Preliminary study on the orbit cross-calibration of CMODIS by SeaWiFS*

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Abstract China launched its third spaceship SZ-3 in March, 2002 on which the main remote sensor is the Chinese moderate imaging spectra radiometer (CMODIS). In this paper the properties of CMODIS are firstly introduced briefly. Then, the theory and algorithm of cross-calibration for CMODIS ocean color channels by the sea-viewing wide field-of-view sensor (SeaWiFS) data are discussed in detail. The total radiance (TOA) of four quasi-synchronized crossing ocean areas simulated by SeaWiFS and measured by CMODIS are compared and the calibration coefficients are derived from the relationship between them. Finally, the *in-situ* water leaving radiance data are used to validate the calibration results. The results show that the cross-calibration method could provide reasonable precision for ocean color measurement.

Keywords: **CMODIS, SeaWiFS, cross-calibration.**

Most areas of China Seas belong to case 2 water, and the algorithm based on the ratio of green to blue is not suitable to those areas[1] because two or more substances with different optical properties are presented which do not co-vary with chlorophyll a concentration. These might be water with exceptional plankton blooms (such as red tides), discolored by retained and organic suspended materials and the dissolved organism material (DOM), such as acids. It is, therefore, essential to develop more channels with more sensitive sensors for Chinese coastal water detection. One sensor (CMODIS) has been developed by Shanghai Institute of Physics and Technology (SIPT) and tested on the spaceship Shen Zhou-3 (SZ-3) which was launched in March 2002 and its orbit is non-sun-synchronous at altitude of 343 km. CMODIS has totally 34 channels (30 channels of 20 nm wavelength in the spectral range of 0.403 ~ 1.043 μm, and four infrared channels with 2.15 ~ 2.25 μm, 8.4 ~ 8.5 μm, 10.3 ~ 11.3 μm and 11.5 ~ 12.5 μm) and its instant field of view is 1.2 mr with 1024 pixels one line and quantification of 12 bits.

The key to ocean color remote sensing is the radiance measurement accuracy, because the water leaving radiance is only about 5% to 10% of the total radiance arriving at the sensor at the satellite altitude[1]. It is necessary to guarantee the accuracy of water leaving radiance measurement of about 5% (relative error) to meet the chlorophyll accuracy of about 30 % in case 1 water[2]. When a sensor has been in orbit, it is important to take orbit calibration to make up some deficits of the pre-launch calibration in the laboratory. Two kinds of data could be used for orbit calibration: one is *in situ* measurement data, so-called *in situ* field calibration, and the other one is satellite data with higher radiance measurement accuracy, so-called crossing-calibration. In this paper, SeaWiFS data are used for CMODIS orbit calibration.

1 Mechanism of orbit crossing calibration

In principle, if two sensors measure the same target under the same observation condition, the measured radiance of the target by two sensors should be the same. So, for one unknown sensor its accuracy in the orbit could be calibrated by another sensor with higher accuracy by the comparison of the radiance measured by two sensors respectively. The SeaWiFS accuracy of radiance measurement is higher than 5 percentage (relative error)[3], so CMODIS is possible to be calibrated by SeaWiFS, even though two sensors have their own observation geometric parameters which depend on the zenith of the sun and sensor, and azimuth between sensor and sun, supposed to be

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$(Q_0, Q_v, \Delta\phi)^{swf}$ and $(Q_0, Q_v, \Delta\phi)^{CMODIS}$ for SeaWiFS and CMODIS observation geometry respectively[4]. First, the normalized water leaving radiance is possible to be calculated by SeaWiFS, and the type of aerosol can also be decided by the SeaWiFS also with observation geometry $(Q_0, Q_v, \Delta\phi)^{swf}$, by means of atmospheric correction algorithm. Then the total radiance arriving at CMODIS will be simulated with the observation geometry $(Q_0, Q_v, \Delta\phi)^{CMODIS}$ by means of the known water leaving radiance and aerosol type from SeaWiFS for the same target, such as clear water target. Finally the calibration coefficients can be derived by the comparison of the total radiance measured by CMODIS and simulated with SeaWiFS data. The mechanism of CMODIS crossing calibration by SeaWiFS data is shown in Fig. 1.

