Extraction of the atmospheric path radiance in relation to retrieval of ocean color information from the TM and SeaWiFS imageries

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Abstract: The ocean signal that reaches the detector of an imaging system after multiple interactions with the atmospheric molecules and aerosols was retrieved from the total signal recorded at the top of the atmosphere (TOA). A simple method referred to as "Path Extraction" applied to the Landsat-TM ocean imagery of turbid coastal water was compared with the conventional dark-pixel subtraction technique. The shape of the path-extracted water-leaving radiance spectrum resembled the radiance spectrum measured *in-situ*. The path-extraction was also extended to the SeaWiFS ocean color imagery and compared with the standard SeaWiFS atmospheric correction algorithm, which relays on the assumption of zero water leaving radiance at the two NIR wavebands (765 and 865nm). The path-extracted water-leaving radiance was good agreement with the measured radiance spectrum. In contrast, the standard SeaWiFS atmospheric correction algorithm led to essential underestimation of the water-leaving radiance in the blue-green part of the spectrum. The reason is that the assumption of zero water-leaving radiance at 765 and 865nm fails due to backscattering by suspended mineral particles. Therefore, the near infrared channels 765 and 865nm used for deriving the aerosol information are no longer valid for turbid coastal waters. The path-extraction is identified as a simple and efficient method of extracting the path radiance largely introduced due to light interaction through the complex atmosphere carried several aerosol and gaseous components and at the air-sea interface.

1. Background

It is well known that the radiance measured at the top of the atmosphere is primarily composed of the atmospheric scattered radiance due to air molecules and aerosols, air-sea interface reflected radiance and the transmitted water-leaving radiance. The water leaving radiance of coastal ocean represents normally less than 20% of the total radiance and less than 10% or often 1% of the total signal is attributed to the water leaving radiance of open oceanic waters. Therefore, it is very essential to remove the atmospheric and ocean surface effects before retrieval of the oceanic constituents of interest. An ultimate goal of the atmospheric correction performed on ocean color imageries acquired by the space borne ocean sensors is to retrieve the water leaving radiance at the sea level from the total radiance recorded at the top of the atmosphere (T_{TOA}). Though there have been several investigations carried out to perform the atmospheric correction on the ocean color imagery, many of them are exclusively developed for case-I waters (For example, Gordon, 1987) where the water-leaving signal is very low compared to coastal oceans. Many researchers noticed that the case-I atmospheric correction algorithm produced errors throughout visible domain. For instance, the SeaWiFS atmospheric correction algorithm developed by Gordon and Wang (1994) relays on the assumption of zero water leaving radiance at the longer wavelength bands (765 and 865nm). This assumption can be nearly valid for oceanic waters where phytoplankton and its associated materials dominate the variation of optical properties. In coastal waters, the water leaving radiances are not close to zero at these wavelengths, especially from 660 to 865nm, due to backscattering by suspended particulate matter. Under this assumption, the near infrared channels 765 and 865nm used for deriving aerosol information are no longer valid for turbid waters. MERIS case-II water products overcome this problem by modeling of the absorption and backscattering properties of sediment –laden water at three wave bands 705, 775 and 865nm (Aiken and Moore 1997). Ruddick *et al.* (2000) modified the standard SeaWiFS atmospheric correction algorithm by assuming the ratio of water-leaving reflectances normalized by the sun-sea atmospheric transmittance to be spatially homogeneous at 765 and 865nm. The result of such an assumption has significantly improved the standard SeaWiFS atmospheric correction algorithm over the turbid coastal waters. One should note that the absorption and backscattering properties of turbid waters are highly variable due to the activation of certain physical processes.

