Regional Vicarious Gain Adjustment for Coastal VIIRS Products

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ABSTRACT

As part of the Joint Polar Satellite System (JPSS) Ocean Cal/Val Team, Naval Research Lab –Stennis Space Center (NRL-SSC) has been working to facilitate calibration and validation of Visible Infrared Imaging Radiometer Suite (VIIRS) ocean color products. By relaxing the constraints of the NASA Ocean Biology Processing Group (OBPG) methodology for vicarious calibration of ocean color satellites and utilizing the Aerosol Robotic Network Ocean Color (AERONET-OC) system to provide *in situ* data, we investigated differences between remotely sensed water leaving radiance and the expected *in situ* response in coastal areas and compare the results to traditional The Marine Optical Buoy (MOBY) calibration/validation activities.

An evaluation of the Suomi National Polar-Orbiting Partnership (SNPP)-VIIRS ocean color products was performed in coastal waters using the time series data obtained from the Northern Gulf of Mexico Wave_CIS AERONET-OC site. The coastal site provides different water types with varyingly complex CDOM, sedimentary, and chlorophyll components. Time series data sets were used to develop a vicarious gain adjustment (VGA) at this site, which provides a top of the atmospheric (TOA) spectral offset to compare the standard MOBY spectral calibration gain in open ocean waters.

Keywords: VIIRS, Vicarious Calibration, Vicarious Gain Adjustment, Coastal Remote Sensing, Satellite Ocean Color, Coastal Validation.

1. INTRODUCTION

Space-based ocean color sensors measure radiance at the top of the atmosphere (TOA) at a number of discreet wavelengths ($Lt(\lambda)$). An atmospheric correction is then used to separate out the portion of the TOA signal associated with the radiance upwelled from between the TOA and above the sea surface to derive the water leaving radiance (Lw). On- orbit calibration is used to improve the accuracy of satellite data for use in quantitative oceanographic applications that make use of the remote sensing reflectance (Rrs) and normalized water leaving radiance retrievals (nLw). The calibration is intended to adjust the instrument-atmosphere system to obtain normalized water-leaving radiances that agree with the ground truth measurements. The methodology is independent of the satellite sensor or source of ground truth data but is specific to the atmospheric correction algorithm, therefore it is an instrument-atmosphere system level calibration[4, 8].

Extensively studied by NASA's Ocean Biology Program Group (OBPG), the vicarious calibration is an inversion of the forward processing algorithm resulting in a ratio of predicted (vLt) to observed TOA radiance (Lt). When a set of 20 – 40 high quality (vLt/Lt) relationships are obtained, they are averaged representing an average gain. This average gain is referred to as the vicarious gain and is a correction factor applied to the Lt by the processing software, in our case Naval Research Lab's (NRL) Automated Processing System (APS) v 5.4. APS is an automated regional processing software tool used for research, development and analyses and also for operational product generation for Navy products. The APS uses the software package, n2gen, which is derived from the l2gen software used by NASA. The effect applying the

vicarious gain in processing is to adjust the sensor channel response to minimize the average difference between expected water leaving radiance and the retrieved water leaving radiances for nominal geometries and environmental conditions[4].

2. METHODOLOGY

In this study, we utilize the NASA OBPG visible band vicarious calibration technique[4,8] where we force the SNPP-VIIRS sensor's visible channel radiances into agreement with observed normalized water leaving radiances nLw by defining a sensor channel "gain". Quantifying the uncertainty of the *in situ* bio-optical measurements is critical to support satellite calibration/validation (cal/val) activities and the development of remote-sensing algorithms and statistical models that convert radiometric measurements (water leaving radiance or surface reflectance) to geophysical data products (chlorophyll a and others). The quality of calibration and subsequent validation activities and conversion algorithms cannot be better than that of the data sets of ocean properties used to create them.

The vicarious calibration process begins by performing the initial image processing of the input VIIRS Lt using APS. For the initial processing, APS uses the standard atmospheric correction of Gordon/Wang[5] with the Stumpf NIR iteration[7] and assumes perfect sensor calibration (unity gains) to obtain the nLw at a pixel of known radiance. The various atmospheric components (Lr, La, transmittances, etc.) and pointing-angles are saved during this process. The nLw from the *in situ* sensor (convolved MOBY or hyper spectral model shifted AERONET) is then run through the inversion where the atmospheric components are added back creating an expected Lt from the view of the VIIRS. This expected Lt is the vicarious TOA radiance (vLt). In a perfect system in which all components are computed accurately, the vLt and original Lt should have a ratio of 1.0.

$$gain\ (\lambda)\ =\ v(Lt(\lambda))\ /\ Lt\ (\lambda), \tag{1}$$

where Lt is the satellite measured top of the atmosphere radiance at specific channel and the v(Lt) is the *in situ* measured nLw vicariously propagated to the TOA *(processing inversion)*.

In situ data collected for cal/val uses the same measurements and methodologies; however calibration quality data requires lower measurement uncertainties. This means that the sampling site should exhibit minimal natural variability (oceanic and atmospheric), in order to reduce the total uncertainty[6]. Today, the ocean color community views *in situ* data as having variable quality, and therefore these data should be ranked by quality for different purposes (from highest quality to lowest): calibration, validation/algorithm development, general research and monitoring. Guidelines for calibration/validation field programs are:

1. Data should be collected in a stable environment - spatially & temporally homogeneous; of known atmospheric conditions and sufficiently far from land (> *5km*);
2. Take all steps necessary to produce good water leaving radiance data -- measurements should have well defined uncertainties quantified, collected using ocean color community approved protocols, and use calibrated instruments (pre/post-cruise calibrations that are traceable);
3. Collect *in situ* data as close to the time of satellite overpass as possible, preferably in a time-series (within 3 hours), and, if possible, utilize continuous data that will enable greater numbers of match-up retrievals and allow for assessment of products for successive missions;
4. Make use of globally distributed *in situ* data to fully represent the wide range of geophysical conditions that remote sensing is expected to observe; and
5. Apply consistent data processing with clear QA/QC processes.

