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Hyper Spectral Reflectance From Coastal And Estuarine Waters Of Goa

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Abstract: The hyper spectral signature of the coastal and estuarine waters of Goa, on a cloud free day, has been computed considering the zenith and azimuthal geometry of sun, satellite and object. The computation begins with the spectral extraterrestrial solar irradiance on the day of observation. Based on single scattering albedo with non-scattering ozone layer and scattering air molecules and attenuating aerosols, within the atmosphere, the model computes the down welling irradiance at the sea surface. From the illumination of the sea surface and further interaction of light with hydrosols and water molecules the model computes the radiance emanating from water body for every 1 nm in the 400 – 700 nm spectral range. The computation agrees spectrally with the observations of L_w, measured using a radiometer, within rms error of ± 9.0%, ± 13.9%, ± 22.0% , ± 16.0%, ± 6.5% , ± 11.9% , ± 11.4%, at wavelengths 412, 443, 490, 510, 555, 670 and 683 respectively. A correlation (R^2) of 88%, 94%, 90% and 93% is obtained between the measured and computed radiances.

1. INTRODUCTION

The coastal zones of the world in general and that of India in particular need to be monitored constantly as they are the most populated and utilized areas of the earth. One of the major issues related to coastal zone is coastal water quality (coastal pollution) to assess the ecological imbalance. The heterogeneous and dynamic nature of the coastal water body demands a new technique for a synoptic analysis of water quality. The feasibility of deriving the chlorophyll (chl) concentration from its influence on the spectral composition of the radiances backscattered by the upper oceanic layers (ocean colour) was demonstrated by Clarke *et al* [1]. This ultimately leads to the application of remote sensing technique to estimate coastal water constituents for various applications like identification of fishery potential zone and coastal pollution. Ocean Colour Monitor (OCM) flown on IRS – P4 (Indian Remote Sensing Satellite), is an instrument specifically designed to address these coastal zone related issues [2]. As an Indian state, Goa, depends on mining and tourism industry for the economy. The transportation of the iron ore in connection with the industry is mainly through the estuaries of Goa viz: Mandovi and Zuari. Hence the seepage of iron ore from barges carrying the ore completely alter the photic zone of the estuaries. The optical range (400 – 700 nm) of electromagnetic radiation (EMR) with peak energy at 500 nm gets attenuated due to these impurities. This in turn reduces the energy required for photosynthesis by primary producers leading to ecological imbalance. Therefore estuaries of Goa, need to be monitored continuously. The attenuation of EMR depends on the type and amount of hydrosols viz: organic (particulate and dissolved) and inorganic materials in the water column. Hence from the careful examination of backscattered radiance, it is possible to analyze the hydrosol.

The standard algorithm of band - ratio technique fails in coastal waters as in addition to chlorophyll and its accessory pigments, inorganic and dissolved materials (DOM) present in these waters which in turn modify the incident light. In their studies Carder *et al* [3] and Walsh *et al* [4] found that the remotely sensed signal of the coastal ecosystem indicates that about 50 % of the chlorophyll biomass sensed by Nimbus coastal zone colour scanner (CZCS) might be an artifact. Such a situation in coastal waters is mainly due to presence of dissolved organic matter of terrestrial origin [5]. In highly turbid estuarine and coastal waters, neither the dark pixel technique nor the clear water approximation to remove the effect of atmosphere works. Hence sensing the coastal waters remotely is the problem of interacting with a complex and highly non-linear system for which simple solutions based on empirically derived colour ratios are insufficient. In the present study an attempt has been made to compute radiance emanating from water column for every 1 nm in the spectral range 400 – 700 nm (hyper spectral signature).

2. METHODS

The approach involved is Beers law formalism as adopted by Leckner [6] and Brine and Iqbal [7] and the radiative transfer concept conceived by Gordon [8] wherein the total radiance received by an optical sensor is the sum of contribution by different constituents of atmosphere and ocean.

