Inherent optical properties of water measured in situ and from multispectral imageries – A case study on waters south of Singapore

Alice Wang-Cheng Heng
Centre for Remote Imaging, Sensing and Processing
National University of Singapore, Blk SOC1 Level 2, Lower Kent Ridge Road, Singapore 119260, Singapore.
crshwca@nus.edu.sg

Chew Wai Chang
Centre for Remote Imaging, Sensing and Processing
National University of Singapore, Blk SOC1 Level 2, Lower Kent Ridge Road, Singapore 119260, Singapore.
crshcwc@nus.edu.sg

Jiangcheng He
Centre for Remote Imaging, Sensing and Processing
National University of Singapore, Blk SOC1 Level 2, Lower Kent Ridge Road, Singapore 119260, Singapore.
crshj@nus.edu.sg

Narvada Dewkurun
Centre for Remote Imaging, Sensing and Processing
National University of Singapore, Blk SOC1 Level 2, Lower Kent Ridge Road, Singapore 119260, Singapore.
crshdn@nus.edu.sg

Soo Chin Liew
Centre for Remote Imaging, Sensing and Processing
National University of Singapore, Blk SOC1 Level 2, Lower Kent Ridge Road, Singapore 119260, Singapore

Abstract: The depth of light penetration in water is one important factor that restricts coral growth. The inherent optical properties of water, in particular, the absorption and backscattering coefficients are important quantities that determine the depth of light penetration. Semakau Landfill is an off-shore landfill of Singapore. However, it is also home to rich marine life. It is desirable to monitor the water quality efficiently. We measured the absorption and backscattering coefficients of the waters along the western coast and compared the backscattering coefficients with those extracted from multispectral imageries acquired from Landsat and IKONOS. Our results show that there is little spatial variation in water properties in the small region. Moreover, the particle absorption coefficient is insignificant at 650 nm and 676 nm. This allows us to extract the backscattering coefficients from satellite imageries using a modified version of the quasi-analytical algorithm. The extracted backscattering coefficients agree quite well with the measured values.

Keywords: inherent optical properties of water, backscattering coefficient, coastal waters

1. Introduction

Light penetration in water depends on the absorption and scattering properties of the water. Quantitatively, the absorption and scattering properties can be measured by the absorption and scattering coefficients of the water using instruments such as the ac-9 by WET Labs, Inc.[1] Such measurements can be used to characterise the waters at specific stations. On the other hand, remote-sensing imageries offer synoptic views which are difficult, if not impossible, to obtain using in situ measurements alone. Maps showing spatial distribution of particle backscattering coefficients of water derived from remote-sensing imageries can be used to monitor sedimentation and hence water turbidity.

The objective of our study is to characterise the waters around an offshore island south of Singapore and to validate our algorithm for extracting particle backscattering coefficient and absorption coefficient from multi-spectral imageries.[2,3]

2. The Study Area
Pulau Semakau is a small island south of the main island of Singapore. It was converted into an offshore landfill by surrounding it and an adjacent small island with a rock bund. In order to maintain the quality of the surrounding waters, the bund is lined with an impermeable membrane and a layer of marine clay to keep the used water in the landfill within the landfill space. The landfill started operations in 1999. As can be seen in Fig. 1 there are fringing reefs and patch reefs off the shores of the island. The patch reefs are submerged at high tide and exposed at low tide. One concern is the increasing turbidity of the waters due to increased sedimentation.

![Image of study area with land masked out. The image is approximately 6.5 km by 5.0 km. It was acquired on 2002 Oct 11. The red marks indicate the locations at which measurements were made on June 30, 2005. The yellow rectangle shows the area over which the computed coefficients are averaged after the shallow regions have been masked out.](image)

**3. Instruments, Imageries and Methods**

3.2 *In situ* measurements

*In situ* measurements were performed using the ac-9. It measures spectral volume absorption coefficient (minus water), $a_p(\lambda)$, and spectral volume beam attenuation coefficient (minus water), $c_p(\lambda)$, in nine wavelengths: 412, 440, 488, 510, 532, 555, 650, 676 and 715 nm. The spectral volume scattering coefficient, $b_p(\lambda)$, can be easily computed as follows:

$$b_p(\lambda) = c_p(\lambda) - a_p(\lambda)$$

We applied scattering corrections as described in [5]. The locations at which measurements were made are shown in Fig. 1. The particle backscattering coefficient, $b_{pp}(\lambda)$, is estimated from the spectral volume scattering coefficient by assuming the ratio, $b_{pp}/b_p$, to be 0.02 [6].

