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The Atmospheric Correction of ROCSAT-1 OCI Imagery— Part II: OCITRAN-2

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ABSTRACT

The algorithms used to establish the atmospheric correction model, OCITRAN-2, are demonstrated in detail. This study uses the difference between the total radiance and the Rayleigh scattering radiance at 865nm to determine the air mass character for estimating the aerosol scattering radiance and the water leaving radiance. The result indicates a high correlation between the estimates using the OCITRAN-2 and the SeaDAS models. Detailed analysis shows that the correlation coefficient can be up to 0.83 when the chlorophyll concentration is less than 10 mg/m^3. The OCITRAN-2 result was more accurate than that of the OCITRAN-1 using the concept of clear water method, indicating that the improvements in multiple Rayleigh scattering in the OCITRAN-2 are solid. Analysis results also suggest that the process to reduce the radiance contamination by neighboring cloud edge and thin cloud pixels should be improved.

(Key words: Atmospheric correction, Rayleigh scattering, Aerosol)

1. INTRODUCTION

After the successful launch of ROCSAT-1 in January 1999, OCI data for monitoring ocean color information has become available. Liu et al. (1999a) have developed a series of Ocean Color Imager Transmittance/radiance computation codes (OCITRAN) with a single scattering algorithm to retrieve the water leaving radiance from measured radiance. Unfortunately, no OCI images were available at the time to test the algorithm. Hence, to date Liu et al. have used the SeaWiFS data and its operational atmospheric correction package, SeaDAS, to compare the results estimated by OCITRAN series models. In Part I, the concept of clear water is shown to estimate the atmospheric aerosol influence (Liu et.al., 1999b).

Clearly, the error caused by the single Rayleigh scattering is larger than that in multiple Rayleigh scattering algorithm, especially at greater solar zenith angles (Gordon et.al., 1988;

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Eckstein and Simpson, 1991). In this study, the Rayleigh scattering is modeled with multiple scattering consideration. In this study, the method of assessing the aerosol scattering contribution is investigated again. The definition of air mass character follows Gathman (1983). The atmospheric correction procedure of OCITRAN-2 is shown in Figure 1. Since the major goal of OCI is to measure the variation of ocean color, the cloud and land cover area should be masked out. In order to obtain practical oceanic information, the sun glint pixels are masked out if the sun glint probability is greater than 1.5 (McClain and Yeh, 1994). In Figure 1, the shadow parts indicate the aerosol scattering radiance algorithm in OCITRAN-2.

The chlorophyll concentration estimation uses an empirical algorithm, such as "modified cubic polynomial (MCP)", named "ocean chlorophyll 2 (OC2)," in which the result analyzed by OC2 is significantly consistent with in situ data (O'reily et. al., 1998). In section 2, the multiple Rayleigh scattering is demonstrated, and the reason for adopting the single aerosol scattering is explained. In section 3, the experimental results, in which two SeaWiFS image sets covering the Taiwan area and the South China Sea, are analyzed. Finally, conclusions are drawn and suggestion is made in section 4.

2. ATMOSPHERIC CORRECTION

The total radiance, observed by the OCI sensor, could be the summation of several factors described in part I. The algorithm for estimating the aerosol effect was demonstrated in Liu et al. (1999a). In this study, the method to improve the estimation of aerosol scattering radiance is modified further. Rayleigh scattering effect modeling is another important area for improvement. In this study, the air mass character is used to estimate the aerosol condition, and the multiple scattering algorithm for Rayleigh radiance computing is utilized.

The multiple scattering for Rayleigh radiance can be modeled as (Gordon et al., 1988),

$$L_r(\lambda) = F_0'(\lambda) I(\lambda,\theta,\theta_0,\Delta\phi) \,, \tag{1}$$

$$I(\lambda,\theta,\theta_0,\Delta\phi) = \sum_{k=0}^{2} I_k(\lambda,\theta,\theta_0)\cos(k\Delta\phi) \,, \tag{2}$$

where λ is the wavelength, k is the Fourier component index, $\Delta\phi$ is the difference between reflected sunlight azimuth angle and satellite azimuth angle, $I(\lambda,\theta,\theta_0,\Delta\phi)$ is the Rayleigh coefficient, and $I_k(\lambda,\theta,\theta_0)$ is the Fourier coefficient of the Rayleigh radiance, which is azimuth angle dependent. In this study, one set of Fourier coefficients related to every two degrees change of satellite or solar azimuth angles are computed in advance, and the multiple scatter radiance of Rayleigh effect is computed with the set of Fourier coefficients. θ and θ_0 are the satellite and solar zenith angles, respectively, $F_0'(\lambda)$ is the solar irradiance after the atmospheric extinction, which can be expressed as

$$F_0'(\lambda) = F_0(\lambda) t_{oz}(\lambda,\theta_0) t_{oz}(\lambda,\theta) t_{wv}(\lambda,\theta_0) t_{wv}(\lambda,\theta) t_{ox}(\lambda,\theta_0) t_{ox}(\lambda,\theta) \,, \tag{3}$$