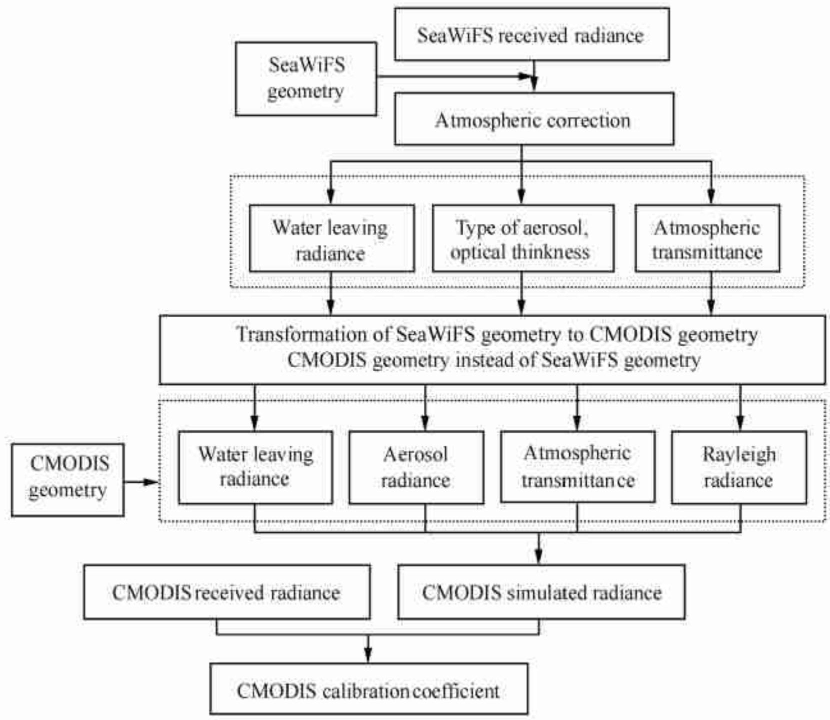

Fig. 1. The diagram of mechanism of CMODIS crossing calibration by SeaWiFS.

The procedures of the CMODIS crossing calibration are as follows:

The aerosol single scattering albedo of band 865 nm of SeaWiFS, $[\rho_{as}(865)]^{SWF}$, and the normalized water leaving radiance $[L_{wn}]^{SWF}$ of SeaWiFS's different bands are calculated by atmospheric models.

The total radiance arriving at CMODIS is simulated in the CMODIS observation geometry $(Q_0, Q_v, \Delta\phi)^{CMODIS}$ and by means of $[\rho_{as}(865)]^{SWF}$ and $[L_{wn}]^{SWF}$ as the following:

(i) Calculation of the down and up transmittance of ozone, $[t\text{-oz-sol}]^{CMODIS}$, $[t\text{-oz-sen}]^{CMODIS}$.

(ii) Calculation of Rayleigh scattering $[\rho_r]^{CMODIS}$.

(iii) Calculation of multi-scattering $[\rho_a]^{CMODIS}$ by the single scattering

$$\rho_{as} = (\tau_a \varpi_a P_a)/4(\cos\theta_0 \cos\theta_v). \quad (1)$$

The single scattering of CMODIS band 865 nm $[\rho_{as}(865)]^{CMODIS}$ is calculated by

$$[\rho_{as}(865)]^{CMODIS} = [\rho_{as}(865)]^{SWF} Z \times \frac{P_a(\theta_0, \theta_v, \Delta\phi)^{CMODIS}}{P_a(\theta_0, \theta_v, \Delta\phi)^{SWF}} \times \frac{[\cos\theta_0 \cos\theta_v]^{SWF}}{[\cos\theta_0 \cos\theta_v]^{CMODIS}}. \quad (2)$$

Here, the aerosol type and optical thickness of CMODIS are supposed to be the same as SeaWiFS's. The aerosol of different bands of CMODIS can be extracted by $[\rho_{as}(865)]^{CMODIS}$, then the aerosol multi-scattering of different bands of CMODIS could be derived by $[\rho_a]^{CMODIS}$;

(iv) Calculation of atmospheric down and up transmittance $[t\text{-sol}]^{CMODIS}$, $[t\text{-sen}]^{CMODIS}$.