Transmittance of solar energy through atmosphere:

The spectral solar energy on a surface at ground level specific to a solar zenith angle (θ_s) is

$$I(\lambda) = H\,0\lambda\ Tr\lambda\ Ta\lambda\ To\lambda\ Tw\lambda\ Tmg\lambda\ Cos\_\theta s \qquad (1)$$

where $H_{0\lambda}$ is the extra-terrestrial solar irradiance, $T_{r\lambda}$ is the transmittance due to rayleigh atmosphere while $T_{a\lambda}$, $T_{o\lambda}$,$T_{w\lambda}$, $T_{mg\lambda}$, are the transmittance due to aerosol atmosphere ozone atmosphere, transmittance due to water vapour and that due to mixed gases present in the atmosphere. By assuming a single scattering albedo, the passage of solar flux through the atmosphere is subjected to transmission loss due to air molecules, aerosols, ozone, water vapour and mixed gases. Hence the solar flux reaching the sea surface comprises both direct and diffused radiances. The characteristics of these molecules and amount and type of these particles can be expressed by inherent optical properties such as the spectral extinction coefficients which include absorption and scattering. Knowing these coefficients and the corresponding phase function P, the equation of radiative transfer can be solved for a vertically in-homogeneous plane-parallel atmosphere -ocean system. In the present paper, the attempt is to analyze the hyper spectral signature from the water column through coupled radiative transfer process. The total radiance, $L\_sat\ (\lambda)$, at the top of the atmosphere (TOA), when a space-borne optical sensor looks down is [9]

$$Lsat\,(\lambda) = Lw\,(\lambda)Td(\lambda)+Lsky\,(\lambda)\,Td(\lambda)+Lpath\,(\lambda)+ Lsun(\lambda)T(\lambda)+ Lbottom\,(\lambda)T\,b(\lambda) \qquad (2)$$

Where "$T_d(\lambda)$" is the diffused transmission while "$T\,(\lambda)$" is the direct transmittance and "$T_b(\lambda)$" is the transmittance from bottom of the study area to the surface. Where L_{path}, the path radiance is that part of sunlight scattered in the atmosphere, never reaching the ocean surface but entering the field of view of the space borne sensor. L_{sky}, the surface reflected skylight is that part scattered in the atmosphere and, Fresnel reflected at the water surface and passed through the atmosphere to the sensor. L_{sun}, the direct transmitted sunlight, Fresnel reflected at the surface and diffusely (i.e. scattered) transmitted to the sensor. L_w, the water leaving radiance is that portion of light penetrating the sea surface, scattered in the water, back transmitted through the sea air interface and transmitted through the atmosphere into the sensor. L_{bottom} , the radiance reflected from the bottom topography of the area of study.

Effects of water constituents in different parts of optical spectrum:

The hyper-spectral upwelling irradiance from the water body could be split as follows.

$$E_u(\lambda) = E_u w(\lambda) + E_u c(\lambda) + E_u s(\lambda) + E_u y(\lambda) + E_u b(\lambda) \quad (3)$$

$E_u(\lambda)$ is the upwelling irradiance while $E_u w(\lambda)$, $E_u c(\lambda)$, $E_u s(\lambda)$, $E_u y(\lambda)$, $E_u b(\lambda)$ are the respective contributions from water, chlorophyll, sediment, yellow substances and from the bottom. $E_u b$, in the above equation being the contribution from the bottom of the coastal waters, is a noise for the signals from the water molecules and other constituents. Hence to avoid $E_{\_u}b$, water samples have been collected from those stations where the depth of the station is 3 times more than the secchi disc depth [10]. Therefore the last term in the equation (3) is insignificant. $E_u(\lambda)$, on the left hand side of Eq. (3), could be expressed as the product of reflectance and downwelling irradiance (4). At this juncture, a term remote sensing reflectance (R_{rs}) has been brought in and is defined as

$$R_{rs} = L_w/E_d \quad (4)$$

E_d is the down welling irradiance while the sub-surface reflectance is

$$R = E_u/E_d = \pi . L_w/E_d = \pi . R_{rs} \quad (5)$$

In the above equation, π is not valid as the sea surface is not a perfect Lambertian reflector. Hence π, is replaced by 'Q' factor. Therefore

$$L_w = R. E_d/Q \quad (6)$$

The sub-surface reflectance, R in equation (5) could be expressed as a combination of reflectance from different constituents of water body

$$R = E_u/E_d = E_u w/E_d w + E_u c/E_d c + E_u s/E_d s + E_u y/E_d y. \quad (7)$$