MOBY[2] and BOUée pour l'acquiSition d'une Série Optique à Long termE (BUSSOLE) buoys are the primary cal/val sites and both comply with the above calibration guidelines. Data from these buoys have been the primary basis for the on-orbit vicarious calibrations of the USA Sea-viewing Wide Field-of-view Sensor (SeaWiFS), the Japanese Ocean Color and Temperature Sensor (OCTS) and Global Imager (GLI), the French Polarization Detection Environmental Radiometer (POLDER), the USA Moderate Resolution Imaging Spectrometers (MODIS, Terra and Aqua), the Japanese Global Imager (GLI), and the European Medium Resolution Imaging Spectrometer (MERIS).

Due to the fact that the MODIS sensor is aging, the satellite oceanography community is working to have the VIIRS mission be operational as soon as possible. With this goal, a revised methodology was developed to do perform real time cal/val activities. The revision requires modification to data guidelines above and relaxation of the exclusion criteria currently recommended by the NASA OBPG. To expedite the cal/val processes and expand data availability, we utilize the level 1.5 AERONET-OC real time coastal data although they don't necessarily meet the spatial and temporal homogeneity requirements (*primarily point 1 above),* they have been successfully used to monitor sensor stability and provide sufficient "matchups" in real time to calculate and monitor the gain (vLt/Lt relationship) over time[1,3].

To support operational processing, we utilize data from the MOBY buoy and follow the OBPG steps for calculating an average gain, vicarious calibration. All available from a defined time period (*January 2012 to April 2013*) nLw retrievals produced using the NRL APS processing capability where a satellite measurement had an AERONET-OC measurement taken within 3 hours of the overpass are accumulated. All satellite imagery used to determine the gains must have no flags *(exception being the ocean flag).* The exclusion criteria applied to the data set are: wind speed must be less than 8 m/s, the maximum aerosol optical thickness (AOT) must be less than 0.2 as measured by the MOBY buoy, the nLw values must be between 0.001 and 3.0, the maximum solar zenith angle = 70 degrees and maximum sensor zenith angle = 56 degrees. The resulting average gains at the MOBY site are referred to as g01 within our processing system.

We apply the same basic screening technique using the AERONET-OC at the WaveCIS site in waters of the Gulf of Mexico, but relax the constraints to remove records flagged as: atmospheric failures, navigation failures, cloud/ice, high LT, seaice, high satellite zenith angle, high solar zenith angle, epsilon out of range, high glint, max AER iteration, high polarization, moderate sun glint, coccolithophores. The exclusion criteria are: wind speed must be less than 8 m/s, the maximum aerosol optical thickness (AOT) must be less than 0.2 as measured by the AERONET, the nLw values must be between 0.001 and 3.0, the maximum solar zenith angle = 70 degrees and maximum sensor zenith angle = 56 degrees. Specific for this analysis all data prior to July 1, 2013 was excluded. The reason for this was an instrument level calibration was implemented at the SDR level in late June 2013. The resulting average gains at the WaveCIS site are referred to as g02 within our processing system.

During data processing with the NRL APS v 5.4 software, the derived gain factors are applied during APS image processing to adjust the top of the atmosphere radiance, ultimately correcting for undetermined post launch changes to the instrument. It is important to note that, all of our average gain calculations are expressed as fractional gain factors (vLt/Lt) and are derived from initially processing the imagery with unity gains.

3. RESULTS

The *in situ* data from MOBY and AERONET-OC along with coincident satellite retrievals of water leaving radiance (nLw) values were assembled daily to establish a time series. The initial process involved monitoring the time series of nLw retrievals with minimal constrains -- include all valid (non – zero) data from the *in situ* and the satellite with a 3 hour matchup. This is shown in Figure 1 as the seasonal stability of open ocean water leaving radiances (nLw) at the MOBY site. The data was collected from Jan 1, 2012 to April 30, 2013. The x-axis is labeled in sequential days starting at Jan 1, 2012. The diamond markers represent all available nLw retrievals produced using the NRL APS processing capability where a satellite measurement had an AERONET-OC measurement taken within 3 hours of the overpass – prescreened data used for determining the gain. The y triangle markers are overlain to indicate records that pass flagging and exclusion criteria. Matchups used to determine the average gain for the site must have no flags *(exception being the ocean flag)* and exclusion criteria are: wind speed must be less than 8 m/s, the maximum aerosol optical thickness (AOT) must be less than 0.2 as measured by the MOBY buoy, the nLw values must be between 0.001 and 3.0, the maximum solar zenith angle = 70 degrees and maximum sensor zenith angle = 56 degrees. The screening process leaves 25 of the original 82 matchups for calculating the average gain at MOBY (g01).

The procedures outlined in Figure 2 and Figure 3 establish the real time evaluation and constraints for coastal matchups using the AERENET-OC nLw (Level 1.5) data for a regional vicarious gain adjustment. Procedures are based on examining spectral shapes, atmospheric correction, data consistency, and spatial homogeneity and time differences (satellite vs. *in situ*). Figure 2 shows the time series characterizing the seasonal stability of coastal water leaving radiances (nLw) at the WaveCIS site. The data was collected from Jan 1, 2013 to March 20, 2014. The diamond markers

