

## **Comparison of Measured and Satellite Derived Spectral Diffuse Attenuation Coefficients for the Arabian Sea**

SURESH T\*, MADHUBALA TALAULIKAR, ELGAR DESA, S.G.P. MATONDKAR,  
ANTONIO MASCARENHAS

National Institute of Oceanography, Goa-403004, India

### **Abstract**

We present here the results of our study that compare the spectral diffuse attenuation coefficients,  $K_d(\lambda)$  measured in the Arabian Sea with those derived from ocean color satellite sensor, SeaWiFS using three algorithms, of which two are empirical data driven and a semi-analytical algorithm. This evaluation will allow us to determine the types of algorithms to be adopted for the ocean color satellite sensor such as OCM-2 for the region. The measurements were carried out in all water types and the mean values of the measured spectral  $K_d(\lambda)$  are 0.105, 0.092, 0.077, 0.082, 0.11, 0.49 ( $\text{m}^{-1}$ ) for wavelength,  $\lambda$  at 412, 443, 490, 510, 555 and 670nm respectively, which is equivalent to water with chlorophyll value of about  $1 \text{ mgm}^{-3}$ . The maximum values of the measured  $K_d$  correspond to waters with chlorophyll of about  $8 \text{ mgm}^{-3}$ . Though the satellite derived  $K_d(\lambda)$  are found to be overestimated in all bands, we have observed good correlations between the measured and satellite derived values in all bands, and excluding the band at 670nm, the mean absolute percent deviations are observed to be less than 50% in all bands. The performance of the data driven empirical methods are found to be consistent in all the bands, except at the red band of 670nm, which is uncorrelated with the measured values and have large errors. The performances of the empirical methods depend on the accuracy of the band ratios of the retrieved remote sensing reflectance. Though the performance of the semi-analytical algorithm is found to be spectrally varying, with large positive bias observed in the blue regions, this algorithm is recommended for hyperspectral applications. The performance of the semi-analytical algorithm could be improved by having a robust algorithm to derive accurately spectral inherent optical properties of absorption and backscattering coefficients from the satellite data.

---

\*Corresponding Author. Email address:suresh@nio.org

## 1. Introduction

Solar light entering the water is a source of energy for various biological, chemical and physical interactions in the ocean. Diffuse attenuation  $K_d(\lambda)$  is an important apparent optical property (AOP), that provide information about the attenuation of the spectral downwelling solar irradiance  $E_d(z,\lambda)$  with depth  $z$  in water. Information about  $K_d(\lambda)$  is important for studies related to the heat budgets (Lewis *et al.*, 1990, Morel and Antoine 1994), photosynthesis and primary productivity models (Platt, 1986, Sathyendranath *et al.*, 1989), to classify water types (Jerlov, 1976) and it can be an important parameter to describe the transparency of water.(Suresh *et al.*, 2006). The  $K_d(\lambda)$  is strongly correlated with phytoplankton chlorophyll concentration, thus they provide an association between biology and optics.(Morel and Maritorea, 2001).

One of the earliest products derived from the ocean color satellite sensor, CZCS (Coastal Zone Color Scanner) that stood the test of time has been the  $K_d(490)$  (Austin and Petzold, 1981, 1986). This has become a standard product available from most of the ocean color satellite sensors. It was of recent that the spectral  $K_d(\lambda)$  was made available from the satellite processing software SeaDAS (<http://seadas.gsfc.nasa.gov>), with an algorithm derived from the semi-analytical methods. (Lee *et al.*, 2002).

## 2. Method

$K_d(z, \lambda)$  (unit =  $m^{-1}$ ) is given as

$$K_d(z, \lambda) = -\frac{1}{E_d(z, \lambda)} \frac{dE_d(z, \lambda)}{dz} \quad (1)$$

The  $K_d(z, \lambda)$  as defined above is at depth  $z$  with  $z$  increasing downward from the surface of water. It is an apparent optical property that varies with the angular distribution of light. (Gordon and McCluney, 1975, Preisendorfer, 1976, Kirk, 1984, Gordon, 1989). The solar irradiance entering the water will be attenuated following the Beer-Lambert law.

$$E_d(\lambda, z) = E_d(\lambda, 0)e^{-K_d(\lambda, z)z} \quad (2)$$

A complete description of  $K_d(z, \lambda)$  as defined by equation (1) require that  $E_d(z, \lambda)$  be measured at fine interval, which is not possible during field measurements using radiometers and often the  $E_d(z, \lambda)$  need to be extrapolated to the surface. Since  $K_d(z, \lambda)$  varies with depth, it is usually represented as an average value.(Lee *et al.*, 2005). The average  $K_d(z, \lambda)$  over the layer between two depths  $z_1$  and  $z_2$  is given as

$$K_d(z_2 - z_1, \lambda) = \frac{-1}{z_2 - z_1} \ln \frac{E_d(z_2, \lambda)}{E_d(z_1, \lambda)} \quad (3)$$

Here we define another important parameter often used with ocean color remote sensing, the penetration depth,  $Z_{90}$  defined as  $Z_{90} = \frac{1}{K_d}$ . This is an important parameter for the ocean color remote sensing studies as it defines the depth from which 90% of the contribution of the water

leaving radiance emerges to the surface and is detected by the satellite sensor. (Gordon and Clark, 1980).

## 2.1. Data

The measurements were carried out in the Arabian Sea (Latitude 15.15–21.63° N, Longitude 68.20–73.72° E) during three cruises on the research vessel, *ORV Sagar Kanya* specifically SK-149C (15 to 29 November, 1999), SK-152 (30 March to 12 April, 2000) and SK-171 (3 to 17 November, 2001). (see figure 1). The cruise stations included varied water types with turbid and productive coastal stations to deep oceanic oligotrophic sites and also locations with *Trichodesmium spp.* and diatom blooms (Bhattathiri *et al.* 1996) . The transparency of the water indicated by the Secchi depth, varied from shallow depth of less than 5m in the coastal waters, to a maximum depth of 30m in the clear open ocean. (Suresh *et al.*, 2006).

