New Polarization Correction for MODIS Aqua Ocean Color: Recent Results and Remaining Challenges

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1. Background

The top-of-atmosphere (TOA) radiances (I_t) leaving the earth are partially linearly polarized. The Stokes vector for partially linearly polarized light with polarization direction ? and degree of polarization P (0<P<1) is given by
$\mathbf{I}_t = [I_t,Q_t,U_t,V_t] = \mathbf{I}_{Unpol.} + \mathbf{I}_{Pol.} = I_t*[1-P,0,0,0] + I_t*[P,\cos ??,\sin 2?,0]$
The MODIS Aqua responsivity depends on the polarization of the measured radiance, this means the measured radiance I_m is different from I_t. I_m needs to be converted into I_t. The MODIS Aqua polarization sensitivity was characterized prelaunch. A polarization filter was placed between a light source and the MODIS aperture and turned around its axis, varying the polarization direction ? from -180^0 to $+180^0$.The MODIS polarization sensitivity is a function of scan angle, so this procedure was performed at scan angles -45^0, -22.5^0, 0^0, $+22.5^0$, and $+45^0$. Results for MODIS bands 8 (412nm) and 15 (748nm) are shown in Figs. 1 and 2 for nadir viewing. The expected result is a two-cycle variation proportional to $(1+m_{12}*\cos 2?+m_{13}*\sin 2?)$, see Fig.1. Band 15 shows a four-cycle effect (see Fig.2) that is an artifact of the measurement setup that potentially obscures the two-cycle effect. The stars show the measurements, the solid lines show the fitted two-cycle variation. The MODIS polarization coefficients m_{12} and m_{13} are retrieved from the fits.

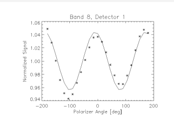


Fig. 1

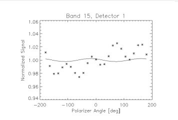


Fig.2

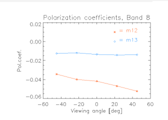


Fig.3

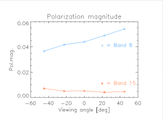


Fig.4

Figs. 3 above show the MODIS polarization sensitivity coefficients m_{12} and m_{13} as a function of scan angle for band 8. The polarization magnitude (or amplitude), defined as $P_m = (m_{12}^2+m_{13}^2)^{1/2}$ is shown in Fig.4 for bands 8 and 15. **The maximum value is 5.5% in band 8.** It can be seen that for large viewing angles, corresponding to large angles of incidence on the MODIS scan mirror, the polarization sensitivity is highest for band 8, as it is for most other bands, but not for band 15.

The Stokes vector components for the TOA radiances ($\mathbf{I}_t$) are calculated (assuming Rayleigh scattering) in a different coordinate system than the prelaunch measurements. The two coordinate systems are related through the angle ? . The equation to convert the radiances measured by MODIS (I_m) into I_t is: $I_m / I_t = 1 + m_{12}(Q_t/I_t \cos 2? + U_t/I_t \sin 2?) + m_{13}(-Q_t/I_t \sin 2? + U_t / I_t \cos 2?)$. Polarization parameters for a MODIS swath over the Pacific Ocean are shown in the figures below for band 8 for August 14, 2002. Note that both the MODIS polarization sensitivity (Fig.4) and the TOA degree of polarization (Fig.5) increase at the end of scan, so the TOA polarization corrections can be large (up to 3.5% in Fig.7).

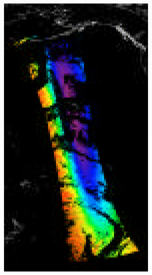


Fig.5: Degree of polarization

0.0 [dimensionless] 0.7

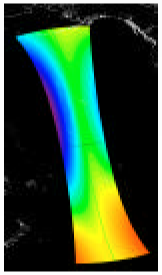


Fig.6: Q_t component

-5.8 [mW cm^{-2} sr^{-1} ? m^{-1}] 5.4

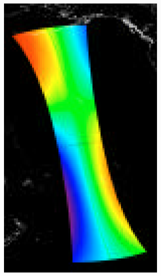


Fig.6: U_t component

-5.8 [mW cm^{-2} sr^{-1} ? m^{-1}] 5.4

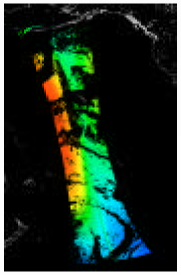


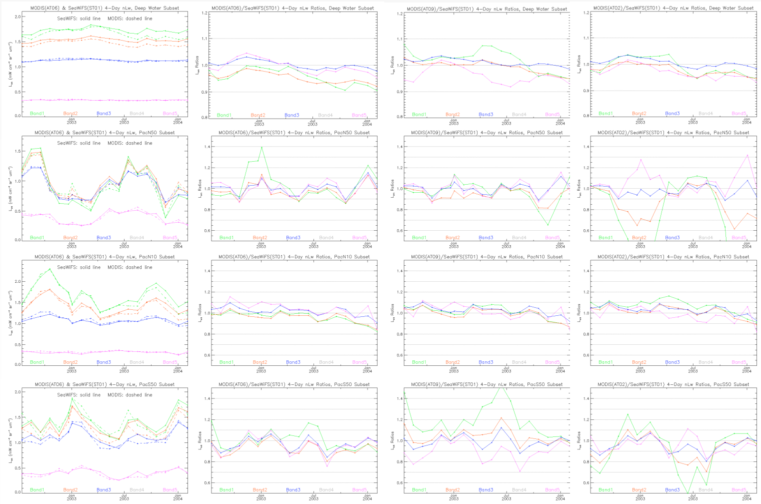
Fig.7: Polarization correction I_m / I_t

