Collection and corrections of oblique multiangle hyperspectral bidirectional reflectance imagery of the water surface

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Event: SPIE Remote Sensing, 2017, Warsaw, Poland
Collection and Corrections of Oblique Multiangle Hyperspectral Bidirectional Reflectance Imagery of the Water Surface

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ABSTRACT

Hyperspectral images of coastal waters in urbanized regions were collected from fixed platform locations. Surf zone imagery, images of shallow bays, lagoons and coastal waters are processed to produce bidirectional reflectance factor (BRF) signatures corrected for changing viewing angles. Angular changes as a function of pixel location within a scene are used to estimate changes in pixel size and ground sampling areas. Diffuse calibration targets collected simultaneously from within the image scene provides the necessary information for calculating BRF signatures of the water surface and shorelines. Automated scanning using a pushbroom hyperspectral sensor allows imagery to be collected on the order of one minute or less for different regions of interest. Imagery is then rectified and georeferenced using ground control points within nadir viewing multispectral imagery via image to image registration techniques. This paper demonstrates the above as well as presenting how spectra can be extracted along different directions in the imagery. The extraction of BRF spectra along track lines allows the application of derivative reflectance spectroscopy for estimating chlorophyll-a, dissolved organic matter and suspended matter concentrations at or near the water surface. Imagery is presented demonstrating the techniques to identify subsurface features and targets within the littoral and surf zones.

Keywords: remote sensing, oblique imagery, hyperspectral remote sensing, multispectral imagery, shallow subsurface sensing, geospatial mapping application, water quality, satellite imagery, fixed platform sensing, georeferenced imagery, image rectification, derivative reflectance spectroscopy.

1. INTRODUCTION

1.1 Background

Hyperspectral imagery offers unique benefits for detection of land and water features because of the information contained within reflectance signatures. These signatures directly show relative absorption and backscattering features of targets [1]. Hyperspectral imagers acquire hundreds of spectral bands or channels simultaneously. Because of the narrow bandwidth characteristics of the data acquired by hyperspectral imagers, some earth resource problems can be investigated in greater spectral detail for material composition and detection. The value of a hyperspectral imager also includes its ability to provide a high spatial resolution reflectance spectrum for each picture element (pixel) in the image. The reflectance spectrum in the region from 0.4 to 2.5 μm can be used to identify a large range of surface cover materials that cannot be identified with broadband, low-spectral-resolution imaging systems such as the Landsat MSS, TM, and SPOT satellites. Traditionally, hyperspectral imagers are affixed to aircraft that collect data continuously as the aircraft flies over a target area. Hyperspectral cameras that collect data in a pushbroom manner are flown over tracks of land and water and allow for real time image processing during collection.

There are, however, many disadvantages to airborne remote sensing acquisition. Inaccuracies in elevation and position, the terrain of the earth’s surface, and structures such as buildings and highways all present problems to sensing systems using aircraft for data collection [2]. As elevation changes with the aircraft or the terrain, the pixel resolution changes as well causing potential image spatial distortions. Techniques are available that can be used to correct for these deficiencies and changes of the topography, but can be time consuming and require additional sensors such as inertial motion units (IMUs) and higher resolution GPS for corrections. The financial costs incurred to conduct these operations are also significant. The recent Worldview-3 satellite program, including the launch on the Atlas-5 rocket into orbit was a $650 million expenditure [3]. The cost to obtain imagery from the Worldview-3 satellite is exorbitant as well, with dollar amounts for high-resolution eight-band multispectral images approaching a minimum of $5,800 per scene with no guarantee of clear sky conditions. Additional costs to ensure less than 5% cloud coverage within the area of interest increase the total to a minimum of $8,700 [4]. The cost to collect hyperspectral imagery utilizing aircraft is significantly cheaper than a satellite system, but time, fuel requirements, price of the aircraft (or rental cost), and waiting for weather conditions are all considerations that incur costs. Clouds, haze, rain, and fog over the area of interest are all factors that must be considered when planning an airborne remote sensing operation using an aircraft since these factors may make the data unusable, resulting in increasing of costs and time to acquire high quality imagery.

A ground based HSI collection approach offers a potentially less expensive alternative which removes extended atmospheric path radiance and provides extremely small spatial resolution for exploring geophysical variables and targets. To meet this objective in a shallow water environment, a relatively new and novel technique was developed for collecting hyperspectral imagery using a fixed platform. A hyperspectral imager was placed on a rotation stage above the water, but near the shore as shown in Figure 1. The sensor collects pixels in a vertical array and the pushbroom motion allows the sensor to sweep across the surface with the use of the motorized stage. The resulting high oblique HSI image produces pixel sizes or ground sampling distances (GSD) on the order of several mm to cm scales, depending upon the altitude and distance of the sensor to the shoreline [5]. It is also notable to mention that a fixed location ground-based high oblique hyperspectral image does not require corrections for yaw, pitch, and roll that would need to be applied with imagery acquired from an aircraft or vessel.

