

Development of Hyperspectral remote sensing capability for the early detection and monitoring of Harmful Algal Blooms (HABs) in the Great Lakes

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Hyperspectral imagers have significant capability for detecting and classifying waterborne constituents. One particularly appropriate application of such instruments in the Great Lakes is to detect and monitor the development of potentially Harmful Algal Blooms (HABs). Two generations of small hyperspectral imagers have been built and tested for aircraft based monitoring of harmful algal blooms. In this paper a discussion of the two instruments as well as field studies conducted using these instruments will be presented. During the second field study, in situ reflectance data was obtained from the Research Vessel Lake Guardian in conjunction with reflectance data obtained with the hyperspectral imager from overflights of the same locations. A comparison of these two data sets shows that the airborne hyperspectral imager closely matches measurements obtained from instruments on the lake surface and thus positively supports its utilization for detecting and monitoring HABs.

I. Introduction

Two generations of small lightweight Hyperspectral Imaging Systems have been developed by engineers at the National Aeronautics and Space Administration's (NASA) Glenn Research Center (GRC) and the Ohio Aerospace Institute (OAI). The systems consist of a pushbroom hyperspectral imager, a point spectrometer, a three axis inclinometer, a Global Positioning System (GPS) receiver and a data acquisition and control computer. Both generations of Hyperspectral Imagers (HSI) are sensitive in the visible and near infrared portion of the spectrum. The point spectrometer is included to measure incident solar irradiance and also is used to measure atmospheric effects. The three axis inclinometer and GPS receiver are included to record the position and attitude of the sensor so that the hyperspectral data can be georeferenced.

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II. Science Background

NASA Glenn Research Center and the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) are collaborating to utilize an airborne hyperspectral imaging sensor suite to forecast and monitor Harmful Algal Blooms (HABs) in the western basin of Lake Erie and Saginaw Bay in Lake Huron. The HABs can be very dynamic events. They often form, spread and then disappear within a 4 to 8 week time period in late summer. They are a concern for human health, fish and wildlife because they commonly contain a potentially toxic algae, *Microcystis*. *Microcystis* can contain the toxin microcystin. In the Great Lakes one of the most common forms of microcystin is Microcystin-LR, which also happens to be one of the most toxic forms of microcystin. Because of this potential toxicity there is a need for the blooms to be detected early and continually monitored.

In the U.S., the Great Lakes are the single most important aquatic resource from an economic, geographic, international, ecological, and societal perspective. The Great Lakes represent the largest supply of surface freshwater in the world. Combined, the lakes cover an area of over 94,000 square miles (245,000 square kilometers) and contain 5,400 cubic miles (23,000 cubic kilometers) of water. The Great Lakes contain about 18 percent of the world's surface freshwater supply and over 80% of the U.S. supply¹. The Great Lakes coastline of 6,700 miles is the nation's longest and provides over 500 beaches for recreational activities. Unlike other coastal waters, the Great Lakes provide drinking water to over 40 million U.S. and Canadian citizens so water quality (as well as water security) is thus an important concern for the region. The Great Lakes provide about 56 billion gallons of water DAILY for municipal, agricultural, and industrial use. The region's 60 million people place significant demands on this water resource for drinking water, transportation, recreation, food production, and manufacturing.

One of the threats to water quality in the Great Lakes is *Microcystis aeruginosa*, which is the dominant bloom-forming, toxic cyanobacterium occurring in the Great Lakes. *Microcystis aeruginosa* produces a suite of cyclic heptapeptide hepatotoxins, known as microcystins - the most important of which is microcystin-LR. *Microcystis* has (again) become a dominant component of the summer phytoplankton in both Saginaw Bay and western Lake Erie. Moreover, preliminary studies have verified the presence of the cyanotoxin, microcystin, in both systems^{2,3,4}. As such, the recent expansive blooms of *Microcystis* have caused considerable concern due to aforementioned dependence on these waters as a resource and the health risks attributable to microcystins.

This resurgence of nuisance cyanobacteria (and apparent selection for one dominant taxon) has been attributed to the long-term effects of massive populations of non-indigenous zebra mussels. The mussels promote the blooms of toxic *Microcystis* through selective rejection of the pseudo-feces during the filtration process^{3,5,6}. Because of the establishment of large populations of non-indigenous mussels in many regions of the Great Lakes, it has been predicted that *Microcystis* will establish summer dominance in mesotrophic/eutrophic regions⁵.

Because of the increased incidence of cyanobacterial blooms in these important freshwaters systems and the public health concerns attributable to microcystins, much attention has been given to *Microcystis* blooms and associated toxins within important water resources. Despite very limited studies, relatively high concentrations of microcystin have been found in Saginaw Bay, western Lake Erie, and in the western region of Lake Ontario^{2,3,4}. In 1995, microcystin concentrations in Saginaw Bay and western Lake Erie exceeded the World Health Organization's limit of 1 µg/l for drinking water (based on microcystin-LR)^{3,7}. Microcystin concentrations were measured at 3.5 mg/l in Saginaw Bay in July 1995, and estimated to be as high as 24 mg/l in western Lake Erie in September 1995³. In a shallow harbor in western Lake Ontario, microcystin concentrations were as high as 400 mg/l in the summer of 2001⁴.

