Corrections to the MODIS Aqua Calibration Derived From MODIS Aqua Ocean Color Products

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***Abstract*—Ocean color products such as, e.g., chlorophyll-a concentration, can be derived from the top-of-atmosphere radiances measured by imaging sensors on earth-orbiting satellites. There are currently three National Aeronautics and Space Administration sensors in orbit capable of providing ocean color products. One of these sensors is the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite, whose ocean color products are currently the most widely used of the three. A recent improvement to the MODIS calibration methodology has used land targets to improve the calibration accuracy. This study evaluates the new calibration methodology and describes further calibration improvements that are built upon the new methodology by including ocean measurements in the form of global temporally averaged water-leaving reflectance measurements. The calibration improvements presented here mainly modify the calibration at the scan edges, taking advantage of the good performance of the land target trending in the center of the scan.**

***Index Terms*— Calibration, image sensors, remote sensing.**

I. Introduction

THE feasibility of deriving ocean color products (e.g., water-leaving radiances[1] and chlorophyll-a concentration) was demonstrated by the Coastal Zone Color Scanner, which was launched in 1978. It provided limited global coverage over a period of eight years. The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) provided full global coverage from 1997 to 2010, adding critical bands in the VIS and NIR spectrum. Since then, there have been four more sensors providing ocean color products with full global coverage: 1) two Moderate Resolution Imaging Spectroradiometer (MODIS), which were launched in 1999 on the Terra satellite and in 2002 on the Aqua satellite; 2) the MEdium Resolution Imaging Spectrometer, which was launched in 2002 on the ENVISAT platform; and 3) the Visible Infrared Imager Radiometer Suite (VIIRS), which was launched in 2011 on the Suomi NPP satellite. The ENVISAT mission ended April 8, 2012, due to a communication loss with the satellite. Of the remaining three sensors in orbit, MODIS Aqua is the most heavily used by oceanographers because the VIIRS data are still in beta stage (unvalidated) and the MODIS Terra products are compromised by sensor artifacts [6]. Therefore, MODIS Aqua ocean color data are crucial for continuing the ocean color climate data record started by SeaWiFS. All future references in this paper to MODIS will refer to the MODIS on Aqua (the calibration status of MODIS Terra up to 2011 is described by Meister and Franz [10]; a recalibration of MODIS Terra using the results for MODIS Aqua described in this paper was implemented in 2013).

TABLE I
Center Wavelengths of the MODIS Ocean Color Bands

Band	8	9	10	11	12	13	14	15	16
Wavelength [nm]	412	443	488	531	547	667	678	748	869

Ocean color products are extremely sensitive to radiometric trending errors. SeaWiFS achieved long-term trending accuracy on the order of 0.1% [2], with lunar calibrations being the primary calibration method. Although MODIS is capable of viewing the moon as well, it cannot base its calibration on the moon the way SeaWiFS did. The main reason is that the MODIS radiometric degradation has been strongly scan angle dependent. Since the moon is measured by MODIS through the space view port [14] at a fixed angle (at the beginning of scan), additional calibration sources are needed to determine the radiometric degradation at the remaining scan angles.

An onboard solar diffuser is central to the calibration of the MODIS ocean color bands [15]. It is viewed by MODIS in the second half of the scan, providing another calibration source at an angle sufficiently different from the lunar view angle. For MODIS bands 8–12 (see Table I), these two calibration sources provided a calibration that, with only minor adjustments (e.g., destriping [11], seasonal gain corrections [12], etc.), resulted in reasonable trends for ocean color products [4] during the early years of the mission. Note that, for bands 13–16, solar diffuser measurements were the sole calibration source because the lunar measurements of these bands are partially saturated.

However, starting from 2008, it became clear that additional corrections were necessary for bands 8 and 9 in the later part of the mission. These corrections are described in [9]. These corrections used the ocean color products from the SeaWiFS instrument as a vicarious calibration source. Unfortunately, the demise of SeaWiFS in 2010 required a new approach.

In 2011, the MODIS Calibration Support Team (MCST) developed a new method for determining the radiometric degradation of the MODIS bands [13]. In the case of MODIS Aqua, desert sites are now used to support the derivation of the radiometric degradation as a function of scan angle for bands 8

Manuscript received April 15, 2013; revised November 18, 2013; accepted December 10, 2013. Date of publication January 27, 2014; date of current version May 22, 2014.

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Digital Object Identifier 10.1109/TGRS.2013.2297233

[1] See Franz *et al.* [5] for a recent definition of the term.

