looks bad, recalibrate and make a new save file.
- Be sure to note differences between files on the data sheet, especially if many files have the same base name.
- After sampling is complete, put disassemble the equipment and put everything away carefully in order to keep it safe.

C. Common problems

If the screen seems to freeze for no reason or simply does not display a spectrum, it may be because of an accidental click. The touch pad is very sensitive when slightly wet and therefore often causes the program to zoom in. Normally, clicking on two places on the graph creates a box on which to zoom. If the screen seems frozen, it is probably because a single click has occurred accidentally. Click again on the graph to complete the operation. If horizontal scale does not go from 266 nm to 1075 nm or the vertical scale does not go from 0 to 65535 for raw DN or 0 to 1.1 for reflectance, the graph has probably zoomed in. To correct this, click "axes" on the display menu and click "restore defaults".

D. Other measurements

In addition to the direct analysis of the water (Secchi depth, chlorophyll, etc.) remember to take digital camera pictures as well as a GPS point if there is a satellite.

V. Reading the spectroradiometer's output files

A. Using ViewSpec Pro

The ViewSpec Pro program installed on the laptop can be used for simple analysis of the spectra collected with the spectroradiometer. As the only program capable of reading the output files, its primary purpose is to convert these files into ASCII text in order to be read by other programs, such as Excel. There should be an icon for ViewSpec Pro on the desktop. Note that in order to open multiple files in ViewSpec Pro they must be in the

same folder and must be opened by shift-clicking or control-clicking. The program will not open a new file if others are currently open.

B. Creating a graph

1. Highlight the appropriate spectrum files by clicking and dragging. If none are highlighted the program acts as if all were selected.
2. Select the graph option on the view menu to see a graph of the selected spectra.
3. Because of the noise in the UV, the vertical scale will initially be so large that the spectra are invisible. To see them, zoom in several times by clicking and dragging.
4. Several options to customize the graph, including zooming out are available on the menu triggered by right clicking on the graph.

In order to print these graphs, export them as .jpg's and print those. More can be done if graphs are generated with exported data, however.

C. Exporting spectra as text files

This option allows spectroradiometer data to be read by other programs. To generate text files:

1. Use the setup menu to select change the output directory to "c:\spectra\text exports"
2. Select or highlight all files to be converted
3. Select "ASCII export" on the process menu
4. Click the "include header information" box so that relevant data is also included in the text files. Then click ok. This should create text files in the output directory with the same names as the data files.
5. Repeat the export, this time selecting "export to single file". This will generate one file with all selected spectra, making it easier to use, but will not have a header.
6. Name this combined file after the lake (eg. Mendota-all).
7. Use cut and paste in the Windows Explorer to move the text files and original data files to the appropriate location on the network (see below).

Headers contain information on the options selected during spectrum capture. Note that the program erroneously reports calibration times three hours too early but the minutes and seconds are correct. Headers can also be viewed using an option on the view menu.

D. Organization of spectroradiometer data on the network

All new output files from the spectroradiometer for the SLOI project are stored in the following location:

\\Tidris\Resac\Sloi\hh_FieldSpec\data\

Within this directory, spectra are further organized by how or where they were collected (such as DNR lakes). Each lake should also have its own subdirectory listing the lake name and date. Because they have the same filenames as the original spectroradiometer output files, ASCII text files created with ViewSpec Pro should be placed in their own separate folder. The original output files can only be read with ViewSpec Pro on the laptop but should be placed on the server as a backup. The text directory should include both the files of the individual spectra with headers and the file that contains a summary of all spectra.

E. Averaging data with ViewSpec Pro

Another useful feature of the program is the statistics option on the process menu. It works only on selected files and can export the mean, median, or standard deviation of them (the user can name the file). Be sure to set the correct output directory before using this option.

VI. Graphing spectral data

A. Viewing spectral data in Excel

Graphs generated in Excel are somewhat nicer than the built in graphing feature of ViewSpec Pro. It is therefore useful to quickly create an Excel graph file for each lake. To do this:

1. Open the file that contains all spectra for the lake in Excel
2. Delete the rows corresponding with noisy data. Usually the portions of the spectrum below 350 nm and above 900 nm are too noisy to be useful and should be deleted. Furthermore these wavelengths are not of interest to the SLOI project and over 300 data points will remain.
3. Delete columns corresponding with any obviously flawed data.
4. Convert all cells except for those in the wavelength column to percentage format because they are reflectance data.
5. The graph should be a scatter plot with lines but not markers, plotting all reflectance spectra against the wavelength column.
6. The title should include the name of the lake and the date, and the reflectance and wavelength axes should be labeled.

