Backscattering of light by coastal waters using hyperspectral in-situ measurements: A case study off Veraval, Gujarat, India

Arvind Sahay, Prakash Chauhan, P. V. Nagamani, Nivedita Sanwalani and R. M. Dwivedi
Marine and Coastal Environment Division, Marine and Earth Sciences Group
Space Applications Centre, Ahmedabad 380015, India
[E-mail: sahayarvind@gmail.com]
Received 6 May 2010; revised 24 December 2010

Backscattering of coastal waters of Arabian Sea off Veraval, Gujarat, India has been reported using Quasi Analytical Algorithm (QAA) inversion method. The same is compared with the in-situ measurements. Present study compares the backscattering coefficient retrieved from QAA with the measured values of backscattering at 470 and 700 nm. Retrieved backscattering coefficient using QAA lies between 0.0005-0.0047 m⁻¹ at 470 nm and 0.00006-0.0040 m⁻¹ at 700 nm. This is compared with the measured backscattering coefficients. Root mean square error (RMSE) has been computed, taking logarithm (to base 10) of the measured and modeled values. RMSE for 470 nm is 0.21 and for 700 nm is 0.23. Mean percentage error has also been computed which is 19.19% at 470 nm and 43.90% at 700 nm. Field measurements show that the QAA approach overestimates the backscattering coefficient at 470 nm and 700 nm (19.19% and 43.90% respectively) in the coastal waters of Gujarat. This is possibly due to the wavelength model used in the computation of backscattering at various wavelengths.

[Keywords: Inherent Optical Properties, algorithm, backscattering coefficient, quasi analytical, ocean colour]

Introduction

Inherent Optical Properties (IOP) are those optical properties, which are independent of variations in the angular distribution of the incident light field, and are solely determined by the type and concentration of substances present in the medium. Scattering and absorption are two basic inherent optical properties of the seawater. Different methods of retrieval of inherent optical properties were suggested by different researchers. These methods include analytical, semi analytical, quasi analytical, linear matrix inversion and artificial neural network etc. Loisel and Stramski developed an analytical inverse algorithm to retrieve the total absorption, scattering, and backscattering coefficients from the irradiance reflectance just beneath the surface and the mean vertical diffuse attenuation coefficient over the first optical depth based on Monte Carlo and Hydrolight simulations. Quasi Analytical Algorithm (QAA) was developed by Lee et al. to derive inherent optical properties of ocean waters. The Linear Matrix Inversion (LMI) algorithm was developed by Hoge and Lyon. This approach of Artificial Neural Network (ANN) inversion is studied by several researchers (Doerffer et al., Doerffer and Schiller, Schiller and Doerffer). ANN algorithm is having capability to invert directional water leaving radiance directly into absorption and scattering coefficients or concentrations of different constituents present in coastal waters. GSM (Garver Siegel Maritorena) semianalytical ocean colour model was initially developed by Garver and Siegel and later updated by Maritorena et al. The GSM model is based on the quadratic relationship between the remote sensing reflectance (Rrs) and the absorption and backscattering co-efficients from Gordon et al. In the present study backscattering coefficient at 470 nm and 700 nm has been retrieved using QAA approach by Lee et al. (2002).

The aim of the present study is (i) to retrieve the backscattering coefficient (m⁻¹) of the coastal waters of Veraval (Gujarat, India) using hyperspectral in-situ data by Quasi Analytical Algorithm i.e QAA approach (ii) to validate it with the field measured backscattering coefficient. In the field backscattering is measured by the scattering meter at 470 and 700 nm. The root mean square error (RMSE) and the mean % error have been computed to validate the results.
Materials and Method

The coastal cruise Sagar Kripa was conducted to study the optical characterization of the shallow coastal waters Off Veraval coast, Gujarat in the NE Arabian Sea. The study area (Fig. 1) lies between 19.5°N to 21°N latitudes and 69.5°E to 71.5°E longitudes. The rational of choosing small area was to study the shallow coastal water response for the retrieval of IOPs. The optical measurements from the hyperspectral radiometer were extended from the 10 meters depth to 40 meters depth extending to near shelf waters or open ocean Off Veraval, Gujarat.