represent all nLw retrievals produced using the NRL APS processing capability where a satellite measurement had an AERONET-OC measurement taken within 3 hours of the overpass. The square markers overlay the original points indicating records that pass the flag screening criteria, (i.e. remove records flagged as: atmospheric failures, navigation failures, cloud/ice, high LT, seaice, high satellite zenith angle, high solar zenith angle, epsilon out of range, high glint, max AER iteration, high polarization, moderate sun glint, coccolithophores). The triangle markers are an overlay to indicate records that subsequently pass the exclusion criteria: wind speed must be less than 8 m/s, the maximum aerosol optical thickness (AOT) must be less than 0.2 a measured by the AERONET, the nLw values must be between 0.001 and 3.0, the maximum solar zenith angle = 70 degrees and maximum sensor zenith angle = 56 degrees. Specific for this analysis all data prior to July 1, 2013 was excluded. The reason for this was an instrument level calibration was implemented at the SDR level in late June 2013. The screening process leaves 23 of the original 82 matchups for further analysis.
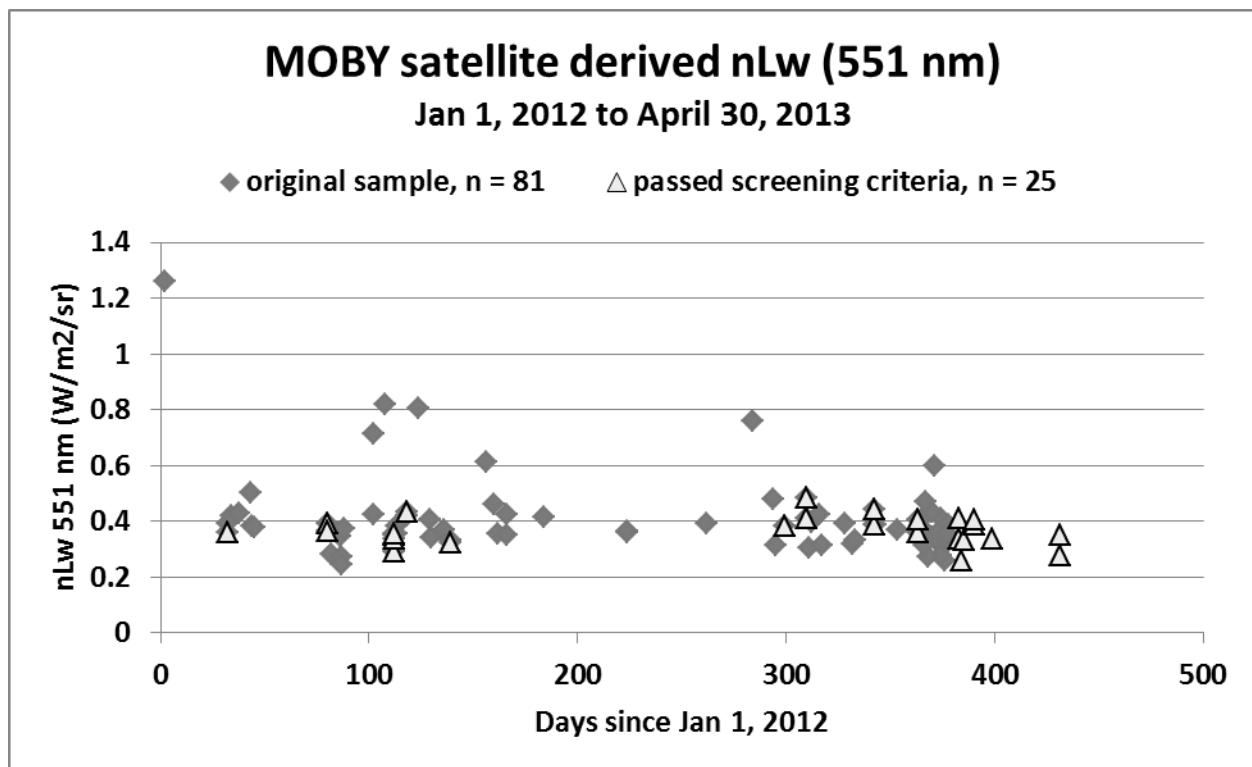

Figure 1 shows a time series characterizing the seasonal stability of open ocean water leaving radiances (nLw) at the MOBY site from Jan 1, 2012 to April 30, 2013. The x-axis is labeled in sequential days starting at Jan 1, 2012. The diamond markers represent all available nLw retrievals produced using the NRL APS processing capability where a satellite measurement had an AERONET-OC measurement taken within 3 hours of the overpass. The triangle markers are overlain to indicate records that pass flagging and exclusion criteria. All satellite imagery used to determine the gains must have no flags *(exception being the ocean flag)*. The exclusion criteria for the MOBY data set are: wind speed must be less than 8 m/s, the maximum aerosol optical thickness (AOT) must be less than 0.2 as measured by the MOBY buoy, the nLw values must be between 0.001 and 3.0, the maximum solar zenith angle = 70 degrees and maximum sensor zenith angle = 56 degrees. The screening process leaves 25 of the original 81 matchups for calculating the average gain at MOBY (g01).