0.965 [dimensionless] 1.035

2. New Interpretation of Prelaunch Characterization

The MODIS prelaunch polarization characterization measurements are poorly documented regarding the angle of the rotating polarizer relative to MODIS. Specifically, it was not clear whether
1) 0^0 on the polarizer is into the flight direction of MODIS or perpendicular to it, and
2) whether positive angles of the polarizer correspond to a clockwise or counterclockwise rotation.
Item 1) determines the sign of the polarization coefficient m12, item 2) determines the sign of m13. Unfortunately, there is still no absolute certainty regarding item 2), but it has become clear that a wrong definition was used regarding item 1) in the Aqua and Terra processing up to early 2004. Furthermore, the magnitude of the polarization coefficients was clearly wrong in most cases. These polarization coefficients produced dramatically different ocean color radiances for MODIS when compared to the SeaWiFS radiances. The OCDP group has produced several time series for Aqua (ATXX) and SeaWiFS. Specifically:
- AT02 contains polarization coefficients similar to the ones pre-2004
- AT06 contains polarization coefficients with correct magnitudes and angle definitions currently assumed to be accurate
- AT09 is similar to AT06, but uses a different assumption about angle definition in item 2)
The magnitude of m13 is usually much smaller than the magnitude of m12 (see Fig.3), thus it is critical to be correct about item 1). The impact of item 2) is still significant, as can be seen by comparing the time series results below. The left column shows the radiances for SeaWiFS (solid line) and MODIS Aqua (dashed line), AT06. Band 1 corresponds to the 412nm band, band 2 to 443nm, band 3 to 488nm, and band 5 to 550nm. The remaining columns show the ratios of Aqua time series over the SeaWiFS time series. The plots in the top line are for the deep water subset, in the second line for the PacN50 subset, the third line for the PacN10 subset, the bottom line for the PacS50 subset. The Pacific subsets contain regions with longitudes from -150^0 to -170^0 and latitudes of 10^0 intervals (e.g., PacN50 reaches from $+40^0$ to $+50^0$ latitude). It can be seen that the strongest differences between the Aqua time series is at high latitudes, and the AT06 time series agrees best with the SeaWiFS radiances.The bifurcation in AT06/ST01 for deep water (ratios for bands 3 and 5 are higher than ratios of bands 1 and 2) is expected for the average chlorophyll concentration of deep water because of slightly differing wavelengths between the corresponding bands of Aqua and SeaWiFS.

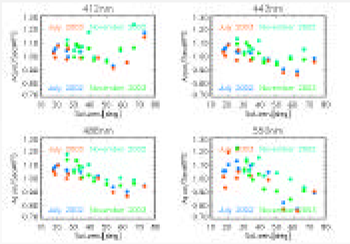
AT06 and ST01 | AT06/ST01 | AT09/ST01 | AT02/ST01



3. Current Radiance Products

OCDP has used a limited Aqua time series (consisting of only 4 days out of each month to reduce computing time) to evaluate the impact of calibration changes (e.g. polarization, glint masking, ocean surface BRDF, cloud threshold, etc.) as well. The current best calibration algorithms are applied in AT15, some results are shown below. At this point, the agreement between SeaWiFS and Aqua is very good, and it is unclear whether remaining differences are due to the calibration of SeaWiFS, Aqua, or if they are geophysical.

It is interesting to look at the ratios Aqua/SeaWiFS for a specific month for the different latitudes of the Pacific zonal regions (latitudes from -50^0 to $+50^0$ in 10^0 intervals, longitude is always from -150^0 to -170^0). The solar zenith angle does not change monotonically from south to north for these comparisons. If the ratios are plotted versus the average solar zenith angle (see plots below, solar zenith angle has 0^0 at the zenith), a trend emerges: the Aqua radiances decrease relative to SeaWiFS with increasing solar zenith angles, especially at 488nm and 550nm. The reason for this is so far unknown. Possible reasons are the atmospheric correction, ocean surface BRDF, or remaining polarization errors. The data points shown below are the ratios of the water leaving radiances for July and November.



4. Conclusions

The huge differences between the Aqua and SeaWiFS water-leaving radiances from the pre-2004 processing at high latitudes have been significantly reduced for the highly polarized bands with the new polarization correction. The remaining seasonal variations between Aqua and SeaWiFS (up to 20% in normalized water-leaving radiances at high latitudes) are spectrally consistent and not necessarily caused by polarization.

5. Outlook

There are several issues regarding polarization that still need to be addressed:
- The discontinuity in the polarization correction at nadir (see Fig.7).
- Bands 13 and 14 have a similar four-cycle effect as band 15. The polarization correction for these three bands is therefore still questionable.
- It is possible that the striping seen in the Aqua images is (partly) produced by an unknown detector specific polarization (band specific polarization coefficients are used currently).
- The polarization sensitivity and the degree of polarization of the TOA radiances increase at the end of the scan. Methods are tested to separate response-versus-scan (RVS) effects from the scan angle dependency of the polarization sensitivity.

A detailed description of the MODIS AQUA polarization correction is available online at http://oceancolor.gsfc.nasa.gov/DOCS/polcor.pdf. For further questions, please contact meister@simbios.gsfc.nasa.gov.

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