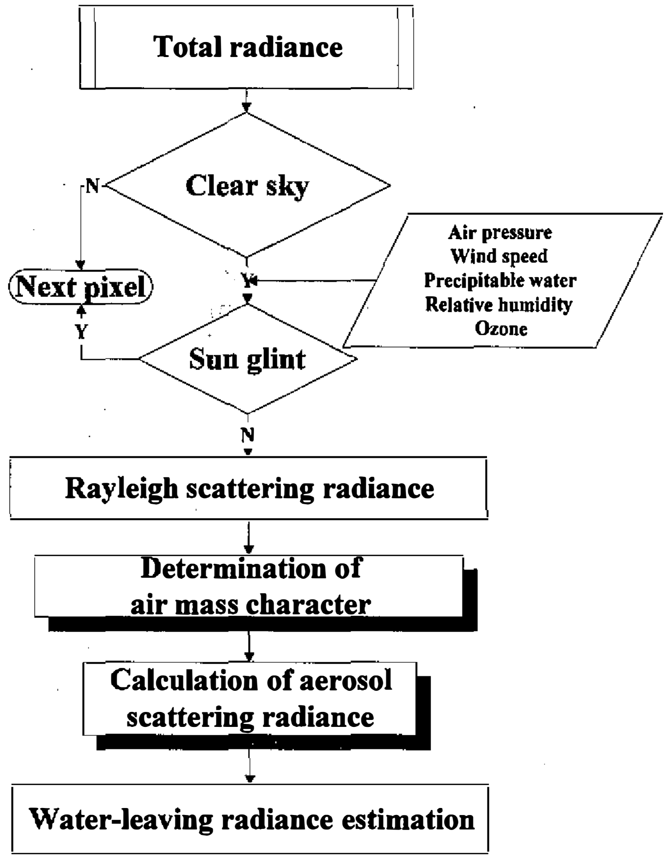


Fig. 1. Flowchart of the atmospheric correction of OCITRAN-2 model. The shadow parts indicate the aerosol scattering radiance algorithm in the OCITRAN-2.

where $t_{oz}(\lambda,\eta)$ is the ozone transmittance. $\eta=\theta_0$ indicates the path from solar to the observed position. $\eta=\theta$ represents the path from the observed position to the sensor. $t_{wv}(\lambda,\eta)$ is the water vapor transmittance, and $t_{ox}(\lambda,\eta)$ is the oxygen molecular transmittance. $F_0(\lambda)$ is the solar radiance flux at the top of the atmosphere and varies with the solar-terrain distance, which can be computed by

$$F_0(\lambda)=\overline{F}_0(\lambda)\left[1+0.0167\cos\frac{2\pi(D-3)}{365}\right]^2, \qquad (4)$$

where $\overline{F}_0(\lambda)$ is the mean solar radiance flux at the top of the atmosphere, and D is the date of the year (D=1 on January 1 and 365 on December 31, Gordon et.al., 1983).

Contrary to the multiple scattering in the Rayleigh scattering computation of this study, the single scattering algorithm is used in aerosol scattering computation. Under clear sky conditions, the extinction coefficient of atmosphere aerosol is about $2x10^{-2}$ km^{-1}. In other words, the extinction path is about 50km and is clearly thicker than the thickness of the stratosphere layer. In the troposphere layer, the coefficient and path are about $2x10^{-4}km^{-1}$ and 5000km, respectively. Surely, the path is considerably greater than the thickness of the troposphere layer (Buglia, 1986). These comparisons suggest that the single scattering model can be employed to replace the multiple scattering model to reduce the computational time without losing the accuracy. Hence, in this study, the single scattering model for aerosol radiance computation is used. Although other studies have showed that the single scattering model results tend to be underestimates compared to those for the multiple scattering estimates, especially in optically thick conditions, the single scattering model fortunately can obtain relative accuracy in thin optical paths. Since most of the OCI data is on open ocean, the single scattering approximation is acceptable.