WCIS satellite retrieved nLw (551 nm)
Jan 1, 2013 to March 20, 2014

◆ original sample, n = 82   ■ pass flag screening, n = 50   △ pass exclusion criteria, n = 23
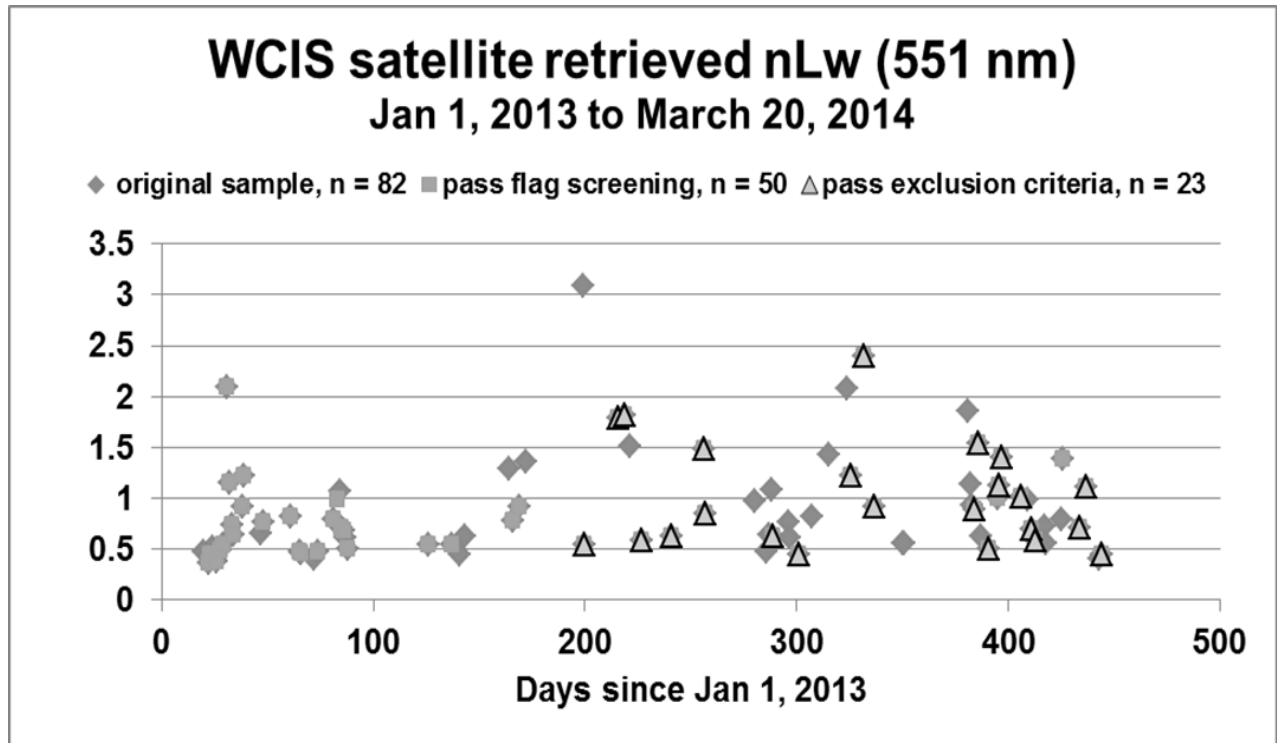
Figure 2 shows the time series characterizing the seasonal stability of coastal water leaving radiances (nLw) at the WaveCIS site. The data was collected from Jan 1, 2013 to March 20, 2014. Diamond markers represent all nLw retrievals produced using the NRL APS processing capability where a satellite measurement had an AERONET-OC measurement taken within 3 hours of the overpass (n = 82). The square markers overlay the original points indicating records that pass the flag screening criteria, (i.e. remove records flagged as: atmospheric failures, navigation failures, cloud/ice, high LT, seaice, high satellite zenith angle, high solar zenith angle, epsilon out of range, high glint, max AER iteration, high polarization, moderate sun glint, coccolithophores), (n = 50). The triangle markers are an overlay to indicate records that pass exclusion criteria: wind speed must be less than 8 m/s, the maximum aerosol optical thickness (AOT) must be less than 0.2 as measured by the AERONET, the nLw values must be between 0.001 and 3.0, the maximum solar zenith angle = 70 degrees and maximum sensor zenith angle = 56 degrees. Specific for this analysis all data prior to July 1, 2013 was excluded (n = 23). The reason for this was an instrument level calibration was implemented at the SDR level in late June 2013.

Figure 3 shows the spectral gains (the modeled *in situ* Lt and the Lt measured by the satellite) vLt/Lt prior to the manual screening. Evaluation of the spectral shape of the gains leads to the removal of Series 6, 17, 18 and 19. As mission average calibrations have been shown to reach stability after 20 – 40 high quality calibration samples in Franz et al, 2007, consideration must be given to balance the strictness of criteria for removal and preservation of sample size. By removing the four obvious outliers, we push the limits of calibration stability as there are only 19 samples left for determination of the gain. As additional data becomes available, we can monitor the vLt/Lt over time which should indicate when/if updates to the regional VGA are warranted.
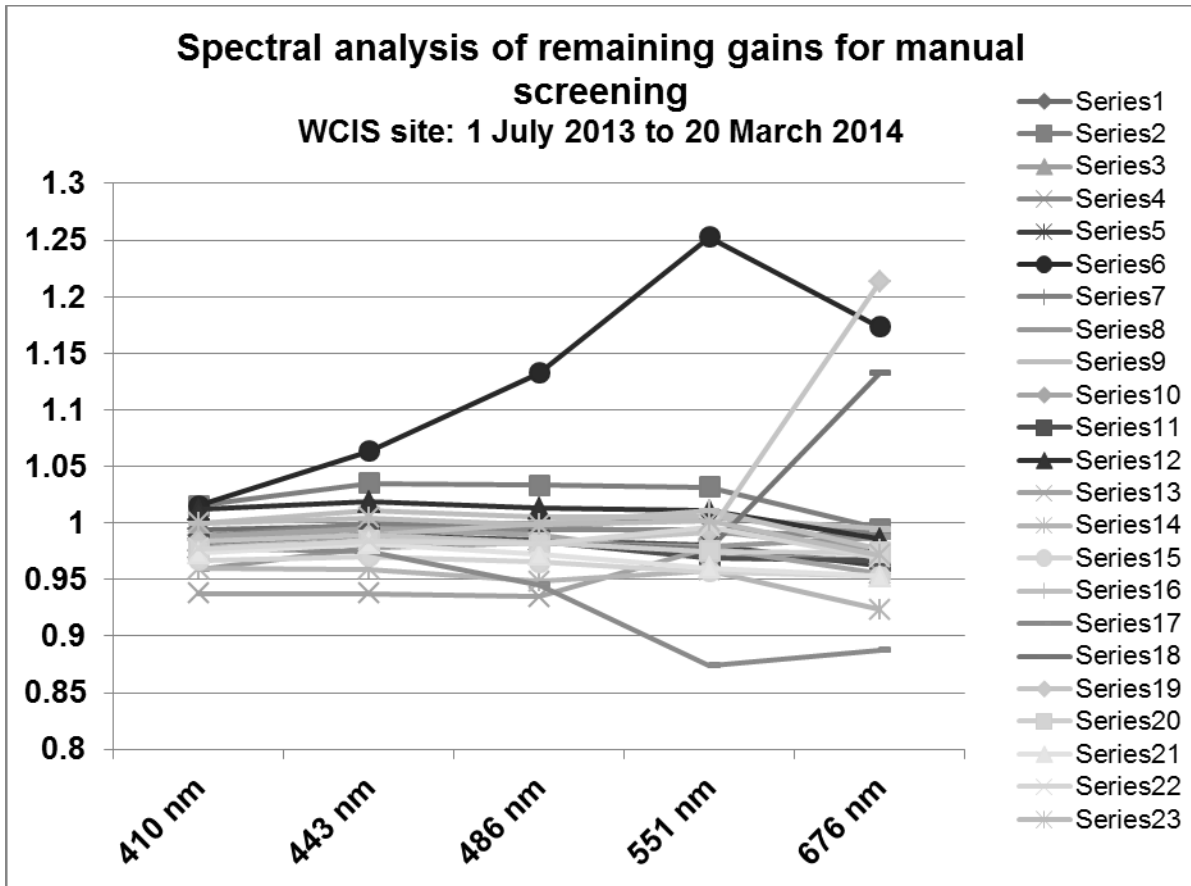
Spectral analysis of remaining gains for manual screening
WCIS site: 1 July 2013 to 20 March 2014