The data was collected using Satlantic (http://www.satlantic.com) underwater hyperspectral radiometer. The backscattering coefficients of the particles (b_{bp}) have been measured by using Wetlabs ECO series IOP scattering meter (http://www.wetlabs.com) at 470 and 700 nm wavelengths. The following equation is used for the calculation of the computation of (b_{bp}) using following equation by Boss et. al.\[13]

\[
b_{bp}(\lambda) = 2\pi X \beta_p(\lambda) 
\]

where X = 1.1 and \(\beta_p\) is the volume scattering of the particles and is given by the following relation \(\beta_p(\lambda) = \beta(\lambda)-\beta_w(\lambda)\)

where \(\beta(\lambda)\) = total volume scattering as measured by the instrument and

\[
\beta_w(\lambda) = 1.38(\lambda/500)^{-4.32}(1+0.35/37)10^{-4}(1+\cos^2\theta)(1-\delta)/(1+\delta)) 
\]

\[\delta = 0.09, \theta = 117^\circ \]

S=Salinity obtained from water properties

The radiometer has two units: one is the reference unit, which floats on the surface and collects the data of surface irradiance. The second unit is the profiler, which collects the data of upwelling radiance and downwelling irradiance in profiling mode. It collects the data in the bandwidth range of 350-700 nm with a spectral resolution of 3 nm. Downwelling irradiance \(E_d(0^\circ,\lambda)\) and upwelling radiance \(L_u(0^\circ,\lambda)\), at various stations have been collected using the data from the profiler unit of the hyperspectral radiometer in the range 350-700 nm below the seashore. Similarly the surface irradiance \(E_s(0^\circ,\lambda)\) has been collected at the surface of the ocean in the range of 350-800 nm. Chlorophyll-a value has been measured and is varying from 0.5-11.6 mg-m^{-3}.

The Quasi Analytical Algorithm (QAA) approach uses remote sensing reflectance as input for the retrieval of IOP. To compute remote sensing reflectance following equation (3) has been used

\[
R_{rs}(\lambda) = \frac{L_u(\lambda)}{E_d(\lambda,0^\circ)} 
\]

The approach of Lee et. al.\(^3\) (2002) is used to derive the inherent optical properties of the coastal waters of Gujarat. This methodology uses different step as following. In the first step the above surface remote sensing reflectance would be converted to below surface remote sensing reflectance (r_{s}) using

Figure-1(a)—False Colour Composite of IRS-P4 OCM image of North East Arabian Sea including part of study area in India 1(b) Study area, sampled stations are shown by dots in figure 1(b) during 17-20 October 2007 off Veraval coast of Gujarat in India
equation (4) and the function $u(\lambda)$ is determined using equation (5).

$$r_n(\lambda) = \frac{R_{rs}(\lambda)}{0.52 + 1.7 R_{rs}(\lambda)}$$  \hspace{1cm} \text{(4)}  \\
where $r_n$ - remote sensing reflectance (below surface) and $R_{rs}$ - remote sensing reflectance (above surface).

$$u(\lambda) = \frac{-g_0 + \left[(g_0)^2 + 4g_1r_n(\lambda)\right]^{1/2}}{2g_1}$$  \hspace{1cm} \text{(5)}  \\
where $g_0 = 0.0895$ and $g_1 = 0.1247$.

The second step is the estimation of absorption coefficient ($a$) at 555 nm reference wavelength empirically using equation (6). The step for the computation of reference wavelength at 555 nm is given as following Lee et. al. 3

$$a(555) = 0.0596 + 0.2[a(440) - 0.01]$$  \hspace{1cm} \text{(6)}  \\
and $a[440]$ is determined by the following equation:

$$a[440] = \exp(-2.0 + 1.4\rho + 0.2\rho^2), \text{ where } \rho = \ln\left[\frac{r_n(440)}{r_n(555)}\right]$$  \hspace{1cm} \text{(7)}

The third step is the calculation of backscattering coefficient ($b_{bp}$) at 555 nm from $u(555)$ and $a(555)$ using equation (8). This step is analytical for computing the particle backscattering at 555 nm wavelength and is given by

$$b_{bp}(555) = \frac{u(555)a(555)}{1 - u(555)} - b_{bw}(555)$$  \hspace{1cm} \text{(8)}  \\
Fourth step is the computation of particle backscattering coefficient at other wavelengths (than 555) using equation (9). The formula used in the fourth step is following

$$b_{bp}(\lambda) = b_{bp}(555) \times (555/\lambda)^Y$$  \hspace{1cm} \text{(9)}  \\
where $b_{bp}(555)$ is calculated by equation (8)

Fifth step is the estimation of wavelength dependence (parameter $Y$, say) of the particle backscattering coefficient using equation (10). The computation of the exponent value $Y$ and is given by equation (10)

$$Y = 2.2 \times \left\{1 - 1.2\exp[-0.9\frac{r_n(440)}{r_n(555)}]\right\}$$  \hspace{1cm} \text{(10)}  \\
where $Y$ is the exponent used in the relation of backscattering.