Bearing this in mind, a special attempt is made in the present study to correct the atmospheric effects in the visible and near infrared domains of ocean color imageries. A simple method is presented to extract the path radiance (L_{atm} $+L_{a-s}$) from the total radiance recorded at the top of the atmosphere (L_{TOA}), hereafter referred to as Path Extraction. The path extraction is principally simple, but more effective, for retrieving the water leaving radiance that carries immense information on biophysical state of the oceanic upper layer. The path radiance is here assumed to be made of photons scattered by the air molecules and aerosols, and also possibly reflected at the air-sea interface. In the strictly sense, the radiance backscattered by ocean-atmosphere system is primarily composed of the atmospheric path radiance and the desired water leaving radiance. It can be defined as $L_{TOA} = L_{atm}+L_{a-s}+L_w$. Where L_{atm} and L_{a-s} are the atmospheric radiance and the reflectance radiance at air-sea interface respectively. L_w is water-leaving radiance. The main assumption of the path-extraction is that the least signal of a few pixels of a given image is attributed to the path-radiance of atmosphere and the air-sea interface. The criterion for the selection of least signal values is that the difference between least values of a few pixels should be minimum. If there is a great difference, the path-radiance will essentially underestimate the water-leaving radiance throughout visible wave bands. For open oceanic waters, only a least pixel value can be assumed to be the path radiance, since the averaged value of a few pixels leads to underestimate the desired water-leaving radiance. We test this method on the TM ocean imagery of highly turbid coastal waters of Korea. It is also extended to the SeaWiFS ocean color imagery of the southern coastal sea. The spectral form of the path-extracted water leaving radiance is then compared with the water-leaving radiance spectra of the standard SeaWiFS atmospheric correction algorithm.

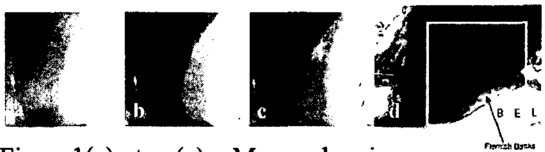
2. Results and Discussion

The results of path extraction method attempted on the Landsat-TM ocean imageries acquired over the southern coastal seas of Korea during 1999/05/05 and 1999/05/02 are presented in this section. This region is relatively shallow in nature and the depth ranges from 5 to 60m. The suspended sediment concentration varies from place to place and the maximum suspended sediment concentration is between 5~120g/m^3. The chlorophyll concentration ranges from 0.7 to 45mg/m^3. Similarly, the DOM absorption coefficient varies from 0.1~1.0m^{-1} at 400nm.

Prior to the retrieval of water leaving radiances from the digital number (DN) of TM or MSC bands, it must be radiometrically calibrated. The following expression is used to convert the digital number to radiance units.

$$L_\lambda = L_{min} + (L_{max}-L_{min}) \times BV_{ijk} / C_{max}$$

where L_λ is the total radiance at the top of the atmosphere (mW/cm^2/μm/sr) and L_{min} and L_{max} are the calibration constants. BV_{ijk} represents the brightness value of a pixel (i,j) and L_{max} is the maximum digital value for the image (e.g. 8-bit sensor - 255). Figs. 1(a) to (c) represent the total radiance measured at the top of the atmosphere (L_{TOA}) in the TM center wavelength bands (nm), 560, 660 and 830 respectively. It is observed that the brighter region in the images of VIR wavebands represents suspended sediment matters. A similar signature can also be observed in the Flemish Banks of Belgium (Fig. 1d) (Ruddick *et al.* 2000). Fig. 2 illustrates the total radiances (L_{TOA}) and the path-extracted water leaving radiances of different categories of turbid waters. The water-leaving radiance values constantly increase from green to red wavebands and decrease toward the near infrared waveband. Even at low concentration, it never reaches zero value in the near infrared spectral domain. Fig. 3 shows the path radiance extracted from the TM imagery (1999/05/05). It decreases with increasing wavelength and very low value is observed at the NIR waveband. Fig. 4a compares the potential use of path-extraction



Figs. 1(a) to (c): Maps showing the total radiance measured at the top of the atmosphere (L_{TOA}) (mW/cm^2/μm/sr) in the center wavebands (nm), 560, 660 and 830 of the Landsat-TM imagery (1999/05/05) of the southern coastal waters of Korea. (d) The total radiance measured at the top of the atmosphere at 765 nm by SeaWiFS in the Belgium coastal waters (Ruddick *et al.* 2000).