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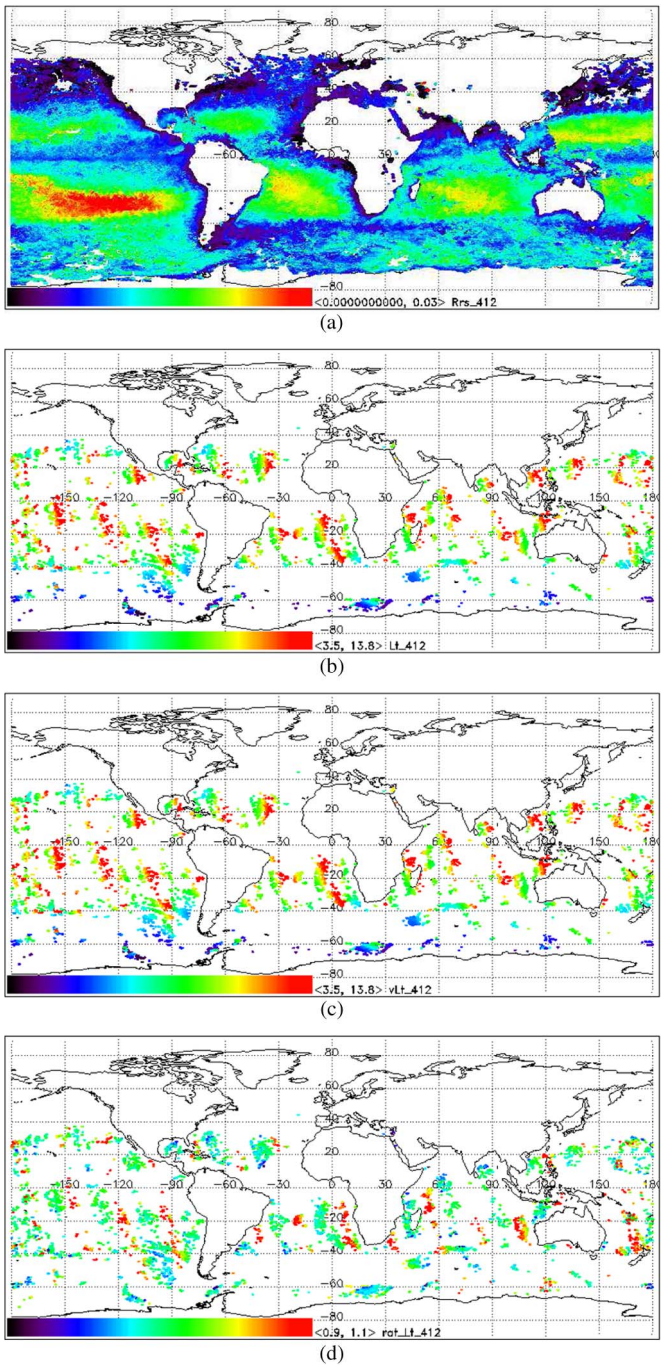


Fig. 1. (a) SeaWiFS Rrs at 412 nm, 15-day L3 file (days 53–77 of 2009). (b) Measured TOA radiance L_m at 412 nm as measured by MODIS Aqua on day 65 of 2009. (c) Vicarious TOA radiance vL_t at 412 nm (from SeaWiFS L3). (d) Ratio L_m/vL_t.

and 9. These new corrections have been applied to the MODIS products in 2012 with the "MODIS Collection 6" release in early 2012. The analysis presented in this paper starts with the MODIS Collection 6 calibration as provided by MCST.

In Section II, we briefly describe the cross-calibration approach developed by the Ocean Biology Processing Group (OBPG) that is central to this paper. In Section III, we use the cross-calibration approach to demonstrate that the MODIS Collection 6 calibration approach produces results that lead to consistent ocean color products for the central parts of the scan,

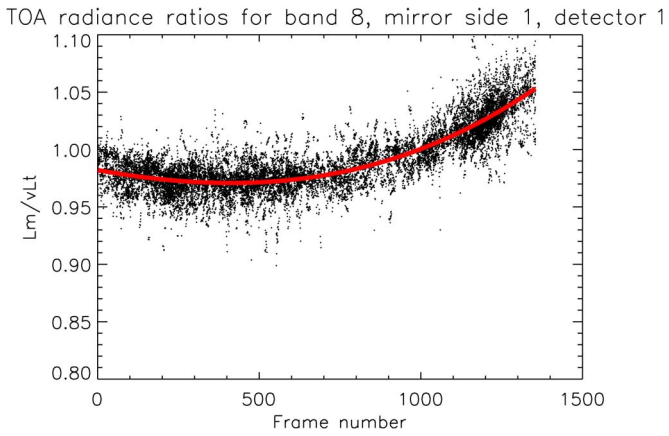


Fig. 2. (Red line) Correction coefficients M_{11} as a function of frame number, derived from the (black dots) ratios L_m/vL_t (see Fig. 1 for geographic distribution) for MODIS band 8, detector 1, mirror side 1, day 65 of 2009.

but not for the edges of the scan. Then, in Section IV, we apply the cross-calibration approach using only MODIS data from the central part of the scan as a calibration source in order to improve the calibration at the scan edges.

II. Methodology

The methods underlying the analysis presented in this paper have been presented before; thus, only a short summary will be given here.

The temporal anomaly plots show the difference of a global average of an ocean color product from the annual cycle as a function of time. The temporal anomaly plots used in this paper are based on the global average for deep-water ocean (depth $>$ 1 km). The scan angle anomaly plots show the level-2 (L2, unaggregated) ocean color product as a function of scan angle for a given day, divided by the corresponding level-3 (L3) bin [averaged over time (seven days) and area (9 km $\times$ 9 km)] and averaged over deep-water regions. A more detailed explanation of the algorithms used for the temporal anomaly plots and the scan angle anomaly plots is given in [6].