Therefore,

$$R = R_w + R_c + R_s + R_y \quad (8)$$

The above equation is mathematically straight forward and perfectly fit for the open ocean; case I waters, as in the open ocean, *R* is a function of water molecules, chl and its co varying substances. But in the estuarine and coastal waters, case II waters, *R* is not only a function of water molecules and chlorophyll but also a function of other constituents such as dissolved organic and inorganic matters. Therefore reflectance from different constituents in case II waters bound to overlap and that makes sub-surface reflectance in this region not additive. Adopting the relation suggested by Joseph [11], the radiative transfer within the water column has been analyzed. The sub-surface reflectance *R* in Eq. (8) is

$$R = (k - a)/(k + a) \quad (9)$$

Where '*k*' and '*a*' are the diffused attenuation and absorption coefficients. Since *k* and *a* have contributions from water molecules hydrosols and dissolved organic matters, these could be expressed as the product of the basic vector (specific coefficients of each constituent) and the corresponding concentration. This helps in computing the actual reflectance specific to a particular species of chl. Then the total reflectance spectrum can be expressed as a linear combination of the product of basis vector (relative reflectance spectra) and the corresponding concentration.

In-situ observations:

In-situ observation involves generating optical properties of both atmosphere and water column. Observations have been carried out during winter 2000. Water samples collected on 23rd February is from estuary while those on 1st 3rd and 7th April 2000 have been from the coastal waters of Goa. On 3rd, two observations have been carried out. One at 1230 hrs and other at 1510 hrs. All days except on 23rd a Satlantic radiometer (irradiance meter) has been used to measure $E_{\_d}$ (Down welling Irradiance), and

$L_{\_w}$ (Water leaving radiance). Aerosol spectral optical depth has been derived using a 5 channel EKO sun photometer with filters centered at 0.368, 0.500, 0.675, 0.775 and 0.862 μm respectively. From sun photometer measurements, the columnar spectral optical depth τ (λ) has been estimated following Langley plot method. The details are given in Moorthy *et al.* [12]. The meteorological data such as relative humidity, atmospheric pressure, wind are measured from different hydrographic stations during the cruise in March – April 2000.

3. RESULTS AND DISCUSSION.

Using the methodology described above, hyper spectral signature has been modelled. Since the outgoing radiance is computed for every 1nm in the spectral range of 400 – 700 nm, the overlapping of the radiance from different constituents is prevented and thus contribution of each constituent of the water column is well depicted (Fig 1).

TABLE 1: Optical properties of water column and atmosphere. RH is the humidity, V the wind speed, ω_a is the single scattering albedo, α is the wavelength exponential while β is the atmospheric turbidity factor, P the atmospheric pressure, wv is the water vapour content, θ_s and θ_v are the zenith angles of sun and satellite respectively.Chl_a, sed and A_y 440 are the chlorophyll, sediment concentrations and absorption due to yellow substances at 440 nm.

Days	RH %	V m/s	ω_a	α	β	P mb	wv	θ_s	θ_v	Chl_a Mg/m3	Sed Mg/l	A_y440 m-1
1/4/2000	74	3.8	0.96	0.28	0.34	1005.5	4.84	15.29	0	1.783	2.771	0.027
3/4/2000	85	1.6	0.96	0.29	0.36	1005.7	5.31	15.56	0	1.230	4.849	0.027
7/4/2000	77	0.2	0.96	0.30	0.27	1007.6	4.60	16.97	0	0.445	2.338	0.023
3/4/2000	85	4.5	0.96	0.26	0.38	1007.8	5.02	45.0	0	0.385	0.692	0.027