Figure 3 shows the remaining spectral gains (the modeled *in situ* Lt and the Lt measured by the satellite) vLt/Lt prior to the manual screening. Evaluation of the spectral shape of the gains leads to the removal of Series 6, Series 17, Series 18 and Series 19. As mission average calibrations have been shown to reach stability after 20 – 40 high quality calibration samples in Franz, et al 2007, consideration must be given to balance the strictness of criteria for removal and the preservation of sample size. By removing the four obvious outliers, we push the limits of calibration stability. As additional data becomes available, we can monitor the vLt/Lt over time, which should indicate if/when an update to the VGA coefficients are warranted.

Figure 4 shows the average gains for the MOBY and WaveCIS sites. The MOBY site had 25 records contributing to the final average (g01) while the 19 records passed screening criteria for the WaveCIS site. The standard deviation indicates there is no statistical difference between the gains derived from the two sites. The standard deviation of the MOBY gains (vicarious calibration, g01) is smaller than the uncertainty from the WaveCIS site (VGA, g02).

MOBY vicarious calibration coefficients and WCIS derived green water vicarious gain adjustment (VGA)
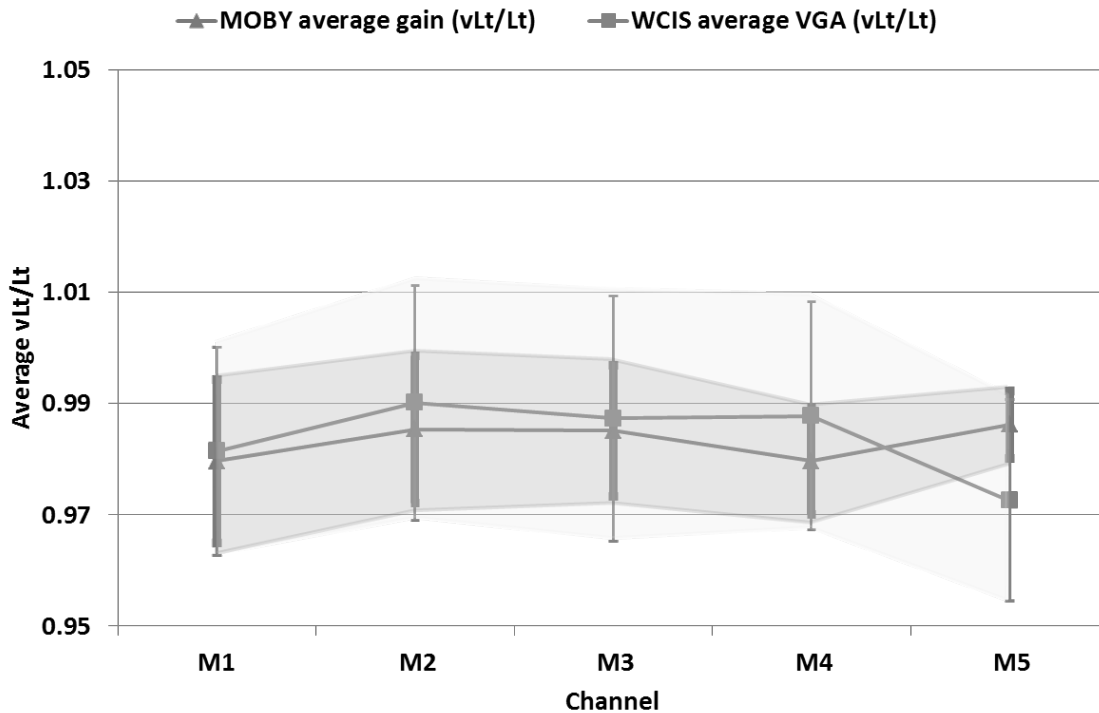
Figure 4 shows the MOBY average gain as blue triangles as compared to the WaveCIS derived average gain in squares. The shaded standard deviation indicates there is no statistical difference between the gains derived from the two sites. The standard deviation of the MOBY gains (vicarious calibration) is smaller than the uncertainty at the WaveCIS site (VGA).

To validate the effect of using the MOBY (vicarious calibration) and WaveCIS (VGA), we implemented the various gains within APS to process the VIIRS imagery and calculate the radiometric matchup statistics for the satellite and *in situ* observations used to derive the average gains, respectively.