The cross-calibration method was introduced by Kwiatkowska *et al.* [8] and applied to MODIS on Terra. Its first application to MODIS on Aqua is described in [9]. In each case, coefficients were derived, which corrected the MODIS top-of-atmosphere (TOA) radiances and the MODIS polarization sensitivity as a function of time and scan angle, minimizing the difference to SeaWiFS L3 ocean color products. The coefficients are defined by Gordon *et al.* [7], i.e.,

$$L_m = M_{11} \cdot (L_t + m_{12} \cdot (Q_t \cos 2\alpha + U_t \sin 2\alpha) + m_{13}(-Q_t \sin 2\alpha + U_t \cos 2\alpha)) \quad (1)$$

where (L_t, Q_t, U_t) are the first three components of the Stokes vector at the TOA, L_m is the radiance measured by MODIS, and α is a rotation angle to adjust for different reference frames used in the calculation of Q_t and U_t. The coefficients M_{11}, m_{12}, and m_{13} are derived as a function of time; scan angle; and for each MODIS detector, mirror side, and bands 8–14. For M_{11}, a value of 1.0 corresponds to no correction relative to the MCST calibration. For m_{12} and m_{13}, values of 0.0 correspond to no

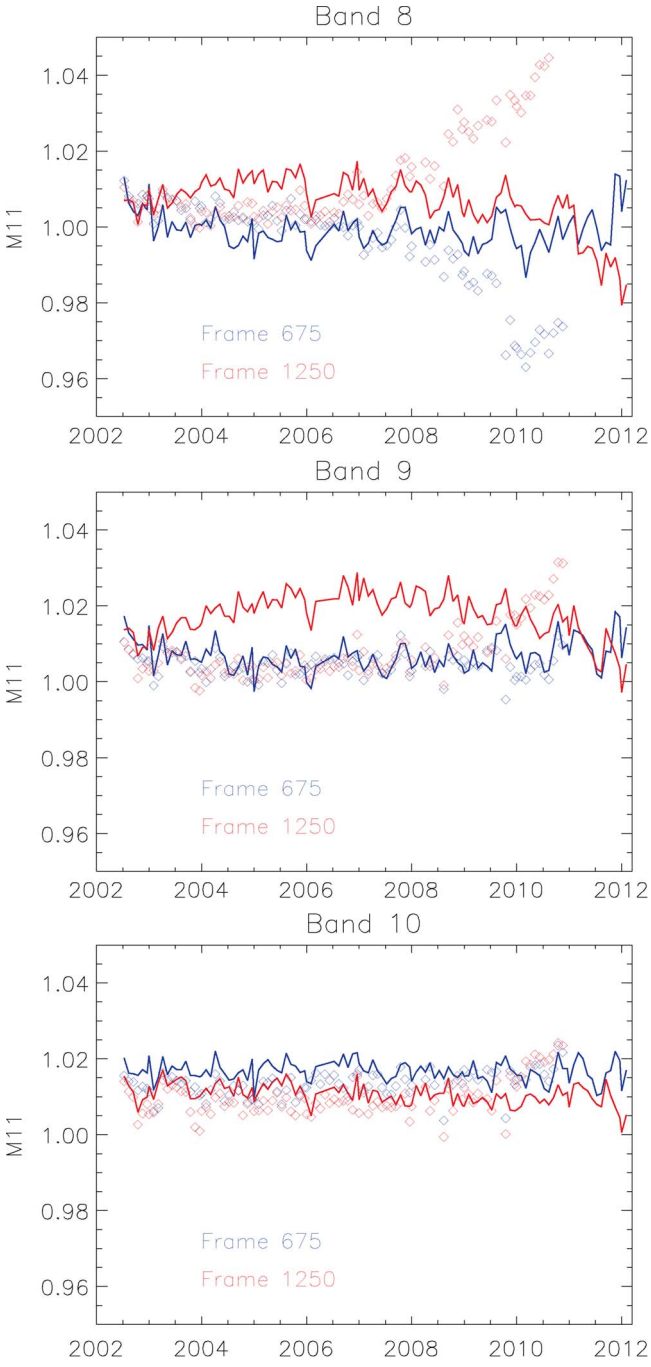


Fig. 3. Cross-calibration coefficients M_{11} for (diamonds) MODIS Aqua (with old MCST calibration) to SeaWiFS monthly measurements (R2010.0) and (solid line) MODIS Aqua (with new MCST calibration) to SeaWiFS climatology at nadir (frame 675) and end of scan (frame 1250). Data are for mirror side 1, detector 1, bands 8–10 (see plot title), without temporal averaging.

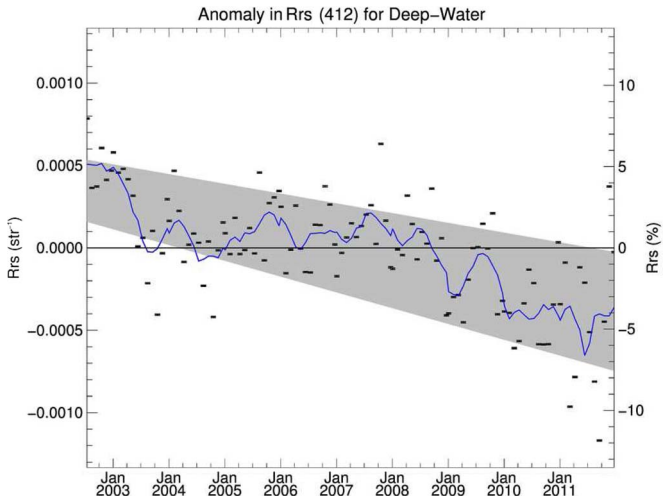


Fig. 4. Temporal anomaly plot for MODIS Aqua Rrs at 412 nm (band 8), using MCST's new MODIS Collection 6 calibration approach. The temporal anomaly is the difference to the mean seasonal cycle. The mean seasonal cycle is calculated by averaging the MODIS Aqua data for each month of the year over all years of the mission. Black dots show anomalies for each month (averaged over four days, for each month), blue line shows anomalies smoothed over time (seven-month boxcar average), and the gray area shows the range of linear trends (derived from 2σ uncertainties of the linear fit). See Section II and [6] for further details regarding the calculation of the temporal anomaly.

sensitivity to polarization. Note that for MODIS Terra, a significant change in polarization sensitivity was derived, whereas for MODIS Aqua, no significant change in polarization sensitivity was detected, and therefore, the prelaunch polarization sensitivities are applied, and only M_{11} are retrieved. A separate paper is in preparation, which focuses on the on-orbit change in the polarization sensitivities for both MODIS instruments.

