RETRIEVAL OF WATER OPTICAL PROPERTIES FROM EIGHT-SPECTRAL BAND WORLDVIEW-2 SATELLITE IMAGES

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ABSTRACT: Conventional ocean color satellites sensors are not very suitable for inland and coastal waters applications due to their low spatial resolutions. High spatial resolution satellite sensors are required to monitor the water quality of inland and coastal waters. The conventional high-resolution satellites such as Landsat, SPOT and IKONOS have limited number of spectral bands. In comparison, the Worldview-2 satellite has 8 spectral bands in the visible to near-infrared (NIR) region with 2-m spatial resolution. The additional spectral bands enable better modeling of water reflectance in terms of the water optical properties. The extra bands also facilitate better atmospheric correction of the images. In this paper, we describe our attempt in deriving water intrinsic optical properties (absorption and backscattering coefficients) from WorldView-2 data. Atmospheric correction was first performed to correct for the effects of Rayleigh scattering and gaseous absorption. The last two NIR bands were used for correcting surface glints and aerosol scattering. The 723 nm band (the so-called red-edge band) was found to be noisy and unusable due to high absorption by atmospheric water vapor. We apply the Quasi-Analytical Algorithm (QAA) on the remaining five bands to retrieve the water absorption and backscattering coefficients from reflectance. The standard QAA (Z. P. Lee et al., IOCCG Report 5, Chapter 10) requires a set of wavelengths different from those available in WorldView-2 data. Thus, we derived the values of the coefficients in the QAA applicable to WorldView-2 spectral bands using the synthesized dataset from IOCCG Report 5. The reflectance data in the test dataset were aggregated to the WorldView-2 spectral bands using the sensor spectral response functions. QAA for WorldView-2 was applied to images of coastal and inland waters in Singapore to derive maps of absorption and backscattering coefficients which can be used to derive some water quality parameters such as turbidity, transparency, penetration depth for photosynthetically active radiation and colored dissolved organic matter.

1. INTRODUCTION

High spatial resolution satellites are required to monitor the water quality of inland and coastal waters. With additional spectral bands, the derivation of these qualities would be more accurate. With the launch of the WORLDVIEW2 sensor, it would be possible to implement algorithms that requisite additional spectral bands. In this paper, we implemented the Quasi-Analytical Algorithm (QAA) (Lee, Carder and Arnone 2002), which requires fairly low computing resources. This was an important consideration as high-spatial resolution satellites usually contain more information and up to 15 million pixels for the case of the WORLDVIEW2 sensor. In principle it is possible to perform full spectral fitting using semi-analytical equations, however that would require a long temporal duration even with present day computing powers.

The algorithm implemented needs to be optimized for the derivation of water optical properties as it was developed for spectral bands found on conventional ocean color sensors. The optimization was done with simulated test data from IOCCG. The test data consists of above and underwater remote sensing reflectance, absorption coefficients and backscattering coefficients covering different types of waters. The test data was convolved into the eight spectral bands of the WORLDVIEW2 sensor.

Atmospheric correction was performed on the WORLDVIEW 2 data before the optimized QAA algorithm was implemented to derive the optical properties of water. Atmospheric optical properties such as scattering transmittance and path reflectance were computed with a Radiative Transfer code, 6S (Vermote, et al. 1997).

2. MATHMATICAL FORMULATION

Satellite sensors capture the radiance emanating from the surface of water where a large part of the signal is contaminated with light scattering in the atmosphere. In order to derive optical properties of water, the signal from the atmosphere needs to be removed. The total signal measured by the sensor normalized by the extra-terrestrial irradiance which is known as the top-of-atmosphere reflectance, is given as,

$$\rho_{TOA}(\lambda) = T_{gas}(\lambda)\left(\rho_a(\lambda) + \rho_r(\lambda) + T^{\downarrow}(\lambda)T^{\uparrow}(\lambda)\rho_w(\lambda) + \rho_{gl\,\mathrm{int}}(\lambda)\right) \tag{1}$$

