Early Ocean Color Results from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS)

Robert Evans, Katherine Kilpatrick and Edward Kearns
University of Miami Rosenstiel School for Marine and Atmospheric Science
4600 Rickenbacker Causeway, Miami, Fl.33149 USA

Sea Surface Temperature results will be presented at Breakfast (Terra session), Friday the 13th.

The NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) was launched in December of 1999. Before the MODIS ocean data can be fully utilized by the scientific community, the performance of both the complex sensor system and the algorithms must be evaluated. The sensor characterization examines several issues, including detector-to-detector discrepancies within wavebands, variations in the mirror response as a function of angle of incidence, differences in characteristics between mirror sides, effects of spatial and spectral cross-talk, and problems associated with polarization and sun glint.

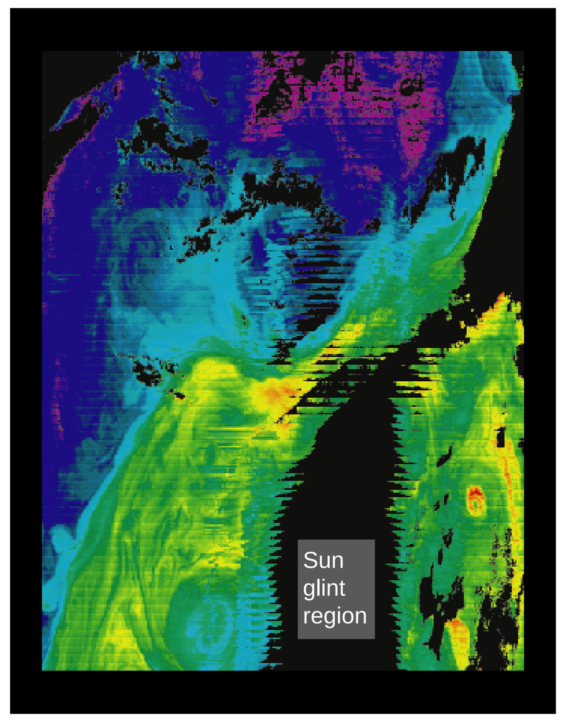


Figure 1. Level 2 1-km nLw_443 unmodified. East Coast U.S. May 8th, 2000 (L1b v2.4.3, 129:1545). Note non-physical structure extending from black sun glint region

Early at-launch images (Fig.1) demonstrated severe striping and discontinuities in both the along and cross scan direction.

Sensor characterization and use of revised calibration tables produces a dramatically improved image (Fig. 2).

Corrected images are remarkably full of detail, even in oligotrophic regions

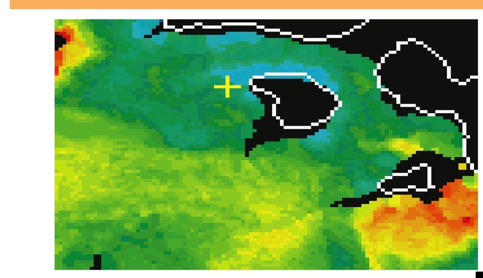


Figure 10. Corrected nLw443, + location of Hawaii MOBY. 102:2105

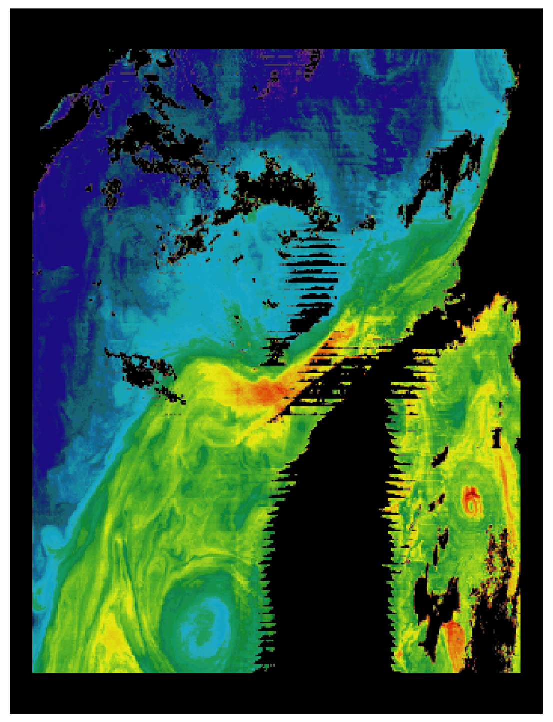


Figure 2. Level 2 1-km nLw_443 corrected East Coast U.S. Jagged appearance of glint edge is due to variations in scattering from top to bottom of detector array.