The spectral diffuse attenuations were derived from the downwelling irradiance profiles measured using the multipsectral radiometer with wavelengths at 412, 443, 490, 510, 555, 670 and 683nm (this last channel is to detect fluorescence). The free falling profiling radiometer has three sensors, with two sensors integrated in the profiling unit for measuring upwelling radiance and downwelling irradiance and another unit used as a reference to measure surface irradiance. (<http://www.satlantic.com>). The data are acquired online and processed using the proprietary software of the instrument ProSoft as per the NASA protocol (Mueller *et al.*, 2002). The diffuse attenuation profiles were obtained from the downwelling irradiance data,  $E_d(z, \lambda)$ , which were analyzed following the standard approach. (Smith and Baker, 1981). The data given here are for the measurements carried out during clear sky, noon period and with solar zenith angles less than 35°. We have not included the data at 683nm. In order to compare with the satellite derived products, the depth profile data of the measured  $K_d(z, \lambda)$  are averaged over the  $Z_{90}$  as given below to derive the average measured  $K_d(\lambda)$  for each station.

$$K_d^{meas}(\lambda) = \frac{1}{Z_{90}} \int_0^{Z_{90}} K_d(z, \lambda) dz \quad (4)$$

The mean values of the measured  $K_d(\lambda)$  are 0.105, 0.092, 0.077, 0.082, 0.11, 0.49 ( $m^{-1}$ ) for wavelength  $\lambda$  of 412, 443, 490, 510, 555 and 670nm respectively. These values of  $K_d(\lambda)$  correspond to waters with chlorophyll value of about  $1 \text{ mgm}^{-3}$  considering the Case-1 algorithm. (Morel and Maritorena, 2001). The mean chlorophyll in the Arabian Sea, except under bloom conditions, is reported to be less than  $1 \text{ mgm}^{-3}$ . (Matondkar *et al.*, 2006).

We have used the Level\_1A SeaWiFS data collected from the satellite receiving station HGOA at National Institute of Oceanography, Goa, India. We have processed the SeaWiFS ocean color satellite data for the corresponding days during the cruise using the software SeaDAS Version 5.0 (<http://seadas.gsfc.nasa.gov>) and with the meteorological data for the day. Atmospheric correction algorithm used was “Multiscattering with 2- band model selection -NIR” with maximum iterations of 10. Residual and out of band correction was enabled. For the flags, default thresholds were used.

## 2.2. Algorithms

Here we describe briefly the three algorithms used for deriving the spectral diffuse attenuation coefficients from the SeaWiFS data. The three algorithms are  $Kd\_Lee$ ,  $Kd\_Austin$  and  $Kd\_Morel$ .

The  $K_d$ \_Lee are derived at the spectral bands of SeaWiFS in the SeaDAS software, while the spectral values of  $K_d(\lambda)$  calculated from  $K_d$ \_Austin and  $K_d$ \_Morel are obtained using the satellite derived products from the SeaWiFS data,  $K_d(490)$  and chlorophyll *a* respectively.

### 2.2.1. $K_d$ \_Lee

$K_d(\lambda)$  can be modeled as a function of the inherent optical properties, absorption and backscattering and like other AOPs, it is also dependent on the sun angle. The  $K_d(\lambda)$  is modeled into a form derived using the radiative transfer equations (Stavn and Weidemann, 1989), which is given as

$$K_d(\lambda) = m_0 a(\lambda) + v b_b(\lambda) \quad (5)$$

The parameters  $m_0$  and  $v$  were modeled using the Hydrolight software (<http://www.sequoia.com>) that simulates the underwater light field. (Lee *et al.*, 2005). The parameter  $m_0$  depends on the solar zenith angle and is approximated as,  $m_0 = 1 + 0.005\theta$ , where  $\theta$  is the solar zenith angle in air and the parameter  $v$  is modeled as a function of the absorption coefficient,  $a(\lambda)$ . The following empirical relationship provide the value of  $K_d(\lambda)$  as a function of absorption and backscattering coefficients.

$$K_d(\lambda) = m_0 a(\lambda) + m_1 [1 - m_2 e^{-m_3 a(\lambda)}] b_b(\lambda) \quad (6)$$

where  $m_0$ ,  $m_1$ ,  $m_2$  and  $m_3$  are coefficients whose values depend on the depth and solar zenith angle,  $a(\lambda)$  and  $b_b(\lambda)$  are the spectral absorption and backscattering coefficients respectively. In SeaDAS, however optimal values are used with  $m_1 = 4.18$ ,  $m_2 = 0.52$  and  $m_3 = -10.80$ . The quasi analytical algorithm, QAA (Lee *et al.*, 2002) is used to determine  $a(\lambda)$  and  $b_b(\lambda)$  using the remote sensing reflectance,  $R_{rs}(\lambda)$ , which is derived from the Level\_2 satellite data after the atmospheric correction and other procedures in the SeaDAS software.

### 2.2.2. $K_d$ \_Austin

The spectral variations of  $K_d(\lambda)$  are found to have a strong spectral co-variations. Hence using  $K_d(\lambda)$  at any one wavelength as reference, relationships are found for the  $K_d$  at other wavelengths. The coefficients were obtained using  $K_d(490)$  as reference and the following relationship allowed to determine the spectral  $K_d(\lambda)$ . (Austin and Petzold, 1986).

$$K_d(\lambda) = K_w(\lambda) + M(\lambda)[K_d(490) - K_w(490)] \quad (7)$$

The spectral value of diffuse attenuation of pure water  $K_w(\lambda)$  and the coefficients  $M(\lambda)$  were derived for the spectral bands of SeaWiFS. (Austin and Petzold, 1986). The  $K_d(490)$  is a standard product derived using SeaDAS, given as ' $K_{490}$ '.

One of the earliest empirical methods to derive diffuse attenuation at 490nm used simple band ratio of water leaving radiance from the ocean color satellite data of Coastal Zone Color Scanner (CZCS). (Austin and Petzold, 1981). Diffuse attenuation at 490nm,  $K_d(490)$  is still a widely accepted parameter used for various applications. The algorithm has gone through various modifications with change of parameters and bands keeping the basic structure the same. Austin and Petzold (1986) used the ratio of water leaving radiance,  $L_w(\lambda)$  at 443 and 550nm, which was modified to suit the bands of satellite sensor SeaWiFS using ratio of normalized water leaving

radiance  $L_{wn}(\lambda)$  at 443 and 555nm (Mueller and Trees, 1997). Since the normalized water leaving radiance at 443 derived from SeaWiFS often resulted in underestimation of its value, this band was replaced with the band at 490nm. This also improved the estimation of  $K_d(490)$ . The refined empirical relation to derive  $K_d(490)$  from the satellite data is given below. (Mueller, 2000). The value of  $K_w(490)$  which is considered as the diffuse attenuation coefficient for pure water, was derived for clear water and had the value of  $0.022 \text{ (m}^{-1}\text{)}$  (Smith and Baker, 1981). The value of  $K_w(490)$  after reanalysis was adjusted to an optimum value of  $0.016 \text{ (m}^{-1}\text{)}$ . (Mueller, 2000). The empirical relationship for  $K_{490}$  in SeaDAS is given as

$$K_d(490) = K_w(490) + aX^b \quad (8)$$

where  $X = L_{wn}(490)/L_{wn}(555)$ ,  $K_w(490) = 0.016$ ,  $a = 0.15645$  and  $b = -1.5401$ .