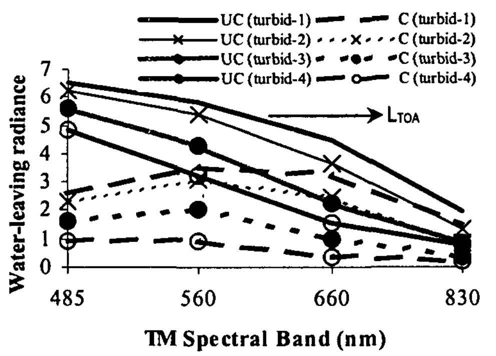


Fig. 2. Comparison of the total radiance measured at the top of atmosphere (L_{TOA}) ($mW/cm^2/\mu m/sr$) and the path-extracted water-leaving radiances ($mW/cm^2/\mu m/sr$) in the TM imagery (1999/05/05) of the highly turbid waters. UC- Uncorrected (total radiance at the L_{TOA}); C- path-extracted.

with the case-II water atmospheric correction algorithm and the turbid water algorithm (spatial homogeneity) proposed by Ruddick *et al.* (2000). It is seen that the path- extraction yields the water leaving radiance in all wave bands while other two algorithms retrieve the same from blue to red wavebands. This is due to the assumptions in these algorithms. However, the turbid water algorithm improved the standard SeaWiFS algorithm by assuming the ratio of water-leaving reflectances normalized by the sun-sea atmospheric transmittance to be spatially homogeneous at 765 and 865nm. They observed that the standard SeaWiFS atmospheric correction algorithm essentially underestimates the water-leaving radiances throughout shorter wavelengths due to removal of the excessive aerosol path radiance at these wave bands. The large errors were attributed to the assumption of zero water leaving radiance at the two near infrared bands (765 and 865nm). According to Ruddick *et al.* (2000), the turbid water algorithm gives good reproduction of the water-leaving radiance spectral form, with the

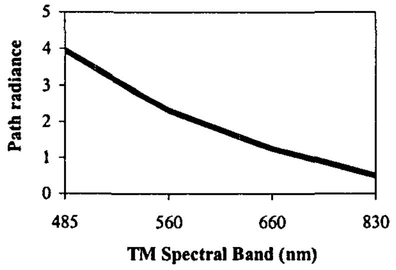


Fig. 3. Path radiance ($mW/cm^2/\mu m/sr$) extracted from the TM imagery (1999/05/05).

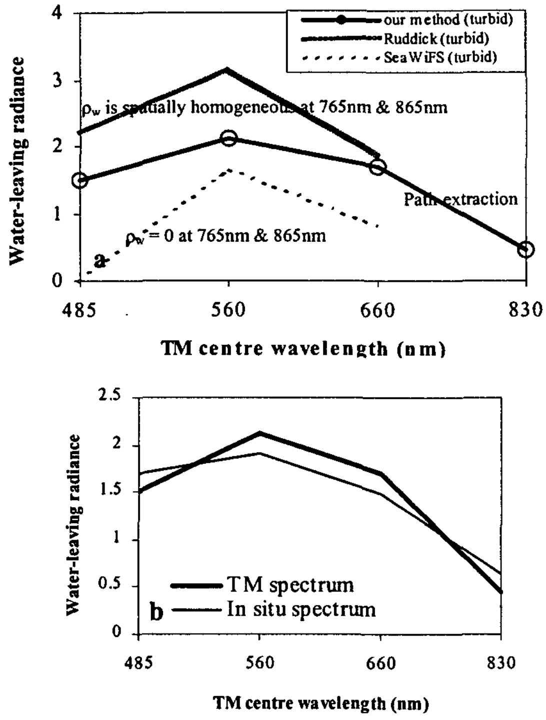


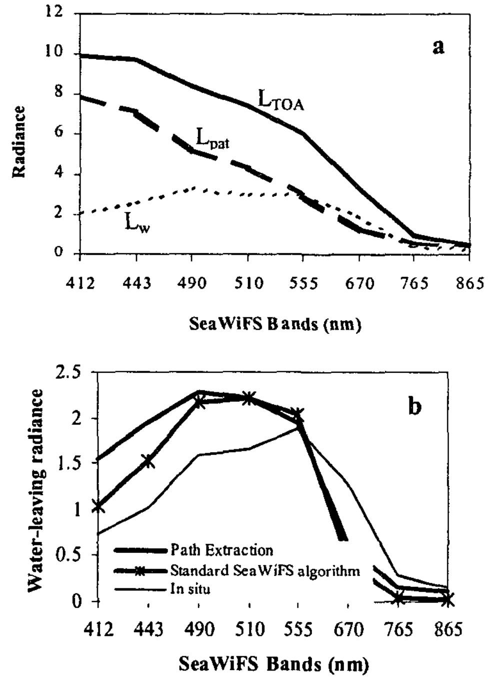
Fig. 4a. Comparison of the water-leaving radiances ($mW/cm^2/\mu m/sr$) derived from the standard SeaWiFS atmospheric correction algorithm, turbid water algorithm (spatial homogeneity) proposed by Ruddick *et al.* (2000) and "path-extraction" method. (b) Comparison of *in situ* and the path-extracted water-leaving radiance spectra.