Algal blooms can be very dynamic events, changing significantly day to day. Monitoring such events with even high resolution satellite data is not suitable by itself because such data does not have the temporal resolution (owing to infrequent repeat pass coverage) needed to monitor the quickly changing blooms. These events are well suited for complementary aircraft based monitoring because the blooms are dynamic and they can spread over a large area.

Table 1. Comparison of monitoring methods

Observation Method	Observation Frequency	Resolution
Satellite Landsat TM	Once every 8 days	30 meter
Satellite MODIS	2/day	1km
Satellite MERIS	Every 2-3 days	300m
Satellite SeaWiFS	1/day	1km
Research Vessel In situ	Flexible	Point
Aerial Monitoring	Hourly	1- 5 m

The added value of aerial monitoring may be seen in the comparison shown in Table 1 between the various ways in which the algal blooms can be monitored. In situ sampling provides many high accuracy physical measurements at a point or a group of points. Satellites can provide measurements over a large area but the frequency of observation can be low for high resolution imaging. Aerial Monitoring is, therefore, complementary because of better control over the frequency and resolution of measurements which is important as we attempt to understand rapidly changing blooms. With aerial monitoring, lower concentrations are potentially detectable because of higher spatial and spectral resolution. Also, using aircraft allows the quick locating of areas of interest and the guiding of in situ sampling to areas of high interest even under cloud cover. Tailoring instrumentation to suit a particular problem is easier with aircraft than with satellites since the satellite instrumentation is not accessible once the satellite is launched.

III. Hyperspectral Imaging Suites

A. Generation I Hyperspectral Imager Sensor Suite

A multi-disciplinary team of researchers, scientists, engineers, and technicians from GRC, NOAA GLERL and the Ohio Aerospace Institute have in a very short time period of 8 months, designed, developed, integrated, and flight tested a highly specialized suite of instruments for aerial water quality measurement. The suite of instruments consists of a GRC designed point spectrometer, a GRC-designed hyperspectral imager, a commercial-off-the-shelf (COTS) GPS receiver, a COTS three axis gyroscopic-stabilized inclinometer, and a GRC-designed data acquisition system. The GRC hyperspectral imager obtains wavelength-resolved images of the lake in narrow 2 nm wide bands of light. The hyperspectral imager wavelength range is 400 nm to 900nm, thus allowing 250 distinct spectral bands. The resulting 3-dimensional data block consists of a stack of images from the imager acquired as the aircraft passes over areas of interest. The point spectrometer significantly adds to the capability of the instrument suite because it can provide highly accurate measurements of the incident solar radiation as well as measurements of the atmospheric water vapor content. This combined sensor suite provides accurate spectral radiometric measurements of the lake constituents, which will translate into an ability to detect lower concentrations of pollutants and harmful algal blooms.

The entire suite of instruments weighs less than 2.3 kg and uses less than 15 watts of power. This makes the package very flexible in terms of the aircraft that it can be deployed on. Because of the instrument flexibility the team was able to mount the instrument, shown in Figure 1, on the avionics door of a T 34 aircraft and obtain the desired data in a very cost effective manner. The environmentally-sealed instrument package uses three windows to provide optical access and is mounted on the T 34 avionics bay door with a forward-facing aerodynamic fairing.

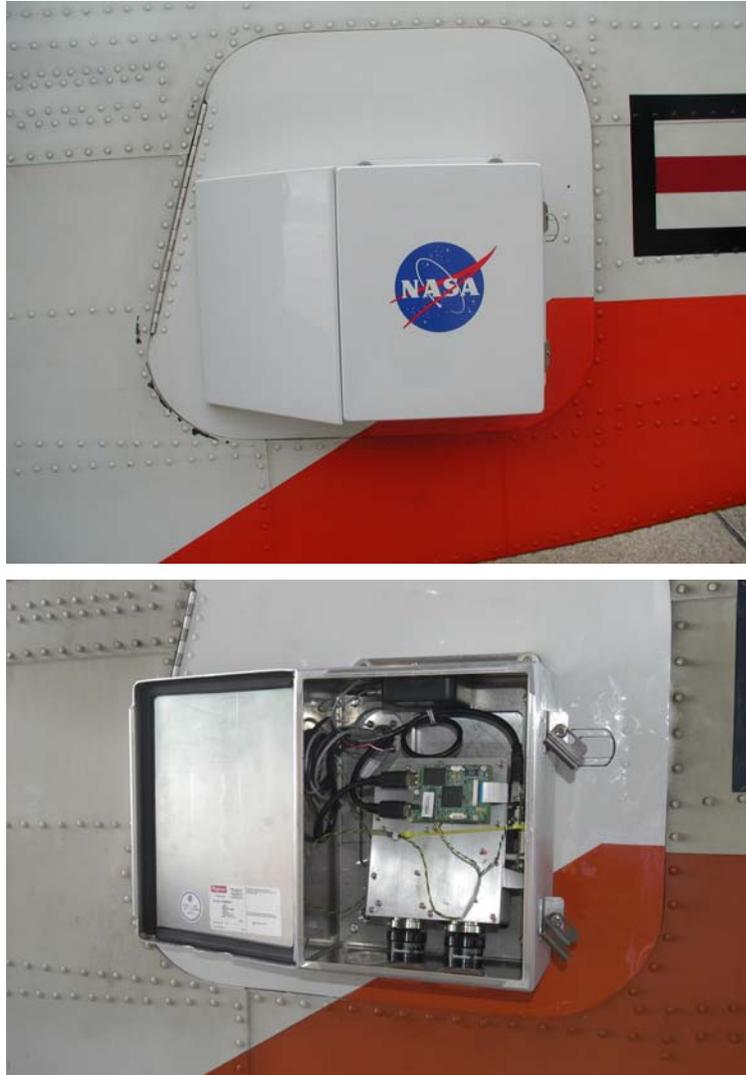


Figure 1. The instrument package mounted on the T-34 avionics bay door. The three optical windows face downward (not shown). The external enclosure measures approximately 8 in x 10 in x 4 in thick.