3.2 Multispectral imageries

Sensors on board satellites like Landsat, SPOT and IKONOS record reflected solar radiances in broad spectral bands. Image data from such satellites can be used to study spatial distribution of sediment (e.g. [3] and [4]). However, such sensors are typically designed to image land cover rather than signals from water and so the signal to noise ratio and...
radiometric resolution are not ideal for quantitative measures of water properties. We therefore do not expect to extract the particle backscattering and absorption coefficients with high precision.

Fig. 3 shows our algorithm, which is adapted from the quasi-analytical algorithm proposed by Lee, Carder and Arnone in 2002 [5]. For the algorithm to work, two assumptions must hold: firstly, the upwelling light from the water in the near infra-red channel is negligibly small so that the signal in this channel, after correcting for atmospheric reflectance from gas molecules (Rayleigh scattering), yields the signal contribution from aerosol and sea-surface. Secondly, the particle absorption coefficient in the red band is negligibly small compared to the absorption of sea water (~0.4 m⁻¹). Our measurements over this study area shows this to be true – the absorption coefficients at 650 nm is less than 0.01 m⁻¹ (Fig 3).

1. Convert digital number to top of the atmosphere reflectance, \( \rho_{\text{toa}} \)
2. Correct for ozone absorption.
3. Subtract the Rayleigh scattering reflectance from \( \rho_{\text{toa}} \)
4. Mask out the land and estimate the aerosol and surface reflectance from the corrected NIR band. Subtract this value from the corrected reflectance for the green and red bands to obtain the corrected reflectance: \( \rho(b) \), \( b = \text{red, green} \)
5. Convert the corrected reflectance to remote-sensing reflectance: \( R_{\text{rs}}(b) = \rho(b)/\pi \).
6. Convert the above surface remote-sensing reflectance to below surface remote-sensing reflectance:

\[
R_{\text{br}}(b) = \frac{R_{\text{rs}}(b)}{0.52 + 1.7 R_{\text{rs}}(b)}
\]

7. Compute \( u = b_b/a + b_b \) the ratio of backscattering coefficient, \( b_b \) to absorption coefficient \( a \) using the model: \( R_{\text{rs}} = 0.0895u + 0.1247u^2 \)
8. Compute the particle spectral volume backscattering coefficient at red band using:

\[
b_b(\text{red}) = \frac{u(\text{red})}{1 - u(\text{red})} a(\text{red})
\]

9. Assuming the particle spectral volume backscattering coefficient can be modeled using

\[
b_{bp}(\lambda) = X\left(\frac{550}{\lambda}\right)^{0.5}, \text{ compute } b_{bp}(\text{green}).
\]
10. Finally, the spectral volume absorption coefficient at green can be computed:

\[
a(\text{green}) = \left(\frac{1 - u(\text{green})}{u(\text{green})}\right) b_b(\text{green})
\]

Fig 2. Algorithm for extracting IOP from multi-spectral imageries.

We do not have any remote-sensing imagery on the day that in situ measurements were made. Instead, we have a set of Landsat 7 ETM+ acquired on 2002 Oct 11 and a set of IKONOS acquired on 2005 May 4, about two month before the data collection on 2005 June 30. However, spectral volume backscattering coefficient and spectral volume absorption coefficients are inherent optical properties of water. For the study region, these values are not expected to change drastically unless there are severe environmental changes. On the contrary, considerable effort is made to maintain the quality of the water.

Our algorithm is expected to be valid only for optically deep waters. Therefore, in addition to the land and clouds, the shallow water regions were masked out. For the purpose of comparing the values extracted from the image data and the in situ measurements, we concentrated on the small rectangle area shown in Fig. 1.

4. Results and Discussion

4.1 In situ measurement results
The spectral volume absorption coefficients and spectral beam scattering coefficients are shown in Fig. 3. Among the 6 stations, there is little variation in the spectral volume absorption coefficients. This is to be expected as the distance between the farthest stations is only about 1.5 km. However, there is about 10% variation about the median value for the backscattering coefficient. This could be due to the movement of the waters due to the changing tide. The data were collected over a period of four and a half hours.

Fig. 3 Spectral absorption coefficients and scattering coefficients. The dots are the ac-9 measurements.
The average values are summarized in Table 1.