The cross-calibration method is illustrated in Fig. 1. The input data are shown on the top: the SeaWiFS truth data [see Fig. 1(a); temporally averaged ocean color product, in this case, Rrs at 412 nm][2] and the TOA radiance measured by MODIS Aqua [see Fig. 1(b)]. For the solar and viewing geometry of the MODIS Aqua data, the SeaWiFS Rrs is converted to TOA radiance by an inverse atmospheric correction (see [5]), using information about the aerosols derived from the MODIS Aqua NIR bands (i.e., it is implicitly assumed that the MODIS NIR bands do not need corrections). The resulting vicarious TOA radiance vL_t is shown in Fig. 1(c). Qualitatively, the results look very similar to the TOA radiances measured by MODIS Aqua. However, the ratio of the two [see Fig. 1(d)] reveals that there are differences on the order of several percent.

The corrections are derived for each mirror side and detector. As an example, the ratios L_m/vL_t in Fig. 1(d) only for mirror side 1 and detector 1 are shown as a function of frame number in Fig. 2 [note that frame number (1–1354) is proportional to scan angle (-55° to $+55^\circ$) for MODIS Aqua]. A fourth-order polynomial as a function of frame number is fitted to the data (red line in Fig. 1).[3] The values of this polynomial are the correction coefficients M_{11} for this particular day, band, detector, and mirror side. Before applying the correction to MODIS Aqua data for ocean color processing, the correction coefficients M_{11} are temporally smoothed by fitting a fifth-order polynomial as a function of time.

III. Cross Calibration of MODIS to SeaWiFS

This section will demonstrate that the new MCST calibration (Collection 6 release 2012) produces superior results relative to the previous calibration. The previous calibration was evaluated

[2]Rrs is remote sensing reflectance (see [1] for a definition); it is essentially the normalized water-leaving radiance divided by the solar irradiance.

[3]Note that, in [9], a third-order polynomial was used; a fourth-order polynomial was chosen to match the MCST approach, which also uses a fourth-order polynomial.