B. 2006 Field Operations using the Generation I HSI

During September 2006, the formation of a significant algae bloom in the Kelly's Island area of Lake Erie and a second smaller bloom that formed in Maumee Bay were observed. On August 17 HSI data was acquired at the same time that GLERL took in situ measurements. The data that we acquired on September 5 was not accompanied with water sampling but satellite data from the MODIS instrument on Terra was available for comparison.

During the August 17th and September 1st overflights of western Lake Erie no blooms were visible. A photograph, in Figure 2, shows that there were areas that did have a deeper green appearance on September 1st. Four days later, on September 5th, another overflight was conducted, and on this day algal blooms, shown in Figure 3, were observed. These series of observations show that the formation of algal blooms can be very dynamic.



Figure 2. Picture of a forming algal bloom on September 1. Algal coloration is visible in Lake Erie Western Basin near the Bass Islands. The algae looks to be very cohesive and does not mix well with the sediment.



Figure 3. An open water bloom west of Middle Bass Island on September 5, 2006.

An image of the Lake Erie area, shown on Figure 4, taken from a satellite on September 5th is directly comparable to the HSI data taken on the same day. An enlargement of the area around the Lake Erie islands is shown in Figure 5. This enlargement contains the blooms that were photographed in Figure 3. It can be seen that because the resolution is approximately 500 m, it is very difficult to tell where the blooms were present, which is shown in the yellow box in Figure 5.



Figure 4. Image from MODIS Terra on September 5, 2006.



Figure 5. Enlargement of the Lake Erie island area from the September 5, 2006 Terra image shown in Figure 4. The yellow box shows the approximate location and extent of the hyperspectral data shown Figures 6 and 7.

However, the HSI data as seen in Figures 6 and 7, which approximately covers the area in the yellow box on Figure 5, clearly shows the algal bloom. An airborne HSI very nicely compliments data obtained from a satellite. While it is not as easy to cover the area shown in Figure 4 with an aircraft, it is also not possible to observe small, but important formations, such as those shown in Figure 6, with low to moderate resolution satellite data. With higher spectral and spatial resolution it should be significantly easier to detect the onset of an algal bloom with an aircraft based HSI than is possible with existing orbital assets. Note that the two images of the algal bloom in Figures 6 and 7 illustrate that the bloom has different reflectivity at different wavelengths.

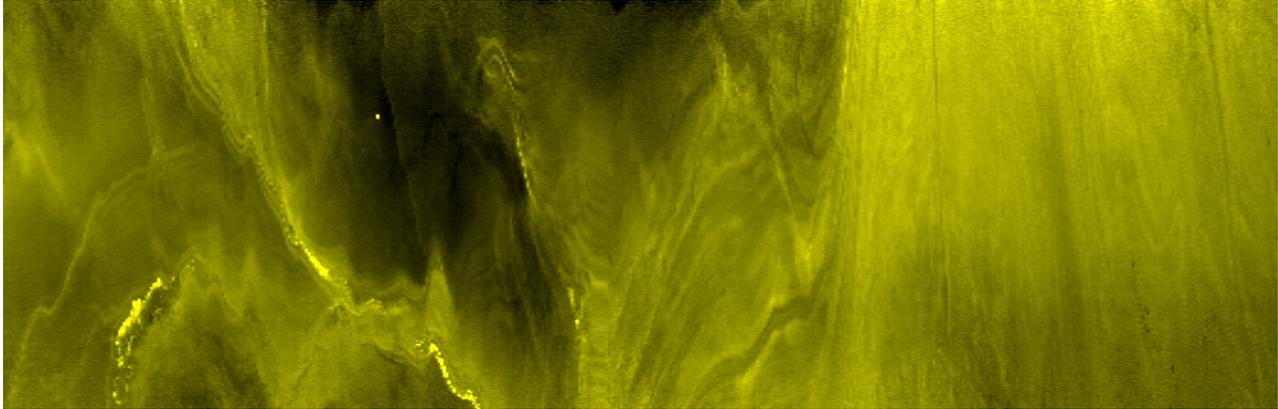


Figure 6. Hyperspectral Image of algal bloom centered at 532 nm.