Figure 1. The HSI imaging system is fixed to a tripod near shallow water. The sensor collects pixels in a vertical direction and sweeps across the surface with the use of a motorized stage in a pushbroom fashion. This produces a high oblique hyperspectral imagery of the marine environment (adapted from Levaux, 2012 [1]).
Oblique images are common in aerial photography and are obtained for a scene photographed at oblique angles to the earth’s surface. These images have a wide field of view (compared to images taken at nadir viewing angles) and therefore can cover a large expanse or areas as can be seen in Figure 2. The oblique angle, i.e. the angle formed by the optical axis of the camera with respect to the z-axis of the world coordinate system, of the oblique images in Figure 2 varies between 73 to 103 degrees. This falls in the category of high oblique photography. In photogrammetry, a nadir or vertical image has a small tilt angle, typically on the order of five degrees, whereas a low oblique image is considered to be one that has between 5 and 30 degrees of tilt, and high oblique image has greater than 30 degrees of tilt [2].

![Image of oblique images](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Figure 2. Uncorrected high-oblique hyperspectral images collected at Turkey Creek (top), Indian Harbour Beach (middle), and Eau Gallie Causeway, FL. The images were collected using the ground-based, fixed speed platform using a motorized stage [13]. Turkey Creek and Indian Harbour Beach data was collected 8 and 9 July 2016 respectively, and the data from Eau Gallie Causeway was collected 10 May 2017. All data was collected during times of no cloud coverage and overhead Sun.

Depending on the elevation angle from nadir, the scale within the image scene varies considerably [6]. Imaging with larger view angles brings in seriously geometric distortions. Other issues, such as terrain, slope, elevation, and curvature of the Earth, are important, but are secondary to the issue of increasing view angle from nadir. The projected ground pixel size (GSD) increases as the sensor viewing angle in the Z-direction increases, and results in a high oblique image cube as the pushbroom sensor is rotated. The collected image cube thus has a projected pixel resolution that decreases as distance increases from the sensor compared to a nadir viewing image [7]. The resulting imagery at nadir (using a ground based HSI platform) has pixel sizes on the order of just a few mm per pixel. But as the viewing angle increases away from the nadir, the pixels (GSD) become much larger, increasing to greater than 10 cm² per pixel near the 90° elevation (horizontal). Figure 3 and Figure 4 below depict the concept of increased surface area as a function of increased elevation from nadir with respect to the viewing angle. The result of this increase in pixel size (and therefore an increase in surface area covered by each pixel) is an increase the magnitude of the BRF as the viewing angle increases away from the nadir viewing angle and location. Figure 5 shows how the BRF spectral reflectance signatures increase as a function of changing viewing angle that one needs to correct when using high oblique hyperspectral imagery. Once this has been corrected, new applications arise in high oblique imagery since most of the Earth surface radiance reaching the sensor aperture is related to direct reflectance from the target.
Figure 3. Representation of the increase of surface area covered per pixel (see the increased distance covered under the black and white pixels) with increasing elevation from nadir.

Figure 4. Representation of the increase of surface area covered per pixel with increased distance from the hyperspectral imager. At the first distance, the imager collects one pixel. As the distance increases, the pixel covers an increasingly greater surface area.

Figure 5. BRF spectral reflectance signatures show the increase in reflectance as a function of changing viewing angle that needs to be accounted for in oblique HS image analysis used to estimate the concentrations of constituents in the water. Spectra collected by the authors on 8 July, 2017 at Palm Bay, Florida.
Almost all objects in nature exhibit what is referred to as a bidirectional reflectance distribution function (BDRF). That is, the reflectance of a surface depends on both the direction of the incoming irradiating flux and the direction along which the reflected flux is measured or the "look angle". Thus the distribution of reflected flux from a surface depends on the geometry of the measurement. In particular, for flux from a small radiant source it depends on (1) the angle of incidence, θi, of the flux at the surface, (2) the azimuthal angle ϕ of the plane of incidence with respect to a direction across the surface, (3) the angle to the surface normal from which the flux is detected, θr; (4) the azimuthal angle ϕr of the plane of reflection, (5) the solid angle subtended by the source at a point on the surface, and (6) the solid angle subtended by the entrance pupil of the sensor at the surface [8]. The BRDF unit is [sr⁻¹] and is mathematically written as:

$$\text{BRDF}(θ_i, ϕ_i, θ_r, ϕ_r; λ_k) = \frac{L_r(θ_i, ϕ_i; θ_r, ϕ_r; λ_k)}{E_i(θ_i, ϕ_i; λ_k)} ,$$

where:

- $E_i$ = Incident Irradiance [W m⁻² nm],
- $L_r$ = Reflected Radiance [W m⁻² sr⁻¹ nm],
- $θ_i$ = Solar Zenith Angle with respect to Nadir [radians],
- $ϕ_i$ = Solar Azimuth Angle clockwise from the North [radians],
- $θ_r$ = Sensor Zenith Angle with respect to Nadir [radians],
- $ϕ_r$ = Sensor Azimuth Angle clockwise from the North [radians],
- $λ_k$ = Wavelength of Spectral Band [nm].