For the following analysis, minimal screening criteria were applied to mimic a more operational testing scenario. Data were limited to within 3 hours with typical *in situ* screening. The satellite was selected as a single pixel unless specifically noted otherwise. The standard exclusionary angles were used, removing viewing angles above 56 degrees and 70 degrees for the satellite and solar zenith angles, respectively. Level 2 quality flags were used to remove records affected by atmospheric failure, navigation failure, clouds/ice, land, high LT, high glint, and max aerosol iteration failure. After accounting for exclusion criteria and processing techniques, the *in situ* data was directly compared to the satellite data to validate the coastal algorithm and track satellite performance over time.
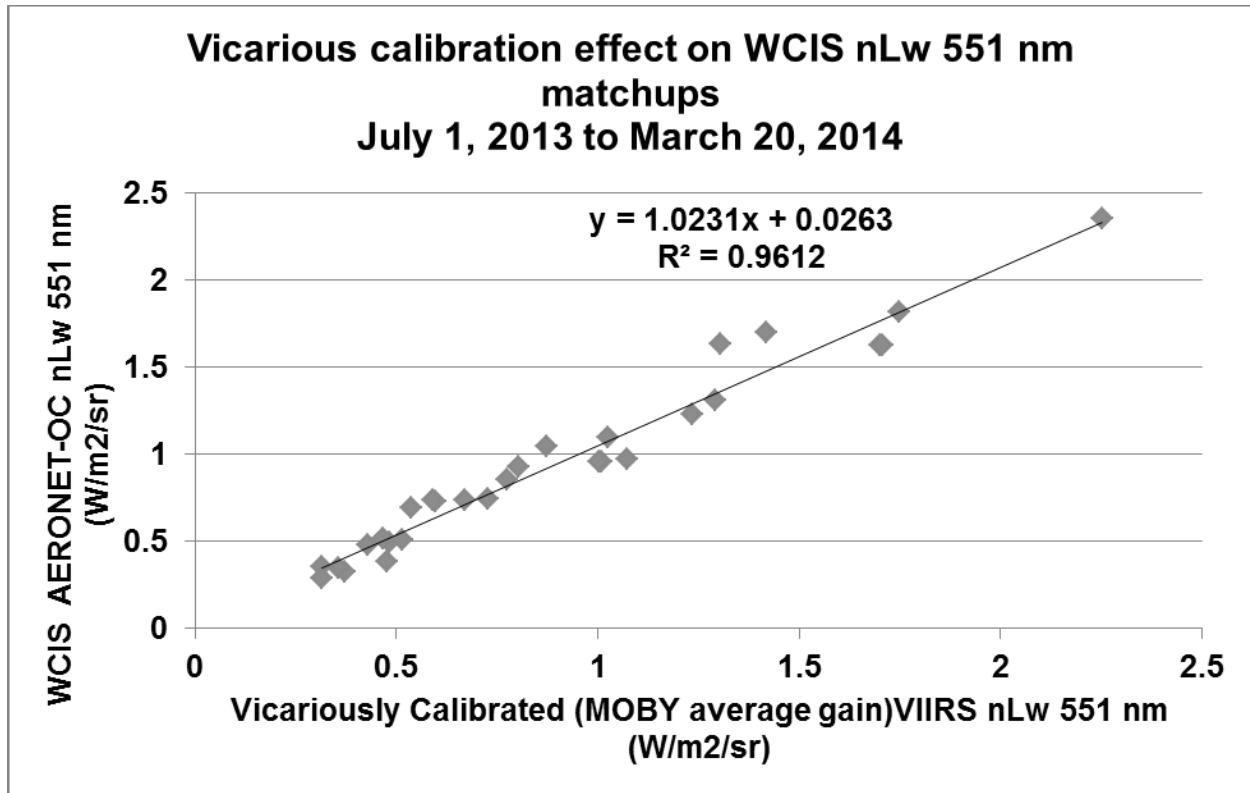
Figure 5 shows the effect of applying the MOBY derived gain on the nLw retrievals at 551 nm. The samples used for this figure come from the Jan 1, 2013 to March 20, 2014 original data, n = 81. Data prior to the SDR calibration were excluded as were any image/*in situ* pairs where the imagery did not produce a valid retrieval (negative 410nm, clouds, navigation failure), and obvious outliers where it could not be determined if the anomaly was due to the *in situ* or satellite data. The data were not screened for exclusion criteria (wind speed, AOT, etc) nor flags beyond those which result in retrieval failure. It is important to point out that this shows the efficiency of the MOBY calibration in green waters for the current time period.

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Figure 6 shows the effect of applying the WaveCIS VGA on the nLw retrievals at 551 nm. The samples used for this figure come from the original data, n = 82. Data prior to the SDR calibration were excluded as were any image/*in situ* pairs where the imagery did not produce a valid retrieval (negative 410nm, clouds, navigation failure), and obvious outliers where it could not be determined if the anomaly was due to the *in situ* or satellite data. The data were not screened for exclusion criteria (wind speed, AOT, etc.) nor flags beyond those which result in retrieval failure. A more appropriate test of the efficacy of the green water calibration will begin to accumulate as data is acquired outside of the derivation of the VGA period.