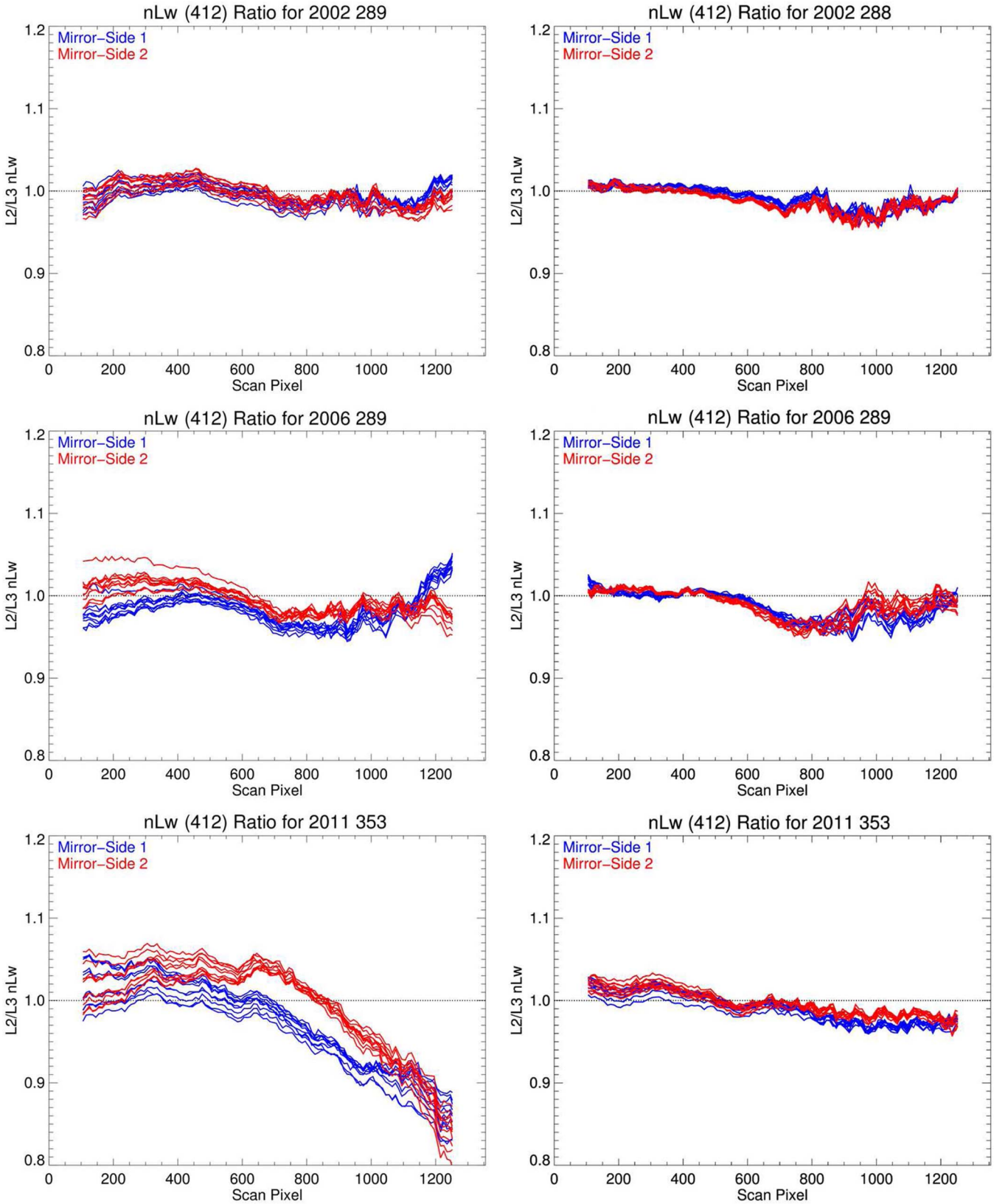


Fig. 5. Response versus scan plots for MODIS Aqua Rrs at 412 nm (band 8) in (top) late 2002, (middle) late 2006, and (bottom) late 2012, (left) using MCST's new MODIS Collection 6 calibration approach and (right) adding the cross-calibration correction.

in a previous paper ([9]), and some of the previous results will be shown here for comparison purposes. The cross-calibration coefficients from the paper of Meister *et al.* will be compared with the cross calibrations derived using the new MCST calibration and the SeaWiFS monthly climatology (a climatology needs to be used to retrieve data beyond the end of the SeaWiFS mission). Note that these cross-calibration coefficients are only used here; the following section describes the approach for the

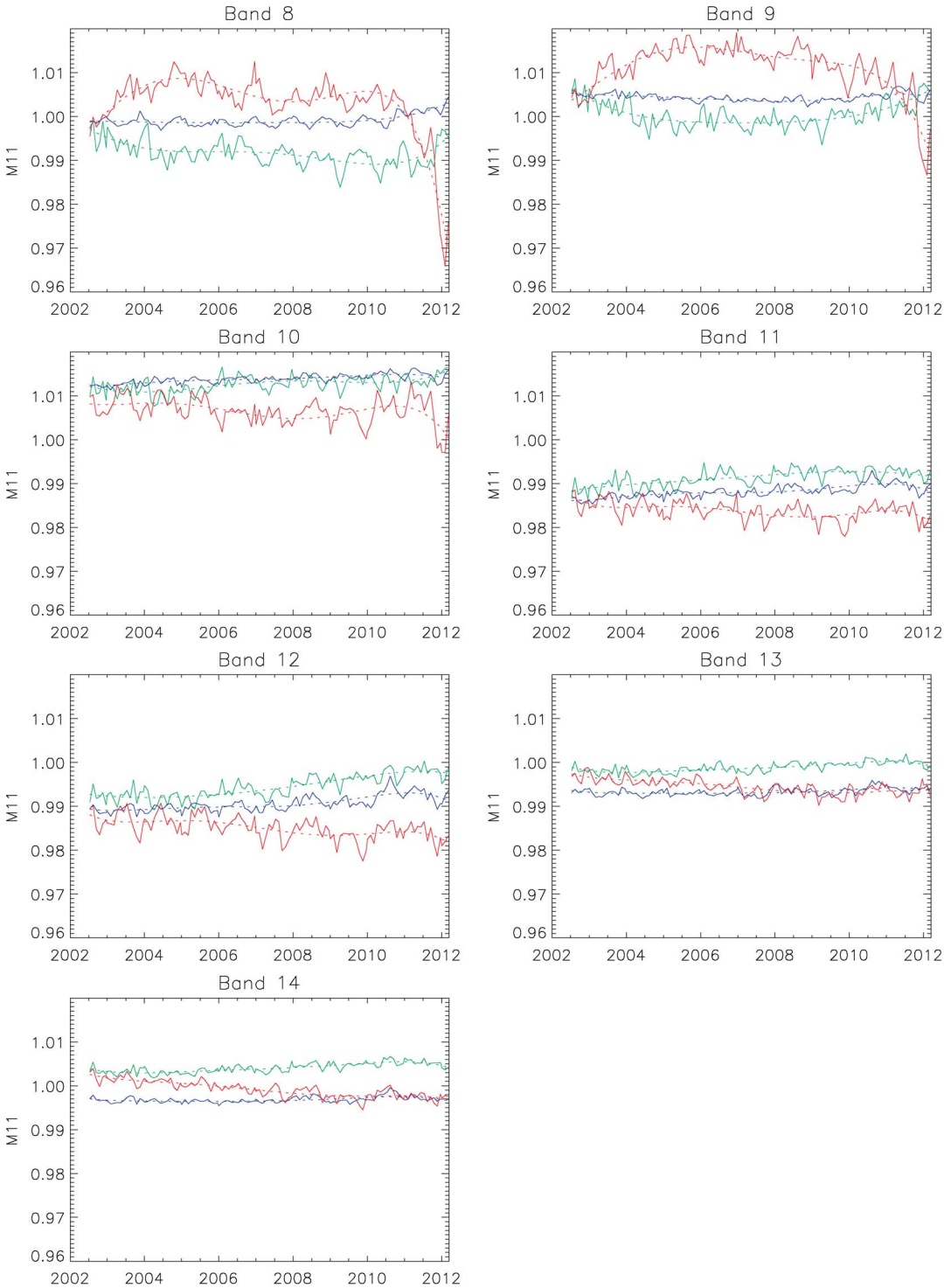


Fig. 6. Cross-calibration coefficients M_{11} for MODIS Aqua to itself at beginning of scan (green, frame 100), nadir (blue, frame 675), and end of scan (red, frame 1250). Data are for mirror side 1, detector 1. The solid line shows the original M_{11} from each month; the dashed line shows the M_{11} after temporal smoothing (fitting a third-order polynomial as a function of time).

derivation of the cross-calibration coefficients that are applied in the operational ocean color processing.