A calibrated Lambertian (perfectly diffuse) reflectance panel can be used to estimate the incident irradiance ($E_i$) by measuring the reflected radiance ($L_p$) from the diffuse reflector [8] [9]. This technique is known as the Bidirectional Reflectance Factor (BRF) as first described by Slater (1980) [8]. A bidirectional reflectance factor (BRF) was also defined by Sandmeier, 1999 [10] as the radiance reflected from a surface in a specific direction divided by the radiance reflected from a lossless, Lambertian reference panel measured under identical illumination geometry. Mathematically, this is written as shown in equation 2, and is unitless [11]:

$$\text{BRF}(θ_i, ϕ_i, θ_r, ϕ_r; λ_k) = \frac{L_r(θ_i, ϕ_i; θ_r, ϕ_r; λ_k)}{L_p(θ_i, ϕ_i; θ_r, ϕ_r; λ_k) * L_{p-c}(λ)} ,$$

where:

- $L_p$ = Radiance from the reflectance panel [W m⁻² sr⁻¹ nm],
- $L_p$ = Pixel Reflected or Upwelling Radiance [W m⁻² sr⁻¹ nm],
- $L_{p-c}$ = Interpolated coefficients of the Lambertian reflectance panel,
- $θ_i$ = Solar Zenith Angle with respect to Nadir [radians],
- $ϕ_i$ = Solar Azimuth Angle clockwise from the North [radians],
- $θ_r$ = Sensor Zenith Angle with respect to Nadir [radians],
- $ϕ_r$ = Sensor Azimuth Angle clockwise from the North [radians],
- $λ_k$ = Central Wavelength of Spectral Band [nm].

Anisotropy in remote sensing is defined as a property of an object to reflect radiance dependent upon the direction of the Sun with regards to the sensor. This type of object is referred to as a non-Lambertian object or target. If one normalizes all BRFs to the value obtained at the nadir (normal to the reflection plane) viewing geometry, one obtains a reflectance-anisotropy factor (ANIF) that changes at each wavelength, and accounts for the deviation of reflectance from that measured at nadir [12]. ANIFs can be used to analyze the spectral variability in BRF and BRDF data and allows separation of spectral BRF and BRDF effects of spectral signatures of targets [10]. When examining BRF spectra from varying sensor positions it becomes clear that BRFs by themselves do not reveal much in terms of reflectance anisotropy. Sandmeier, 1999 [10] suggested one needs to emphasize the direction-related reflectance anisotropy with respect to a reference direction, and thus to divide each non-nadir measurement by the nadir BRF measurement (Feingersh, et al., 2009). Mathematically, ANIF is written as:

$$\text{ANIF}(θ_i, ϕ_i, θ_r, ϕ_r; λ_k) = \frac{\text{BRF}(θ_i, ϕ_i; θ_r, ϕ_r; λ_k)}{\text{BRF}_0(θ_i, ϕ_i; θ_r, ϕ_r; λ_k)} ,$$

where $\text{BRF}_0$ is the uncorrected BRF for the nadir measurement.
where:

\[
\begin{align*}
\text{BRF} &= \text{Bidirectional Reflectance Factor of pixel [unitless]}, \\
\text{BRF}_n &= \text{Bidirectional Reflectance Factor of pixel at nadir [unitless]}. 
\end{align*}
\]

Once the ANIF value has been obtained, the reciprocal of this value yields a BRF Correction Value (\(\text{BRF}_{\text{COR}}\)) which can be applied to correct for off-nadir BRF values [12]. Mathematically, the \(\text{BRF}_{\text{COR}}\) is written as:

\[
\text{BRF}_{\text{COR}}(\theta_i, \phi_i, \theta_r, \phi_r, \lambda_k) = \frac{1}{\text{ANIF}(\theta_i, \phi_i, \theta_r, \phi_r, \lambda_k)},
\]

where:

\[
\begin{align*}
\text{BRF}_{\text{COR}} &= \text{BRF Correction Factor [unitless]}, \\
\text{ANIF} &= \text{Anisotropy Factor [unitless]}. 
\end{align*}
\]

Using the \(\text{BRF}_{\text{COR}}\) value, an off nadir pixel BRF signature can be corrected to that of an approximate nadir spectral signature using the following equation [9]:

\[
\text{HSI}_{\text{COR}}(\theta_i, \phi_i, \theta_r, \phi_r, \lambda_k) = \text{HSI}(\theta_i, \phi_i, \theta_r, \phi_r, \lambda_k) \times \text{BRF}_{\text{COR}},
\]

where:

\[
\text{HSI}_{\text{COR}} = \text{the corrected hyperspectral image}. 
\]

Applying these equations to each pixel of the high oblique hyperspectral image cube will normalize the spectral reflectance signatures to that of a nadir angle viewing hyperspectral image. Techniques can then be applied to rectify and georeference the hyperspectral image cube which will allow for constituent change and detection across the shallow water body.

2. TECHNIQUES & METHODS

2.1 Hyperspectral Imager and Instrument Components

A hyperspectral imaging system is placed upon a triple action panhead tripod near shallow water environments, within viewing distance of a shoreline or the horizon when scanning large water bodies (i.e. the ocean or bays). The pushbroom sensor sweeps the shoreline with the use of a Zaber T-RS motorized rotation stage system while the pushbroom sensor produces a high oblique hyperspectral image cube of the shallow water setting. A JVC High Definition video recorder was also co-mounted to collect HD video of the shallow water scene during rotation. The hyperspectral pushbroom imaging system custom developed by the first author is capable of recording 64 to 1024 spectral channels which can be selected prior to data collection using custom designed software [5]. The system has 1,376 spatial channels and uses a Peltier cooled 2/3 inch high quantum efficiency (QE) CCD with 12 bit digital resolution. The imaging system utilizes a calibrated 36° field of view (FOV) Schneider C-mount lens. The known FOV of the lens is used to determine the elevation angle from nadir on the high oblique hyperspectral cube. Leveling of the system for applying corrections is assisted by resting an 18mm circular bubble level on the HSI lens prior to sweeping (this ensures a 90° elevation angle (\(\theta\)) from nadir). The pushbroom imaging camera system was operated using a Fujitsu ST 6012 pen-tablet computer connected via a fiber optic cable and an external PCI bus configuration [13].