error of the order of ± 0.01 for turbid pixels. It is noted that though the turbid water algorithm yields improved results over the standard SeaWiFS atmospheric algorithm, the assumption of spatial homogeneity is no longer valid when the ratios of aerosol reflectance and the water-leaving reflectance become heterogeneous at 765nm and 865nm. This is evident if we consider Figs. 1a and b. In these conditions, the path-extraction method has proven useful in retrieving the water-leaving radiance spectra, which are in good agreement with our *in situ* spectra as seen in Fig. 4b. Fig. 5 represents the suspended sediment concentration map of a part of the southern coastal waters. The suspended sediment concentrations (1 to 11g/m^3) were derived after applying the path-extraction and TM SS algorithm.

Path-extraction was also extended to the SeaWiFS ocean color imagery of the southern coastal sea of Korea because the SeaWiFS was exclusively designed for ocean color observations. The SeaWiFS imagery acquired over the southern sea on 1998/10/21 was selected for this study and processed with the standard SeaWiFS atmospheric correction algorithm, which is available in SeaDAS software.

The water leaving radiances retrieved from Level 1A SeaWiFS product using standard atmospheric correction algorithm are shown in Figs. 6a and b. For testing the path-extraction method, the digital counts of Level 1A raw data were first converted to the total radiance (mW/cm^2/μm/sr) at the level of the top of the atmosphere using the SeaWiFS band sensitivity and pre-launch calibration standards. Finally, we obtained the water-leaving radiance spectra

Fig 5. Suspended sediment ´ concentration estimated from the Landsat-TM image (1999/05/21) using path-extraction method and TM <SS> algorithm.



Figs. 6(a). Illustrates the total radiance, atmospheric path radiance and the path extracted water-leaving radiance (mW/cm^2/μm/sr). (b) Comparative performance of the measured and extracted water-leaving radiances.

from the total radiance (L_{TOA}) using the path-extraction approach as described in the earlier section. Figs. 6a illustrates the total radiance (L_{TOA}), path radiance (L_{path}) and the path-extracted water leaving radiance (L_w) spectra. It is clearly evident that the standard SeaWiFS algorithm leads to essentially underestimate the L_w values through out the shorter wave bands and produce large errors for extremely turbid coastal water [<SS> Conc. >100 (g/m^3)] (Fig. 6b). It should be noted that the *in situ* spectrum coincidently collected during the SeaWiFS overpass (1998/10/21) resembles the path-extracted water-leaving radiance spectrum. A small discrepancy between the *in situ* and the path-extracted water-leaving radiances is seen in the short wavebands of the SeaWiFS. The reason is that the *in situ* spectrum was derived from point measurement, while the path-extracted water-leaving spectrum was based on pixel measurement (1.13×1.13km), which is caused by the sub-pixel variability. The standard SeaWiFS atmospheric correction algorithm yields low L_w values in the visible wavebands. For the convenience, the L_{TOA} can also be converted to reflectance using the following equation,

$$\rho(\lambda\theta_s\theta_v) = \pi L(\lambda\theta_s\theta_v)/F_o(\lambda)\cos\theta_s$$

From this study, it is seen that the assumption of zero water-leaving radiances at 765 and 865nm and the spatial homogeneity is no longer valid for these regions, since the backscattering properties of these waters are highly variable. Thus, path-extraction is found to be more useful and is an alternate approach for atmospheric correction of ocean color imageries of such complex oceans.

3. Conclusion

A special attempt has been made to investigate the problems of the atmospheric correction of the ocean color imageries of the highly turbid waters. Compared to the standard SeaWiFS atmospheric correction algorithm, the path-extraction appears to perform well for the high spatial and high spectral resolution ocean color imageries of case-II waters. However, this method cannot be directey applied to case-I water, where the optical properties are dominated by phytoplankton. Thus, our further research would involve in optimizing the path-extraction method for the purpose of extracting the chlorophyll concentration from case-I waters.

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