7. Adjust axes to display only the relevant parts of the spectra (350 nm to 900 nm).
8. If any of the spectra now appearing are drastically different in shape from the others, they are probably the result of mistakes. They should be removed from the graph and their columns should be deleted. Also, reflectance values significantly higher than 20% are likely to be mistakes. In general, all of the spectra for the same lake on the same day should be approximately the same shape, although the magnitude of these readings can vary dramatically.
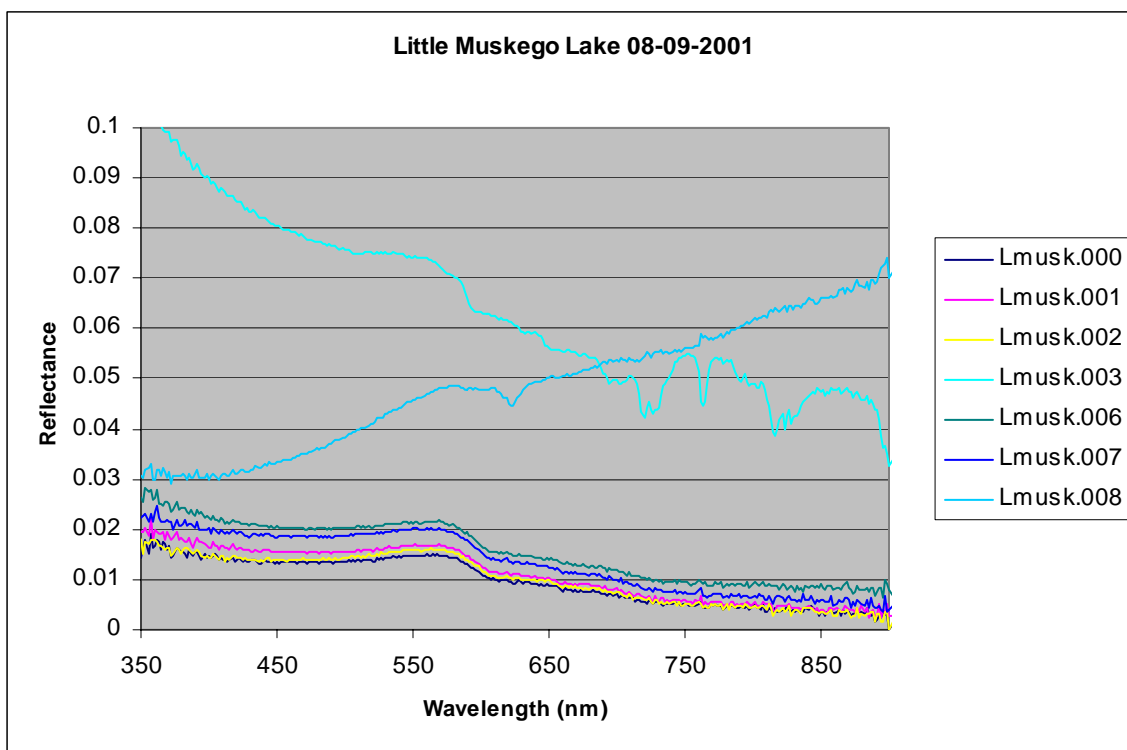9. Once the graph is completed, save it as an Excel document in the lake's text files directory

Figure 1: in the graph above Lmusk.008 should not be used because it is the wrong shape and was probably an error. Lmusk.003 is also probably an error due to magnitude problems. The other five spectra are similar in shape and have reasonable magnitudes.

B. Interpretation of initial graphs

Important information about the lakes and the quality of the data can be determined by examining the shape, magnitude, and noise levels of the spectra. All of the following are qualitative observations:

In general, lakes with high chlorophyll-*a* concentrations but low DOC will have large peaks in the green wavelengths, around 570-575 nm. The boggy (high DOC) lakes will be relatively flat instead and should have a lower total reflectance across all wavelengths. There is also a peak around 700 nm and a minimum near 670 nm; these are associated