Here  $L_{wn}(\lambda) = R_{rs}(\lambda) \cdot F_0(\lambda)$ , where  $F_0(\lambda)$  is the extraterrestrial solar irradiance at the top of the atmosphere at wavelength  $\lambda$  and is a constant value.

### 2.2.3. $K_d$ \_Morel

This method finds applications in determining the spectral  $K_d(\lambda)$  using only the biological parameter chlorophyll a concentration, without making any radiometric or light measurements in water. Hence this algorithm is found to be used widely by the community, as it depends only on the estimated or measured chlorophyll value.  $K_d(\lambda)$  is very well correlated with chlorophyll for Case-1 waters and this method is based on an empirical relationship between spectral  $K_d(\lambda)$  with chlorophyll.  $K_d(\lambda)$  can be approximated as a contribution from pure water  $K_w(\lambda)$  and contributions from all biogenic components, detritus and dissolved organic colored matter.  $K_{bio}(\lambda)$ . (Morel and Maritorena, 2001).

$$K_d(\lambda) = K_w(\lambda) + K_{bio}(\lambda) \quad (9)$$

Considering for Case 1 waters, the  $K_{bio}(\lambda)$  is considered to be a function of chlorophyll alone and the relationship is given as

$$K_d(\lambda) = K_w(\lambda) + \chi(\lambda)C^{e(\lambda)} \quad (10)$$

where  $K_w(\lambda)$  is the diffuse attenuation coefficient due to pure water. ( $\text{m}^{-1}$ ),  $\chi(\lambda)$  and  $e(\lambda)$  are coefficients determined from statistical analysis conducted on field data and  $C$  is the chlorophyll a concentration ( $\text{mgm}^{-3}$ ).

The chlorophyll is a standard product ‘chlor a’ derived in the SeaDAS from the SeaWiFS data. The chlorophyll a algorithm is based on the blue-green ratios of remote sensing reflectance at two wavelengths,  $R_{rs}(\lambda_i)/R_{rs}(\lambda_j)$ ,  $\lambda_i$  is one of three available blue-green regions (namely  $\lambda_i = 443, 490$  and  $510\text{nm}$ ) and  $\lambda_j = 555\text{nm}$ . In the refined 4-band algorithm OC4, the largest of the three ratios,  $R_{rs}(443)/R_{rs}(555)$ ,  $R_{rs}(490)/R_{rs}(555)$ , and  $R_{rs}(510)/R_{rs}(555)$  is used. The updated empirical relationship known as OC4V4 is used in SeaDAS. (O’Reilly *et al.*, 2000).

## 3. Results and Discussion

We have used the data measured on the day and close to the time of the satellite pass. After discarding data with negative values and few outliers, we have used data from 38 stations. Here for

comparison the  $K_d(\lambda)$  from SeaWiFS using three methods are given as  $K_d^{sea}(\lambda)$  and the measured  $K_d(\lambda)$  are given as  $K_d^{meas}(\lambda)$ . The  $K_d(\lambda)$  derived from the SeaWiFS are assessed using the indices of mean of Root mean Squared Error (RMSE), mean of the absolute percentage difference (apd) (Lee *et al.*, 2005) and coefficient of determination ( $r^2$ ) and mean percent deviation (MPD) or bias and they are defined as given below. (N= total data analyzed).

$$apd = \exp \left[ \text{mean} \left| \ln \left( \frac{K_d^{sea}}{K_d^{meas}} \right) \right| \right] - 1 \quad (11)$$

$$RMSE = \sqrt{\frac{\sum (K_d^{meas} - K_d^{sea})^2}{N}} \quad (12)$$

$$MPD = \left[ \frac{1}{N} \sum_1^N \frac{(K_d^{sea} - K_d^{meas})}{K_d^{meas}} \right] \times 100\% \quad (13)$$

We analyze the performance of the methods and they are summarized below.

### 3.1. Kd\_Lee

This is a semi-analytical algorithm, unlike the other two, which are data driven empirical methods. Kd\_Lee algorithm require absorption  $a(\lambda)$  and backscattering coefficient  $b_b(\lambda)$  which are derived using the semi-analytical methods in the QAA algorithm and they are parameterized in terms of  $R_{rs}(\lambda)$ . (Lee *et al.*, 2002). Thus the performance of the algorithm depends a lot on the accuracy of  $R_{rs}(\lambda)$  values being retrieved from the satellite data. This method requires inherent optical properties, and the empirical methods are not robust enough to derive them from satellite data as compared to the chlorophyll and  $K_d(490)$ . Unlike other methods, the parameters involved are more and hence the chances of the accumulation of errors. The performance of the algorithm is found to be better in the 443, 490 and 555nm with  $r^2 > = 0.5$  (see figure 2 and table 1), which are attributed to the better accuracy of the retrieval of  $a(\lambda)$  at these bands.(Melin *et al.*, 2007).  $K_d(\lambda)$  is generally found to be overestimated in most of the bands. (see figure 2. The line through the origin indicates the 1:1 variations). Its performance at the lower wavelength of 412nm is comparatively very low and it is found to overestimate the values to a greater factor than the other two methods. This is due to the overestimation of absorption at 412nm band, as has been observed by others (Melin et al, 2007). The figures of deviations from the measured values given by apd and MPD are found to decrease with the increase in wavelengths. (see table 1). The mean absolute percentage deviation including the band at 670 nm is about 52 % from the measured values.

### 3.2. Kd\_Austin

The performance of the algorithm of Kd\_Austin depend on the values of  $K_d(490)$ . Here the performance of  $K_d(490)$  is comparable to the other two algorithms.(see figure 3 and table 2). Unlike the Kd\_Lee algorithm, there are not much spectral variations in the error. The correlation is found to be consistent in all the bands, except at the 670 nm, which is similar to the observations reported by others. (Melin *et al.*, 2005).(see table 2). Since the algorithm for  $K_d(490)$  depends on ratio of  $L_{wn}(490)$  and  $L_{wn}(555)$ , the error will depend on the ratio of these bands, rather than their absolute values. However it has to be noted that  $K_d(\lambda)$  is a function of absorption and backscattering

coefficients (see equation (5)), and the ratio of  $L_{wn}(490)$  and  $L_{wn}(555)$  does not assure a proportional increase in absorption and backscattering coefficient. (Carder *et al.*, 1999). Better accuracy in retrieving  $K_d(490)$  will improve the performance and allow to retrieve spectral values of  $K_d(\lambda)$  with less error in all the spectral bands. Here too the values are overestimated in most of the bands, with relatively higher deviations observed in the lower bands.(see figure 3 and table 2). The  $K_d(490)$  algorithm has been developed using the field data of  $K_d(490)$  below  $0.25m^{-1}$  hence this method may not hold true for higher  $K_d(\lambda)$  values. (Mueller,2000). As for the spectral relationship proposed by Austin and Petzold (1986), only data with with  $K_d(490) < 0.160$  were used for the developing this algorithm. Since band at 670nm did not match well with the measured values, without considering the band at 670nm, the mean absolute percent of deviation for all other bands is about 43%.