The signal arising from scattering with molecular gases $\rho_r(\lambda)$ and particulate matter $\rho_a(\lambda)$ in the atmosphere is known as path reflectance. The upward $T^{\uparrow}(\lambda)$ and downward $T^{\downarrow}(\lambda)$ transmittances arise due to light scattering with the atmosphere. The total signal is also affected by gaseous absorption, which is reflected as the gaseous transmittance term $T_{gas}(\lambda)$. The ultimate aim is to derive the water leaving reflectance $\rho_w(\lambda)$ from the $\rho_{TOA}(\lambda)$

3. OPTIMISNG QUASI-ANAYTICAL ALOGITHM

3.1 Quasi-Analytical Algorithm

The quasi-analytical algorithm (Lee, Carder and Arnone 2002) derives the inherent optical properties (IOPs) of water with semi-analytical equations via simple empirical relations. The algorithm offers fast and fairly accurate derivation of (IOPS) from optically deep waters. The algorithm takes the above water reflectance $R_{rs}(\lambda)$ and reduces to a simple function consisting of the absorption $a(\lambda)$ and backscattering $b_{bp}(\lambda)$. Both are inherent optical properties of water, which affects the colour of water. $R_{rs}(\lambda)$ is converted into the underwater reflectance $r_{rs}(\lambda)$ via,

$$r_{rs}(\lambda) = \frac{R_{rs}(\lambda)}{(0.52 + 1.7R_{rs}(\lambda))} \tag{2}$$

and expressed as,

$$r_{rs}(\lambda) = g_0 u(\lambda) + g_1 u(\lambda)^2 \tag{3}$$

with

$$u(\lambda) = \frac{-g_0 + \sqrt{g_0^2 + 4g_1 r_{rs}(\lambda)}}{2g_1} \tag{4}$$

where $u(\lambda)$ is a function of the absorption and backscattering coefficients,

$$u(\lambda) = \frac{b_b(\lambda)}{b_b(\lambda) + a(\lambda)} \tag{5}$$

The absorption coefficient is a linear sum of the contributions from various optical constituents,

$$a(\lambda) = a_w(\lambda) + a_g(\lambda) + a_\phi(\lambda) \tag{6}$$

Absorption of CDOM is modeled as,

$$a_g(\lambda) = a_g(440)\exp^{S(440-\lambda)} \tag{7}$$

Absorption of phytoplankton is modeled as,

$$a_{\phi}(\lambda) = a_{\phi}(440)\hat{a}_{\phi}(\lambda) \tag{8}$$

The spectral basis function $\hat{a}_{\phi}(\lambda)$ is dependent on locality and species of the phytoplankton.

Likewise, the backscattering coefficient is a linear sum of the contributions from various constituents,

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda) \tag{9}$$

The backscattering of particles is modeled as,

$$b_{bp}(\lambda) = b_{bp}(\lambda_0)\left(\frac{\lambda_0}{\lambda}\right)^{\eta} \tag{10}$$

where η governs the spectral behavior of the modeled backscattering coefficients.

Therefore if the backscattering coefficient can be derived at a reference wavelength λ_0, it is possible to model the coefficients at other wavelengths with a given value of η. From which $a(\lambda)$ can be derived from equation (7).

The algorithm has been optimized to first estimate the absorption at a reference wavelength λ_0 of either 550, 555 or 560 nm depending on the type of sensors.