Results and Discussion

Measured normalized water leaving radiance and remote sensing reflectance (with wavelength 300-700 nm) in the study area are shown in Figure 2 and Figure 3 respectively. Forty different radiometric samples have been plotted for distinct sampling locations in the study area. The normalized water leaving radiance variation with wavelength shows a peak around 555 nm and another peak are observed at around 670 nm. Figure 3 shows the remote sensing
reflectance \( (sr^{-1}) \) variation with the wavelength. Wavelength variations are similar to those of normalized water leaving radiances.

Figure 4(a) above shows the field measured total particle backscattering coefficient at 470 and 700 nm. Equation (1) by Boss et al.\textsuperscript{13} is used for the measurement of \( b_{bp} \) in the field using ECO series IOP scattering meter. Figure 4(b) shows the retrieved particle backscattering coefficient from 400-700 nm wavelengths in the study area using equation (9) of the QAA approach by Lee et al.\textsuperscript{3} (2002). The 40 different curves show the 40 different profiles of the retrieved backscattering coefficient at distinct sampling locations. Spectral shapes of the curves show the higher values at around 470 nm in the waters and the value for each profile decreases with wavelength i.e. at 700 nm the values are less in each one of these profiles as compared to 470 nm. The retrieved backscattering coefficient lies between 0.00055-0.0047 m\(^{-1}\) at 470nm and 0.000061-0.0040 at 700 nm.

The particle backscattering decreases with increasing wavelength. Since the backscattering decreases with wavelength the decrement can be estimated by exponent value (Y) from the field measurements of spectral backscattering coefficients, using power law as following

\[ b_{bp}(\lambda) \propto (\lambda)^{-Y} \]  \hspace{1cm} \ldots (11)

where Y is the power exponent which has been computed using two wavelengths i.e. 470 and 700 nm respectively. The exponent value, Y derived from QAA approach lies between 0.04-1.22 for the different stations whereas the value of Y derived from field measurements are 0.30-1.87. Researchers have used various models to compute Y in such a way that it should represent the constituent backscattering. For example to calculate Y for clear natural waters Smith and Baker\textsuperscript{15} suggested model for Y, for phytoplankton absorption Morel\textsuperscript{16} suggested model for Y and for nonabsorbing backscatter such as coccolith; Gordon et al.\textsuperscript{12} suggested model for Y. The reference wavelength can also be chosen arbitrarily but clearly should be chosen where the backscatter is expected\textsuperscript{4}.

In the present study we have chosen the reference wavelength 555 nm (green) as it is coastal waters of Veraval region of Gujarat and is dominated by high phytoplanktons. The measured chlorophyll range lies between 0.5-11.6 mg-m\(^{-3}\) and as is evident from Figure 5; which is a histogram plot of chlorophyll

![Histogram of chlorophyll concentration](image)

Figure 5—Histogram of chlorophyll concentration. X-axis is the chlorophyll concentration and y-axis is the frequency of number of stations.

![Field measured and retrieved backscattering coefficient](image)

Figure 4(a)—Field measured total particle backscattering coefficient and 4(b) retrieved total particle backscattering coefficient from 40 samples of the cruise Sagar Kripa during 17-20 October 2007, in the study area.
concentrations with number of stations. Figure 6 is 1:1 comparison of computed exponent Y from field measurements and from Lee’s method. It is evident that the power value Y is underestimated (36.49%) using Lee’s method when compared with 1:1 line of field measurements. Figure 7 is the comparison of measured versus derived total backscattering coefficient (b_b) at 470 nm (blue region of the wavelength). Figure 8 represents the comparison of measured versus derived total backscattering coefficient (b_b) at 700 nm.

Figure (9) shows the variation of power exponent Y with chlorophyll and a good fit (coefficient of determination, $R^2=0.86$) has been obtained as following

$$Y = -0.341 \times \ln(X) + 0.886 \quad \ldots (12)$$

It is clear that the exponent value Y decreases logarithmically, as chlorophyll increases. The higher backscattering caused at lower wavelength is dominated by detritus not by chlorophyll pigments in the study area.

The variation of $R_{rs}$ for various water types has been shown in Figures 10(a), (b), (c) and (d) respectively ranging from low to high chlorophyll.

![Figure-6—Comparison of computed Y from field measurement and Y using Lee’s method](image1)

![Figure-7—Comparison of measured total particulate backscattering coefficient (b_b) at 470 nm versus derived b_b using QAA approach by Lee et al. (2002)](image2)

![Figure-8—Comparison of measured total particulate backscattering coefficient (b_b) at 700 nm versus derived b_b using QAA approach by Lee et al. (2002)](image3)

![Figure (9)—Variation of power exponent Y with chlorophyll](image4)
Figure 10(a) shows the variation of $R_{rs}$ for chlorophyll ranging from 0-1 mg/m$^3$. The remote sensing reflectance peak (0.001-0.003 sr$^{-1}$) is shown in the range of 450-500 nm which is in the blue region. Figure 10(b) shows the variation of $R_{rs}$ for chlorophyll ranging from 1-5 mg/m$^3$. The remote sensing reflectance peak (0.001-0.005 sr$^{-1}$) is centered at 550 nm which is in the green region. Similarly there is not much change in $R_{rs}$ values when the chlorophyll is ranging from 5-10 mg/m$^3$ as shown in Figure 10(c) or when the chlorophyll range is from 10-12 mg/m$^3$ as shown in Figure 10(d).