with chlorophyll-*a*. These features should be visible regardless of DOC in the absence of overwhelming noise. The boggy lakes, in fact, have spectra that are nearly flat except for this minor peak; if they have low chlorophyll they are even flatter. The chlorophyll-dominated lakes' spectra appear very low beyond 740 nm in relation to the areas closer to the peak. Based on a single sample (Crystal Lake) it appears that lakes low in both chlorophyll and DOC have their green peaks around 540 nm instead of 570 nm but otherwise similar in shape to higher chlorophyll lakes. All spectra from the same lake should have the same features.
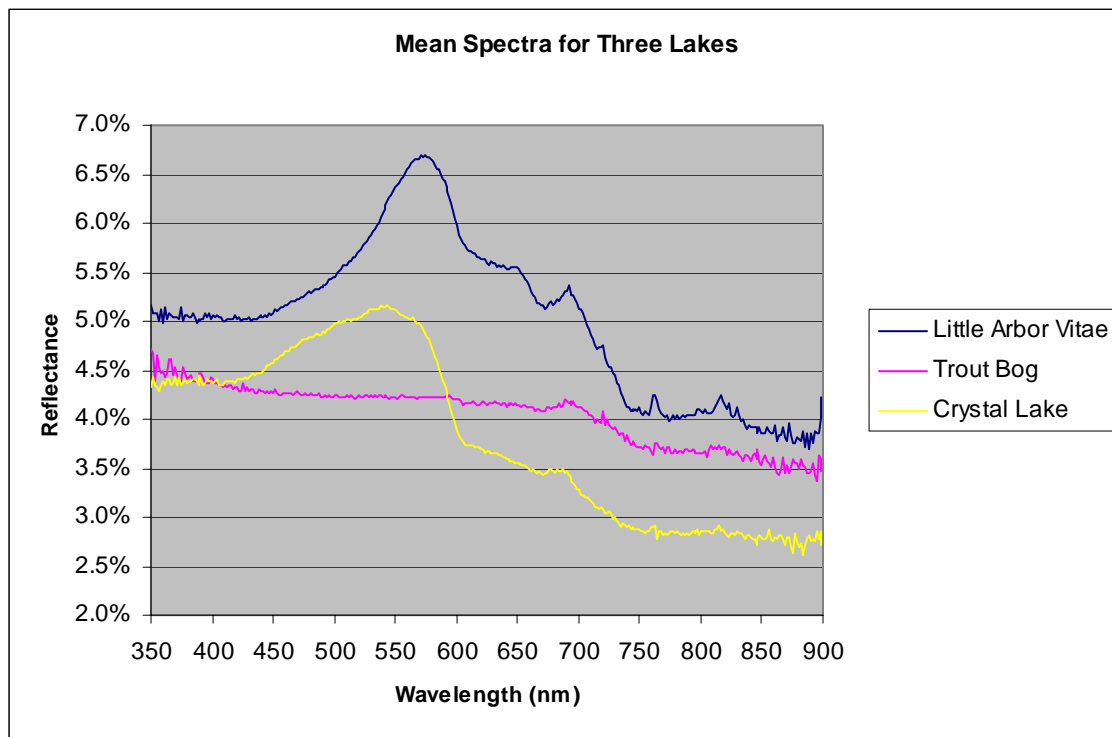

Figure 2: Little Arbor Vitae is a high chlorophyll lake. Trout Bog has high DOC. Crystal lake has relatively clear water.

If all spectra from the same lake have approximately the same magnitude of reflectance, the data is remarkably consistent. More commonly, there is a wide range of magnitudes. There are many possible causes for this discrepancy including reflection off of moving waves and changing lighting conditions. Often a series of measurements made in rapid succession will have similar magnitudes but not always. It is useful to examine the headers of these files to check when they were calibrated and to find out about other conditions. The data sheet may also provide clues. If there is sufficient evidence that one or more of the spectra do not accurately portray the lake's reflectance, they can also be removed from the graph. For example there may be a single spectrum that has higher reflectance values than all the rest. Note that studies have shown that above-water reflectance measurements made with this type of instrument have an inherently high variability due to many factors. Toole et al (2000) summarize the causes of this variability and suggest a wind speed based correction for water movement effects. These

effects generally increase reflectance, so the lower magnitude spectra may generally be more accurate.