Figure shows the calibration between the radiometer readings and simulated signature and the respective hyper spectral signature from the water column corresponding to 1st and 3rd April 2000. The figure shows a gradual decrease in energy towards longer wavelength with peak energy at short wavelength (approx. around 450 nm). A shift in the peak from shorter to longer wavelength is imminent with the variation of hydrosols (table II). Over the full spectral range the shape of the radiance is broadly determined by the spectral absorption by yellow substance in the blue, absorption by chlorophyll, carotenoids and water in the red region. To ascertain the accuracy of computation, the measured and computed radiance, are compared. Under the prevailing atmospheric and oceanic conditions, the simulated values match with the measured values. The spectral rms error has been found to be ± 9.0 %, ± 13.9 %, ± 22.0 %, ± 16.0 %, ± 6.5 % , ± 11.7 % , ± 11.4 %, at wavelengths 412, 443, 490, 510, 555, 670 and 683 respectively. The rms error reveals that the combined effect of both chl and DOM are responsible for such a variation at 490 nm. For wavelength below 490 nm, the out going radiance is controlled mainly by DOM and chlorophyll (chl), while those above 490 nm are controlled by chl and sediment. The correlation (R^2) between the measured and computed radiances from different hydrographic stations are found to be 88% ,94%, 90 % and 93% respectively. Though there is a high correlation, an offset is seen on the axis where computed signature is taken. This could be related to radiometric measurements errors due to effect of surface waves and calibration changes. As calibration has been performed before the field trip, the offset might have occurred due to the former. In addition there can be many reasons for the discrepancy. These are due to model retrieval error, human error in measurement or due to both. For example, the time lag in the collection of water sample and radiometric measurements, the selection of a pair of near infra-red (NIR) wavelengths to compute α (the wavelength exponent) and β, the turbidity factor in the atmosphere, so as to correctly incorporate the effect of atmosphere on down welling irradiance. Uncertainties associated with path length amplification factor and variability of the optical properties of the GF/F filters can also impart error as per Mitchell (1990). Moreover the water constituents, used as an input to compute the water signature, are derived from a liter water sample while the measured values are those from whole volume. During in-situ observation, as utmost care has been taken to have the radiometric measurements within few minutes of the collection of water sample, the error due to time lag is ruled out. Care has been taken to derive α and β on the basis of the τ_a variation on respective days. Therefore the variation due to this factor is also ruled out.

4. SENSITIVITY OF THE MODEL

Table (I) shows the optical properties of atmosphere and water corresponding to the different days of observation. The sensitivity of the model is examined in the coastal and estuarine regions by subjecting the model with the acceptable variability of the water constituents. For this, spectral signature has been simulated for a range of chlorophyll concentration, by keeping the sediment and yellow substance constant (Table II).

TABLE 2: Displacement of maximum energy to the longer wavelength in association with an increase in the chlorophyll concentration. Meteorological parameters, sun angle, view angle, concentration of sediment and a_y440 are kept constant.

Chl (μg/l)	Wavelength of Primary maxima nm	L_w associated with primary maxima (μw/cm²/nm/sr)	Energy at 644 nm (μw/cm²/nm/sr)	Energy at 685 nm (μw/cm²/nm/sr)
0.001	450	0.2756	-----	------
10.00	481	0.2581	0.2130	0.1873
20.00	535	0.2730	0.2422	0.2145
30.0	535	0.2880	0.2669	0.2370
40.0	535	0.3013	0.2881	0.2588
50.0	535	0.3123	0.3060	0.2750
60.0	535	0.3219	0.3220	0.290
70.0	535	0.3281	0.3364	0.3040
80.0	535	0.3375	0.3489	0.3159

The flexibility of the model has also been shown by computing the global down welling irradiance to different meteorological parameters. For this, two sets of different meteorological parameters and solar variables presented in Gregg and Carder [13] have been used. For the set of data corresponding to 11th April 1989 with a wavelength exponent for turbidity function, α, 0.3, the range of down welling irradiance (E_d) is between 0.92 – 1.52 w/m²/nm, while the data corresponding to 23rd September 1988 with α 1.9, E_d is in the range 0.32 – 0.57 w/m²/nm. The computations perfectly match with the highs and lows of those published by Gregg and Carder [12].

In the sensitivity analysis, the spectral signature from water body has also been computed for two sun angles. A realistic range of sun elevation within which operational satellite observation seen to be most successful has been chosen viz: $50^0 7'$ and $19^0 10'$. Out of these two angles, $50^0 7'$ has been chosen for the sensitivity of the meteorological parameters while $19^0 10'$ for water parameters. At $50^0 7'$ the atmospheric path length ($1/\cos_{\theta s}$) is nearing double than at nadir, thus provides a reasonable