3. EXPERIMENT RESULTS AND DISCUSSION

The SeaWiFS images used in Part I are utilized again in this study. In addition, one extra set of OCI images is used to test the OCITRAN-2 procedure. In Part I, the concept of clear water was used to estimate the atmospheric condition. The results indicated that the method is simple and practical, but the estimated water leaving radiance seemed to be overestimated for turbid ocean waters. Hence, the difference between the observed radiance and Rayleigh scattering radiance at the 865nm channel is here employed to determine the air mass character and to estimate the aerosol effect. Detailed discussion is given by Liu et al. (1999a).

After the making improvements in Rayleigh scattering modeling, evaluating the accuracy of the OCITRAN-2 is another important task. The SeaDAS model is employed again in this part for comparison with the OCITRAN-2 estimation. Since the SeaDAS has been tested and improved over the past several years and it is the official operational package for SeaWiFS data atmospheric correcting, the accuracy of SeaDAS is considered reliable.

Figures 2 and 3 show the water leaving radiance derived from two SeaWiFS data sets at 555nm using the OCITRAN-2 correction, respectively. It is clear that the water leaving radiance around the Taiwan area (Figure 2) is larger than the water leaving radiance around Dong-Sha Island (Figure 3). Around the Taiwan area, the coastal zone area has higher water leaving radiance and the values are greater than 1.0 $mW/cm^2/\mu m/sr$. In the southern Taiwan ocean area, the water leaving radiance is smaller, about 0.2~0.5 $mW/cm^2/\mu m/sr$, probably because the water is deeper or the water mass constitution over there is different. The area marked in red in Figure 2 indicates that the water leaving radiance is greater than 1.0 $mW/cm^2/\mu m/sr$ as estimated by OCITRAN-2 whereas the SeaDAS result is less than 1.0 $mW/cm^2/\mu m/sr$. A detailed check shows that these red areas are located around coastal zones, cloud edges or thin cloud areas. This suggests that the satellite observed radiance is polluted by neighboring cloud or land pixels. Hence, the OCITRAN-2 needs to be improved under such conditions. Compared to the Taiwan area, the water leaving radiance around the South China Sea has small values (< 1.0 $mW/cm^2/\mu m/sr$). This indicates that the water mass property in this area is clearer or is influenced by the Kuroshio.

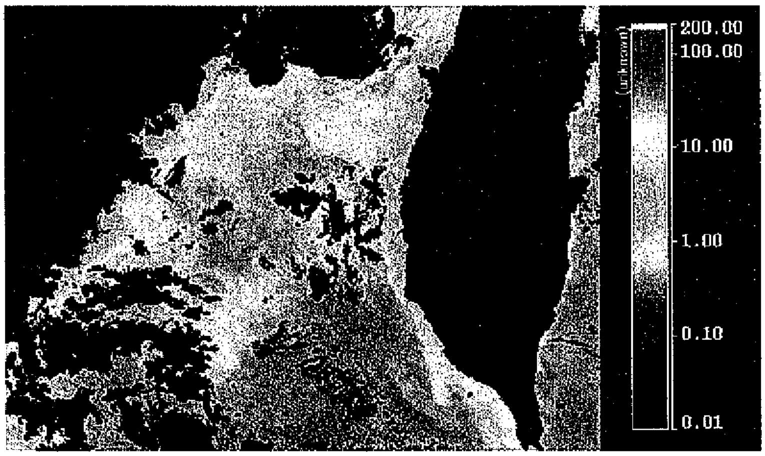


Fig. 2. The water leaving radiance ($mW/cm^2/\mu m/sr$) estimated with SeaWiFS 555nm channel data acquired on August 22, 1998.

Fig. 3. Same as Fig. 2, except on March 27, 1999.

After the water leaving radiance is derived, the chlorophyll concentration is also derived by OCITRAN-2 and SeaDAS, and the results of two models are compared. In these comparisons, the area marked in red mentioned above is excluded. The correlation coefficients of water leaving radiance at 490 and 555nm channels derived from the SeaWiFS data acquired on August 22, 1998 by OCITRAN-2 and SeaDAS are 0.753 and 0.941, respectively. The correlation coefficients are 0.549 and 0.716, respectively, for the SeaWiFS acquired on March 27, 1999 (Figure 4). The result of chlorophyll concentration is shown in Figure 5, and the correlation coefficients between OCITRAN-2-derived and SeaDAS-derived chlorophyll concentrations are 0.831 and 0.860 for Taiwan Strait and the South China Sea area, respectively. Figure 5 also shows that the concentration derived by OCITRAN-2 is less than that derived by SeaDAS when the concentration value is greater than 10 mg/m^3, and that these abnormal pixels mainly were located around coastal zone area. Because there are no field-measured data, the accuracy of OCITRAN-2 estimates around the coastal zone area still requires future study.