### 3.3. Kd\_Morel

The performance of this algorithm depends solely on the accuracy of the chlorophyll a derived from the satellite data. Considering that the algorithm OC4V4 to retrieve chlorophyll a is robust and applicable to global waters, the error in deriving chlorophyll a will depend on the accuracy of the retrieved  $R_{rs}(\lambda)$  from the satellite data and their ratios. Despite the fact that the algorithm depends on the accuracy of the chlorophyll a retrieved from the satellite data, the performance of this algorithm is better than other methods given here. The mean absolute percent deviation of all bands, except the band at 670nm is 36%, which is lower than other two methods and the  $r^2$  values are found to be consistent in all the bands. (see figure 4 and table 3). However this approximate relationship for deriving  $K_d(\lambda)$  as the sum total of contribution from water and constituents from water and may not be applicable to Case 2 and turbid waters. (Morel, 1988, Morel and Maritorena, 2001). This method is developed for  $K_d(490) < 0.15m^{-1}$  or water with an equivalent chlorophyll value of  $2.4 \text{ mgm}^{-3}$  of Case-1 water. Our earlier study has shown that chlorophyll values derived from SeaWiFS were overestimated which is reflected here in the values of  $K_d$ . (Elgar *et al.*, 2001). The error analyses indicate that the performance of the Kd\_Morel is comparable to the Kd\_Austin. (see figure 4).

### 3.4. Inter comparison of algorithms

Here we look at the inter comparison of  $K_d(\lambda)$  obtained from the SeaWiFS data using the three algorithms, Kd\_Lee, Kd\_Austin and Kd\_Morel. Comparing the derived values of Kd\_Austin and Kd\_Morel with that of Kd\_Lee, the performance is found to be good in all the bands, with Kd\_Austin scoring over Kd\_Morel. Here too we observe that the values derived by Kd\_Austin and Kd\_Morel are underestimated, with large deviations being observed in the blue bands. This is consistent with our earlier observation, wherein maximum error was observed at 412, while comparing the Kd\_Lee derived from the satellite data and the measured values. (see table 4 and 5).

The comparison of Kd\_Morel and Kd\_Austin are found to be very good, with high correlation ( $r^2 > 0.98$ ) and low apd. (see table 6). This shows that the error observed in comparing the measured and the values derived from the SeaWiFS using the empirical algorithms Kd\_Austin and Kd\_Morel, are only due to the derived  $R_{rs}(\lambda)$ , while the error observed in Kd\_Lee could be due to the  $R_{rs}(\lambda)$  and also due to the algorithms used to derive absorption and backscattering coefficients. In the empirical relations of deriving  $K_d(490)$  in Kd\_Austin and chlorophyll in Kd\_Morel, it is the band ratio of  $R_{rs}(\lambda)$  that needs to be derived with accuracy rather than the absolute value of  $R_{rs}(\lambda)$ . Hence it is the shape of the  $R_{rs}(\lambda)$  that matters to derive  $K_d(\lambda)$  from the satellite data with better accuracy.

#### 4. Conclusion

The measured spectral diffuse attenuation coefficients of the Arabian Sea have been compared with those derived from the satellite sensor, SeaWiFS using three algorithms. The three algorithms are Kd\_Austin and Kd\_Morel which are data driven, while the Kd\_Lee is a semi-analytical algorithm.

- The satellite-derived values of  $K_d(\lambda)$  from all three algorithms overestimate in the blue bands. The performance of all the algorithms depend on the satellite derived  $R_{rs}(\lambda)$  and its shape.
- The data driven empirical algorithms, Kd\_Austin and Kd\_Morel derive the spectral  $K_d(\lambda)$  values using the coefficients for the corresponding bands from a look-up table. The Kd\_Lee does not make use of any such spectral tables to derive  $K_d(\lambda)$ , and can be used to derive at any wavelengths. Hence it will be better suited for hyperspectral applications.
- The performance of the Kd\_Lee algorithm depend on the accuracy of values of absorption and backscattering coefficients, which are obtained from the satellite derived data using semi-analytical relationships using  $R_{rs}(\lambda)$ . The large error seen in the blue wavelengths compared to other wavelengths indicate that similar pattern of errors are also observed in the absorption and backscattering coefficients.(Melin *et al.*, 2005). Though the derived values are overestimated in the red band of 670nm, it is found to be well correlated to the measured values.
- The Kd\_Morel algorithm is developed for the Case 1 waters and its performance will depend on the accuracy of the satellite derived chlorophyll values. Our earlier validation studies for the Arabian Sea indicate that the chlorophyll values derived from SeaWiFS were overestimated and thus it is expected to be reflected in the  $K_d(\lambda)$  values derived using this empirical relationship.(Elgar *et al.*, 2001). Except for the band at 670nm, its performance is found to be consistent in all bands.
- The spectral values derived using Kd\_Austin depend on the accuracy of the  $K_d(490)$ . The algorithm used for  $K_d(490)$  is also a data driven algorithm, which is found to be valid for  $K_d(490) < 0.25 \text{ m}^{-1}$ .(Mueller, 2000). For large values of measured  $K_d(490)$  such as in turbid and coastal waters, the values derived from satellite data could be underestimated.(Melin *et al.*, 2007). In our study, the spectral values derived from Kd\_Austin are found to be well correlated with the measured values and the absolute percentage deviations are also consistent in all the bands, except at 670nm.
- The empirical relationships will largely depend on the data type and will match better if the data is of similar type as used for developing the algorithms.
- It is now proposed to develop and refine algorithms for better spectral algorithms for the waters of Arabian Sea using hyperspectral radiometer data and other optical and biological parameters and proven radiative transfer tools such as Hydrolight. (<http://www.sequoia.com>) for the recently launched OCM-2 satellite sensor.