The integration time, frame rate, and number of spectral and spatial channels can be software selected for optimizing the dynamic range for different scenes. Calibration and testing of the hyperspectral imaging system for circular rotation velocity is necessary in order to produce square pixels. In order to conduct these calibrations square targets are placed in a scene. Multiple scanning sequences were performed to establish the scanning rate of the computer controlled rotation stage in relation to the integration time and number of channels selected on the hyperspectral camera. Figure 6 shows a hyperspectral image collection with three 4 x 4 feet square spectrally calibrated targets. Examination of the number of pixels in the vertical and horizontal is accomplished in order to determine the angular rotation velocity (radians sec\(^{-1}\)) or rate to produce equal number of pixels in the x, y directions [13]. This process ensures square pixels are collected.
Figure 6. Hyperspectral imagery used to calibrate the mechatronics rotation stage rotation rate (radians sec\(^{-1}\)). This is a true color unenhanced hyperspectral RGB image display using channels at 683.5 nm, 529.1 nm and 487.7 nm, and the three square calibration squares can be found in the center and at the edges of the HSI.

The custom software can also display three channel (RGB) imagery as the remote sensing platform scans while the rotation stage moves. Additionally, selected pixel specific spectral signatures can be displayed in real time during an image cube acquisition in order to optimize both the scan rate and integration time of the CCD sensor in order to use the full dynamic range of the CCD camera. This capability also minimizes pixel saturated spectra within a scene while maximizing the full dynamic range desired. The pen-tablet also displays real time GPS position, an IMU connection status, the CCD temperature, integration time selected, and frame rate. The custom touch screen or pen tablet system software also allows calibration of the IMU at a GPS location in order to offset the vertical z-axis and magnetic deviation at the beginning of each recording. Before use, radiance calibrations and spectral line sources are used to ensure the wavelength-channel calibration has not changed, and the radiance values of the system have not drifted from the prior laboratory calibration using calibration spheres. Figure 7 is a system description of the software-hardware HS imaging sensor system MCIA or Card Bus cards [13].

Figure 7. Example (left) of a spectral signature being displayed along with integration time and number of bands being collected. The system allows for data optimization in real time, such as scan rate and integration time. The computer systems diagram shows the small hyperspectral image system and custom data acquisition interface. The hyperspectral pushbroom imager system can be run on a workstation, touch screen computer, or pen tablet computer using an external PCI card bus system and fiber optical cable to the camera [13].
The software, also custom designed by the first author, is based upon the C language and uses OpenGL for windows and graphical menus. The system is operated via a touch screen computer or pen-tablet running XP, Vista, W7 32bit or 64 bit OS’s with a PC. The system described above requires a constant AC/DC power source in order to operate. Since the majority of aquatic environments of interest are not located within an area with available power, a portable power system was developed to achieve a fast transportable method and thus eliminates the use of long distance extension cords or power outlets. To accomplish this, three rechargeable X2 DC power 12V lightweight lithium batteries were connected to an NPower 1500 Watt digital power inverter. The batteries were charged for approximately 12 hours and were capable of providing over 24 hours of power supply. For ease of use and transportation, the batteries and inverter were secured to a modified backpack system using aircraft grade Velcro and tie-down straps. Figure 8 is a photograph taken during operation that displays the HSI and SE590 sensors running from the Fujitsu pen tablets, and the external PCI bus which are all powered by the portable power supply system. As can be seen, umbrellas and cloth coverings are used to reduce direct sun during operations.

Figure 8. The HSI system in operation at Palm Bay, FL on 7 July 2016. The pen tablet can be seen resting on the deck with the portable power supply system in the red back pack. The PCI bus is shown resting on top of the back pack. The umbrella and white cloth were used to help reduce the temperature of the systems during operation.