The large portion of the gross striping pattern seen in Figure 1 is the result of an unbalanced response between the 10 detectors within a scan line. Multiple detectors must be balanced at the level of the precision of the detectors (i.e. 12 bit system). Detectors must therefore be balanced to better than 0.1% or severe striping will be present.

The best solution to balancing the detectors was to approach the problem from the viewpoint of Lw through the atmospheric correction physics, not total radiance (Lt). With multiple detectors there is real geophysical variability in Lt within a scan due to varying satellite azimuth angle across the detectors. Other factors such as the response-versus-scan angle (RVS), polarization, sun glint (Lg) and mirror side effects further complicate the detector normalization procedure. We used a combined iterative approach to "flat field" the water leaving radiance (Lw) and aerosol radiance (La) fields thereby minimizing the sensor characterization errors via atmospheric correction during the normalization procedure.

Iterative steps in characterization/initialization:

1. Remove Response versus scan angle (RVS).
2. Remove Polarization effects.
3. Adjust detector gains by evaluating Lt.
4. Remove sun glint.
5. Filter aerosol radiance (La) at 750nm and 865nm prior to epsilon calculations.
6. Evaluate resulting satellite Lw fields propagated to the sea surface.
7. Adjust Lt scaling factors based on inter-detector differences in satellite Lw.
   (Lw at detector x - Lw at reference detector 5).
8. Repeat step 2 through 7 until detector differences in Lw's within a given band approach zero (<0.0003)
9. Adjust overall band gains and biases using *in situ* and satellite matchup observations

Inter-Detector gain adjustments

Figure 3 shows a plot of the at-launch relative response of each of the 10 detectors. A general increasing linear response from detector 1 to detector 10 on the order of ~1% is present in all bands. The black line represents the inter-detector response after gains were adjusted by normalizing response to detector 5 and filtering La.

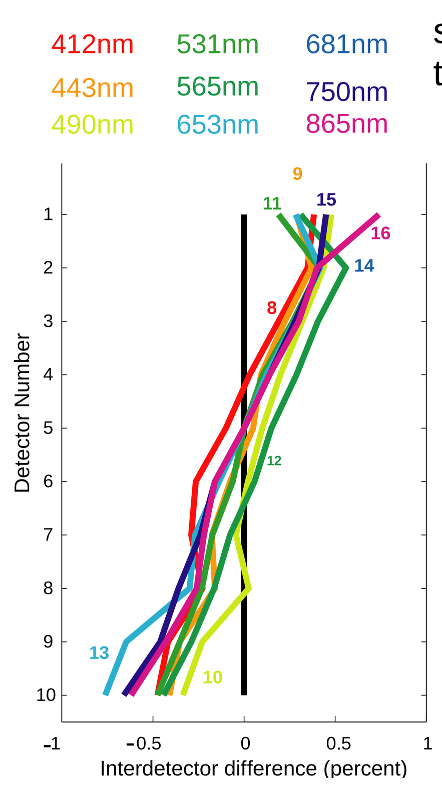


Figure 3. Percent inter-detector modal differences for each visible band.

Digitizer noise

Figure 4 shows effect of noise introduced during sensor A/D conversion, affects $2^n - 1 \rightarrow 2^n$ transitions.

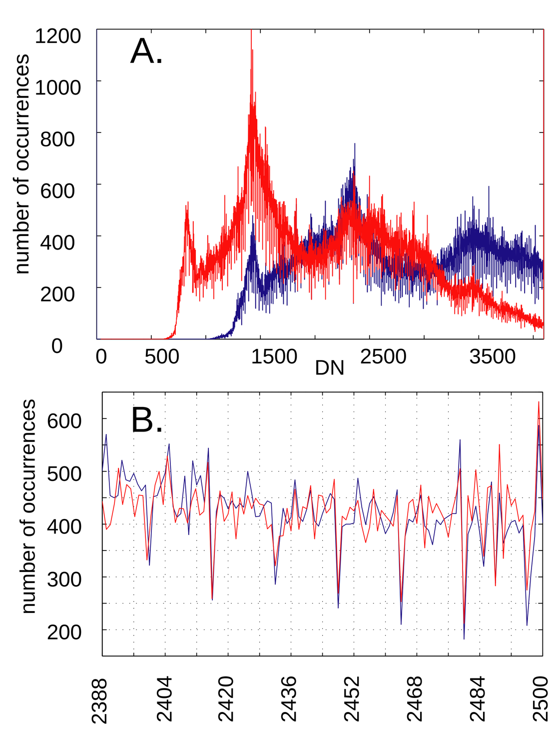


Figure 4. Histogram of digitizer counts.
A. full range B. expanded view of 2000-2500