The presence of excessive noise in the graphs can obscure important features. If all of the spectra collected for the lake are noisy, averaging and smoothing (see below) are possible solutions. If only some spectra are too noisy, it may be prudent to ignore them and use only the best data. All problems such as noise should be noted in order to facilitate their prevention in the future.
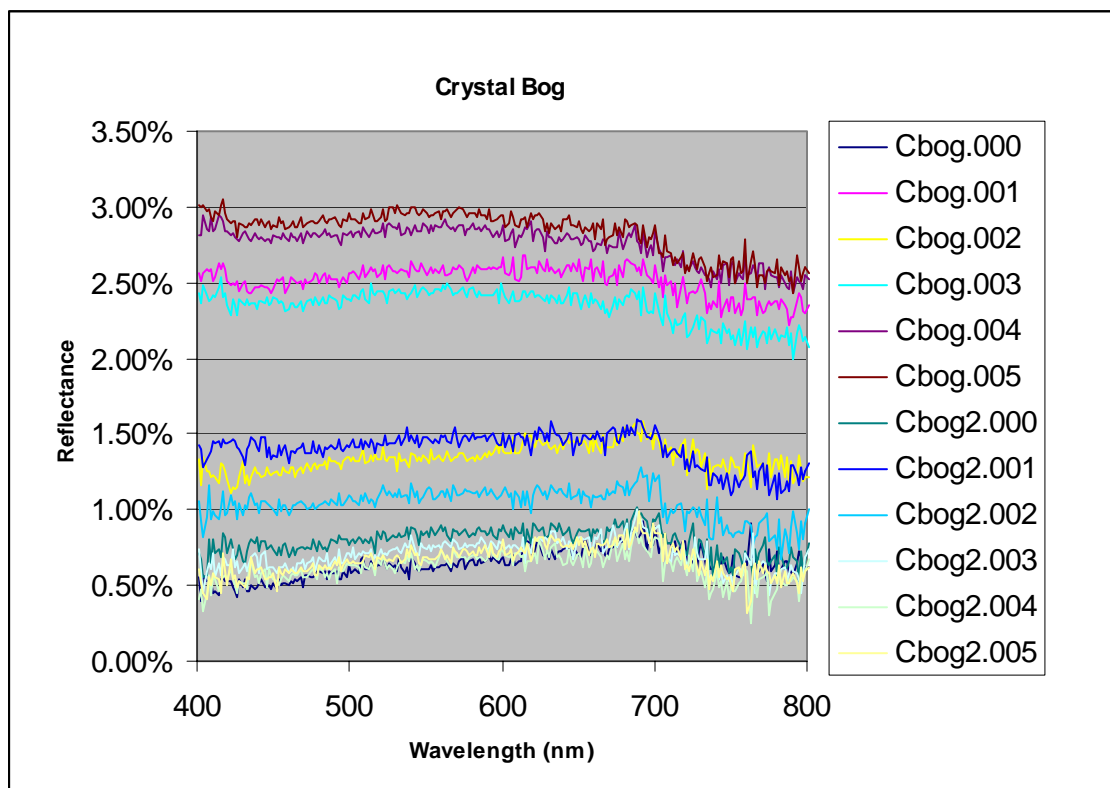

Figure 3: These spectra from crystal bog demonstrate both discrepancies in magnitude of reflectance and excessive noise.

C. Preparing data for further analysis

The largest problem for the analysis of spectroradiometer data is the magnitude discrepancy. This problem makes it difficult to select which set of reflectance values is the most accurate from several options. In the absence of a reliable data set for comparison, there is no choice that is completely satisfactory. If, for a given lake, there are a large number of spectra reasonably close together in magnitude with a few outliers, it is reasonable to use the average of those spectra, which can be computed easily using either Excel or ViewSpec Pro. When there is no clear best set of spectra to average, this is really a judgment call. It may be somewhat better to use lower-magnitude spectra than higher because they appear to correlate better with satellite data (see also Toole et al (2000)). The higher ones appear more likely to be the results of error. Regardless of which spectra are selected, taking the average of several (for each lake individually) is

preferable since it reduces noise and increases accuracy. If the data is going to be normalized, it is best to average all data of approximately the same shape. Once the proper data files have been selected and averaged, combine them into a single Excel document and graph them. This allows direct comparisons between spectra from different lakes.

Normalizing the various spectra can make it easier to compare their shapes. Although the process removes any chance of having the correct magnitudes of reflectance, it preserves ratios among various spectral features, and allows simple visual comparison of these ratios among several spectra. Normalizing the spectra means making the average reflectance value across all wavelengths the same for each spectrum. In order to do this:

1. Cut out the noisier portions of the spectrum (keep 350 nm to 900 nm as above).
2. Calculate the average of each column.
3. Select a value at which to normalize the spectra. A good value to use is the average of one of the middle-magnitude columns (or about 5%). Selecting too high a value will amplify the noise from the low-magnitude spectra too much while selecting a low value will make important features difficult to distinguish.
4. On a new Excel sheet, multiply each data point by the value to which it is being normalized, and divide by its own column average.