2.2 High Oblique Hyperspectral Imagery Collection

Site locations were selected based upon the shallow water environment of a turbid coastal sub estuary of the Indian River Lagoon, Florida (28°02′04.94″ N, -80°34′46.32″ W), along coastal surf zone waters of the nearby Atlantic Ocean (28°08′02.82″ N, -80°34′46.03″ W), and within the brackish waters of the Indian River at Eau Gallie Causeway, Florida (28°07′57.35″ N, -80°37′4.94″ W). The multiple subsurface bottom and rip current features as well as suspended particulate matter within the selected locations made them ideal for meeting the intent of this research. All locations used for data acquisition are situated along the eastern coast of Florida within Brevard County. Additionally, all HSI imagery (seen in Figure 2 above) was obtained during the late morning and afternoon hours of mostly solar zenith elevations and mostly sunny sky conditions. The use of the custom portable HSI system allowed for flexibility with scanning times, meaning that imagery was obtained during times of no cloud coverage. As shown in equations 1 to 5, all corrections for off-nadir viewing angles are a function of azimuth (φ) and elevation (θ) angle. On site, the azimuthal directions were obtained using a standard compass aligned with the laser optic orientations while sweeping. An 18mm bubble level was utilized to ensure that the HSI was sweeping at a 90° elevation angle (θ) orientation from nadir.
Therefore, since the system has 1,376 spatial channels, the exact 90° elevation angle (θ) location on the hyperspectral image cube was at pixel value 688. The known 36° FOV of the Schneider C-mount lens attached to the HSI transmission grating allowed for calculating the upper and lower elevation angles of the hyperspectral image cube (108° and 72°, respectively). With these two angles known, an overlay was then applied to the hyperspectral images to assist in correcting for off-nadir angles for each pixel. Figures 9, 10, and 11 are the results of the completed overlay at Palm Bay, Indian Harbour Beach, Florida.

![Figure 9](image1.png)

**Figure 9.** A true-color hyperspectral pushbroom BRF image (channels 638.4 nm, 547.9 nm, 461.6 nm) at Turkey Creek, FL. The image contains an overlay that displays the azimuth (φ) (blue vertical lines) and elevation (θ) (red horizontal lines) change as the sensor sweeps the scene. The overlay also shows the associated pixel value for each azimuth and elevation target at the scene (bottom x-axis and right side y-axis).

![Figure 10](image2.png)

**Figure 10.** A hyperspectral pushbroom BRF image with contrast enhanced filter (channels 638.4 nm, 547.9 nm, 461.6 nm) at Indian Harbour Beach, FL. The image contains an overlay that displays the azimuth (φ) (blue vertical lines) and elevation (θ) (red horizontal lines) change as the sensor sweeps the scene. The overlay also shows the associated pixel value for each azimuth and elevation target at the scene (bottom x-axis and right side y-axis). The contrast enhanced filter was applied to highlight rip current features and resuspended matter within the surf zone region of the Atlantic Ocean [13].

Applying these overlays onto the hyperspectral image cubes allowed for analysis of pixel BRF signatures as a function of azimuth and elevation, while simultaneously providing pixel number references to *in-situ* and field targets of known distances for ground control point selection and image to image registration.
2.3 Ground Control Point Selection and Pixel Correlation

Selecting oblique imaging field targets on site was critical for successful hyperspectral image georegistration. Targets were placed at known distances and directions from the sensor to be used as ground control points (GCPs) when conducting the image georegistration. Example field targets include floating targets, submerged line targets, black, grey, or white targets placed on shorelines. In-situ scene features or targets were also utilized in the image to image georegistration process and GSD calculation. These targets included pilings, buildings, shorelines, and bridges. Their distance from the HSI sensor was determined using GPS coordinates. A benefit to using in-situ targets was that the features were also present on the satellite imagery used for image to image registration, making the ground control points (GCPs) selection extremely accurate at those locations. Figure 12 shows the use of in-situ field targets and how their distances from the sensor were used to correlate the number of pixels between them.

The data obtained on distances between the object and the sensor were then used for viewing geometry calculations of the ground sampling distances at each scan line and each pixel. Due to the water surface being relatively flat at the selected locations, and the HSI sensor being rotated at a constant 90° elevation angle (θ) from nadir, one can incorporate a straight line overlay onto the hyperspectral image cube of known distances and elevation pixel values away from nadir as shown in Figure 13. This figure was then used to assist in image to image georegistration of the water surface between GCPs onto the base satellite image of the scene.

To ensure that the high oblique image cube is georegistered as close as possible to the ground control points, the shallow water area is segmented into regions of interest (ROIs) in order to reduce the required number of GCPs. Using this technique for determining the ground sampling distances, the pixel values in the ROI are linked to GCPs on a satellite image of the target scene (typically utilizing Google Earth or another free satellite imagery program).
Figure 12. Utilizing in-situ field targets (a piling and the shoreline) and GPS data to calculate the distance and number of pixels at each distance. The left panel shows that the distance from the HSI sensor to the in-situ target is 480 pixels long and covers 90.83ft. At this distance, a horizontal count of 35 pixels is 1ft in width. The center panel shows that from the same GCP to the far shoreline, there are 198 vertical pixels, but now covers over 520ft in distance (as also represented in Figure 2.11). Additionally, the same 35 pixels on the horizontal now cover almost 17ft instead of 1ft.

Figure 13. A hyperspectral image cube of Palm Bay, Florida with an overlay displaying the distance from the sensor to known GCPs (left side y-axis) at the scene and the corresponding elevation pixel value (right side y-axis) on the HSI. Notice the use of in-situ field targets such as the shore-line and signs/piling, the distances of which were measured on-site. This overlay is then used to assist in GCP selection during image registration and georegistration.
2.4 Constituent Detection Using Second Derivative Estimator

Once the image is rectified and georeferenced, an estimation of a second derivative equation can be applied to each pixel on the nadir angle viewing shallow water scene to estimate the relative concentrations of constituents in the water body. Bostater (1991) described a method termed optimal “passive” correlation spectroscopy (OPACS) for selecting the optimal bands from hyperspectral sensor data for use in estimating chlorophyll, DOM, and suspended solids (seston) [14]. From these optimal bands, a method to estimate a second derivative of the spectrum using the equation generalized by Bostater, et al. (1996) and Grew (1980) [15] [16]:

\[ I(\lambda) = \frac{B_2(\lambda)^2}{B_{i-n}(\lambda)B_{i+n}(\lambda)}, \]

where:

- \( B_2(\lambda) \) = The center band (I) at wavelength \( \lambda \),
- \( m \) = The forward channel offset from the center band,
- \( n \) = The backwards channel offset from the center band.