(v) Calculation of water leaving radiance $[L_w]^{CMODIS}$ by

$$L_{wn} = L_w / (t\text{-}sol \times t\text{-}oz\text{-}sol \times \cos(\vartheta_0)). \quad (3)$$

Then, the water leaving radiance $[L_w]^{CMODIS}$ with CMODIS geometry is

$$[L_w]^{CMODIS} = [L_{wn}]^{SWF} \times \lfloor [t\text{-}sol]^{CMODIS} \times [t\text{-}oz\text{-}sol]^{CMODIS} \times \cos(\vartheta_0) \rfloor. \quad (4)$$

(vi) Modified by ozone absorption and wavelength effective for $[\rho_r]^{CMODIS}$, $[\rho_a]^{CMODIS}$, $[L_w]^{CMODIS}$, we have

$$\begin{cases} [\rho_r^*]^{CMODIS} = [\rho_r]^{CMODIS} \times [t\text{-}oz\text{-}sol]^{CMODIS} \times [t\text{-}oz\text{-}sen]^{CMODIS} \times \beta_r \\ [\rho_a^*]^{CMODIS} = [\rho_a]^{CMODIS} \times [t\text{-}oz\text{-}sol]^{CMODIS} \times [t\text{-}oz\text{-}sen]^{CMODIS} \times \beta_a \\ [L_w^*]^{CMODIS} = [L_w]^{CMODIS} \times [t\text{-}oz\text{-}sen]^{CMODIS} \times \beta_w. \end{cases} \quad (5)$$

Here, $[\rho_r^*]^{CMODIS}$, $[\rho_a^*]^{CMODIS}$, $[L_w^*]^{CMODIS}$ are modified by ozone absorption and wavelength effective coefficients, β_r, β_a, β_w are the wavelength effective coefficients of $[\rho_r^*]^{CMODIS}$, $[\rho_a^*]^{CMODIS}$, $[L_w^*]^{CMODIS}$ respectively.

(vii) Simulating the spectrum of $[\rho_r^*(\lambda)]$, $[\rho_{am}^*(\lambda)]$, $\lfloor L_w^*(\lambda) \rfloor$, $[t\text{-}sen(\lambda)]$ with the wavelength range of 400~900 nm by the step 0.5 nm using $[\rho_r^*]^{CMODIS}$, $[\rho_a^*]^{CMODIS}$, $[L_w^*]^{CMODIS}$ and $[t\text{-}sen(\lambda_i)]^{CMODIS}$.

(viii) Finally, simulating the total radiance arriving at CMODIS:

$$\langle L_t \rangle = \langle L_r \rangle + \langle L_a \rangle + \langle tL_w \rangle. \quad (6)$$

Here $\langle L_r \rangle$, $\langle L_a \rangle$, $\langle tL_w \rangle$ are

$$\begin{cases} \langle L_r \rangle = \dfrac{\int ([\rho_r^*(\lambda)] \times F_0(\lambda) \times \cos(\theta_0)/\pi) \times S(\lambda) d\lambda}{\int S(\lambda) d\lambda}, \\ \langle L_a \rangle = \dfrac{\int ([\rho_a^*(\lambda)] \times F_0(\lambda)^* \cos(\theta_0)/\pi) \times S(\lambda) d\lambda}{\int S(\lambda) d\lambda}, \\ \langle tL_w \rangle = \dfrac{\int [L_w(\lambda)] \times [t\text{-}sen(\lambda)] \times S(\lambda) d\lambda}{\int S(\lambda) d\lambda}, \end{cases} \quad (7)$$

in which F_0 is solar irradiance at top of atmosphere, S is wavelength response of CMODIS.

2 Crossing calibration

Based on the mechanism of crossing calibration, it is very important to have the suitable same targets, e.g. crossing cover areas by both of CMODIS and SeaWiFS. The conditions of crossing areas are supposed as

(i) Clear water area without cloud or haze,

(ii) stable atmospheric aerosol during the time gap between CMODIS and SeaWiFS observation,

(iii) homogenous optical prosperity,

(iv) the crossing area is better near satellite nadir,

(v) the observation time between CMODIS and SeaWiFS is not too long, the better within 2 hours. Chooseing more crossing areas (at least two) is necessary. Here, four crossing areas are selected for calibration (Table 1).

