HICO-Based NIR–Red Models for Estimating Chlorophyll-α Concentration in Productive Coastal Waters

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Abstract—We present here results that demonstrate the potential of near-infrared (NIR)–red models to estimate chlorophyll-α (chl-α) concentration in coastal waters using data from the spaceborne Hyperspectral Imager for the Coastal Ocean (HICO). Since the recent demise of the MEdium Resolution Imaging Spectrometer (MERIS), the use of sensors such as HICO has become critical for coastal ocean color research. Algorithms based on two- and three-band NIR–red models, which were previously used very successfully with MERIS data, were applied to HICO images. The two- and three-band NIR–red algorithms yielded accurate estimates of chl-α concentration, with mean absolute errors that were only 10.92% and 9.58%, respectively, of the total range of chl-α concentrations measured over a period of several months in 2012 and 2013 on the Taganrog Bay in Russia. Given the uncertainties in the radiometric calibration of HICO, the results illustrate the robustness of the NIR–red algorithms and validate the radiometric, spectral, and atmospheric corrections applied to HICO data as they relate to estimating chl-α concentration in productive coastal waters. Inherent limitations due to the characteristics of the sensor and its orbit prohibit HICO from providing anywhere near the level of frequent global coverage as provided by standard multispectral ocean color sensors. Nevertheless, the results demonstrate the utility of HICO as a tool for determining water quality in select coastal areas and the cross-sensor applicability of NIR–red models and provide an indication of what could be achieved with future spaceborne hyperspectral sensors in estimating coastal water quality.

Index Terms—Chlorophyll-α, International Space Station (ISS), near-infrared (NIR)–red algorithms, productive coastal waters, remote sensing.

I. INTRODUCTION

REMOTE sensing has become a very valuable and virtually indispensable tool for determining water quality in inland and coastal waters. The concentration of chlorophyll-α (chl-α) in water is a key indicator of the biophysical status of a water body (e.g., [1]) and is one of the primary water quality parameters. The optical complexity of turbid productive coastal waters renders conventional blue–green algorithms unreliable for estimating chl-α concentration (e.g., [2]). Numerous algorithms based on analytical and semi-analytical spectral inversion techniques and band combinations in the red and near-infrared (NIR) regions of the spectrum have been recently developed and successfully validated for estimating chl-α concentration in inland and coastal waters. Matthews [3] and Odermatt et al. [4] have provided comprehensive lists of such algorithms and their associated accuracy values in estimating chl-α concentration. Many of these algorithms were regionally tuned using data from specific water bodies and are limited in their bio-geo-optic scope of application, whereas some algorithms have demonstrated a potential for quasi-universal application to turbid and productive inland and coastal waters from various locations [5]–[10].

The aforementioned reports [3], [4] contain several algorithms that were developed based on data from the MEdium Resolution Imaging Spectrometer (MERIS). MERIS has been a reliable tool for monitoring water quality in coastal waters. The availability of a spectral channel at 708 nm made MERIS preferable over the MOderate resolution Imaging Spectroradiometer (MODIS) for estimating chl-α concentration in turbid productive waters, particularly at low-to-moderate chl-α concentrations, where the results from MODIS are unreliable (e.g., [5] and [6]).

The demise of MERIS in April 2012 has caused a gap in the availability of reliable ocean color data for coastal waters. This data gap is crucial because no hyperspectral or multispectral sensor with similar or better spectral, spatial, and temporal characteristics is scheduled to be launched in the immediate future. The Ocean Land Colour Instrument, which is MERIS’ replacement and will have all the spectral channels of MERIS in addition to a few extra channels, is scheduled to be launched onboard the satellite Sentinel-3 in 2014. Several hyperspectral sensors, such as the Japanese mission Hyperspectral Imager SURF (HISUI), the Italian mission PRecursore IperSpettrale della Missione Applicativa (PRISMA), and the German mission Environmental Mapping and Analysis Program (EnMAP), are either under design or development, with EnMAP being the closest to a launch date, which is tentatively set around 2017–2018.
typically encountered in eutrophic lakes [14]. The spatial extent
runoff from several rivers, resulting in conditions that are
Taganrog Bay and the Sea of Azov are characterized by low
adjoined by Russia on the east and Ukraine on the west. The

II. DATA AND METHODS
A. Study Area and In Situ Measurements

Hyperion, which was launched in 2000, has been used for coastal water studies. However, its signal-to-noise ratio is very low [11], and the sensor is unreliable for quantitatively estimating water quality parameters due to problems such as radiometric instability [12].