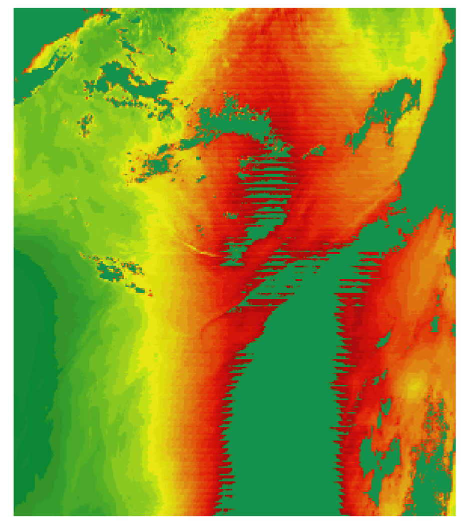


Figure 5. Unfiltered La 865nm Yellow - red region glint contaminated (Lg> 5*La).

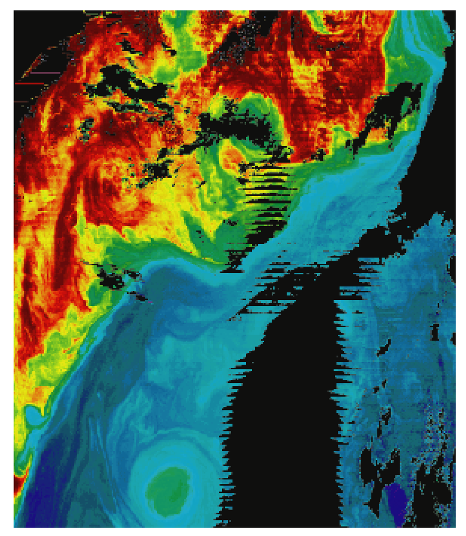


Figure 6. Corrected MODIS chlorophyll. East Coast U.S. Day 129:1545.

Band ratio products e.g. Chl and K490 are less affected by residual sun glint contamination than single band products e.g. a_440nm.

La band filtering prior to epsilon calculation

La is a large fraction of the Lt in the Lw wavebands, as a consequence it is critical that the La fields and therefore the resulting epsilon and aerosol model selection be noise free. Any noise in the process will propagate bad La's into the Lw computation. (Lw = Lt - La - Lg)

To mitigate the noise problem we filtered the 750nm and 865nm wavebands before calculation of epsilon. Filtering of the 750 and 865nm bands is applied only during the epsilon calculation to select the appropriate atmospheric model. The input to the epsilon calculation is the 750/865nm ratio. Filtering these wavebands results in a more uniform ratio across the scene and produced less noise in model selection. To estimate La at the Lw bands, we use the unfiltered La865.

We investigated several filtering techniques to produce uniform La750/La865 fields. We tried the following.

a) 3x3 pixel average
This option suppressed noise but was sensitive to erroneous detector readings (e.g. gains, clouds, digitization errors)

b) Median filter
The median removed problematic outliers but was sensitive to the distribution within the 3x3 box.

c) Median filter with nearest data neighbor averaging
The best approach to creating a nearly noise free ratio for the epsilon calculation was to average the median value and the two data value nearest neighbors in each of the La750 and La865 wavebands.

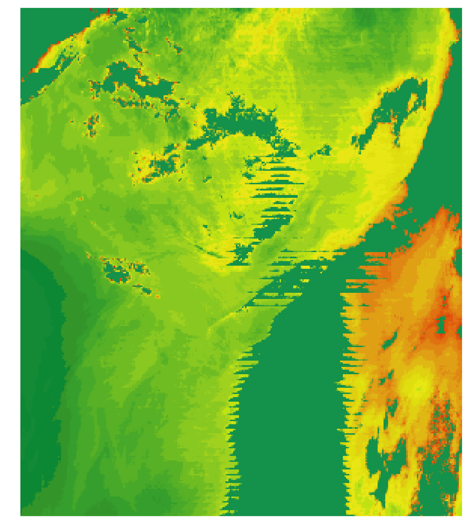


Figure 7. Sun glint removed La865nm.