The underlying goal of computing an approximation of the second derivative is to utilize the nonlinear derivative based, dilating wavelet to enhance the variations in the reflectance spectra signals, as well as in the contrast spectrum signals [15]. These variations directly represent the target and background absorption (hence: concave up) and backscattering (hence: concave down) features within a hyperspectral reflectance image or scene and forms a spectroscopy based scientific basis for development of noncontact optical remote sensing algorithms.

3. RESULTS AND DISCUSSION

3.1 Uncorrected BRF Imagery

Utilizing equation 2, the uncorrected BRF was calculated using ROIs at changing azimuthal (\( \phi \)) and elevation (\( \theta \)) angles for all hyperspectral shallow water scenes. The results of this process yielded an increase in surface reflectance as a function of increasing elevation angle away from the nadir viewing angle. As shown in Figures 3 and 4, this increase can be attributed to the increase in surface area covered as the elevation angle of the hyperspectral sensor moves away from nadir. The BRF signatures, which were calculated between 400 and 700 nm, contain feature information suggesting the presence of chlorophyll, dissolved organic matter (DOM), and/or seston at the different site locations. Figures 14, 15, and 16 below are sections of the Palm Bay, Indian Harbour Beach, and Eau Gallie Causeway, FL hyperspectral images that demonstrate this increase and show the spectral reflectance signatures from each.

3.2 ANIF and BRF\textsubscript{COR} Signatures

As previously defined, the anisotropy factor is a property of an object to reflect radiance dependent upon the direction of the Sun with regards to the sensor (non-Lambertian). Utilizing equation 3, the BRF values from section 3.1 are normalized to the nadir value as a function of wavelength. Doing so allowed for further analysis of the spectral variability of the shallow water images. The ANIF images produced contain unique information concerning the spatial coherence, or lack thereof, of the ANIF factors within the image of the shallow water scene [11]. Mathematically, all nadir values will equal 1, with the values increasing as the BRF exceeds the nadir value. Figure 17 illustrate the ANIF changes by sensor elevation angle across multiple azimuths in the hyperspectral image cube scenes.

The Palm Bay ANIF signature displays a more pronounced increase at approximately 480 nm, and less variability as the wavelengths increase. ANIF values at Indian Harbour Beach, like the BRF calculations, also show a transition from high suspended sediment in the near coastal surf zone to open ocean conditions. Those ANIF signatures that more closely follow the straight-line trend of the nadir ANIF values are representative of the clearer, less turbid aquatic environment. ANIF values that are more pronounced near 580 nm and beyond are indicative of prominent amounts of suspended sands in the water, denoting a more turbid aquatic environment. ANIF values calculated for the Eau Gallie Causeway shallow water scene show the same spatial variability with respect to increased BRF values as the Turkey Creek and Indian Harbour Beach data, however there is lower spectral variability between 72 - 85° elevation angles. This is evident as illustrated by the generally straight line produced when graphing the ANIF values across the spectrum suggesting the signature absorption and backscattered features are constant with increased distance from the sensor. Thus, the non-Lambertian behavior of the water surface is shown to be wavelength dependent that may be attributed to the absorption, reflection, and transmission properties of the water body [10].
Figure 14. Increasing BRF signatures with increased elevation from nadir at 180°ϕ at Palm Bay, FL. The BRF at elevation angle, θ, was determined using ROIs between 72° - 90°. Data collected 8 July 2016.

Figure 15. Increasing BRF signatures with increased elevation from nadir at 90° ϕ at Indian Harbour Beach, FL. The BRF at elevation angle, θ, was determined using ROIs between 72° - 90°. Of particular interest, note the signatures suggest a transition from turbid waters near shore to that of clear water conditions. Data was acquired on 9 July 2016.
Taking the reciprocal of the ANIF values above will produce the correction factor that is applied to the BRFs from Section 3.1 (see equation 4) as a function of elevation and azimuthal angle, as well as wavelength. Figure 18 provides example \( \text{BRF}_{\text{COR}} \) values from each hyperspectral image cube to illustrate the correction factors as they relate to the nadir value (1) by wavelength.

### 3.3 Corrected to Nadir Signatures

Resulting hyperspectral image cubes and corrected to nadir BRF values are presented in the figures below. Correcting the BRFs due to increased surface area covered per pixel to that of a nadir viewing angle now allows for data interpretation through a second derivative estimator and transposition from a high oblique to a nadir viewing image. The corrected BRF spectral signatures for Palm Bay have maintained the responses that indicate chlorophyll and seston concentrations that was expected. The reflectance values have dropped significantly to accurately simulate the spectral response that would have been obtained at that pixel location if the HSI sensor was collecting data at a 0° elevation angle. The uncorrected BRF signatures of this location were on the order of .06 at 72° elevation and upwards of .25 at 90° elevation at the peak values. The same ROIs now peak at values of .04 to .06, which is within the range of the nadir scans taken from the hyperspectral imager and the solid state spectrograph SE590.