Table 1 summarizes the regression results calculated for the MOBY and WaveCIS gains applied during image processing on the nLw retrievals by the satellite (x) compared to the *in situ* (y) as illustrated in Figure 5 and Figure 6. The results show minor improvements (slopes being closer to 1 indicate better calibration and higher r2 indicates the regression represents a better statistical fit) for using the green water VGA at all wavelengths except 486nm however, the slopes are not statistically different.
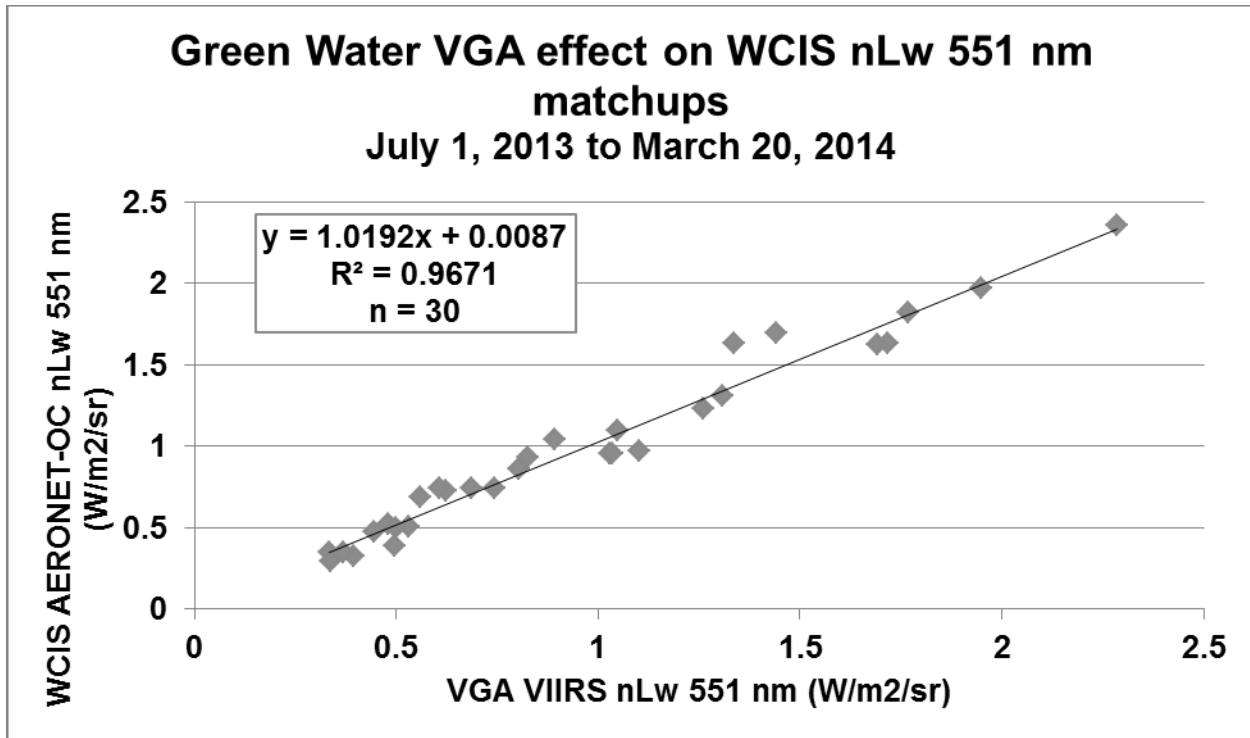
Green Water VGA effect on WCIS nLw 551 nm matchups
July 1, 2013 to March 20, 2014

$y = 1.0192x + 0.0087$
$R^2 = 0.9671$
$n = 30$

Figure 6 shows the effect of applying the WaveCIS VGA on the nLw retrievals at 551 nm. The samples used for this figure come from the original data, n = 82. Data prior to the SDR calibration were excluded as were any image/*in situ* pairs where the imagery did not produce a valid retrieval (negative 410nm, clouds, navigation failure), and obvious outliers where it could not be determined if the anomaly was due to the *in situ* or satellite data. The data were not screened for exclusion criteria (wind speed, AOT, etc.) nor flags beyond those which result in retrieval failure. A more appropriate test of the efficacy of the green water calibration will begin to accumulate as data is acquired outside of the derivation of the VGA period.

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gain set	wavelength	regression equation	R^2
MOBY gains	nLw 410 nm	$y = 0.6151x + 0.1962$	$R^2 = 0.4005$
WCIS gains	nLw 410 nm	$y = 0.6894x + 0.1915$	$R^2 = 0.4213$
MOBY gains	nLw 443 nm	$y = 0.8955x + 0.1248$	$R^2 = 0.7199$
WCIS gains	nLw 443 nm	$y = 0.96x + 0.0819$	$R^2 = 0.7745$
MOBY gains	nLw 486 nm	$y = 1.083x + 0.025$	$R^2 = 0.9096$
WCIS gains	nLw 486 nm	$y = 1.105x + 0.0215$	$R^2 = 0.9317$
MOBY gains	nLw 551 nm	$y = 1.0231x + 0.0263$	$R^2 = 0.9612$
WCIS gains	nLw 551 nm	$y = 1.0192x + 0.0087$	$R^2 = 0.9671$
MOBY gains	nLw 671 nm	$y = 0.8689x + 0.0141$	$R^2 = 0.9337$
WCIS gains	nLw 671 nm	$y = 0.8853x + 0.0389$	$R^2 = 0.9433$

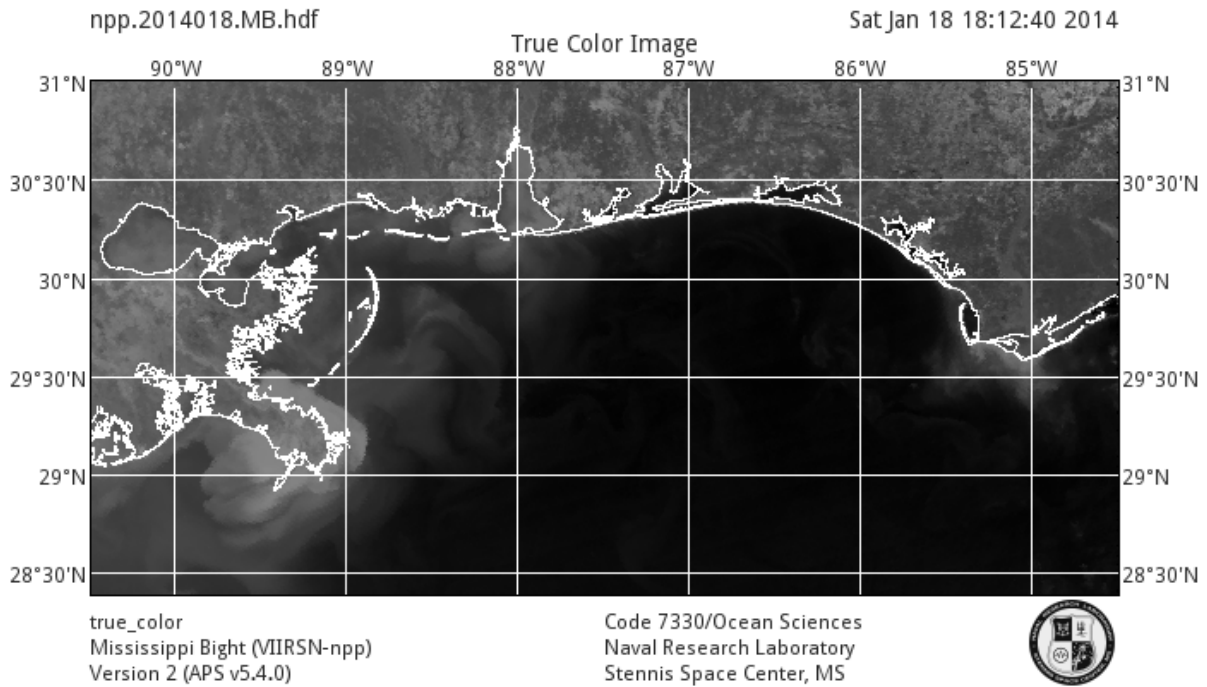Next to evaluate the effect of the two different gains on the VIIRS chlorophyll products, we processed an image from Jan 18, 2014 with the gain sets. Figure 7 shows the true color image from Jan 18, 2014. This image was processed using the