The Hyperspectral Imager for the Coastal Ocean (HICO), built by the U.S. Naval Research Laboratory as a low-cost prototype spaceborne hyperspectral sensor specifically designed for coastal waters, has been operational since October 2009. Spaceborne hyperspectral sensors offer unique advantages over multispectral and airborne hyperspectral sensors for detailed coastal water analysis that can be of much help to environmental decision makers and managers of coastal systems.

Bearing in mind that HICO is a demonstration mission and was not designed as an alternative to sensors such as MERIS, we have used a multitemporal dataset to assess the potential of HICO, in the absence of MERIS, as a tool for quantitatively determining water quality in coastal waters. Previous studies involving large datasets spanning multiple years have demonstrated the consistently high accuracy and operational potential of algorithms based on reflectances in the red and NIR spectral channels of MERIS to estimate chl-a concentration in the Taganrog Bay in Russia [7]–[9]. Using a single image and in situ data from only eight stations, Gitelson et al. [13] showed that HICO can be used to quantitatively detect chl-a and accessory pigments such as phycocyanin and phycoerythrin in water, albeit without any validation of their chl-a algorithm. In this study, we have used data collected from the Taganrog Bay during multiple campaigns in 2012 and 2013 after the demise of MERIS to test the applicability of NIR–red models to HICO data to retrieve accurate quantitative estimates of chl-a concentration. This study also provides an indirect qualitative assessment of the atmospheric correction and radiometric calibration of HICO data, as assessed by the accuracy of chl-a estimates across multiple dates.

B. HICO Data

HICO is a pushbroom sensor that captures data in the wavelength range 350–1080 nm, with a spectral resolution of 5.73 nm. At a nadir viewing angle, its cross-track and along-track ground coverage are 42 and 192 km, respectively, resulting in a total image area of approximately 8000 km². The ground sampling distance is approximately 90 m at nadir, which is fine enough to capture the spatial dynamics of heterogeneous coastal waters (e.g., [19]). A complete description of the sensor characteristics can be found in [20].

As a low-cost instrument, HICO has certain inevitable data quality issues. The sensor does not have a filter to block second-order light at shorter wavelengths from falling on the detector pixels for longer wavelengths. Therefore, the data recorded in the spectral channels between roughly 700 and 1080 nm are contaminated by diffracted second-order light in the wavelength...
range of 350–540 nm. Li et al. [21] have developed an empirical method to correct for the effects of second-order light, which is applied routinely to all HICO images. HICO was calibrated spectrally and radiometrically in the laboratory prior to its launch, but the sensor was not equipped with an onboard light source for post-launch calibration. Therefore, various techniques had to be adopted to monitor the spectral and radiometric stability of the sensor.

Gao et al. [22] reported post-launch shifts in the spectral and radiometric characteristics of the sensor. They used well-defined prominent spectral features such as the oxygen absorption band at 765 nm to examine the spectral stability of the sensor and observed that there were significant spectral shifts in the data. The spectral shift was as high as 1.72 nm in the first few images and progressively decreased until it became fairly stable at approximately 0.9 nm. There was a significant decrease in the radiometric sensitivity of HICO after its launch. The at-sensor radiances from HICO were consistently lower than the at-sensor radiances from concurrently acquired (with the time difference less than an hour) MODIS images and at-sensor radiances simulated using radiative transfer models, particularly in the blue spectral region. Scaling factors were determined to radiometrically correct the at-sensor radiances [22]. However, even with the application of the radiometric scaling factors, the reflectances retrieved after atmospheric correction are often negative, particularly at wavelengths below 450 nm. Therefore, a minimalist approach, assuming very low atmospheric aerosol loading, was adopted in removing the atmospheric effects from the HICO data, using the 6S [23] version of Tafkaa [24].

The focal plane array of HICO contains a back-illuminated charge-couple device (CCD). While the use of a back-illuminated CCD helps increase the sensitivity of the sensor, particularly in the blue spectral region, it can also result in spectral etaloning effects due to multiple reflections of photons between the layers of the CCD, which causes undesired constructive and destructive interference fringes. The effects of etaloning are more pronounced at the NIR wavelengths than at the visible wavelengths because the silicon in the CCD is increasingly transparent at longer wavelengths [25]. To minimize the effects of etaloning, HICO data were smoothed using a Gaussian filter with 10-nm full-width at half-maximum (FWHM) for wavelengths shorter than 745 nm and a filter with 20-nm FWHM for wavelengths longer than 745 nm.