Table 1. Crossing areas used for CMODIS calibration by SeaWiFS

Areas	SeaWiFS observation time	CMODIS observation time	Center longitude	Center latitude
1	2002/06/02/T12:00	2002/06/02/T14:17	123.15°	38.85°
2	2002/06/03/T12:00	2002/06/03/T14:17	128.25°	31.50°
3	2002/06/07/T12:00	2002/06/07/T12:03	123.94°	27.43°
4	2002/06/07/T12:00	2002/06/07/T12:03	120.13°	31.21°

The CMODIS total radiance of top atmosphere (TOA) is simulated for four areas as above discussed procedures, and compared with the measured total radiance of top atmosphere (see Fig. 2). It is obvious that the simulated total radiance $\langle L_t \rangle$ by SeaWiFS is higher than measured radiance L_t by CMODIS, but the relationship between $\langle L_t \rangle$ and L_t is similar and can be derived by regression from the four crossing calibration areas as follows:

$$\langle L_t(\lambda) \rangle = a(\lambda) + b(\lambda) \cdot L_t(\lambda) + c(\lambda) \cdot L_t^2(\lambda), \quad (8)$$

where a, b and c are derived from four crossing areas listed in Table 2, then formula (8) could be applied to calibration of CMODIS data.

Table 2. The crossing calibration coefficients of different channels

Wavelength (nm)	Coe. a	Coe. b	Coe. c	Wavelength (nm)	Coe. a	Coe. b	Coe. c
413	7.764	−0.873	0.0816	613	1.024	0.128	0.0629
433	5.378	−0.460	0.0689	633	0.853	0.139	0.0670
453	4.644	−0.261	0.0572	653	0.619	0.099	0.0700
473	4.159	−0.271	0.0482	673	0.440	0.104	0.0744
493	2.910	−0.137	0.0483	693	0.428	0.040	0.0860
513	2.185	−0.038	0.0475	713	0.743	−0.270	0.1433
533	1.732	0.031	0.0490	733	1.268	−0.720	0.2411
553	1.467	0.029	0.0499	753	0.863	−0.523	0.2324
573	1.223	0.081	0.0539	773	0.549	−0.352	0.2254
593	0.905	0.119	0.0600				