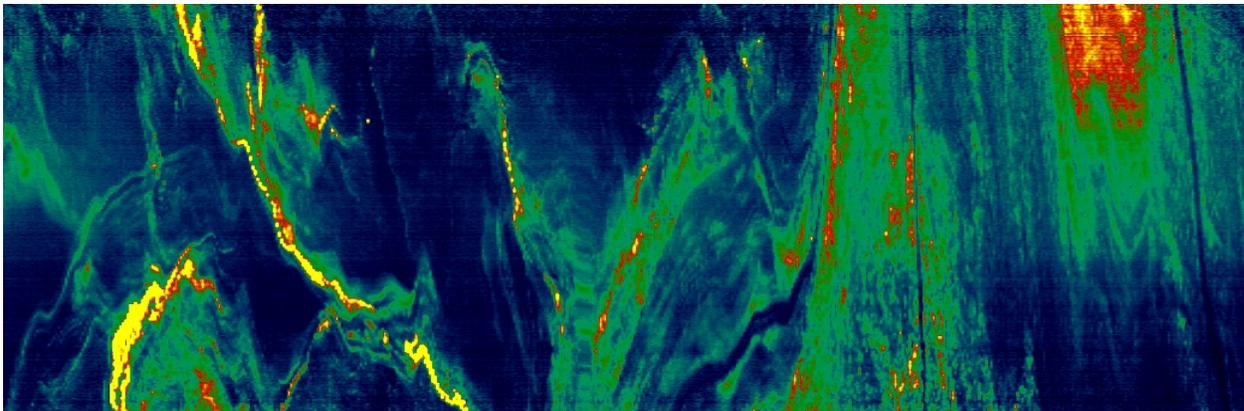


Figure 7. Hyperspectral image of algal bloom centered at 723 nm.

C. Generation II Hyperspectral Imager

A second generation HSI for aerial water quality measurement has been designed, developed, integrated and flight tested. This hyperspectral imager also operates as a part of a suit of instruments. These instruments have been used to obtain spectral measurements of algae in the western basin of Lake Erie and also in Lake Huron's Saginaw Bay during 2007. The entire suite of instruments also consists of a GRC designed point spectrometer, the GRC designed second generation hyperspectral imager, a COTS Global Positioning Receiver, a COTS three axis inclinometer, and a data acquisition system. The second generation hyperspectral imager obtains images of the lake in very narrow bands of light, less than 2.5 nanometers (nm). The wavelength span that the HSI covers is approximately 400 – 900nm. As in Generation I, 250 distinct spectral bands are available resulting in a 3-dimensional data block consisting of a stack of images from the imager acquired as the aircraft passes over areas of interest. The internal optics of the second generation imager have been significantly changed and a cooled imager has replaced the uncooled imager in the first generation. These changes have resulted in a dramatic improvement in the signal-to-noise ratio over the first generation imager.

The entire suite of instruments weighs less than 10 pounds and uses less than 100 watts of power. The second generation imager takes advantage of a modular design. The front lens can be changed to modify the field of view and resolution of the instrument. Also the imager can be changed if higher speed or greater light sensitivity is required. This makes the package very flexible in terms of the platform on which it can be deployed.

D. 2007 Field Operations

The second generation imager was flown in conjunction with a monitoring cruise of the R/V Lake Guardian, an EPA vessel, shown in Figure 8. During this cruise, water samples and radiometric measurements were made of the lake at multiple locations, shown in Figure 9. The radiometric measurements made from the Lake Guardian included

spectral measurements of downwelling irradiance and water leaving radiance. From the ratio of the water leaving radiance and downwelling irradiance a spectral reflectance was obtained. In order to compare the capability of the aircraft HSI to accurately measure water reflectance, the HSI measurements were compared to the in situ measurements. The three data points where in situ measurements will be compared to airborne measurements are denoted as points 885, 1131 and e59 in Figure 9.



Figure 8. In this picture the EPA ship R/V Lake Guardian is seen from the NASA Lear 25 during the concurrent operations in 2007.

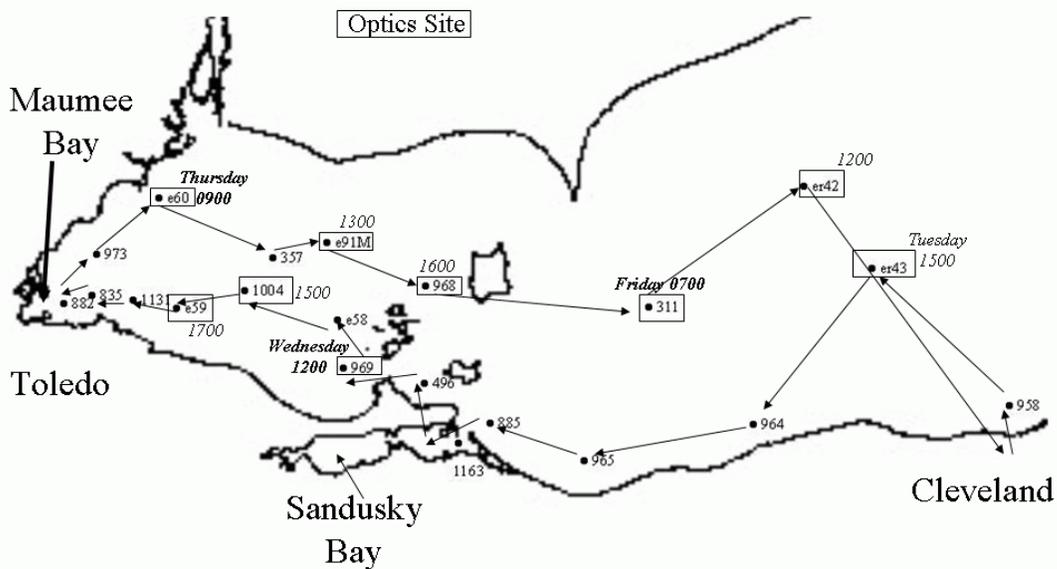


Figure 9. Map of the 2007 water sampling locations in western Lake Erie. The points surrounded by boxes are points where optical measurements were made from the ship.