The absorption at λ_0 is estimated by,

$$a(\lambda_0) = a_w(\lambda_0) + 10^{a1 + a2\chi + a3\chi^2} \tag{11}$$

where,

$$\chi = \log\left(\frac{r_{rs}(443) + r_{rs}(490)}{r_{rs}(\lambda_0) + 5\frac{r_{rs}(667)}{r_{rs}(490)}r_{rs}(667)}\right) \tag{12}$$

From which the particulate backscattering $b_{bp}(\lambda)$ can be estimated by,

$$b_{bp}(\lambda) = \frac{u(\lambda)a(\lambda)}{(1 - u(\lambda))} - b_w(\lambda) \tag{13}$$

The coefficient that governs the spectral shape is estimated empirically by,

$$\eta = 2.0\left(c_1 + c_2 \exp\left(c_3 \frac{r_{rs}(443)}{r_{rs}(555)}\right)\right) \tag{14}$$

The spectral constant S that governs the absorption coefficient for CDOM can be estimated by,

$$S = d_1 + \frac{d_2}{d_3 + \frac{r_{rs}(443)}{r_{rs}(555)}} \tag{15}$$

The coefficients for the empirical estimations of $a(\lambda_0)$, η and S are derived from Hydrolight simulated above water reflectance, $R_{rs}(\lambda)$ at 10 nm spectral bandwidths intervals.

3.2 Spectral Convolution of HYDROLIGHT data in WORLDVIEW 2 channels

The test data from IOCCG (LEE 2006) was computed with generated inputs of absorption and backscattering coefficients at 10 nm spectral resolution. The QAA algorithm was not optimized for use by theWORLDVIEW2 sensor therefore; there is a need to convolve the data into the WORLDVIEW2 spectral bands.

The above water reflectance $R_{rs}(\lambda)$ is convolved into the different WORLDVIEW2 above water reflectance R_{rs}^{i} where the channel is denoted by the superscript i by,

$$R_{rs}^{i} = \frac{\int_{400}^{1000} R_s(\lambda)F_d(\lambda)R_{rs}(\lambda)d\lambda}{\int_{400}^{1000} R_s(\lambda)F_d(\lambda)d\lambda} \qquad (16)$$

Where $F_d(\lambda)$ is the extra-terrestrial irradiance and $R_s(\lambda)$ the spectral response of the WORLDVIEW2 sensor. Likewise, the absorption and backscattering coefficients of various optical components were convolved and centered at the respective WORLDVIEW2 sensors.

3.3 Optimizing Quasi-Analytical Algorithm

The convolved test data of IOCCG (LEE 2006) was used to derive the empirical relationships shown in Equation (13), (15),(16) and (17) which provide estimates for $a(\lambda_0)$, $b_{bp}(\lambda_0)$, η and S. The upper and lower limits for atmospherically corrected satellite data were also derived. The improvement in optimizing the empirical relationship shown in equation (13) can be seen in Figure 2.

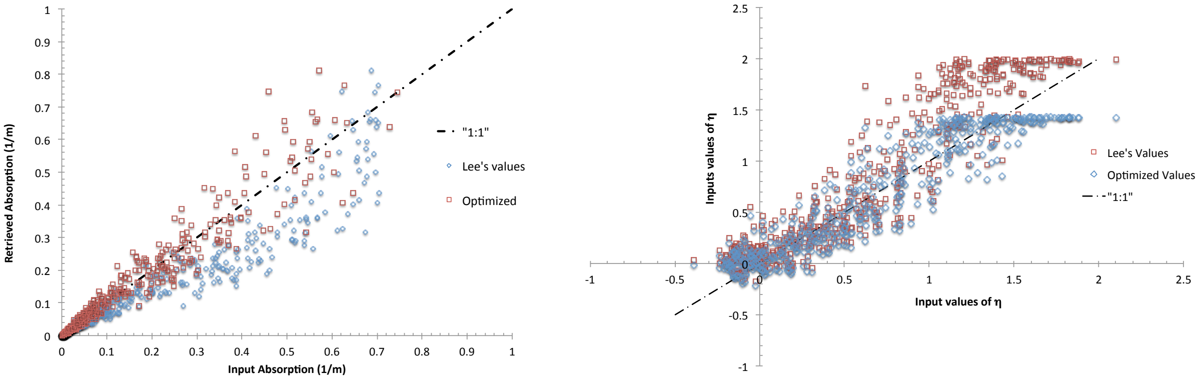

Figure 1. The plot on the left shows derived absorption values from $r_{rs}(\lambda)$ using the standard QAA algorithm values and optimized values from convolved data. The red squares in the plot on the right show that η which is derived from standard values in Lee's QAA algorithm is overestimated while those derived by the optimized values lie mostly on the 1:1 line.