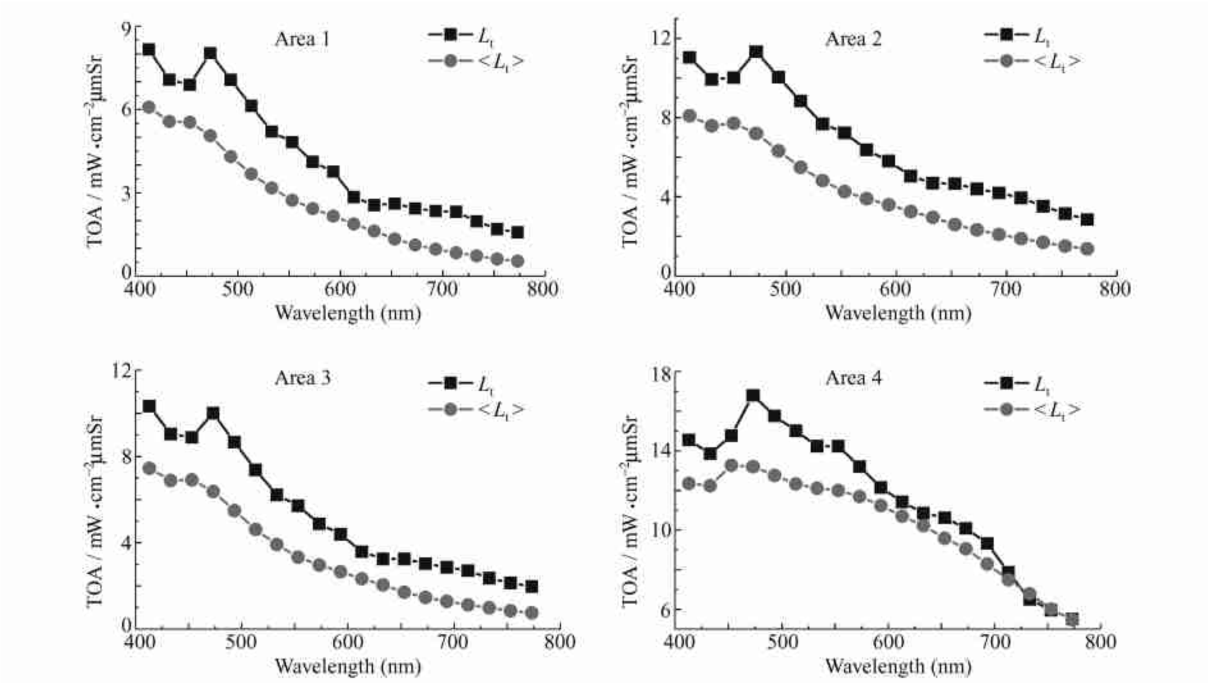

Fig. 2. Comparing the total radiance by simulated $\langle L_t \rangle$ and measured L_t.

3 Results and discussion

In order to test the accuracy of the crossing calibration, the water leaving radiance is calculated from the crossing calibrated data by formula (8) and compared with the water leaving radiance derived from SeaWiFS, whose relative error is less than 7 percent in all of China Seas[5]. The water leaving radiance derived by CMODIS and measured by SeaWiFS is very reasonably correlated, which are derived from CMODIS and SeaWiFS, respectively (see Fig. 3).

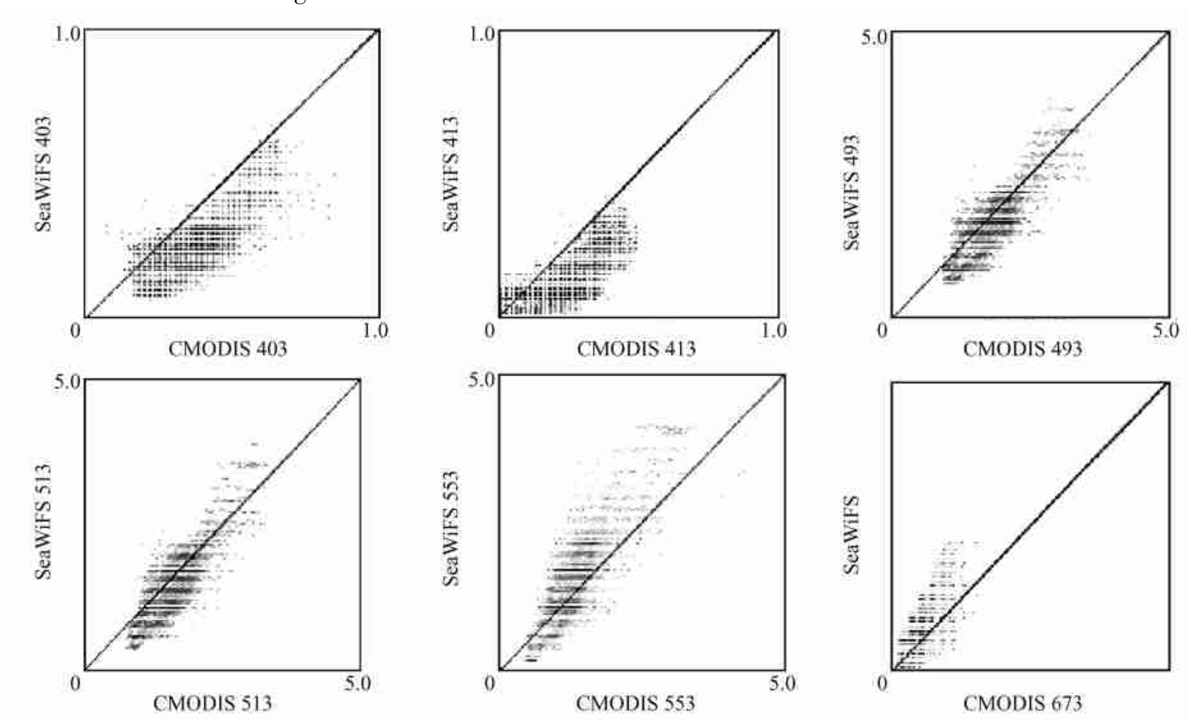

Fig. 3. The comparison between water leaving radiance derived from CMODIS and measured by SeaWiFS.