A graph of the newly normalized spectra can be useful in establishing the different spectral features of the various lakes, but it may be noisy and require smoothing. Smoothing a spectrum reduces noise at the expense of detail. The main reason to do it is to make spectra look better for graphing. It will also effect calculations on some of the smaller features like the 700 nm peak, which will appear less dramatic. If there isn't much noise, using a non-smoothed spectrum will be more accurate and calculations on a noisy spectrum will not be very precise anyway. Therefore the main use of smoothing the data is for visual purposes. The easiest way to smooth the data is with a moving average. Simply create a new sheet in Excel and set each data point equal to the average of itself and the cells immediately above and below it. Taking the average of five points (2 above, 2 below) is sufficient to smooth these spectra although the number can be varied. The graph of the smoothed spectra should appear more readable.
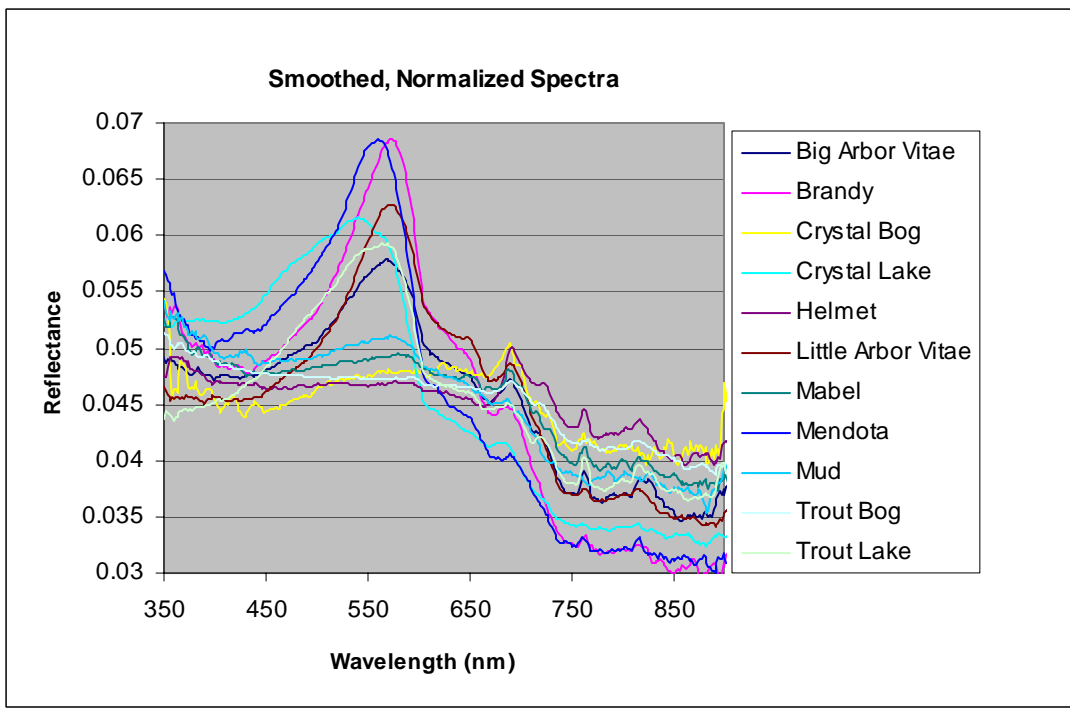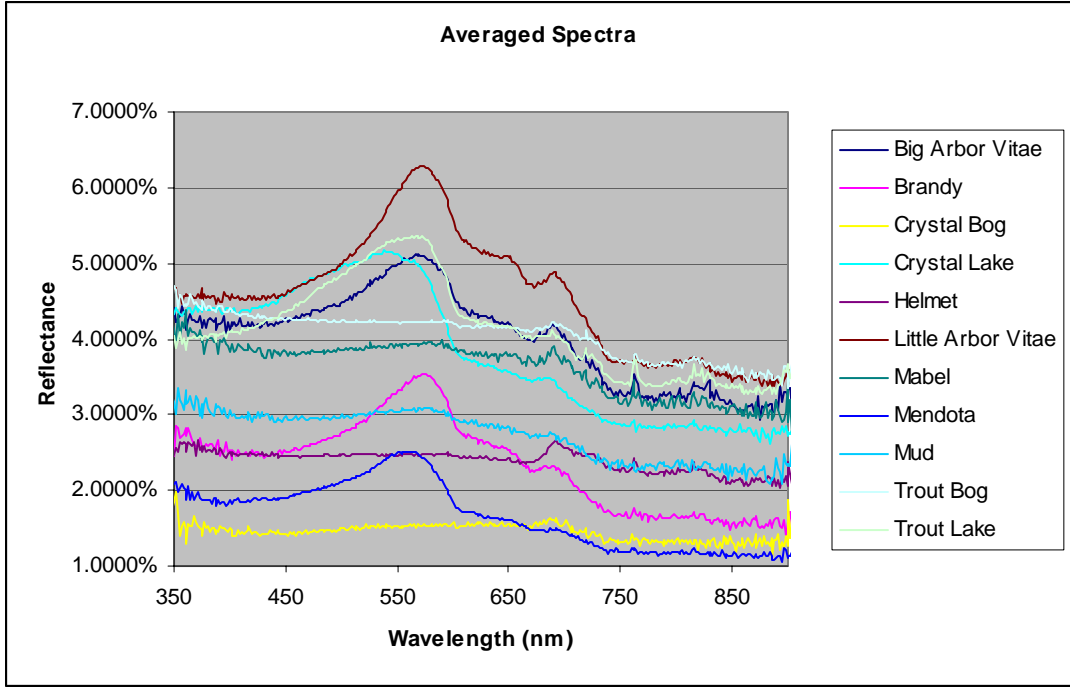
Figure 4: The results of averaging, smoothing, and normalizing.