According to the comparisons between the results processed by the OCITRAN-2 and the SeaDAS models, OCITRAN-2 accuracy for estimating water leaving radiance is basically confirmed. Certainly, in situ data and other reliable data will be crucial for the further confirmation. Figure 6 shows the relative OCI parameters derived by OCITRAN-2 from the OCI data acquired on 02:12 GMT, May 17, 1999. The derived parameters include atmospheric aerosol radiance, aerosol optical thickness, normalized water leaving radiance and chlorophyll concentration. In general, estimates of OCI data using OCITRAN-2 show a reasonable pattern and values. However, field measurements are still necessary to verify the results precisely.

4. CONCLUSIONS

The total radiance observed by satellite at the 865nm channel consisted mainly of Rayleigh scattering and aerosol scattering effects. Because the aerosol effect is strongly correlated to the air mass character, the air mass character can be derived indirectly from the difference between the total radiance and the Rayleigh scattering radiance at 865nm. For some ocean color sensors, like OCI, which use the 865nm channel, this algorithm can provide a convenient

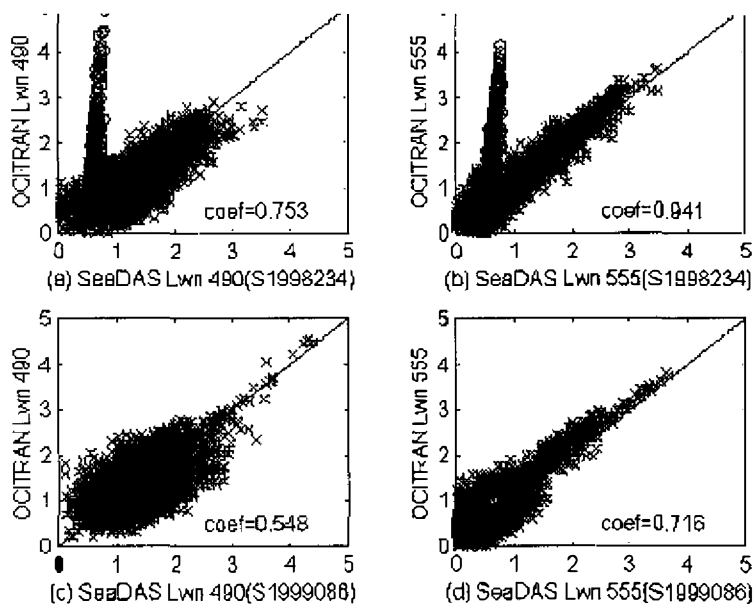


Fig. 4. Comparisons of the water leaving radiance estimated by OCITRAN-2 and SeaDAS. (a) the result estimated with SeaWiFS images acquired at 490nm on August 22, 1998. (b) same as (a), but at 555nm, (c) same as (a), but on August 22, 1998, (d) same as (c), but at 555nm.

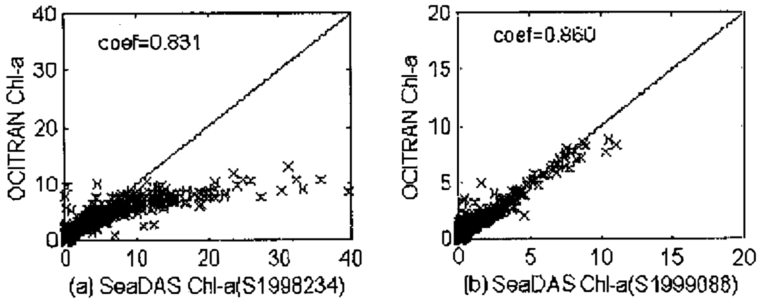
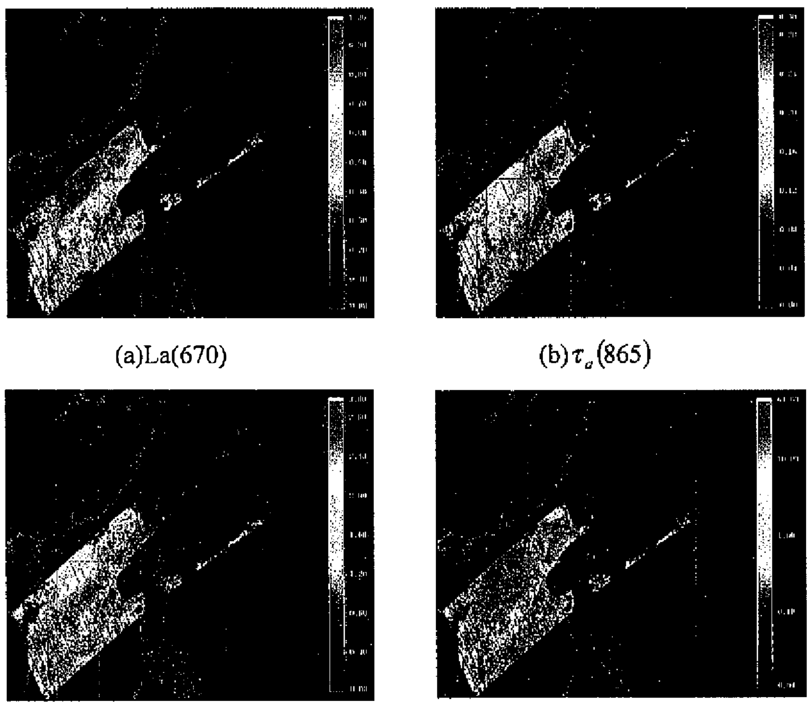