The variation of particle backscattering ($b_{bp}$) with chlorophyll is also discussed in the Figure 11(a) and (b) at 470 and 700 nm. The $b_{bp}$ is proportional to chlorophyll concentration for both the wavelengths. Figure 11(a) describes the backscattering at 470nm which co-varies with chlorophyll with very good coefficient of determination ($R^2=0.86$), however figure 11(b) describes the backscattering at 700nm which co-varies with chlorophyll with a coefficient of determination ($R^2=0.89$).

To validate the above results, two ways of error estimation has been performed. One is the estimation of Root Mean Square Error (RMSE) which has been calculated as following

\[
RMSE = \left( \frac{1}{N} \sum_{i=1}^{N} \left[ \log_{10}\left( \frac{b_{b,\text{measured}}}{b_{b,\text{modeled}}} \right) \right] \right)^{1/2} \quad (13)
\]

and the other is mean % error which is calculated as per following formula

\[
\text{mean % error} = \frac{b_{b,\text{modeled}} - b_{b,\text{measured}}}{b_{b,\text{measured}}} \times 100 \quad (13)
\]

The RMSE in the retrieval of $b_{bp}$ for 470 nm is 0.21 and mean % error is calculated as 19.19 %. The derived $b_{bp}$ for 700 nm is having RMSE 0.23 and mean % error is calculated as 43.90%. Errors may be...
introduced during the in-situ measurements or otherwise. Errors may be due to the calibration of instrument, dark signal, data processing, deployment strategy, sea and sky states. These all factors introduce uncertainties in the radiometric measurements. Measurement protocols along with regular and rigorous calibrations and good characterization of instruments reduce uncertainties in the in-situ measurements. Measurements of biogeochemical variables have their own set of difficulties and resulting uncertainties. Satellite measurements represent a water column weighted average, while in-situ measurements usually come from discrete depths. This may introduce a source of error in collecting in-situ data. Reasons for mismatch in the measured and modeled value are due to possible wavelength-ratio model used in the Lee’s method (exponent Y in equation-10). Another reason for mismatch is due to the assumption of elastic scattering in the modeled data, whereas in water inelastic scattering is also dominant.

Conclusions
The retrieved backscattering coefficient lies between 0.00055-0.0047 m⁻¹ at 470nm and 0.000061-0.0040 m⁻¹ at 700 nm. Retrieved backscattering is compared with field measurements. The field measured backscattering coefficient lies between 0.00011-0.0029 m⁻¹ at 470nm and 0.000026-0.0025 at 700 nm. Thus QAA is overestimating the backscattering coefficients in the coastal waters of Gujarat. The error estimation shows that at higher wavelengths (700 nm compared to 470nm) the retrieval error increases. RMSE in the derivation of bₙ at 470 nm is 0.21 and the mean % error is 19.19%. At 700 nm the error estimation is increased; the RMSE is 0.23 and the mean % error is 43.90%. Higher value of bₙ is possibly due to wavelength model for the computation of Y used in QAA approach by Lee et. al. (explicit from figure-6, Y value are underestimated by 36.49%). The exponent Y is further used in the calculation of bₙ at other wavelengths, so estimating the higher values of bₙ.

Acknowledgements
Authors would like to thank Dr. Ajai, Group Director, MESG and Dr. J. S. Parihar, Deputy Director, Remote Sensing Applications Area, Space Applications Centre, Ahmedabad, for their valuable advice and encouragement. Thanks are due to Dr. R. R. Navalgund, Director, Space Applications Centre, ISRO, for the facilities and keen interest in this work.

References
5 Hoge, F.E., and Lyon, P.E., Spectral parameters of inherent optical property models: Methods for satellite retrieval by
7 Doerffer, R., Heymann, K., and Schiller, H., Case 2 water algorithm for the medium resolution imaging spectrometer (MERIS) on ENVISAT., paper presented at the *Proceedings of the envisat validation workshop*, 2002
8 Doerffer, R., and Schiller, H., Neural Network for retrieval of concentrations of water constituents with the possibility of detecting exceptional out of scope spectra, paper presented at the *Symposium on International Geosciences and Remote Sensing*, Honolulu, Hawaii USA, 2000