VII. Comparing spectroradiometer data with satellite data

Although the purpose of the field spectroradiometer is to provide ground truth for satellite data, its output is very different than any satellite's output. In order to compare

data from the spectroradiometer to the ETM+ on Landsat-7 or similar instruments, several corrections must be made. The hyperspectral data must be aggregated into larger bands in order to resemble Landsat data. This process significantly reduces the detail and accuracy of the spectra, but accomplishes the purpose of comparing it to Landsat. The other factor to worry about is correcting for atmospheric effects. Even instruments like the Hyperion EO-1 that produce hyperspectral data will produce vastly different data from the spectroradiometer due to atmospheric scattering effects. Thus there are many variables to consider before using a field spectroradiometer to validate satellite data from lakes. Studies specifically dealing with this issue, such as Brivio, Giardino, and Zilioli (2001) have addressed some of the problems involved, but many remain.

A. Generating values for Landsat bands from the spectroradiometer

Because the most available data sets for Wisconsin's lakes come from Landsat-5 TM and Landsat-7 ETM+, it is useful to approximate equivalent values for Landsat bands from field spectroradiometer data. The first four Landsat bands (one, blue; two, green; three, red; and four, near-infrared) coincide with the region of the spectrum covered by the spectroradiometer. Thus, to compare simultaneous Landsat and field data, values must be generated for bands one through four of Landsat 7. There is no obvious method to do this accurately, however there are many useful resources available. Much relevant data is available online at the Landsat 7 Science Data Users Handbook, http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html.

One method of generating Landsat-equivalent values from field spectroradiometer data is to take a simple average of all radiometer data points that fall within the band. The wavelengths for the Landsat-7 bands are available in the "instrument calibration" section of the website. For example, to calculate a value for band 2, average all reflectance values corresponding to wavelengths between 530 nm and 610 nm. For this purpose, select the spectrum most representative of the lake.

A more rigorous method uses the relative spectral response (RSR) curves for Landsat-7. These files are available locally at \\Tidris\Resac\Sloi\hh_fieldspec\Satellite_RSR\ as well as on the instrument calibration page from links on the table listing the bands. The files show the relative contribution on a scale of zero to one of each wavelength (counting by 1 nm) towards Landsat's digital number (DN) for each band. Even using these data, it is unclear which method of reconstructing Landsat bands would be most accurate. Obviously, any method that would keep the bands in reflectance units would be preferable. Doing this requires some sort of weighted average in order to maintain values approximately equal to data from the individual wavelengths. Another problem to consider is selecting which range of wavelengths to use for averaging the values. Obviously, selecting too large a range will cause some very low numbers to be averaged in, because of the near-zero regions on the RSR curves. If values that look like reflectance are not necessary, the range problem can be overcome by using a sum instead of an average, thereby including any every non-zero point on the RSR curve. It may also be possible to solve this problem by multiplying constants into the RSR.

One relatively simple method of calculating weighted averages is automated by the spreadsheet document \\Tidris\Resac\Sloi\hh_fieldspec\LandsatTemplate3.xls. This file contains a sheet for each band. The range used for the weighted averages in the calculation is the same range listed on the Instrument Calibration page. The columns represent the following:

- Columns A and B are taken directly from the RSR text files.
- Column C contains the same data as B except that it is normalized to have an average of one over the interval of the band listed on the calibration page.
- Column D is the wavelength list from ASD FieldSpec output files, on a wavelength interval corresponding with the RSR list.
- Column E is a blank column to input data from the spectroradiometer.
- Column F uses a lookup function to interpolate the RSR value from column C appropriate to each wavelength in column B and multiplies it be the radiometer values; the result is the contribution of each individual data point towards the total value for the Landsat band.
- The average in column G is for the band's interval within column F while column H is simply the average of the relevant portions of column E.

To use the template, simply open the relevant spectroradiometer data file in Excel and paste the portion of the reflectance column that corresponds with the wavelength in column D into column E. Excel will automatically compute both the weighted and simple averages.