Mounted on the International Space Station (ISS) platform, HICO orbits around the Earth approximately 16 times a day. Due to constraints on data transmission at the ISS, only one image can be acquired during one full orbit, resulting in a maximum of 16 images per day. The ground coverage of HICO, when viewing nadir, is limited to within 51.6° N and 51.6° S latitudes because of the inclination of the ISS’s orbit. HICO has off-nadir pointing capability (i.e., 30° to the right and 45° to the left), which extends the imaging range by a few degrees depending on the ISS altitude. Repeat coverage of the same area happens intermittently. The ISS does not maintain a constant altitude due to the drag from the Earth’s atmosphere and solar activity and therefore requires periodic boosts to reset its orbit. In spite of the orbital constraints of the ISS, the pointing capability of HICO helps maximize image acquisitions over high-priority targets for continual (though sporadic) monitoring, with images that may be acquired at different viewing and illumination geometries and at time intervals that can be as short as a day or as long as a few weeks.

Table I shows the dates of acquisition of the HICO images used in this study. Three of the five images were acquired during an ascending pass and covered the entire bay (see Fig. 1).

### C. NIR–Red Algorithms

NIR–red algorithms take advantage of the reflectance trough around 670 nm due to absorption of light by chl-α (e.g., [26]) and the reflectance peak in the NIR region due to a minimum in the combined absorption by chl-α and water (e.g., [27]). The magnitude and position of this reflectance peak vary with the concentration of chl-α (e.g., [28]).

Numerous studies based on data collected using field spectrometers, airborne sensors, and spaceborne sensors and data simulated using a radiative transfer model (e.g., [5]–[10]) have demonstrated that the two-band NIR–red model [28]

\[ \text{Chl-α} \propto \left( R^{-1}_{\lambda_1} \times R^{-1}_{\lambda_2} \right) \]

and the three-band NIR–red model [29]

\[ \text{Chl-α} \propto \left( \left( R^{-1}_{\lambda_1} - R^{-1}_{\lambda_2} \right) \times R_{\lambda_3} \right) \]

\((R_{\lambda})\) is the remote sensing reflectance at the spectral channel centered at \( \lambda \) nm. The two-band NIR–red model (e.g., [28]) has been shown to have highly accurate estimates of chl-α concentration in waters of varied bio-geo-optical properties. NIR–red algorithms based on the red and NIR spectral channels of MERIS (\( \lambda_1 = 665 \) nm; \( \lambda_2 = 708 \) nm; \( \lambda_3 = 753 \) nm) have been previously shown to yield accurate estimates of chl-α concentration in the Taganrog Bay [8], [9]. HICO does not have a spectral channel centered at 665 nm but has channels centered at 662 and 668 nm. Therefore, the average of the reflectances at 662 and 668 nm was taken as \( R_{\lambda_1} \). HICO has spectral channels centered at 708 nm (\( \lambda_2 \)) and 754 nm (\( \lambda_3 \)). The following are the NIR–red models based on the spectral channels of HICO.

- **Two-Band HICO NIR–red Model:**

\[ \text{Chl-α} \propto \left( \bar{R}^{-1}_{665} \times R_{708} \right) . \]

- **Three-Band HICO NIR–red Model:**

\[ \text{Chl-α} \propto \left( \left( \bar{R}^{-1}_{665} - \bar{R}^{-1}_{708} \right) \times R_{754} \right) . \]

\( \bar{R}_{665} \) is the average of the reflectances at 662 and 668 nm.

### III. RESULTS AND DISCUSSION

The data collected on July 27 and August 24, 2012 (totaling 16 data points) were used to calibrate the NIR–red models, and the data collected on August 27, 2012; September 18, 2012; and February 28, 2013 (totaling 21 data points) were used to validate the algorithms. The minimum, maximum, median, and mean values of the chl-α concentrations in the calibration dataset were, 27.06, 172.77, 103.03, and 95.92 mg m\(^{-3}\).
Three-Band HICO NIR–Red Algorithm:

\[
\text{Chl-}\alpha = 318.33 \left( R_{665}^{-1} \times R_{708} \right) - 278.15. \tag{5}
\]