Fig. 3 shows the two sets of cross-calibration coefficients for two scan angles: near nadir (frame 675) and close to the end of scan (frame 1250, scan angle of about 46.5°). The band 8 cross-calibration coefficients for the old calibration (diamonds in Fig. 3) show, starting from 2007, a strong increase at the end of scan and a decrease for nadir. On the other hand, the new band 8 coefficients (solid lines in Fig. 3) are much closer to 1, and only starting from 2011, the end of scan data consistently differ from unity. This means that the new calibration approach by MCST is much more consistent with the assumption that there are no long-term trends in the water-leaving reflectance in the global oceans than the previous MCST calibration approach. This is confirmed by the temporal anomaly plot shown in Fig. 4, which shows a decline of the MODIS Aqua 412-nm Rrs of about

5% over ten years. This is a significant improvement over the previous MCST calibration approach, which showed a drop of about 20% (see [9, Fig. 8]) over eight years.

There is an improvement for the other bands as well, as shown for bands 9 and 10 in Fig. 3, but the effect is strongest for band 8.

Fig. 3 shows that some issues still remain. The end of mission decline in band 8 was mentioned earlier; the end-of-scan correction coefficients for band 9 are too low at both the end and the beginning of the mission, but too high in the middle. This is confirmed in Fig. 5, which shows the scan angle anomaly for band 8 at three dates (2002, 2006, and 2011). The ordinate in these plots is the global average of the L2 data from the date given in the plot title, divided by the corresponding seven-day L3 file, plotted as a function of scan angle/pixel (see [6] for further details regarding the scan angle anomaly evaluation procedure). In 2011, the global average is too low at the end of scan relative to the middle and the beginning of scan. Note that, in 2002, there is no apparent scan angle anomaly for band 8.

IV. Cross Calibration of MODIS to MODIS

The use of a climatology (as was done in the previous section) is useful for evaluating different calibration approaches, but it is an unsatisfying calibration approach in itself because the resulting ocean color products will, by design, never show global secular trends. Therefore, a different approach is presented here.

The new MCST approach resulted in cross-calibration coefficients that were close to unity in the center of scan, but some differences at the end of scan (see Fig. 3) and at the beginning of scan (not shown) remain. The differences are concentrated in the first and last 300 frames of the scan. Therefore, we derived L3 global ocean color products with the new MCST calibration approach, using only frames 300–1050. These L3 data were then used as a calibration source (instead of the SeaWiFS climatology) to derive cross-calibration coefficients for all frames (1–1354). The resulting coefficients are shown in Fig. 6. As expected, the coefficients for the center of scan do not show strong temporal dependence, whereas for the scan edges, particularly at the end of scan, there is a trend for most bands.

Note that the strong decrease in M_{11} at the end of scan for bands 8 and 9 was derived for the MCST calibration table version V6.1.15.2. Partly in response to this result, MCST has provided updated calibration tables to the OBPG (V6.1.17.7_OC and later, not used in this paper) that largely remove this effect.

The temporal anomaly based on these new cross-calibration corrections is shown in Fig. 7 for Rrs at 412 nm. The strong downward trend in the data that did not have the cross calibration applied (see Fig. 4) has been removed. It can be also seen that although the data have been cross calibrated to itself, the long-term averages in the Rrs product vary with time (higher than average at the beginning and end of mission, lower from 2010 through 2011). The long-term averages are determined by real physical changes of the observed product and the accuracy of the MCST calibration in the central part of the scan (frames 300–1050).

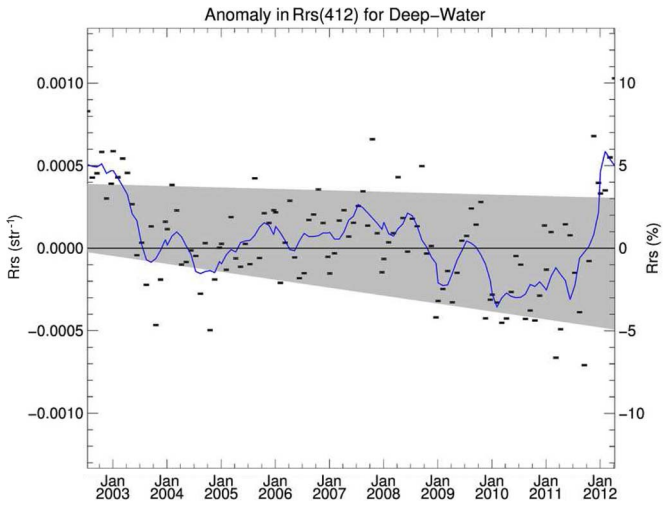


Fig. 7. Temporal anomaly plot for MODIS Aqua Rrs at 412 nm (band 8), using cross calibration of MODIS to itself.