Kd\_Austin and Kd\_Morel would be better suited for waters where the absorption is dominant and low chlorophyll a, such as in Case 1 waters. Kd\_Lee or similar semi-analytical algorithms could be a better choice to be used for all water types and hyperspectral applications. The algorithm Kd\_Lee could improve its performance with refined and robust algorithms to derive absorption and backscattering coefficients with better accuracy.

## Acknowledgement

Authors are thankful to the Director, National Institute of Oceanography for the support. We are also grateful to our colleagues, Ancy Rodrigues, Puneeta Naik and colleagues of Space Application Centre, Ahmedabad. This work was carried out under IRS-P4 OCM satellite validation project funded by Space Application Centre (Indian Space Research Organisation), India and SATCORE (Satellite Coastal And Oceanographic Research) programme funded by INCOIS (Indian National Center For Ocean Information Services) India.

## References

- AUSTIN, R. W. and PETZOLD, T. J., 1981, The determination of the diffuse attenuation coefficient of seawater using the coastal zone color scanner. In *Oceanography From Space*, J. F. R. Gower (Eds.), pp. 239–256 (New York: Springer).
- AUSTIN R.W. AND. PETZOLD T.J,1986, Spectral dependence of the diffuse attenuation coefficient of light in ocean water, *Optical Engineering*, 25, pp. 471–479.
- BHATTATHIRI, P. M. A., PANT, A., SAWANT, S., GAUNS, M., MATONDKAR, S. G. P., MOHANRAJU, R., 1996, Phytoplankton production and chlorophyll distribution in the eastern and central Arabian Sea in 1994-1995, *Current Science*, VOL 71, No.11.
- CARDER, K. L., CHEN F. R., LEE Z. P., HAWES S. K. and KAMYKOWSKI D., 1999, Semianalytic Moderate-Resolution Imaging Spectrometer algorithms for chlorophyll a and absorption with bio-optical domains based on nitrate-depletion temperatures, *Journal of Geophysical Research*, 104, pp. 5403– 5421.
- ELGAR DESA, SURESH, T., MATONDKAR, S. G. P. and DESA, E., 2001, Sea truth validation of SeaWiFS ocean colour sensor in the coastal waters of the eastern Arabian Sea, *Current Science*, 80(7), 854-860.
- GORDON, H. R., 1989, Dependence of the diffuse reflectance of natural waters on the Sun zenith angle, *Limnology and Oceanography*, 34, pp. 1484–1489.
- GORDON, H.R. and CLARK, D.K., 1980, Remote sensing optical properties of a stratified ocean, an improved interpretation., *Applied Optics*, 19, 3428-3430.
- GORDON, H.R. and MCCLUNEY, W.R., 1975, Estimation of the depth of sunlight penetration in the sea for remote sensing, *Applied Optics*, 14, pp. 413-416.
- JERLOV, N. G., 1976, *Marine Optics*.( New York : Elsevier).
- KIRK, J.T.O., 1984, Dependence of the relationship between inherent and apparent optical properties of water on solar altitude, *Limnology and Oceanography*, 29, pp. 350-356.
- LEE, Z. P., DU, K. P., and ARNONE, R., 2005, A model for the diffuse attenuation coefficient of downwelling irradiance, *Journal of Geophysical Research*, C02016, doi:10.1029/2004JC002275.
- LEE, Z. P., K. L. CARDER, and R. ARNONE, 2002, Deriving inherent optical properties from water color, A multi-band quasi-analytical algorithm for optically deep waters, *Applied Optics*, 41, pp. 5755–5772.
- LEWIS, M. R., CARR, M., FELDMAN, G., ESAIAS, W., and MCMCLAIN, C., 1990, Influence of penetrating solar radiation on the heat budget of the equatorial pacific ocean, *Nature*, 347, pp. 543-545.
- MATONDKAR, S.G.P., DWIVEDI, R.M., PARAB, S.G., PEDNEKAR, S., DESA, E.S., MASCARENHAS, A.A.M.Q., RAMAN, M., and SINGH, S.K., 2006, Satellite and ship studies of phytoplankton in the Northeastern Arabian during 2000 – 2006 period, *Proceedings of SPIE*, 6406, vol.6406, 64061I, SPIE, USA, 10.1117/2.1200703.0616.

- MÉLIN F., ZIBORDI G. and JEAN-FRANÇOIS BERTHON, 2007, Assessment of satellite Ocean color products at a coastal site, *Remote Sensing of Environment*, 110(2), pp. 192-215.
- MÉLIN, F., BERTHON, J.F., and ZIBORDI, G., 2005, Assessment of apparent and inherent optical properties derived from SeaWiFS with field data, *Remote Sensing of Environment*, 97, pp. 540–553.
- MOREL A., 1988, Optical Modeling of the upper Ocean in relation to its biogenous matter content (case I waters), *Journal of Geophysical Research*, 93, pp. 10749-10768.
- MOREL, A., and D. ANTOINE, 1994, Heating rate within the upper ocean in relation to its bio-optical state, *Journal of Physical Oceanography*, 24, pp.1652–1665.
- MOREL, A., and MARITORENA, S., 2001, Bio-optical properties of oceanic waters, a reappraisal, *Journal of Geophysical Research*, 106, pp. 7163-7180.
- MUELLER, J. L., and C. C. TREES, 1997, Revised SeaWiFS prelaunch algorithm for diffuse attenuation coefficient K(490), *NASA Technical Memorandum*, TM-104566, 41, pp. 18– 21.
- MUELLER, J. L., C. DAVIS, R. ARNONE, R. FROUIN, K. L. CARDER, Z. P. LEE, R. G. STEWARD, S. HOOKER, C. D. MOBLEY, and S. MCLEAN, 2002, Above water radiance and remote sensing reflectance measurement and analysis protocols, *NASA Technical Memorandum*, TM-2002-210004, pp. 171– 182.
- MUELLER, J.L., 2000, SeaWiFS algorithm for the diffuse attenuation coefficient, K(490), using water-leaving radiances at 490 and 555 nm. In: *SeaWiFS postlaunch calibration and validation analyses: Part 3, NASA Technical Memorandum, 2000-206892 vol. 11*, S.B. Hooker and E.R. Firestone (Ed.), pp. 24–27, (Greenbelt: NASA Goddard Space Flight Center).
- O'REILLY, J. E., MARITORENA, S., SIEGEL, D. A., O'BRIEN, M. C., TOOLE, D., MITCHELL, B. G., *et al.*. 2000, Ocean color chlorophyll a algorithms for SeaWiFS, OC2, and OC4: version 4, In *SeaWiFS postlaunch calibration and validation analyses, Part 3, NASA/TM 206892, 11*, pp. 9–23.
- PLATT, T., 1986, Primary production of ocean water column as a function of surface light intensity, Algorithms for remote sensing, *Deep Sea Res.*, 33, pp. 149– 163.
- PREISENDORFER, R. W., 1976, *Hydrologic Optics, vol. 1, Introduction*, (Springfield)
- SATHYENDRANATH, S., T. PLATT, C. M. CAVERHILL, R. E. WARNOCK, and M. R. LEWIS, 1989, Remote sensing of oceanic primary production, Computations using a spectral model, *Deep Sea Research*, 36, pp. 431–453.
- SMITH, R.C. and BAKER, K., 1981, Optical properties of the clearest natural waters, *Applied Optics*, 20(2), pp. 177-184.
- STAVN, R. H., and A. D. WEIDEMANN, 1989, Shape factors, two-flow models, and the problem of irradiance inversion in estimating optical parameters, *Limnology and Oceanography*, 34, pp. 1426– 1441.
- SURESH T., PUNEETA NAIK, MANGESH BANDISHTE, ELGAR DESA, ANTONIO MASCARANAHAS, and MATONDKAR, S. G. P., 2006, Secchi depth analysis using bio-optical parameters measured in the Arabian Sea, In *Remote Sensing of the Marine Environment, Proceedings of the SPIE, Volume 6406*, Frouin, Robert J.; Agarwal, Vijay K.; Kawamura, Hiroshi; Nayak, Shailesh, Pan, Delu (Ed.), pp. 64061Q.
- SASMAL S K, 1997, Optical Classification of Waters in the. Eastern Arabian Sea *Journal of the Indian Soc iety of Remote Sensing*, 25(2), pp. 73-78.