In order to obtain reflectance data from an airborne instrument, which measures radiance, the irradiance must be known and also the effects from atmospheric scattering and attenuation must be accounted for. The in situ irradiance measurements, shown in Figure 10, are used in conjunction with the airborne radiance measurements to obtain the airborne reflectance values. In this case the irradiance as measured from the R/V Lake Guardian at 10:24 can be used in conjunction with the aerial radiance measurement of point 885 as the aerial measurement happened at

10:25. For the aerial measurements of points 1131 and e59, which occurred at 10:43, there is not a similarly timed in situ measurement of irradiance. In this case the measured values of irradiance at 8:49 and 10:24 have been extrapolated to obtain an estimated irradiance for 10:43.

The atmosphere significantly affects the light gathered by the HSI. Not only does it include light reflected from the lake but light is also gathered that has been scattered by the atmosphere in between the aircraft and the lake. Furthermore, atmospheric constituents attenuate the light reflected from the lake through absorption and scattering. In order to correct for these effects, measurements at multiple altitudes have been made to characterize the atmospheric effects. These measurements were conducted at 300 feet and again at the nominal altitude of 10500 feet. The measurements were made of the same location at these two altitudes. The location that was chosen was in the middle of the lake over deep water. This location provided the most uniform target available. By taking measurements from low altitude and high altitude of the same location, the effects of the atmosphere are directly obtained. To further correct for the atmospheric effects from ground level to 3000 feet the previously measured atmospheric effect from 3000 feet to 10,500 feet was extrapolated to account for the first 3000 feet. This measurement technique was used to correct for the atmospheric effects and obtain a more precise estimate of the water leaving spectral radiance.

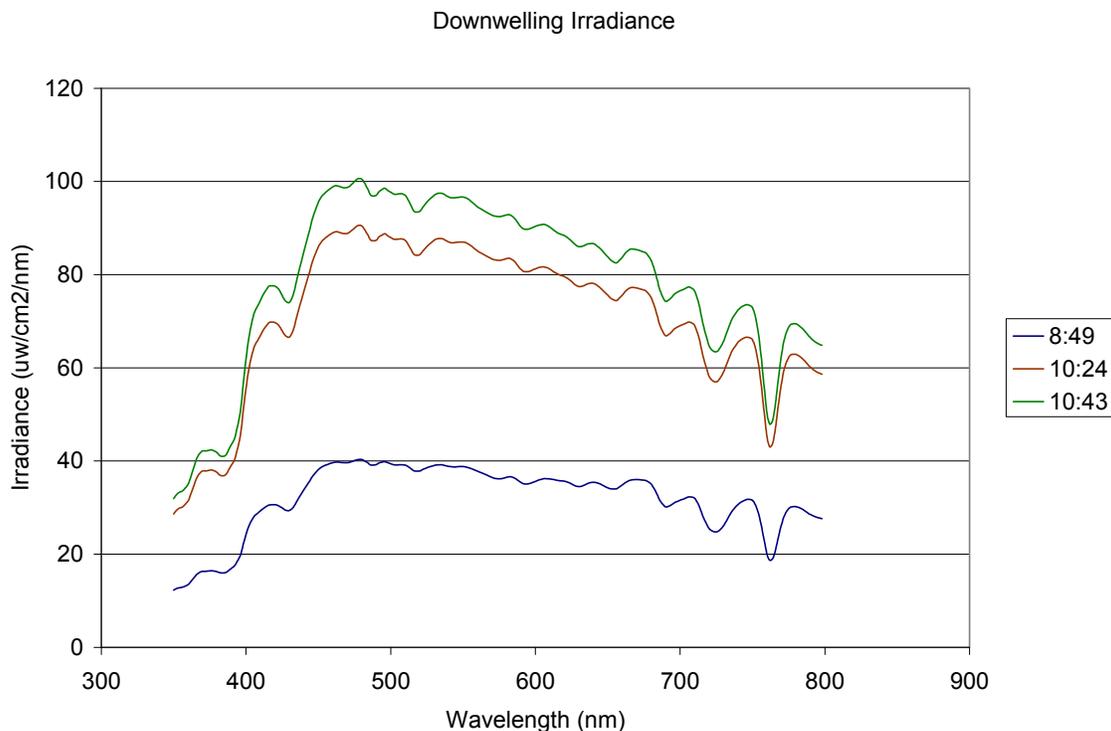


Figure 10. Plot of the downwelling irradiance for September 13. The 8:49 and 10:24 plots are both direct measurements. The 10:43 plot is an extrapolated value derived from the two solar irradiance measurements *that were made earlier in the day*.