The band 8 scan angle trends in 2006 and 2011 of the data processed without cross calibration (plots on the left in Fig. 5) have been removed as well (plots on the right in Fig. 5). A small residual decrease in the water-leaving radiance with increasing frame number (or "scan pixel" in Fig. 5) remains in 2011 even after applying the cross-calibration corrections. The noise around frame 800 in 2002 and 2006 is most likely due to glint (the glint in MODIS Aqua is usually located around that frame or scan angle).

The correction coefficients were derived for all MODIS ocean color bands (except for the NIR bands). Although the corrections are typically on the order of less than 1% for bands 10–14, they result in improved ocean color products [evaluated by scan angle anomaly plots (see Fig. 8 as an example), where the averages are closer to the 1.0 line for the cross-calibrated data].

Despite the small magnitude of the corrections for bands 10–14, the OBPG chose to apply them for bands 8–14. Previously, temporally dependent corrections were only applied for bands 8 and 9 (see [9]). An interesting example is shown in Fig. 8. The lines (each line represents one of ten detectors) are spread around their mean for the plot on the left for frame numbers less than 700; they converge to their mean in the right plot. This means that a detector bias (which results in image striping) at the beginning of scan is corrected by the cross-calibration coefficients. Note that the ratio of TOA radiances to water-leaving radiances in the open ocean is typically around 20 in the green wavelength bands; this leads to larger magnification of a calibation error in the ocean color product than in the blue bands (their ratio is about 10), but it also means that those bands are more sensitive to errors that are not related to the calibration (e.g., errors related to the removal of sun glint).

It is challenging to display the derived cross-calibration coefficients in a concise way because there are several dimensions that need to be considered (temporal, scan angle, spectral, mirror side, and detector). Fig. 9 shows the dependence of the cross-calibration coefficients M_{11} as a function of time for band 8 for both mirror sides and all ten detectors. It can be seen that in 2002, the M_{11} for all detectors and both mirror sides are close

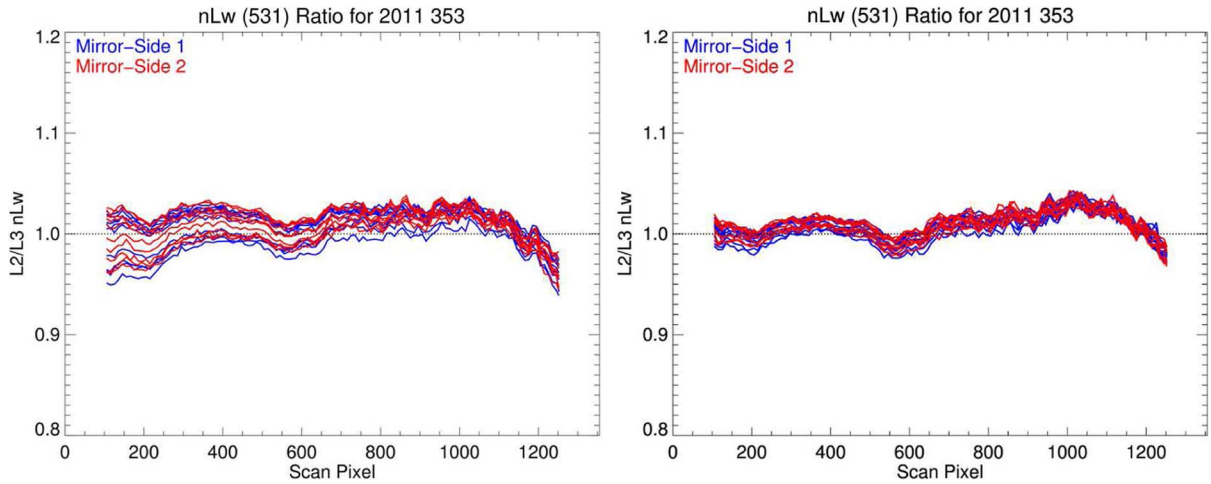


Fig. 8. Response versus scan plots for MODIS Aqua Rrs at 531 nm (band 11) in late 2011, using (left) MCST's new MODIS Collection 6 calibration approach and time-independent scan angle correction and (right) cross-calibration of MODIS to itself.

together for each of the three frames shown. This is consistent with the two top plots in Fig. 5, which show that there is no residual scan angle dependence in any mirror side or detector; therefore, no corrections are needed. In 2006, the two mirror sides clearly differ in Fig. 5, with mirror side 2 higher than mirror side 1 at the beginning and in the middle of the scan and lower at the end of scan. This is consistent with the M_{11} shown in Fig. 9, where mirror side 2 is higher than mirror side 1 in 2006 for frames 100 and 675, but lower for frame 1250. For 2011, both Figs. 5 and 9 show detector variations at the beginning of scan (but no clear mirror side separation) and a distinct separation of the mirror sides in the middle of the scan.

V. Conclusion and Outlook

The new MODIS calibration approach by MCST using desert targets [13] is much more consistent with the assumption that there are no long-term trends in the water-leaving reflectance in the global oceans than the previous MCST calibration approach. This was shown by performing cross calibration of MODIS Aqua to the SeaWiFS climatology (see Fig. 3). The resulting cross-calibration coefficients are much closer to unity with the new MCST calibration than with the previous approach.