Fig. 5. Comparison of chlorophyll concentrations (mg/m^3) estimated by OCITRAN-2 and SeaDAS models. (a) Date on August 22, 1998, (b) date on March 27, 1998.



(a)La(670) (b)τ_a(865)

(c) nLw(490) (d)Chl-a

Fig. 6. Ocean parameters estimated by OCI data acquired at 02:12 GMT, May 17, 1999. (a) Aerosol radiance at 670 nm, (b) aerosol optical thickness at 865 nm, (c) water leaving radiance at 492 nm, (d) chlorophyll-α concentration.

method of assessing the aerosol condition and water leaving radiance.

Although not enough field measurements have been made to confirm the accuracy of

OCITRAN-2 directly, the OCITRAN-2 results still can be evaluated by comparison with SeaDAS estimates. The results show that correlation coefficients of water leaving radiance and chlorophyll concentration are greater than 0.70 and 0.83, respectively. The estimates are more consistent where the chlorophyll is lower than 10 mg/m^3. The high correlation between the OCITRAN-2 and SeaDAS model estimates reveals that the improvements in OCITRAN-2 do promote its accuracy over OCITRAN-1.

The water leaving radiance around cloud edge areas and thin cloud areas seems to be overestimated significantly by OCITRAN-2. Hence, to reduce the radiance contamination by neighboring cloud edges and thin cloud pixels should be added. Of course, field measured data collected in situ to verify the OCITRAN-2 estimation will be crucial for making further improvements in the OCITRAN series.

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REFERENCES

Buglia, J. J., 1986: Introduction to the Theory of Atmospheric Radiative Transfer, Chapter 5, NASA reference publication 1156, 59-103.

Eckstein, B. A. and J. J. Simpson, 1991: Aerosol and Rayleigh radiance contributions to coastal zone color scanner images. *Int. J. Remote Sensing*, **12**, 135-168.

Gathman, S.G. 1983: Optical properties of the marine aerosol as predicted by the Navy model. *Optical Engineering*, **22**, 57-62.

Gordon, H. R, D. K. Clark, J. W. Brown, O. B. Brown, R. H. Enans, and W. W. Broenkow, 1983:Phytoplankton pigment concentrations in the Middle Atlantic Bight: comparison of ship determinations and CZCS estimates. *Appl. Opt.*, **22**, 20-36.

Gordon, H. R., J. W. Brown, and O. B. Evans, 1988: Exact Rayleigh scattering calculations for use with the Nimbus-7 coastal zone color scanner. *Appl. Opt.*, **27**, 862-871.

Gregg, W. W. and K. L. Carder, 1990: A simple spectral solar irradiance model for cloudless maritime atmospheres. *Limnol. Oceanogr.*, **35**, 1657-1675.

Liu, G. R., S. J. Huang, T. H. Kuo, W. J. Chen, and C. Y. Tseng, 1999a: The Atmospheric Effect Correction of the Ocean Color Imager of ROCSAT-1-Simulations and Using SeaWiFS Data as the Example. *TAO, Supplementary Issue*, 99-114.

Liu, G. R., S. J. Huang, T. H. Kuo, 1999b: The Atmospheric Correction of ROCSAT-1 OCI Imagery-Part I: OCITRAN-1. *TAO*, **10**, 855-864.

McClain, C. R., and E. N. Yeh, 1994: Sun Glint Flag Sensitivity Study, NASA Tech. Memo. 104566(13), S.B. Hooker and E.R. Firestone Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 51pp.

O'reilly, J. E., S. Maritorena, B. G. Mitchell, D. A. Siegel, K. L. Carder, S. A. Garver, M. Kahru, and C. McClain, 1998: Ocean color chlorophyll algorithm for SeaWiFS. *J. Geophys. Res.*, **103 (C11)**, 24937-24953.