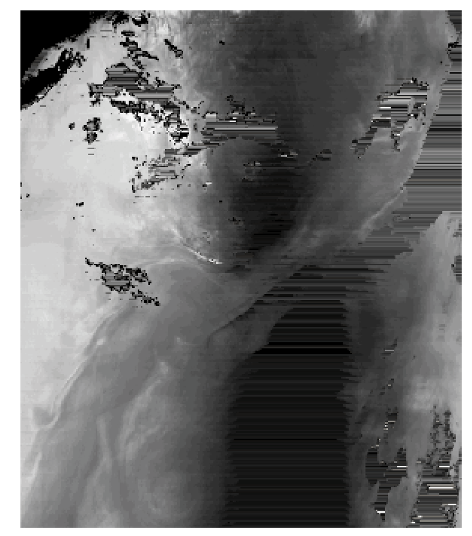


Figure 8. Epsilon 78 using filtered La 750nm and La 865nm in the calculation. Gray scale: light -> dark decreasing values. Striped areas are clouds and glint.

Sun glint

Sun glint influences large portions of the image. Comparisons with Dennis Clark's MOS *in situ* data from the MOCE-6 initialization cruise indicated that satellite Lw's decreased in regions affected by sun glint and at high satellite zenith angles. The retrieved epsilon appeared high, on the order of 1.1 away from the sun glint decreasing to 1.0 as sun glint increased. This suggested that the atmospheric correction over-corrected as the scan approaches the sun glint region in all bands and indicated that the La in the sun glint region was too large. We therefore included a sun glint term to reduce the Lt - Lr - Lg leading into the La calculation. A dramatic improvement in the retrievals in regions adjacent to the main sun glint pattern can be seen in figure 2.

Several approaches to correcting the glint problem were investigated.

a) We assumed sun glint was direct, i.e. no scattering component.	Result: lower Lw's as increasing sun glint was removed.
b) Removed diffuse Rayleigh scattering component of the sun glint.	Result: Lw retrievals showed a spectral behavior. Lw's were correct in the green region but under-corrected in the blue.
c) Included a diffuse aerosol component to the sun glint.	Result: improved Lw retrievals in regions of sun glint contamination with reasonable spectral behavior.

The sun glint reflectance is computed as: **τg = glintsc * zglint * zbst(λ) * t_star(λ)**
Where:
glintsc = 1.65 (sun glitter coefficient scale factor; see problems section for caveats associated value of scale factor)
zglint = sun glitter coefficient using Cox and Munk (1954a,b; 1956) , assumes isotropic wind.
zbst = two-way Rayleigh and Ozone diffuse transmittance; sun - ground - satellite.
t_star = one-way aerosol diffuse transmittance using chosen models; ground - satellite

The glint radiance (Lg) is Lg = τgLt. The new La865 calculation now has the form: **La865 = Lt - Lr - Lf - Lg**
Where:
Lr is the modeled rayleigh radiance; Lf is the modeled sea foam radiance; t is the transmittance factor

The Lw corrected for glint becomes: $tLw_{xx} = Lt_{xx} - Lr - Lg - Lf - La_{xx}$

Polarization

The MODIS sensor has a rotating mirror such that the angle of incidence (AOI) changes dramatically from West to East across the scan line. Initial comparison of MODIS Lw's with Dennis Clark's Hawaii MOBY/MOCE optical buoy data indicated that the satellite Lw decreased with increasing AOI. The loss of the P component of the polarized light field begins to appear at nadir (AOI of ~30^{o}) and is most pronounced on the eastern side of the scan where the satellite zenith angle is high and the AOI approaches 65 ^{o}. We analyzed the instrument polarization tables and computed average polarization for each AOI by spectral band. The result is a new table where the polarization factors are smoothed by AOI and fixed for all detectors across both mirror sides for each spectral band. The new tables produce stable retrievals across detectors adding radiance as a function of AOI.