The spectral reflectance plots of the three points, shown in Figures 11 – 13, show good qualitative agreement between reflectance measured at the surface and the airborne measurement. In Figure 11, it is shown that the in situ measurement location was covered by the HSI overflight. In this case, the in situ measurement was taken on the day after the overflight, so a comparison of the reflectance magnitudes is not valid. It is highly probable that the constituents in the water did not change appreciably as there was no significant lake disturbing weather between the time of the overflight and the time of the in situ measurement. In general the spectral reflectances are very similar. The reflectance peaks at 560 nm and 700 nm, which are characteristic of chlorophyll A, agree in both measurements. Also the absorption peak at 620 - 630 nm, which is characteristic of phycocyanin⁸, agrees in both measurements.

The major difference between the two measurements is that the airborne measurement appears to be relatively too high in the blue portion of the spectrum, near 400 nm. It is believed that this is caused by additional light from atmospheric scattering that has not been corrected for.

A comparison of the data obtained for point 1131 is shown in Figure 12. In this case both of the measurements were made on the same day and the in situ sample point was captured within the HSI data. Here the data shows general agreement with a spectral reflectance profile characteristic of chlorophyll A. Neither plot shows an absorption peak that is characteristic of phycocyanin. The magnitude of the reflectance is fairly close for both measurements. They appear to have a general difference of about 0.002% which is within 7% of full scale. The only major difference is that the airborne measurement reflectance again is much higher than the in situ measurement near 400 nm.

The data for point e59 is shown in Figure 13. In this case, the in situ measurement point fell outside of the hyperspectral data area by about 150 meters so a detailed comparison is probably not appropriate. However the lake constituents probably did not change too drastically in this distance so general observations are appropriate. Both reflectance measurements are fairly close in terms of magnitude. Also, both spectra have reflectance peaks characteristic of chlorophyll without a clearly identifiable absorption peak characteristic of phycocyanin. As in the previous three measurements the big difference between the two spectra is an increased reflectance measured in the blue by the airborne instrument.