The hyperspectral signature should denote an isosbestic (hinge) point across the track of water as you progress from near shore to off shore water conditions due to the presence of resuspended sands and sediment. The spectral responses from the uncorrected BRF did not point to a location of this isosbestic point, but through the application of the methodology applied to correct to a nadir viewing angle, an isosbestic point is clearly observable within the spectral signatures. Figure 20 displays the reflectance signatures along a vertical track from near shore to off shore ocean conditions. The uncorrected signatures show a lack of uniformity compared to the corrected BRFs, which contains an observable isosbestic point at approximately 560 nm. Figure 21 shows the same azimuthal and elevation information as in section 3.1, but with the pixels corrected for the surface area increase.

The corrected BRF spectral signatures at Eau Gallie Causeway have maintained the responses that indicate high concentrations of dissolved organic matter and seston and low concentrations of chlorophyll. The reflectance intensities were normalized to nadir, reducing the peak values from approximately .30 to between .04 and .06. Doing so allows for
better analysis of the spatial and spectral data after conducting the image georegistration and comparing the BRF results from the three water bodies. Figure 22 below exemplifies the spectral responses of the surface water of Eau Gallie Causeway once cross calibrated and corrected to nadir.

![Palm Bay ANIF Signatures](image1)

![Indian Harbour Beach ANIF Signatures](image2)

![Eau Gallie ANIF Signatures](image3)

Figure 17. ANIF signatures from Palm Bay, Indian Harbour Beach, and Eau Gallie Causeway, FL. These signatures also display an increase in value at increasing elevation angles from nadir (shown as the straight line at 1). The ANIF signatures of Indian Harbour Beach show the effect of the transition from turbid to clear ocean water conditions. The ANIF signatures at Eau Gallie Causeway, while also displaying a correlation between increased values away from nadir, yield a relatively uniform signature in relation to the nadir signature. This suggests that there is very little change across the water body regarding absorption/backscatter features.

3.4 Image Registration and Second Derivative Estimator

Following the methodology described in Section 2.3, the high oblique hyperspectral image cubes were transposed into nadir viewing images. Critical to the successful transformation of the images was designation of known distances between the sensor and the GCP (in-situ or field target), as well as selecting ROIs of the shallow water environment for a more accurate geometric transformation. When each image had a geometric transformation applied, most if not all of the pixels within the source image were relocated from their image based spatial coordinates to the new position based on the assigned GCP. When a pixel was relocated and did not map directly onto the center of the satellite base image, but was located somewhere in between the centers of a pixel location, the transposed pixel value was computed by sampling and interpolating the values of the neighboring pixels. This utilized technique is referred to as Nearest Neighbor [17]. In order to rectify and warp multiple ROIs using fewer GCPs and then mosaicking the resulting images together produced better results than warping the entire high oblique image to the base satellite image.
Applying the second derivative estimator to the rectified hyperspectral nadir images requires in-depth analysis of the spectral response signatures within the scenes, along with knowledge of the known absorption and backscatter channels or wavelengths for constituent detection. Absorption and backscattering features of targets or backgrounds are related to constituents in the water. As previously described, Bostater (1991) described a method termed optimal “passive” correlation spectroscopy (OPACS) for selecting the optimal bands from the sensor channels to be used in estimating chlorophyll, DOM, and suspended solids (seston) [14]. An approximation of this second derivative is used to discriminate the different absorption or backscattering features [1]. Equation 6 is applied to each pixel on the hyperspectral image cube giving the pixel a value that estimates the selected optimal bands and thus the spatially varying concentrations of water quality related constituents. Figures 23, 24, and 25 below are the resulting image rectification of the high oblique hyperspectral scenes along with selected constituent estimation results for the second derivative estimations of the scene.

When analyzing the reflectance values for optimal band selection, three factors were taken into consideration. The first factor was the absorption in the blue region of visible light spectrum that is known to be related to absorption of phytoplankton and DOM concentrations. In this spectral region, dissolved organic matter almost entirely masks the absorption peak of chlorophyll at 430 nm. Even where DOM concentrations are low, this masking effect is significant. Therefore, the importance of the DOM reflectance cannot be neglected when remote sensing for chlorophyll is attempted using absorption of phytoplankton in the blue region. The second factor is enhanced backscatter in the green spectral region. This feature is related to light scattering by suspended nonorganic and organic (phytoplankton) particles (seston). The third factor was high absorption in the red region of the visible light spectrum that is strongly influenced by absorption and solar induced fluorescence peak due to phytoplankton. This spectral feature is unique to phytoplankton chlorophyll, and it allows the separate retrieval of chlorophyll concentrations without relying on the 430 nm absorption
peak that is masked by DOM [18]. Based on these factors, the spectral bands that are more suitable for the estimation of water quality are between 645 to 690 nm for chlorophyll and 540 to 590 nm for seston.