4. ATMOSPHERIC CORRECTION SCHEME

The atmospheric optical properties are estimated from the three spectral bands, which are located in the NIR end of the solar spectrum. However we found that the spectral band centered at 723.5 nm is noisy and hence not suitable for the retrieval of atmospheric optical properties. Therefore the spectral bands at 825.0 and 919.4 nm were used for retrieval.

Three different aerosol models were used to compute the atmospheric optical properties using the 6S algorithm (Vermote, et al. 1997). The aerosol models are namely, Maritime, Urban and Biomass burning types. The optical properties computed are $T^{\uparrow}(\lambda)$, $T^{\downarrow}(\lambda)$, $\rho_a(\lambda)$ at different optical thickness, $\tau(\lambda)$. The optical properties were computed at intervals of 0.005, where $0.005 \le \tau(\lambda) \le 1$. However there are three unknowns with only two spectral bands that can be used for retrieval. The three unknowns are $\tau(\lambda)$, $\rho_{glint}(\lambda)$ and aerosol type. Two additional constraints were added, the upper limit for the corrected remote sensing reflectance is given as,

$$R_{rs}(667) = 8R_{rs}(555)^{1.3} \qquad (17)$$

The lower limit is given as,

$$R_{rs}(667) = 0.55 R_{rs}(555)^{1.35} \tag{18}$$

These constraints were derived with the convolved IOCCG data.

The data was first corrected with computed Rayleigh scattering component following equation (3) and the data was corrected for ρ_{glint}. The signal at the last spectral band centered at 914.2 nm was assumed to consist of the surface glint. With that the top-of-atmosphere reflectance was further corrected to give,

$$\rho'_T(\lambda) - \rho_{TOA}(924.5) = \rho_a(\lambda) + T^{\downarrow}(\lambda) T^{\uparrow}(\lambda) \rho_w(\lambda) \tag{19}$$

The signal at 824.5 nm was assumed to be solely from light scattering with aerosols in the atmosphere, and this was used to determine $\tau(\lambda)$ of the atmosphere with pre-computed lookup tables from the three different aerosol models. When the optical thickness $\tau(\lambda)$ is known, values for $T^{\uparrow}(\lambda)$, $T^{\downarrow}(\lambda)$, $\rho_a(\lambda)$ can be determined from pre-computed lookup tables. This was used to derive $\rho_w(\lambda)$. From the derived $\rho_w(\lambda)$, the optimized QAA algorithm can be implemented to obtain optical properties of water.

5. RESULTS

The WORLDVIEW 2 data used for this test was acquired on 24 March, 2010 at 10:18 am local Time. The images are captured at a spatial resolution of 1.8 m with 8 spectral bands. The location is Pulau Semakau which is at the southern islands of Singapore. Pulau Semakau is offshore landfill for Singapore. Coral reefs could be found in the nearby vicinity.

Figure 3. The original real colour image used for the test of the QAA algorithm. The land areas has been masked out showing distinct sediment plumes in the coastal waters.

The atmospheric correction scheme together with the QAA was implemented on the test data. Three different aerosol models were used for the correction scheme. We compared the derived absorption at 547 nm which is the reference wavelength and backscattering at 550 nm with the QAA implemented on standard atmospheric correction scheme using Rayleigh scattering only. Derived optical properties map can be seen in figure 6.