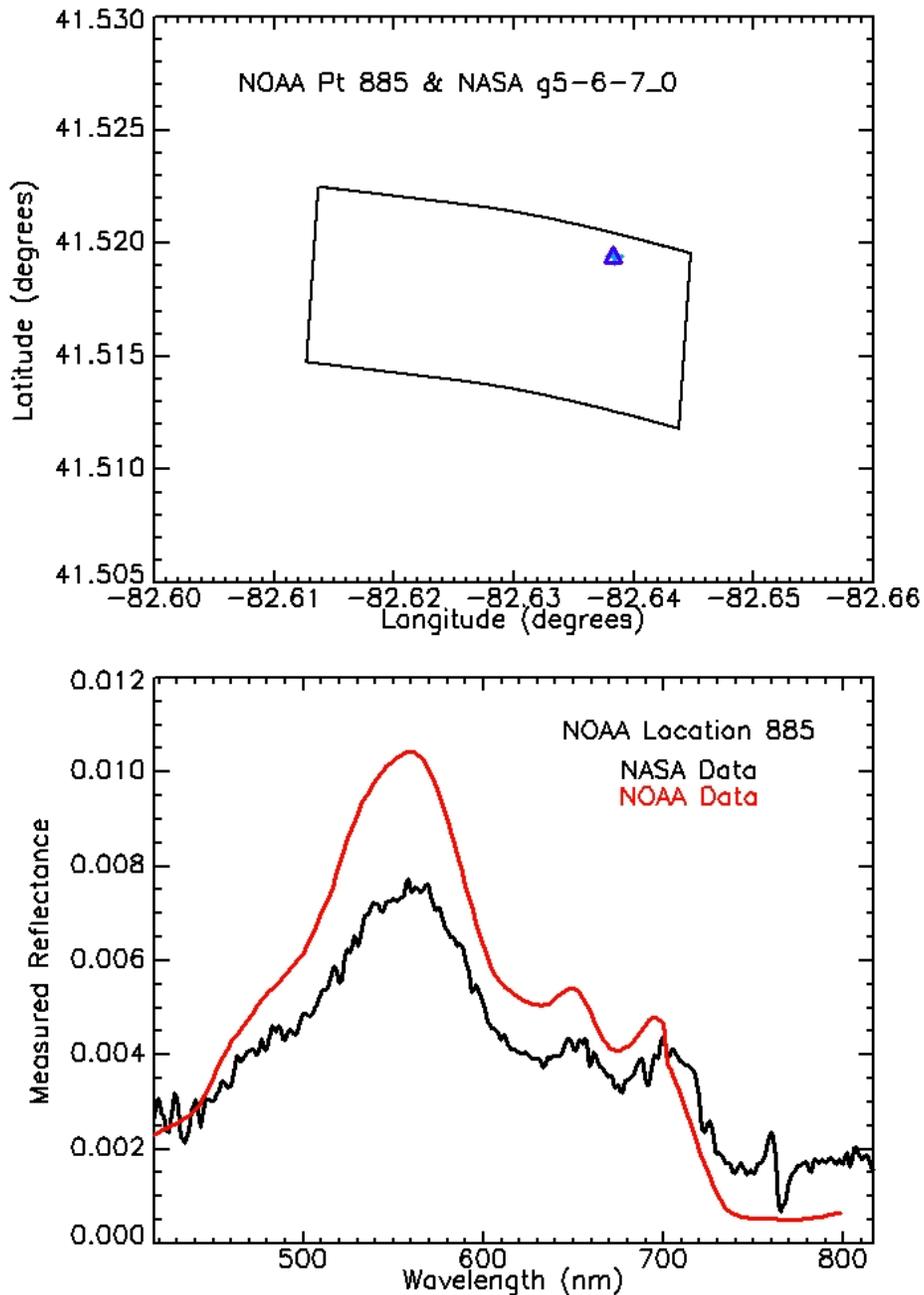


Figure 11. Data acquisition locations and reflectance spectra for point 885. (Top) The area covered by the HSI overflight is outlined. The water sample point falls within the area and is indicated by the blue cross. Hyperspectral data is taken from the same point denoted by blue triangle. (Bottom) Two spectrographs are shown. The red graph is the reflectance spectrum measured on the water from the EPA vessel R/V Lake Guardian. The graph in black is the reflectance as measured by the hyperspectral imager from overflight on the same day.

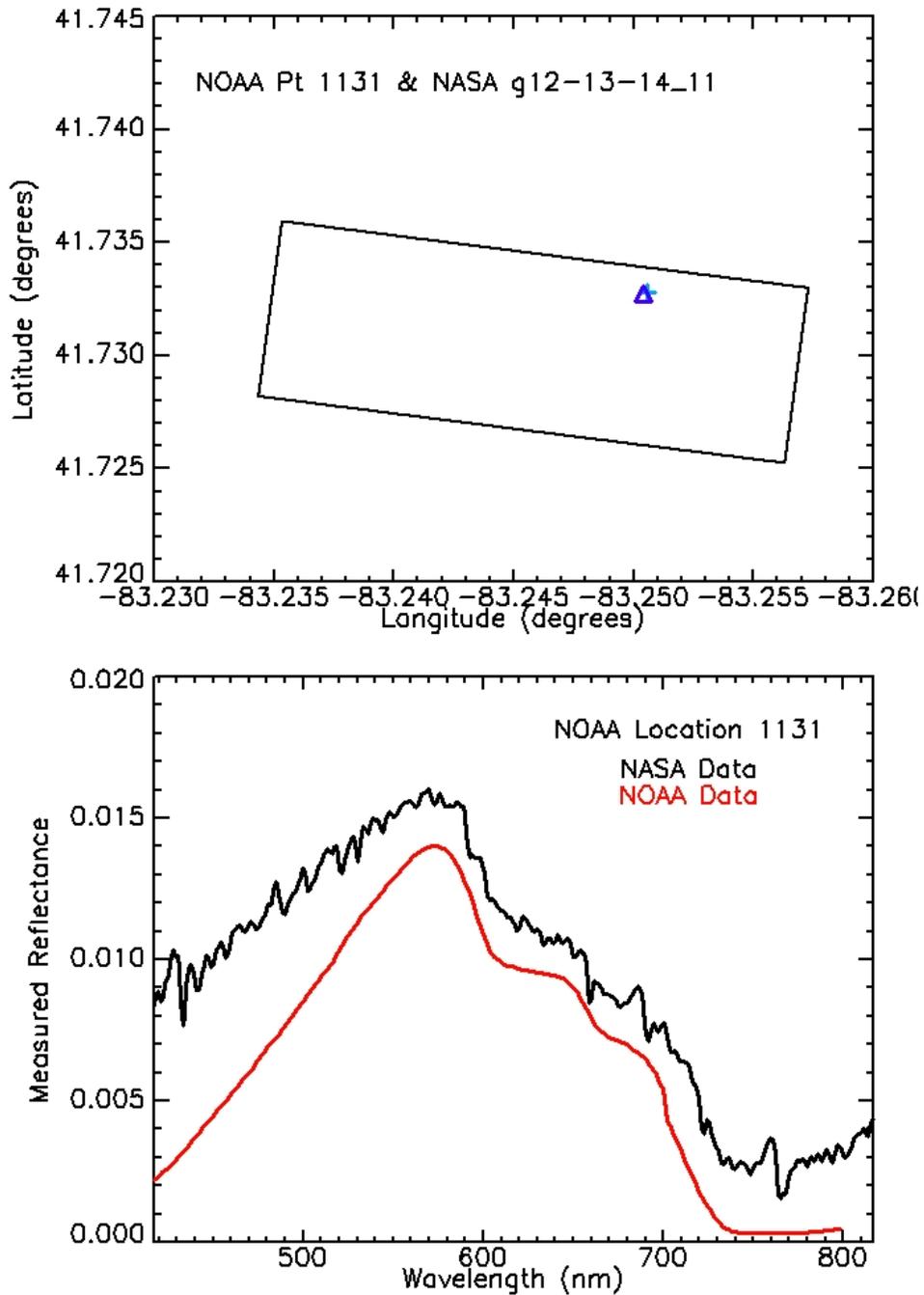


Figure 12. Data acquisition locations and reflectance spectra for point 1131. (Top) The area covered by the HSI overflight is outlined. The water sample point falls within the area and is indicated by the blue cross. Hyperspectral data is taken from the same point denoted by blue triangle. (Bottom) Two spectrographs are shown. The red graph is the reflectance spectrum measured on the water from the EPA vessel R/V Lake Guardian. The graph in black is the reflectance as measured by the hyperspectral imager from overflight on the same day.