Table 1. Average ac-9 measurements

<table>
<thead>
<tr>
<th>wavelength, ( \lambda ) (nm)</th>
<th>spectral volume absorption coefficient ( a_p )(m(^{-1}))</th>
<th>spectral volume scattering coefficient, ( b_p )(m(^{-1}))</th>
<th>Estimated spectral volume backscattering coefficient, ( b_{pb} )(m(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>412</td>
<td>0.89</td>
<td>2.44</td>
<td>0.049</td>
</tr>
<tr>
<td>440</td>
<td>0.55</td>
<td>2.38</td>
<td>0.048</td>
</tr>
<tr>
<td>488</td>
<td>0.26</td>
<td>2.27</td>
<td>0.045</td>
</tr>
<tr>
<td>510</td>
<td>0.19</td>
<td>2.21</td>
<td>0.044</td>
</tr>
<tr>
<td>532</td>
<td>0.13</td>
<td>2.17</td>
<td>0.043</td>
</tr>
<tr>
<td>555</td>
<td>0.09</td>
<td>2.11</td>
<td>0.042</td>
</tr>
<tr>
<td>650</td>
<td>0.0004</td>
<td>1.88</td>
<td>0.038</td>
</tr>
<tr>
<td>676</td>
<td>0.01</td>
<td>1.80</td>
<td>0.036</td>
</tr>
<tr>
<td>715</td>
<td>0</td>
<td>1.76</td>
<td>0.035</td>
</tr>
</tbody>
</table>

The spectral volume absorption coefficients at the red bands (676 nm and 650 nm) are much smaller the spectral volume absorption coefficients of pure water at these wavelengths (which are 0.43 m\(^{-1}\) and 0.36 m\(^{-1}\), respectively). Thus, at these wavelengths, the total spectral volume absorption coefficients are effectively contributed by pure water.

The measured spectral volume scattering coefficient of the water ranged from 1.9 m\(^{-1}\) to 2.4 m\(^{-1}\) at 555 nm. If we assume the ratio of the volume backscattering coefficient to volume scattering coefficient to be 0.02, the volume backscattering coefficient of the water ranged from 0.038 m\(^{-1}\) to 0.048 m\(^{-1}\). At the 650 nm, the backscattering coefficients are between 0.034 m\(^{-1}\) and 0.042 m\(^{-1}\).

4.2 IOP from multi-spectral imageries

Comparison between IOP extracted from multi-spectral imageries and measured IOP can be problematic for two reasons. Firstly, multi-spectral imageries are broad-band. The definition of spectral volume scattering (or absorption ) coefficient strictly refers to the scattering of a monochromatic beam of light. Furthermore, the remote sensor averages the light field over a much bigger spatial area than the ac-9. Nonetheless, the two sets of measurements should not differ too much since they measure similar physical properties in the same units.

Table 2 shows the spectral ranges and results of our IOP extraction.

Table 2. Extracted IOP for the rectangular region shown in Fig. 2

<table>
<thead>
<tr>
<th>Spectral range for nir (nm)</th>
<th>Landsat</th>
<th>IKONOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range for red (nm)</td>
<td>780 - 900</td>
<td>757 - 852</td>
</tr>
<tr>
<td>Spectral range for green (nm)</td>
<td>630 - 690</td>
<td>631 - 698</td>
</tr>
<tr>
<td>Backscattering coefficient for red (m(^{-1}))</td>
<td>Average: 0.030, Standard deviation: 0.006</td>
<td>Average: 0.036, Standard deviation: 0.004</td>
</tr>
<tr>
<td>Absorption coefficient for green (m(^{-1}))</td>
<td>Average: 0.08, Standard deviation: 0.03</td>
<td>Average: 0.05, Standard deviation: 0.01</td>
</tr>
</tbody>
</table>
The spectral ranges of the red bands for the Landsat and IKONOS are quite similar. The extracted backscattering coefficients for the red band agree quite well with the in situ measurements, especially for the IKONOS. This is encouraging as the IKONOS data set was collected about two months before the field measurements while the Landsat image was acquired about two and a half years before the field measurements. There appears to be a slight increase in particle backscattering coefficient from 2002 to 2005.

However, the absorption coefficient for the green band was underestimated in the IKONOS imagery. The value obtained from the Landsat imagery is quite close to the in situ value.

As the atmospheric and sea-surface glint corrections are estimated from the near infra-red band, it is expected that the corrections are underestimated at the shorter wavelengths (green and blue) since no spectral dependency for the corrections are assumed. Consequently, the computed absorption coefficient at the green band will be in error. Moreover the backscattering coefficient is extrapolated to the green band from the computed value at red band. It is not surprising that the standard deviations for the computed absorption coefficients are large.

5. Conclusion

The water in the study site is quite homogeneous in the horizontal extent. There is little variation in the measured spectral volume absorption coefficients. However, there seems to be some variation in the spectral volume scattering coefficients – whether the variations is due to the changing tidal cycle or some scale spatial differences need to be verified. Our algorithm for extraction of backscattering coefficient from multispectral satellite imageries is capable of providing comparable values to in-situ measurements. But the absorption coefficient is considerably underestimated.

References