Figure 19. Palm Bay, FL values now represented an at nadir signature without losing features contained within. The corrected signatures suggest a strong indication of seston, DOM, and a minor absorption from chlorophyll, and can now be used in equation 6 to determine estimated concentrations of different constituents in the water body.

4. SUMMARY AND CONCLUSIONS

This research demonstrates a methodology to estimate relative water constituent concentrations from ground-based high oblique hyperspectral imagery. Using a hyperspectral pushbroom sensing system that is calibrated and rotating the imager at an exact scanning speed associated with the sensor integration time, it is shown that one can obtain a geometrically accurate pushbroom hyperspectral image cube. Correcting for the increase in BRF as a function of increased surface area per pixel as the elevation from the sensor increases is possible by calculating the anisotropy factor and normalizing those values to signatures derived from nadir viewing angle scene data. Using in-situ and field targets at the image cube collection site, it is shown how to transpose a high oblique image into a nadir representation of the scene with high spatial resolution without changing the signatures. To further demonstrate the success of this research in properly correcting high oblique reflectance values to nadir, a comparison between an average surface reflectance signature from each high oblique shallow water scene prior to correcting for off nadir viewing angles and an average surface reflectance once corrected can be made. In Figure 26, the spectral signatures that have not been corrected for off nadir viewing angles (graph A) do not display an isosbestic point that one would expect to see when comparing the different water surface reflectance values.
Figure 20. Average ROI BRF signatures taken from a vertical track extending from the turbid surf zone into non-turbid ocean conditions. The left panel displays the uncorrected BRF image values and does not show a clear isosbestic point. The right panel is the same ROI track on the corrected hyperspectral image, which delineates a clear isosbestic point at ~560nm.

Figure 21. Indian Harbour Beach, FL values now represented an at nadir signature without losing features contained within. The corrected signatures suggest a transition from turbid (backscatter feature) to clear ocean conditions (no absorption of blue wavelengths), but does not contain any indication of chlorophyll. The pixel signatures can now be used in equation 6 to determine estimated concentrations of different constituents in the water body.
The increase of reflectance values due to surface area and path length increasing away from nadir is shown in the uncorrected spectral responses, and is the source of this lack of an isosbestic point. After applying the corrections using the methodology described in Section 3, however, the off nadir spectral signatures are normalized to nadir and the isosbestic point can be seen (graph B). The presence of this point of equal absorption and backscattering, as discussed in Robinson (1985) and Bostater (2011), indicates that the methodology used throughout this research was successful in correcting for off nadir viewing angles [5] [19]. BRF spectral signature interpretation and knowledge of the specific absorption and backscattering features of the targets used allows for constituent detections within a water body by applying a second derivative estimator as a remote sensing algorithm. Relative constituent concentrations in the water can be constructed by applying a high to low gradient color scheme to cube pixel values. The image can then be georeferenced to estimate a nadir viewing image cube that may be useful in correlating water quality spatial change detection.

5. ACKNOWLEDGEMENTS

The imaging system and software used was developed with funding from KB Science. Students in the laboratory have been supported in part by the Northrop Grumman Corporation, NASA KSC, NSF, the US-Canadian Fulbright Program, US Department of Education, FIPSE & Atlantis STARS (Sensing Technology and Robotics Systems) international exchange program and the Florida Dept. of Environmental Protection and Brevard County, Florida. A special acknowledgement is given to Andre Bassette at United Space Coast Cables, Melbourne, Florida, for assisting with construction of a sensor cable used in this research.
Figure 23. The resulting nadir viewing image of Palm Bay, Florida collected on 9 July 2016. This image is produced from image registration of the high oblique, corrected hyperspectral image. The second derivative estimator for chlorophyll concentrations in the bay is shown. The results suggest that the higher concentrations of chlorophyll are located along the southern and eastern shorelines and at the mouth of the creek.

Figure 24. The resulting nadir viewing image of Indian Harbour Beach, Florida collected on 9 July 2016. This image is produced from image registration of the high oblique, corrected hyperspectral image. The image contains corrected BRF signatures that indicate a strong transition of suspended material in the surf zone to clear waters toward the open ocean. The second derivative estimator for seston concentrations at Indian Harbour Beach is also shown. As expected due to the impact of resuspended sands from the breaking of water surface waves and other off-shore water flows, there is a clear change of state from a turbid coastal setting to that of a clear off-shore ocean condition. This image validates the hinge point transition shown in Figure 20.
Figure 25. The resulting nadir viewing image of Eau Gallie Causeway, Florida collected on 10 May 2017. This image is produced from image registration of the high oblique, corrected hyperspectral image. Analyzing the nadir corrected BRF signatures from the rectified and georegistered image cubes, the most prevalent feature was the absorption from dissolved organic matter between 430 and 530 nm. The second derivative estimator for dissolved organic matter (DOM) concentrations at Eau Gallie Causeway is shown and suggests areas of higher DOM absorption along the center and western shoreline areas.

Figure 26. Graph comparison of uncorrected off nadir viewing surface reflectance (graph A) and corrected spectral signatures (graph B) from Palm Bay (Turkey Creek), Indian Harbour Beach, and Eau Gallie Causeway, Florida. The uncorrected signatures do not yield a clear isosbestic point due to variations in average surface reflectance values from increased surface area away from nadir within the shallow water scene.

6. REFERENCES