Table 1 Error analysis of the measured  $K_d(\lambda)$  and the SeaWiFS derived  $K_d(\lambda)$  using Kd\_Lee algorithm

$\lambda$	RMSE	apd	$r^2$	MPD
412	0.130	0.915	0.5	111.64
443	0.090	0.597	0.7	67.05
490	0.052	0.446	0.5	30.58
510	0.036	0.281	0.3	14.12
555	0.030	0.270	0.6	-13.00
670	0.564	0.623	0.4	73.37

Table 2. Error analysis figures of comparison of measured  $K_d(\lambda)$  and the SeaWiFS derived  $K_d(\lambda)$  using Kd\_Austin.

$\lambda$	RMSE	apd	$r^2$	MPD
412	0.072	0.487	0.5	46.51
443	0.074	0.571	0.5	49.89
490	0.050	0.531	0.5	34.47
510	0.039	0.363	0.4	15.30
555	0.029	0.213	0.5	0.42
670	0.054	0.080	0.0	0.41

Table 3. Error analysis figures of comparison of measured  $K_d(\lambda)$  and SeaWiFS derived  $K_d(\lambda)$  using Kd\_Morel.

$\lambda$	RMSE	apd	$r^2$	MPD
412	0.057	0.443	0.5	34.41
443	0.090	0.477	0.5	41.55
490	0.063	0.433	0.5	21.31
510	0.047	0.294	0.6	14.20
555	0.028	0.176	0.5	1.13
670	0.065	0.082	0.1	1.14

Table 4. Error analysis of the comparison of Kd\_Lee and Kd\_Austin derived from the SeaWiFS.

$\lambda$	RMSE	apd	$r^2$	MPD
412	0.040	0.437	0.7	-28.83
443	0.025	0.220	0.9	-16.22
490	0.008	0.081	0.9	-3.08
510	0.020	0.125	0.5	-1.26
555	0.011	0.068	0.7	4.16
670	0.121	0.169	0.1	2.65

Table 5. Error analysis of the comparison of Kd\_Lee and Kd\_Morel derived from SeaWiFS.

$\lambda$	RMSE	apd	$r^2$	MPD
412	0.046	0.514	0.9	-33.18
443	0.041	0.319	0.8	-22.99
490	0.020	0.192	0.8	-14.86
510	0.019	0.093	0.4	-0.61
555	0.008	0.075	0.8	6.16
670	0.116	0.146	0.01	-0.06

Table 6. Error Analysis of the comparison of Kd\_Austin and Kd\_Morel derived from SeaWiFS.

$\lambda$	RMSE	apd	$r^2$	MPD
412	0.022	0.162	0.96	-8.99
443	0.016	0.132	0.96	-5.72
490	0.012	0.134	0.95	-8.80
510	0.007	0.071	0.97	0.77
555	0.008	0.052	0.98	2.36
670	0.010	0.012	0.96	0.18