One technique allows the use of every point in the RSR file but still maintains reflectance units. It is probably the most accurate method available for this type of calculation. This method is in \\Tidris\Resac\Sloi\hh_fieldspec\LandsatTemplate4.xls and it uses a modified version of the equation with the integrals on the calibration page:

(1) The ETM + band weighted spectral radiances, $L_\lambda(b,s)$, for band "b" and sphere level "s" are calculated as:

$$L_\lambda(b,s) = \frac{\int RSR(b,\lambda)L_\lambda(s,\lambda)d\lambda}{\int RSR(b,\lambda)d\lambda}$$

Where:

    $RSR(b,\lambda)$ is the Relative Spectral Response for band "b" at "λ" calculated from component level transmission, reflectance and responsivity measurements,

    $L_\lambda(s,\lambda)$ is the measured spectral radiance of sphere level "s" at "λ"

The method of using it is identical to the other template except for column letters. It uses regular, non-normalized RSR data to calculate the contribution of each wavelength. The new column (F) is simply the RSR interpolated for each wavelength without anything multiplied in. Column G lists the reflectance for the band, calculated by dividing the sum of the individual contributions by the sum of the interpolated RSR's, as suggested by the

equation. Both of the above methods could also be applied to Landsat-4 or 5, or even another satellite by replacing the RSR values.

All three of the above methods (simple average, weighted average, and integral) produce very similar values. Although the integral method may be the most technically correct, a simple average seems sufficient given the results from test data. Regardless of the method used to calculate Landsat band reflectance values from FieldSpec data, it appears that the error in the magnitude of the reflectance data collected is much greater than any errors introduced by the conversion method. Also, given the lack of simultaneous field and satellite measurements, up until the date of this writing, it has been impossible so far to reliably test the accuracy of these methods.

B. Comparison to real Landsat data

Even if satellite and field data are not simultaneous, it is possible to compare the two. The optical properties of lakes, assuming a similar season, should be similar enough from year to year that there should be at least some correlation. Landsat data from the lakes should be extracted with the Signature Editor in ERDAS IMAGINE. Try to choose Areas of Interest (AOI) that represent the parts of the lakes that were sampled in the field, but do not include shorelines or make them too small. Use the GPS points from the data sheets to find the exact locations and take only the surrounding pixels if such information is available. Extract the mean values from each AOI for bands one through four using the signature editor.

Extracted mean values will be raw DN, but there should still be some correlation between these and the values generated by the spectroradiometer if they are graphed against each other in Excel. It is likely that some atmospheric correction is required to see a meaningful correlation, however. The main use of this comparison is that it provides the most direct validation of the satellite.

C. Atmospheric correction of Landsat data

A simple image-based atmospheric correction can dramatically improve the correlation between field and satellite reflectance values. Chavez (1996) provides a reasonable method with his "cosine" model. A model for IMAGINE by Susan Skirvin that computes this correction can be found at:

http://www2.erdas.com/SupportSite/downloads/models/user_models/user_model_2.html

The website includes a downloadable model for six Landsat-5 bands and minimal instruction. It requires modification before it can be run. A modification of the model to include only the four bands in the spectroradiometer's range is available locally:

\\tidris\resac\mark\corrections\corr99high.gmd

The model is somewhat complicated to use. Nearly all of the constants in the first set of equations must be modified. The general form of the equation is the following:

Reflectance = ((-haze + (gain * DN – offset)) * π * D^2) / (ESUN * $\cos^2$ (q))

The following constants must be modified:

- haze = radiance added to each band due to atmospheric effects
- gain and offset = radiometric calibration coefficients of the satellite
- D = distance from earth to sun on the date of the satellite flyover in AU
- ESUN = Solar Spectral Irradiance
- q = solar zenith angle

Note that D and q are the same for each band but the others are different.

For Landsat-7, many of these constants are available online on the "data products" page of the handbook and on the Calibration Parameter Files (CPF) page:

http://edcwww.cr.usgs.gov/l7dhf/ias_folder/cpf.html

This page has appropriate calibration constants based on the date. The following a discussion of how each constant is computed:

D can be interpolated from values on the "data products" page or a similar chart if the date is known.

Q is equal to 90° - solar elevation angle. The solar elevation angle should be available with every Landsat scene. Remember to convert q into radians.

ESUN is available from a chart on the "data products" page or in the SOLAR_SPECTRAL_IRRADIANCES group of the appropriate CPF. Note that for ESUN, gain, and offset the Skirvin model uses values equal to one-tenth of the values listed in the CPF. As long as all three of these are modified consistently, it will not affect the final result.

The gain and offset values are derived from the scaling parameters in the CPF (the "data products" list may be incorrect). Use either the SCALING_PARAMETERS_HIGH group or the SCALING_PARAMETERS_LOW group depending on which mode the satellite was using. To determine whether Landsat-7 was using high gain or low gain, consult the "data properties" page of the handbook. For Wisconsin scenes most of the year, bands one through four are always high gain. Set the offset value equal to LMIN for the appropriate band. The gain is calculated with the following formula:

Gain = (LMAX – LMIN) / 255

The haze value is by far the most difficult value to calculate and it is also the most important constant in determining the final values from the correction. The most common haze value, as suggested by Chavez, comes from the method of Dark Object Subtraction (DOS). The theory behind DOS is that the atmosphere adds a fixed amount of radiance to each pixel and that subtracting this amount would correct it.