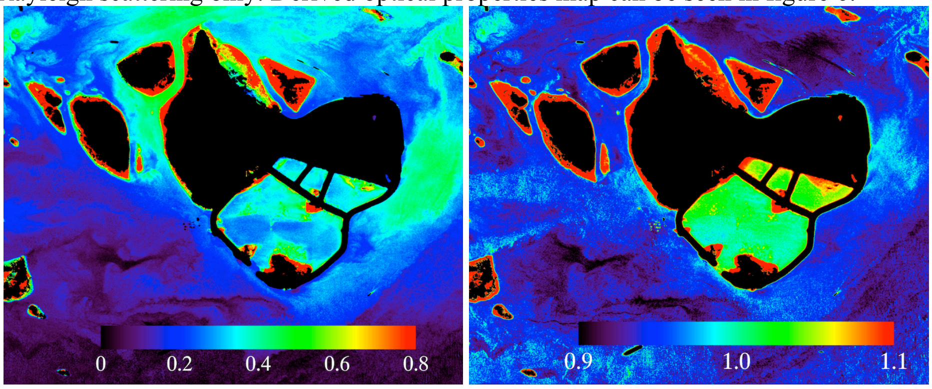

Figure 4. The derived backscattering coefficients at 550 nm is shown on the left while the derive absorption at 547

nm is shown on the right. The optical maps were derived by an assumed aerosol model (biomass burning). We can see that the QAA algorithm was not designed for the retrieval of optical properties over shallow water from the higher values near the coral reefs.

We also sampled derived optical properties from different parts of the image. In this case, we mimicked a boat and selected a route around the island.

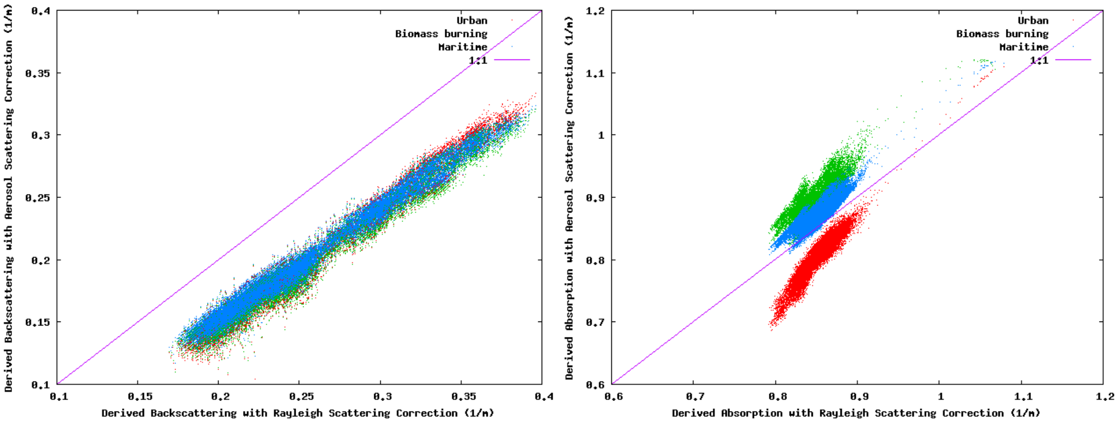

Figure 5. The plots shows derive optical properties along a selected track. The backscattering coefficients are underestimated for all three-aerosol models. For the derived absorption coefficients, we can see that with an assumed model of Maritime aerosols, the absorption is underestimated.

From the derived optical properties, it can be seen that for different aerosol models, the derived optical properties are relatively similar. The backscattering coefficients are quite close in spite of different aerosol models used, however it can bee see that for absorption coefficients, the differences in derived values could vary as much as 20-30 % for different aerosol models used.

6. CONCLUDING REMARKS

We have applied and adapted the QAA algorithm for use on a multispectral high spatial resolution satellite sensor. The derived optical properties are similar in spite of different aerosol models used. However the work done still needs to be refined and validated with field measurements. Future work could also be applying the QAA algorithm to highly turbid waters to derive both atmospheric and water optical properties in tandem.

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