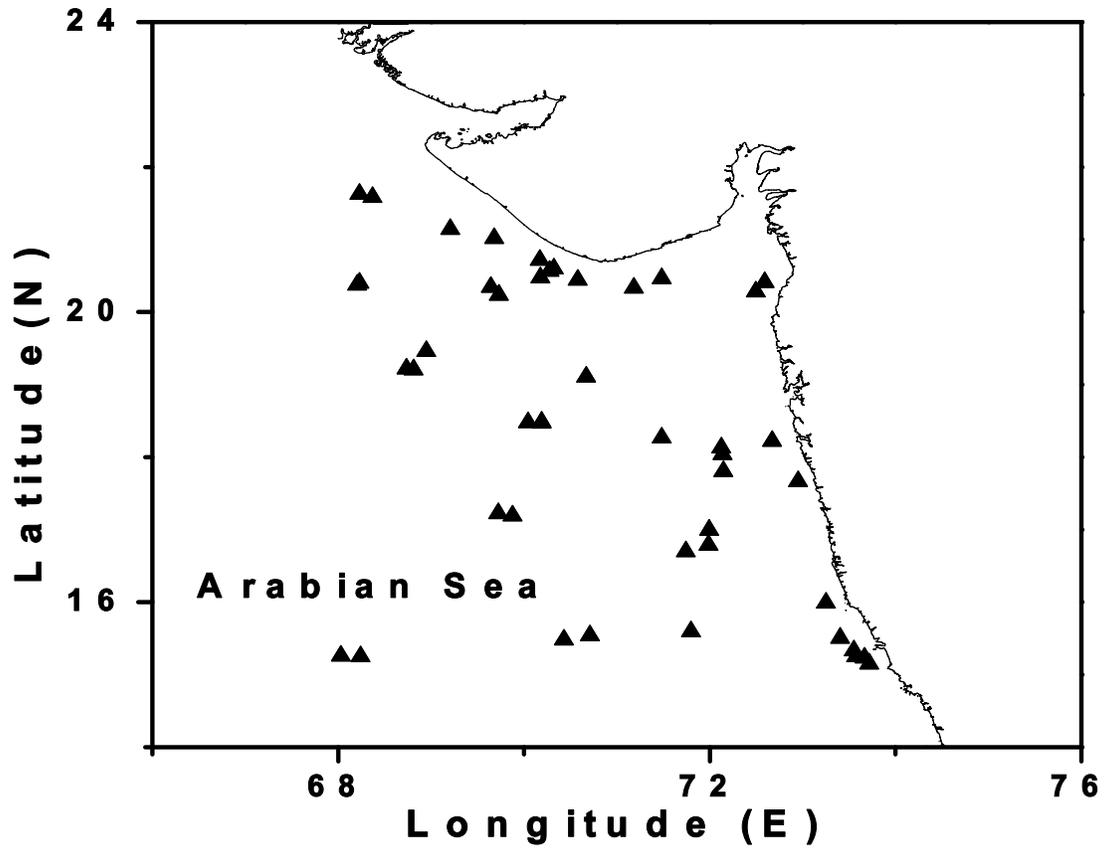


Figure 1. Ship cruise stations in the Arabian Sea where the radiometric measurements were carried out.

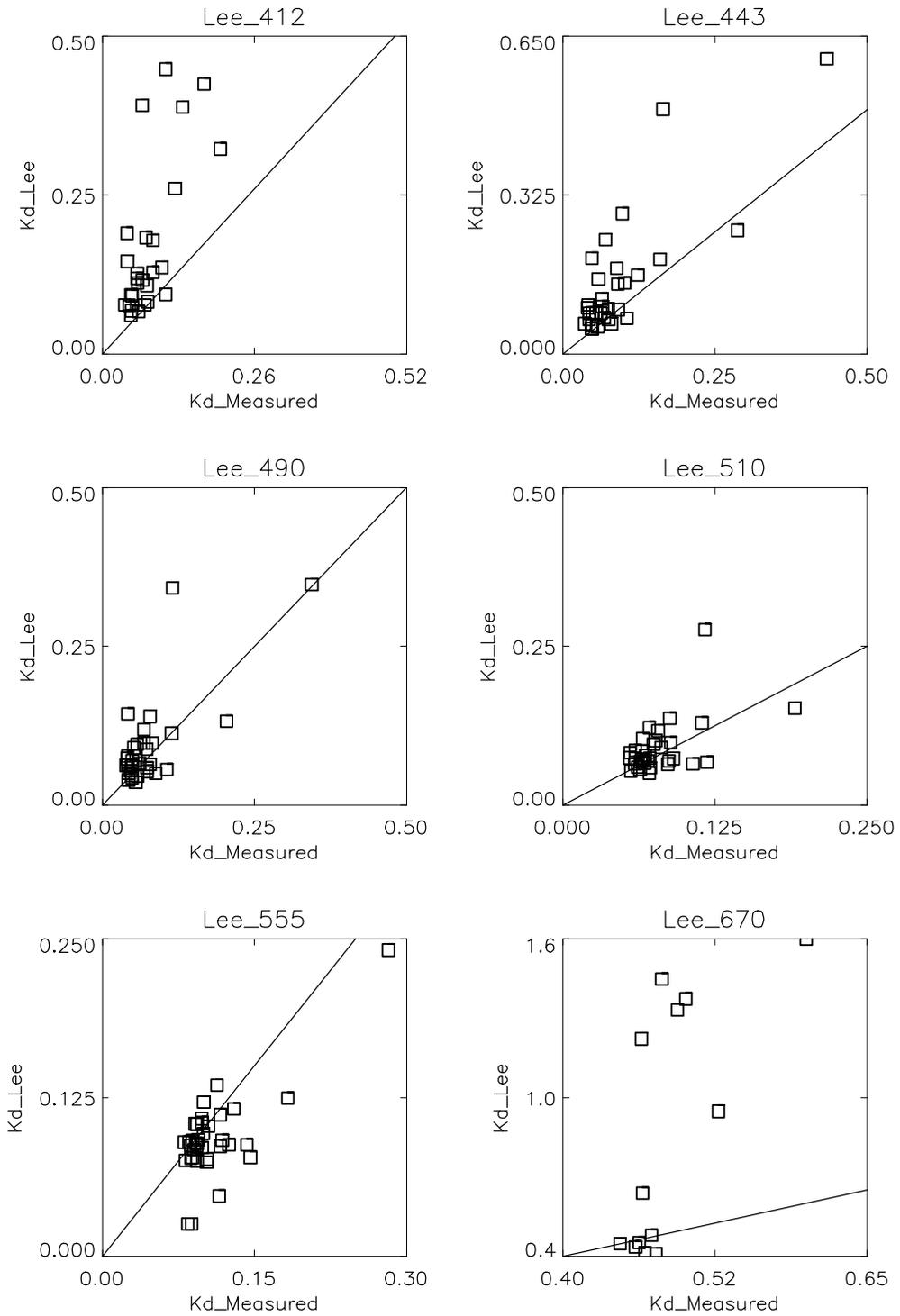


Figure 2. Comparison of the measured spectral  $K_d(\lambda)$  and those derived from SeaWiFS using  $K_d\_Lee$  algorithm.