Spectral gain and bias

Setting of overall band gains:

Aerosol bands: Adjusted gain for band 15 (750nm) relative to band 16 (865nm) to produce "proper" aerosol model. Proper means selecting a model set that deconvolves La from Lw fields and fits expectations as to the aerosols likely to be present in the region. We adjusted the relative balance between bands 15 and 16 until the La865 fronts seen in the East coast image (figure 7) were removed from the Lw fields (figure 6). These gains were then applied to Hawaii granules to verify that the relative balance determined from the East coast also produced consistent aerosol models in open ocean regions.

Visible bands (blue, green, red): Compared satellite and *in situ* observations from the MOCE-6 ship and Hawaii MOBY optical buoy observations. Adjusted satellite sensor gains to obtain Lw agreement.

Lw to La bands: Previous ocean color sensors only required relative calibration between the La and Lw bands. The MODIS Fluorescence Line Height (FLH) product requires an absolute calibration between band 14 (667nm) and band 15 (765nm). We used the FLH and FLH baseline calculations in regions known to show low FLH (Hawaii) to verify that the relative band 15 and 16 gains adjustments produced equivalent fluorescence height and baseline retrievals (i.e. FLH - baseline = 0).

Outstanding issues

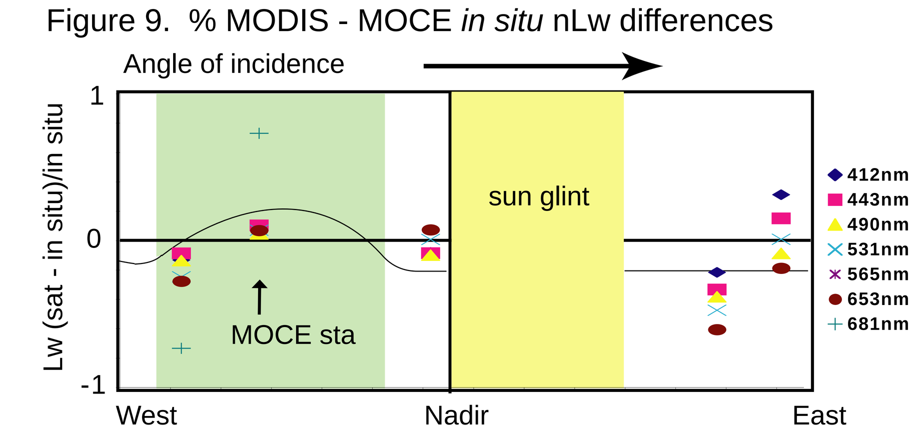
Mirror side ambiguity: Offsets are required to compensate for different reflectivity of the two scan mirror sides; at times mirror side identity is uncertain leading to scan striping. Principally affects 412nm, 443nm, and IR bands.

τ sun glint scale factor (glintsc): Using a glintsc factor of 2.0 produced consistent behavior in Lw's fields, however, examination of global images showed asymmetric chlorophyll behavior from west to east along the scan line. Decreasing the glintsc factor to 1.4 produced consistent Chlorophyll behavior at the expense of the Lw retrievals. A glintsc factor of 1.65 was found to be an acceptable compromise to produce "reasonable" behavior in both Lw and chlorophyll fields. This glint correction is only approximate and needs further development.

Asymmetry in epsilon and Lw fields: Global fields show a persistent asymmetry from west to east. From the sun glint progressing to the eastern side of the image, epsilon and Lw's are uniform in regions of low geophysical variability. Immediately to the west of the sun glint and on the far western side of the image, epsilon and the Lw's tend to be lower; a parabolic shape in both epsilon and Lw retrievals is present as scan angle increases from the west toward the sun glint (figure 9 schematic). This suggests that the response of the 750 and 865nm bands is changing as a function of both satellite and solar zenith angle or our sun glint correction is only approximate.

Location of MOCE station used for calibration: Only a single MOCE-6 station was suitable for use in calibration. This station was located west of the sun glint at a viewing geometry of high epsilon and Lw satellite retrievals (figure 9). Therefore, only the portion of the swath (~60%) with this viewing geometry will produce accurately calibrated Lw retrievals with pixel-to-pixel continuity of <1% .

Figure 9. % MODIS - MOCE *in situ* nLw differences



Cloud test:
A pixel is flagged as cloudy If the surrounding 3x3 pixel box has a Lt678 min-max > 6.0W/m^2/str