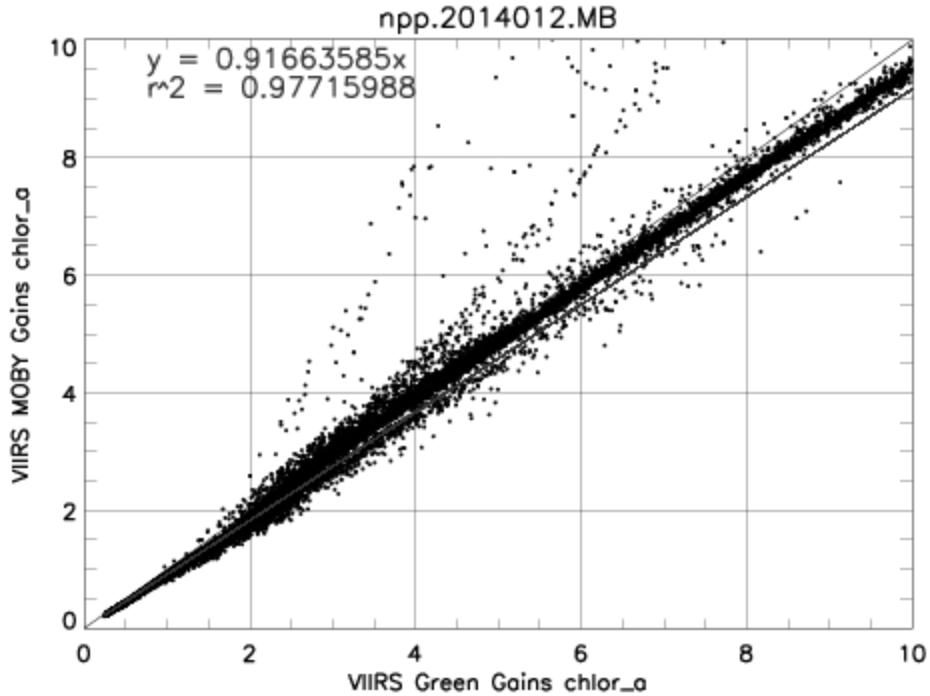MOBY gains and the WaveCIS VGA. The chlorophyll products from the two are compared in Figure 8. Figure 8 illustrates the pixel to pixel matchups from the VIIRS image collected on Jan 12, 2014. The x-axis shows the chlorophyll product derived processing with the green gains and the y-axis shows the chlorophyll results using the MOBY derived vicarious calibration. The effect of the green water gains is a slight reduction of the chl retrieval where values are greater than 8mg/m^3.

Figure 7 shows the true color image from Jan 18, 2014. This image was processed using the MOBY gains and the WaveCIS VGA. The chlorophyll products from the two are compared in Figure 8.

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$y = 0.91663585x$
$r^2 = 0.97715988$

VIIRS MOBY Gains chlor_a (y-axis)
VIIRS Green Gains chlor_a (x-axis)

Figure 8 illustrates the pixel to pixel matchups from the VIIRS image collected on Jan 12, 2014. The x-axis shows the chlorophyll product derived processing with the green gains and the y-axis shows the chlorophyll results using the MOBY derived vicarious calibration. The effect of the green water gains is a slight reduction of the chl retrieval where values are greater than 8mg/m^3.

4. CONCLUSIONS

We have used a three step procedure to constrain the quality of the matchup data used to determine the average gains for vicarious calibration. We modify the procedure used with MOBY and applied relaxed constraint to the AERONET-OC data at the WaveCIS site to calculate a regional vicarious gain adjustment (VGA) in coastal waters. The procedure addresses the criteria for selection to optimize data quality in a near real-time situation which allows a vicarious calibration and regional VGA to be established for each of the VIIRS spectral channels. The channel gains were determining using data from the 2012 to early 2013 time period for the MOBY Site (blue water) and from 2013 to early 2014 for the average VGA for the WaveCIS AERONET-OC site in the Northern Gulf of Mexico (coastal waters).

The procedure for assembling an optimum data set for determining vicarious gains is time consuming. In this procedure we removed 69% of the total number of matchup for the MOBY site and 72% for the WaveCIS site. The blue (g01) and green (g02) gains were determined using 25 and 19 final matchups, respectfully. The results show that by optimizing the selection of matchup points used for determining the gains a strong regression between satellite and *in situ* nLw(λ) is achieved. The standard deviation of the adjustment gains was acceptable and the screening procedure is critical for determining the adjustment.

Due to the uncertainties in the vicarious calibration and VGA processes there is not a statistically significant difference in the blue water (g01) and green water (g02) gains, however; as expected, the blue water gains do have lower standard deviations. Speaking to the effects that the different gains have on the nLw retrievals, it is interesting that overall the green water gains produce better regression coefficients and correlation coefficients regarding the nLw retrievals at the WaveCIS site for this time period. Additional matchups at the WaveCIS site, outside of the VGA time period will strengthen the validity of this assessment.

5. ACKNOWLEDGEMENTS

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