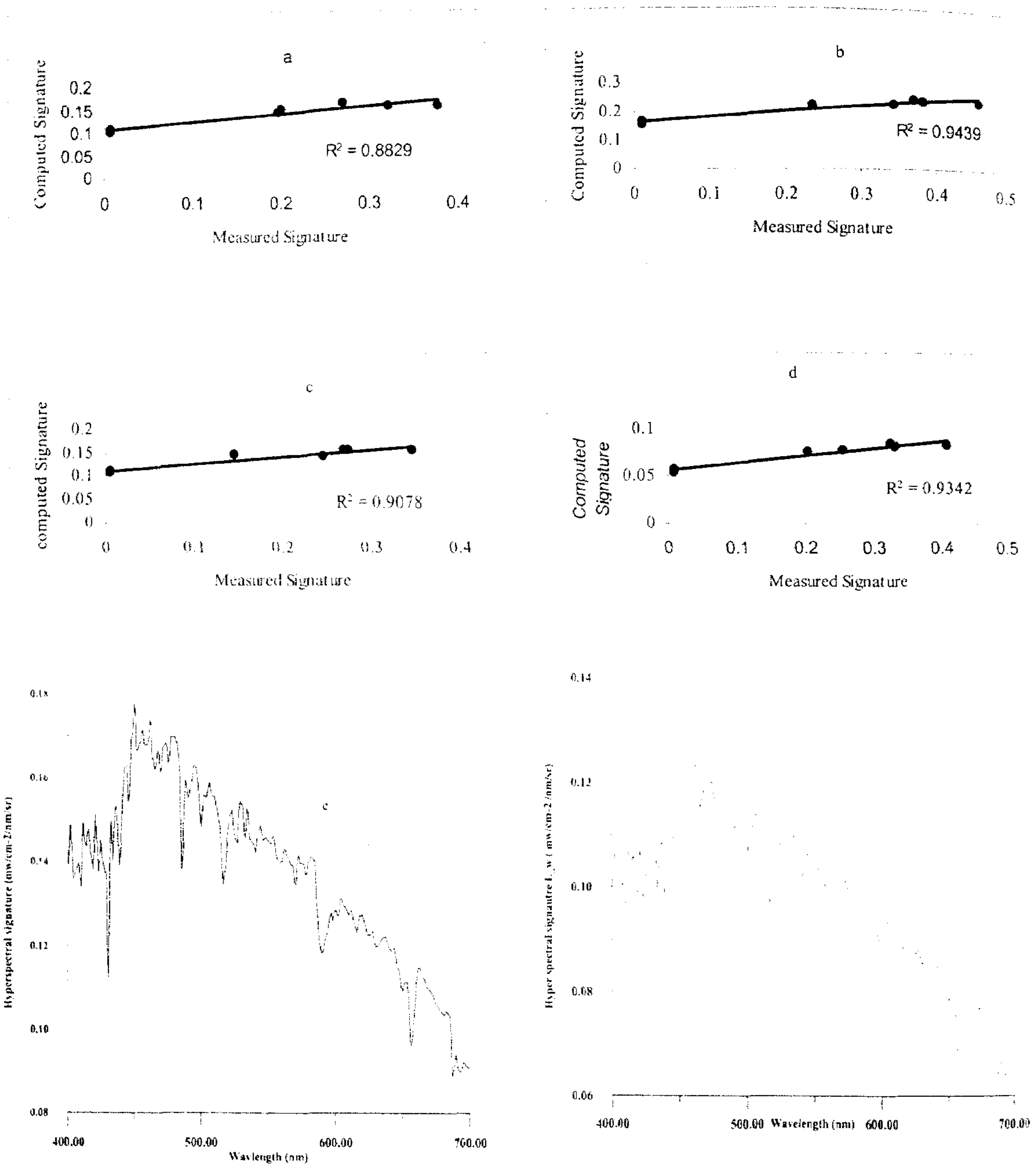

Fig.1. Correlation between computed and measured radiance on a) 1st April 2000 b) 3rd April 2000 at 1230 hrs c) 3rd April 2000 at 1510 hrs and d) 7th April 2000. The hyper spectral signature corresponding to 1st April 2000 and 3rd April 2000 at 1230 hrs are given in e) and f).

representation of the optical effects of atmospheric constituents on down welling irradiance. The sun zenith angle $19^0 10'$ has been selected as it occurs frequently in the tropics. When θ_s is $50^0 7'$ and satellite at zenith, the aerosol radiance is 4.75 $\mu w/cm^2/nm/sr$ while with sun at $19^0 10'$ and satellite at zenith the aerosol radiance is reduced to 1.96 $\mu w/cm^2/nm/sr$. The above experiment has been performed at a wavelength 412 nm. Model has also been subjected to a variation in atmospheric pressure $\pm$ 15mb, an acceptable change under clear skies. It is found that the model is insensitive to such variation in pressure (0.0001 $\mu m/cm^2/nm/sr$) at 412 nm.

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