Three-Band HICO NIR–Red Algorithm:

\[
\text{Chl-}\alpha = 505.05 \left( R_{665}^{-1} - R_{708}^{-1} \times R_{754} \right) + 38.916. \tag{6}
\]

Both NIR–red algorithms yielded accurate estimates of chl-\(\alpha\) concentration when applied to the validation dataset (see Fig. 3). The estimates from the two-band NIR–red model had a root-mean-square error (RMSE) of 20.11 mg m\(^{-3}\) and a mean absolute error (MAE) of 15.62 mg m\(^{-3}\), which corresponded to 14.06% and 10.92%, respectively, of the range of chl-\(\alpha\) concentrations in the validation dataset. The three-band NIR–red model gave slightly better estimates, with an RMSE of 17.73 mg m\(^{-3}\) and an MAE of 13.71 mg m\(^{-3}\), which corresponded to 12.39% and 9.58%, respectively, of the range of chl-\(\alpha\) concentrations. The results also validate the quality and reliability of the atmospherically corrected reflectances from HICO [Fig. 4(a)] for retrieving chl-\(\alpha\) concentration. Chl-\(\alpha\) maps [e.g., Fig. 4(b)] generated using these algorithms illustrated the spatial patterns of chl-\(\alpha\) distribution and matched quantitatively well with \textit{in situ} measurements.

Although the errors are higher in terms of absolute magnitudes and percentages than what were obtained from MERIS data in previous years for the Taganrog Bay [8], [9], the results are still remarkable, considering the range and temporal variations of the chl-\(\alpha\) concentration in the bay and the uncertainties in the radiometric stability and integrity of the HICO data. The current dataset contained higher and a wider range of chl-\(\alpha\) concentrations than the datasets that were used for analysis with MERIS data. The spatial and temporal variations of chl-\(\alpha\) concentration in the bay were also higher than in the previous years. Fig. 5 illustrates significant changes in the chl-\(\alpha\) concentration between August 25 and 27, 2012, as estimated from HICO images using the two-band NIR–red algorithm (5). \textit{In situ} measurements of chl-\(\alpha\) concentrations confirmed such high temporal variations. Such high temporal variations make the calibration and validation of algorithms inherently challenging. For more than 90% of the stations in this study, the time difference between \textit{in situ} and satellite data was a day or less (see Table I), which helped mitigate the effects of high temporal variation. The results also demonstrate that the two- and three-band NIR–red algorithms are largely resistant to the data-quality issues inherent in HICO data.

IV. CONCLUSION

The accuracy of the results obtained from the multitemporal dataset, notwithstanding the issues with the radiometric quality of HICO data and the assumptions contained in the atmospheric correction [22], demonstrates the robustness of the simple two- and three-band NIR–red models and the potential of HICO for estimating chl-\(\alpha\) concentration in optically complex productive coastal waters.

It should be noted that the specific two-band (5) and three-band (6) algorithms developed here are primarily meant for demonstrative purposes and proper caution needs to be exercised in applying them to future HICO data from the Taganrog Bay or elsewhere. The validity of the coefficients of these algorithms is contingent on the validity of the radiometric corrections and the assumptions contained in the atmospheric
correction of the HICO data. It is conceivable that the current atmospheric correction might fail drastically in coastal waters that are adjoining by industrial areas with high and variable atmospheric aerosol loading. Moreover, the radiometric stability of the instrument and, consequently, the validity of the radiometric corrections need to be continually monitored. One has to bear in mind also that the ISS platform does not permit frequent repeat coverage of the same area at regular time intervals. Image acquisitions of the same area are intermittent, with time intervals sometimes as short as a day or as long as several weeks, which places a constraint on the ability to monitor short-term phytoplankton dynamics in coastal waters. Nevertheless, the results presented here demonstrate the utility of HICO in estimating water quality in productive coastal waters, which is of critical value, particularly with the demise of MERIS.

The availability of spectral channels at 662, 668, and 708 nm on HICO makes it possible to obtain chl-α estimates using the two- and three-band NIR–red algorithms with reasonably good accuracies, which is not possible with MODIS or the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data. The fine hyperspectral information contained in HICO data can be also potentially used for water quality analysis beyond merely chl-α estimation, such as algal species distinction and quantification from the bay and elsewhere.

Continued work is planned to acquire more HICO images and in situ measurements on the Taganrog Bay to develop stable NIR–red algorithms that can be routinely applied to HICO data from the bay and elsewhere.

REFERENCES