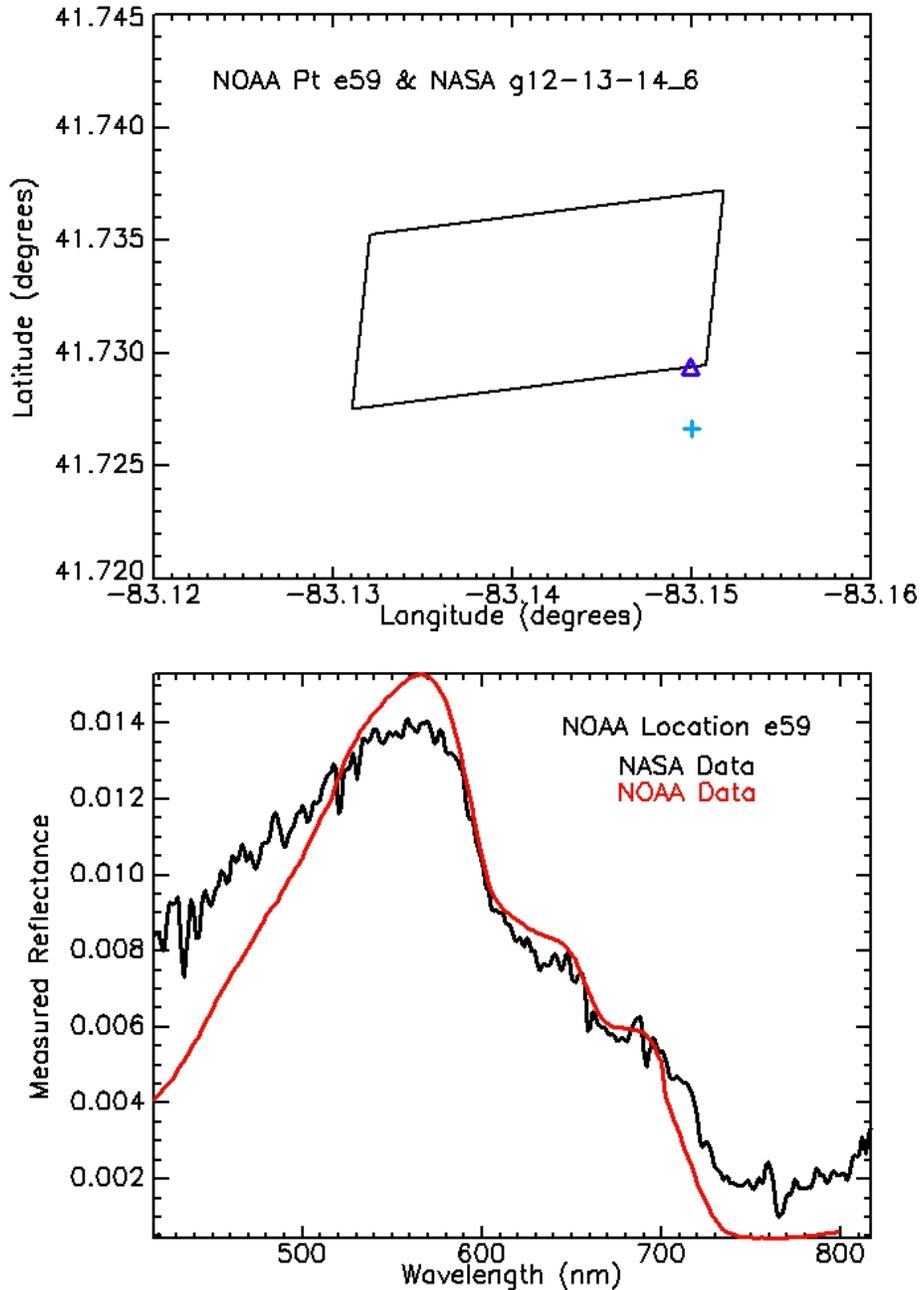


Figure 13. Data acquisition locations and reflectance spectra for point e59. (Top) The area covered by the HSI overflight is outlined. The water sample point falls outside the HSI area and is indicated by the blue cross. In this case the overflight did not cover the water sample location so Hyperspectral data is taken from the nearest HSI data point denoted by blue triangle. (Bottom) Two spectrographs are shown. The red graph is the reflectance spectrum measured on the water from the EPA vessel R/V Lake Guardian. The graph in black is the reflectance as measured by the hyperspectral imager from overflight on the same day.

IV. Conclusion

Two generations of airborne hyperspectral imagers have been developed and tested. The instruments have been designed to be compact and operate on a low power budget so that they are appropriate for many airborne platforms especially unmanned aerial vehicles and high altitude balloons. The primary application of the instruments was to demonstrate the capability of early Harmful Algal Bloom detection by detecting various concentrations of the

pigment phycocyanin as an indicator. The second generation Hyperspectral Imager (HSI) was used to gather data in conjunction with waterborne measurements. In general the airborne measurements show very good agreement with the in situ measurements. The largest area of variance is in the HSI showing a higher reflectance of blue light than the in situ measurement. This is considered an issue with atmospheric correction and this, along with continued study into the sensitivity of the HSI for identifying phycocyanin pigment, will be the subjects of further study.

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