The improvement is largest for the central part of the MODIS scan (frames 300–1050). At the scan edges, residual trends remain, particularly for bands 8 and 9 (412 and 443 nm, respectively). In order to improve the calibration of the scan edges, a L3 (global, temporally averaged) data set was produced from MODIS data using only the central part of the MODIS scan. The scan angle restricted L3 data were used to derive cross-calibration coefficients for all scan angles. As expected, the derived cross-calibration coefficients were close to unity for the central part of the scan. The corrections for the scan edges are up to 3% for 412 nm. They decrease with wavelength to about 0.5% for the red wavelength bands (see Fig. 6). Applying the corrections in the production of ocean color products leads to improvements in the temporal trends of the globally averaged water-leaving reflectances (see Fig. 7) and to the scan angle dependence (Figs. 5 and 8). The corrections presented here are part of the MODIS Aqua reprocessing that occurred in May 2012 (referred to as "R2012.0").

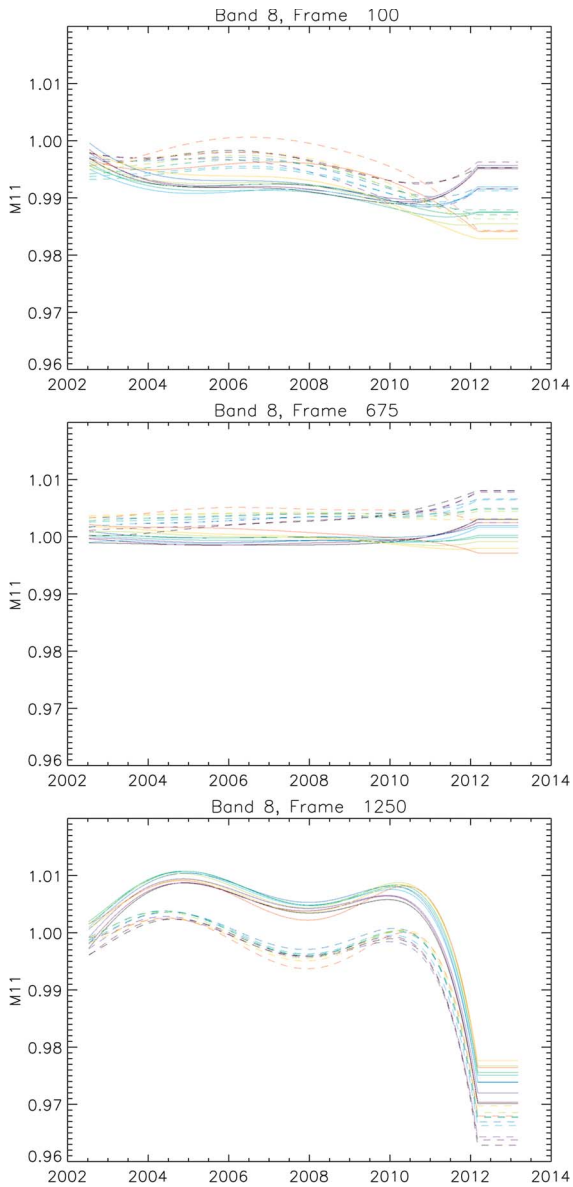


Fig. 9. Cross-calibration coefficients for all ten detectors and both mirror sides for MODIS Aqua band 8. Solid (dashed) lines show mirror side 1 (2). Detectors 1–10 are color-coded from black/purple to orange/red. Frame numbers are (top) 100, (middle) 675, and (bottom) 1250.

The cross-calibration approach was also used in the previous reprocessing ("R2010.0"), but with a fundamental difference: SeaWiFS L3 data were used as a calibration source for bands 8 and 9 (no temporally dependent corrections were applied for bands 10–14). Therefore, the MODIS Aqua data at those wavelengths were not independent products anymore; in effect, they were tied to the SeaWiFS record. The new approach presented in this paper uses only MODIS Aqua data as input for the cross-calibration analysis; therefore, the ocean color products from R2012.0 can be considered independent of SeaWiFS.

As a next step, the OBPG is planning to apply the same methodology to MODIS Aqua bands 1, 3, and 4 (645, 469, and 555 nm, respectively). Initial results indicate that the corrections needed for these bands are small.

The methodology presented here is not applicable to the MODIS on Terra because the radiometric degradation issues on MODIS Terra are much more severe than those on MODIS Aqua [6], such that no extended part of the MODIS Terra scan can be used as a calibration source for the cross-calibration analysis. Instead, the OBPG will use the MODIS Aqua data set as a calibration source for the cross-calibration of MODIS Terra. Therefore, the long-term global trends of the MODIS Terra ocean color products should be identical (or at least very similar) to those of MODIS Aqua. The value of the new MODIS Terra products will be the increased amount of L2 data available, improving daily global coverage.

Data from the VIIRS sensor on Suomi NPP will provide an independent data set that can be directly compared with the MODIS record, potentially even merged. The radiometric degradation trends of the VIIRS sensor (minor degradation in the blue wavelengths, significant degradation for the NIR wavelengths [3]) are very different from those on MODIS; thus, such an analysis should be beneficial for both sensors. Note that, if indeed the largest challenge for the calibration of VIIRS is the calibration of the NIR bands, the cross-calibration method used here is of limited value because it requires well-calibrated NIR bands.

ACKNOWLEDGMENT

The authors would like to thank the staff of the OBPG for their support, as well as J. Sun from MCST.

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