Fig. 3 shows the following phenomenon: (i) The water leaving radiance derived from CMODIS is higher than that from SeaWiFS in the clear water. (ii) The water leaving radiance of channel 413 nm between SeaWiFS and CMODIS is not linearly correlated, because of the limitation of atmospheric correction algorithm for the tested areas in coastal water area of China Seas and the limitation of the calibration accuracy of this channel. (iii) The distribution of water leaving radiance of CMODIS channel 453 nm is very similar to SeaWiFS channel 443 nm (see Fig. 4), but higher, because of a very high concentration of the suspended materials in the Bohai Sea. (iv) The water leaving radiance of channels 490 nm and 510 nm derived from CMODIS and SeaWiFS have a very good correlation.

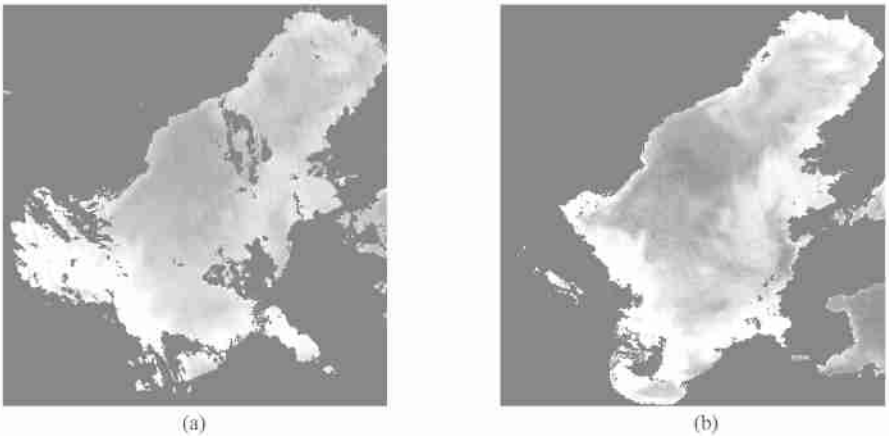

Fig. 4. The water leaving radiance comparison deriving from (a) CMODIS channel 553 nm and (b) SeaWiFS channel 555 nm.

For validation of crossing calibration precision, the water leaving radiance derived from CMODIS is compared with the *in situ* measurement of Taihu area on April 21, 2002. The comparison of the *in situ* average water leaving radiance of close measure points of Taihu with synchronous CMODIS measurement is shown in Fig. 5, which shows that the water leaving radiance derived from crossing calibrated CMODIS data is close to the *in situ* measured data, but it is far off for non-calibrated CMODIS data from the *in situ* data especially the blue bands. So the orbit calibration is necessary for CMODIS, and the crossing calibration is a reasonable method.

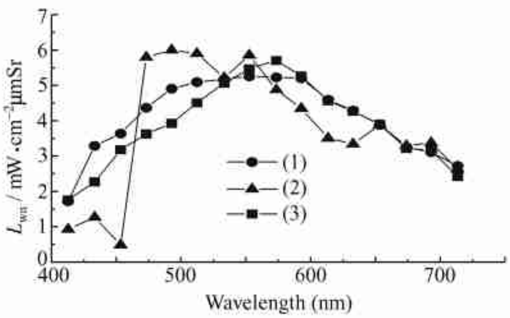

Fig. 5. The comparison of water leaving radiance calculated from crossing calibrated CMODIS data (1) and non-crossing calibrated CMODIS data (2) to the *in situ* measured data (3).

4 Conclusion

(1) The developed technology of crossing calibration could be applied for CMODIS orbit calibration by comparison of the top total radiance measured by CMODIS and simulated by SeaWiFS.

(2) The results also show that the pre-launch calibration of CMODIS is not enough to meet the requirement of radiance measurement, so the orbit calibration is necessary to be done.

(3) Comparing other ways of orbit calibration, the crossing calibration is the practical and economical method for developing countries.

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