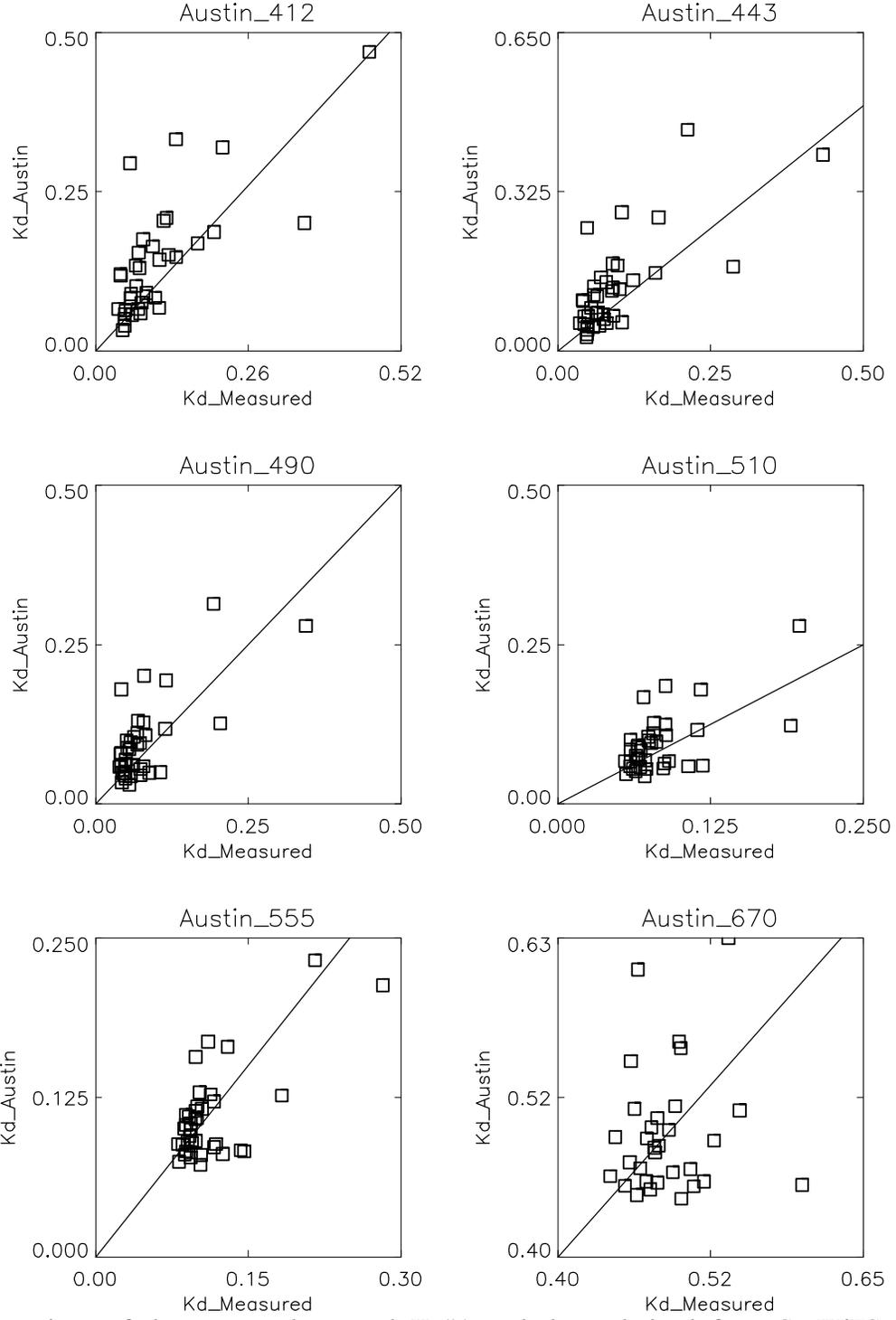


Figure 3. Comparison of the measured spectral  $K_d(\lambda)$  and those derived from SeaWiFS using  $Kd\_Austin$  algorithm.

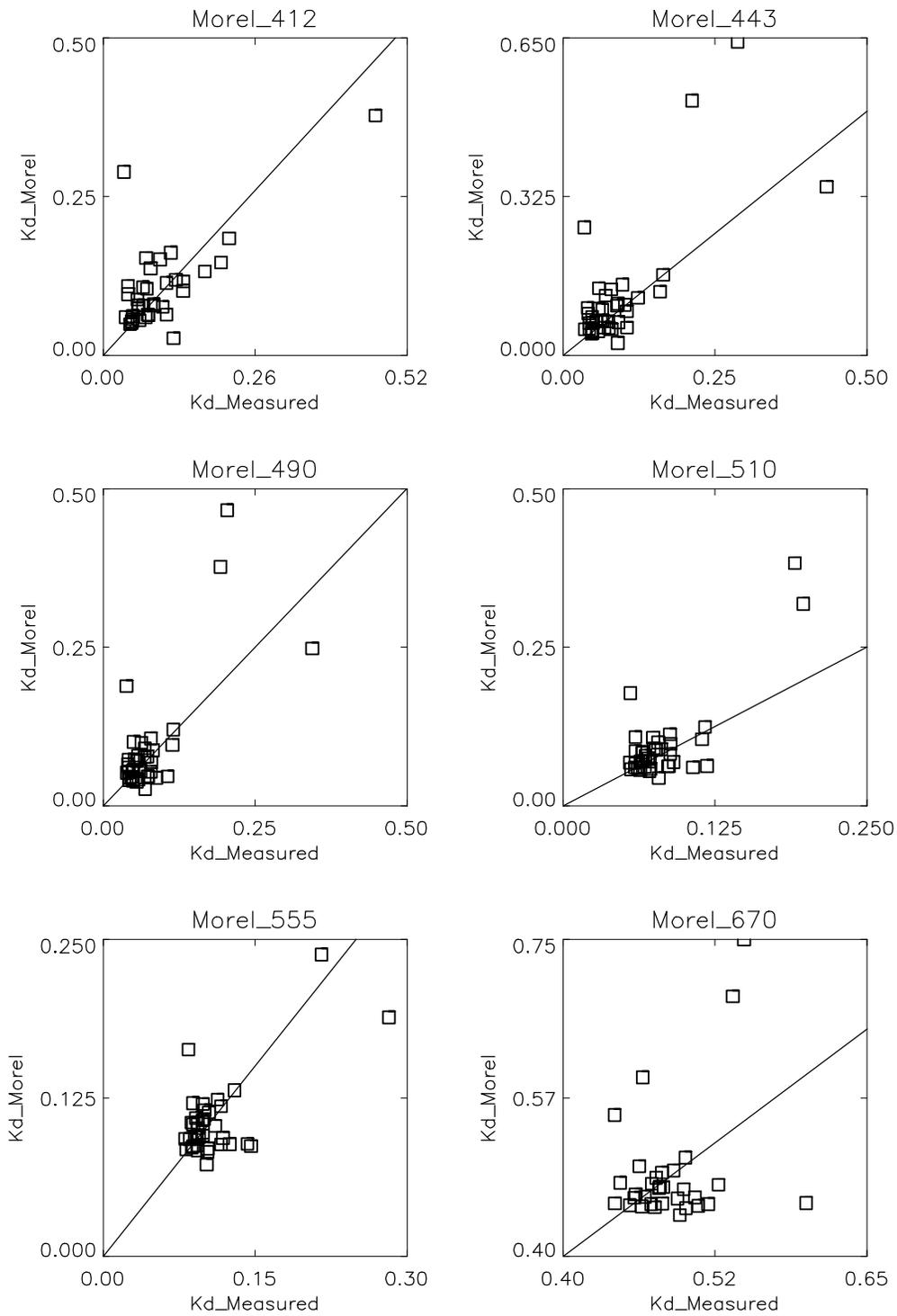


Figure 4. Comparison of the measured spectral  $K_d(\lambda)$  and those derived from SeaWiFS using  $K_d\_Morel$  algorithm.