The haze value is calculated as the difference between the observed radiance for the darkest pixel and the predicted radiance for that same pixel without atmospheric effects. The problem with this system is that the user must assume the actual reflectance of the dark pixel. Skirvin uses a value of 1% reflectance on all bands for the dark pixel. This is not an appropriate assumption when dealing with lake water, however. 1% is much to close to the actual reflectance of the lake and therefore errors would be larger. Additionally, it is likely that the dark object will actually be one of the boggy lakes on the scene. There is no accurate way to deal with this problem, so some assumption must be made. One possible solution is to use a known object instead of a dark object – that is to select one of the measurements from the spectroradiometer, which has known reflectance values. However these reflectance values are determined, use the following formula to calculate the haze correction in radiance units:

$$\text{Haze} = \text{DOraw} * \text{gain} + \text{offset} - ((\text{DOref} * \text{ESUN} * \cos^2(q)) / (\pi * D^2))$$

The constants gain, offset, ESUN, q, and D are the same as in the previous equation.

DOraw is the DN of the dark object. Determine this value by looking at the statistics for the band and finding the minimum. If using a known object instead of a generic 'dark object,' find the actual DN that corresponds with that object by using the GPS point.

DOref is the estimated reflectance of the dark object. If is generic dark object is used this value is purely an estimate, such as 1%, which would be express as a decimal, 0.01. If a known object is used, the value is determined by the spectroradiometer (and the Landsat templates). It must be expressed as a decimal. Remember that each band must have its own value for the haze correction.

Once all of these constants have been entered, run the model. The resulting raster layer will be an atmospherically corrected image. Reflectance values for each band on each lake can be extracted in the same manner as above. If the atmospheric correction worked properly these reflectance values should correlate quite well with the data from the spectroradiometer. If they do not, try again with a different value for the haze correction. Eventually, if an appropriate correction is found, the data should be much improved. The results will not only correlate better with field measurements, but they will also be more accurate when used to estimate water quality parameters.

D. Hyperion

Hyperion is a hyperspectral instrument and therefore more similar to the field spectroradiometer than Landsat-7. This allows them to be compared to each other by interpolation rather than by generating values for bands. The problem is that another method may need to be found for atmospheric correction since applying Chavez's method to hundreds of bands may be too tedious. Regardless, comparing the spectroradiometer data to Hyperion data will enable more accurate estimates of chlorophyll-a and other parameters than Landsat-7 could possibly provide.

VIII. Comparison to water chemistry and clarity

Due to a lack of available data, no attempts have yet been made to correlate readings from the field spectroradiometer to chlorophyll-a, Secchi depth, or other lake water quality parameters. It is very complicated to get accurate results in such a comparison but the methods have been discussed in many papers (eg. Gitelson et al 2000, Sathyendranath et al 2000).

3. Conclusion: application of the protocol

The above protocol is an import component of the SLOI project. Once additional data is obtained, the above procedures will enable significant improvements in techniques for monitoring lake water in Wisconsin. As the project progresses, the following primary applications of the field spectroradiometer are anticipated:

1. Getting spectral data for lakes quickly even on cloudy days and making qualitative of quantitative analyses.
2. Refining algorithms for determining water quality parameters, taking advantage of the instrument's spectral resolution and the fact that does not suffer from atmospheric effects.
3. Using it as a tool to atmospherically correct and validate the satellites.

The spectroradiometer is mainly useful in conjunction with satellites, limnological measurements, or both. It will be used as soon as simultaneous data is available.

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NUMBER: _____

Attendees_____
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Date_____
Location _____
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GPS point I. D./Coordinate_____
Sampling I. D. _____
Start Time _____
End Time _____

Weather Conditions

Temperature (C)	
Precipitation (type)	
Precipitation (amount)	
Wind Speed & Direction	
% Cloud Cover	
Cloud Type/Color	
Sky Color	
Other	

Photograph I. D.	**Description/Direction Facing**

Spectroradiometer

	File Name:	File Name:	File Name:	File Name
Start Time				
End Time				
Distance from Spectralon (m)				
Sampling Angle (degree)				
Distance from Surface (m)				
Facing Direction of Sampling				
RCR file Name				
Change in Weather				
Other				

Water

Site description				
Color				
Clarity				
Suspended Solids				
Surface Movement				
Depth				
Bottom Visible				
Other				

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