The SWIR-based On-Orbit Vicarious Calibration

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Vicarious Calibration (VC)

For ocean color remote sensing, post-launch vicarious calibration is necessary for visible bands.

VC: Calibration of whole system: Sensor + Algorithms

- Account for (by direct measurement or prediction) all of the components of the TOA radiance and
- Compare the results with the sensor-measured radiance.

Sensor-measured reflectance:

$$\rho_t^{(Meas)}(\lambda) = [1 + a(\lambda)]\rho_t(\lambda), \quad a(\lambda) - \text{calibration} \quad \text{error}$$

Computed reflectance:

$$\rho_t^{(Computed)}(\lambda) = \underbrace{\rho_r(\lambda)}_{\text{Computed}} + \underbrace{\rho_a(\lambda) + \rho_{ra}(\lambda)}_{\text{Predicted Using Models}} + \underbrace{t\rho_{wc}(\lambda)}_{\text{Computed}} + \underbrace{t\rho_w(\lambda)}_{\text{Measured}}$$

Calibration Site, e.g., MOBY

H. R. Gordon, "In-orbit calibration strategy for ocean color sensors," *Remote Sens. Environ.*, **63**, 265-278, 1998.

Background for Vicarious Calibration (Cont.)

Corrected reflectance after vicarious calibration (VC):

$$\rho_t^{(Corrected)}(\lambda) = G^{(VC)}(\lambda)\rho_t^{(Meas)}(\lambda) = \left[1 + a'(\lambda)\right]\rho_t(\lambda)$$

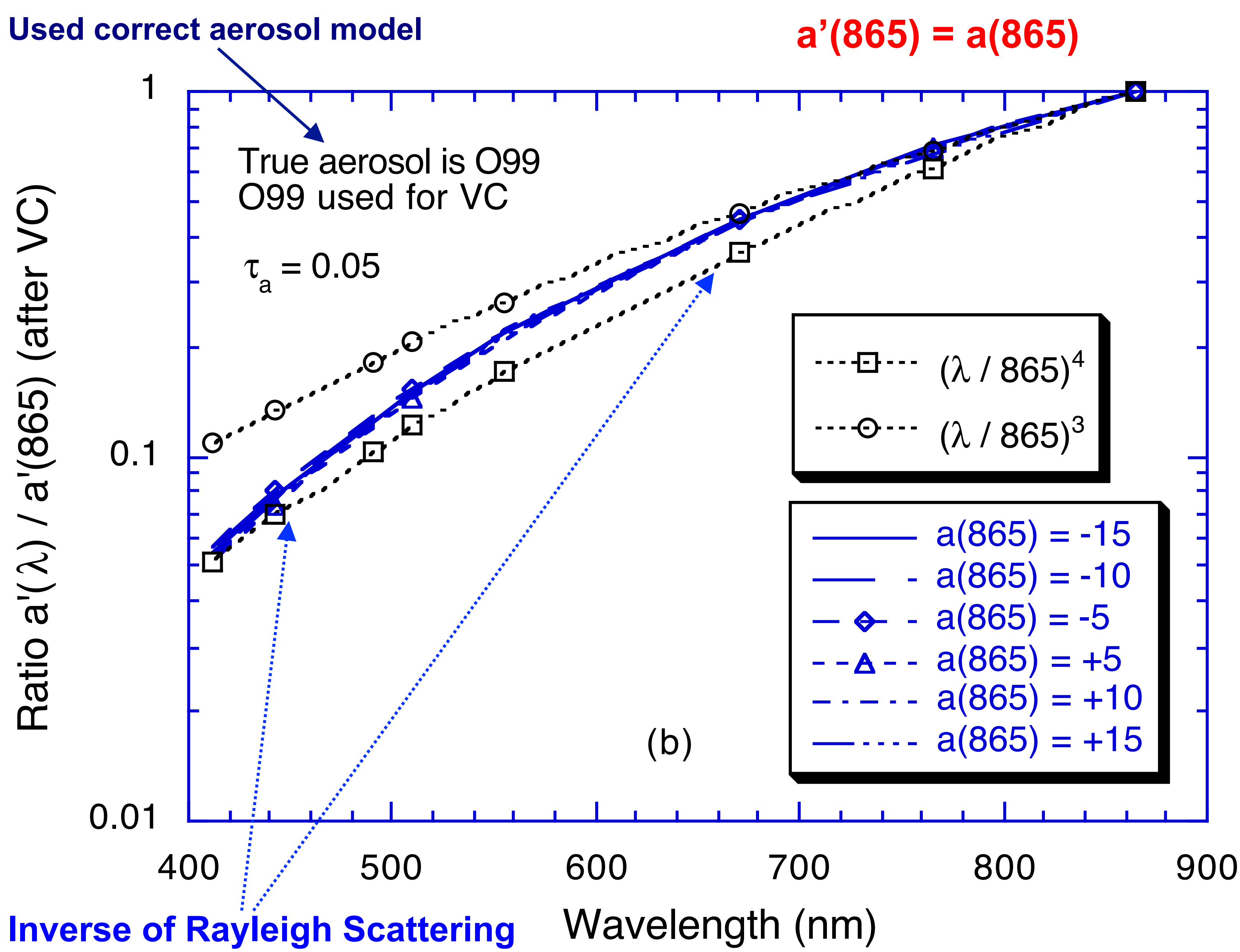
where for a given calibration site (solar and viewing geometry)

$$a'(\lambda) = G^{(VC)}(\lambda)\left[1 + a(\lambda)\right] - 1 = \left[\rho_t^{(Computed)}(\lambda)\right]^{(VC)} \Big/ \rho_t(\lambda) - 1$$

For $\lambda < 865$ nm, $a'(\lambda)$ only depends on $a(865)$ or at the SWIR band), but not on $a(\lambda)$!

Results of VC are independent of the sensor pre-launch calibration for $\lambda < 865$ nm (or SWIR 2130 nm)!!

Wang, M. and H. R. Gordon, "Calibration of ocean color scanners: How much error is acceptable in the near-infrared," *Remote Sens. Environ.*, **82**, 497-504, 2002.



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Vicarious Calibration Methodologies

1. Select MODIS-Aqua images with mostly clear 11x11 pixels (no cloud, no sun-glint, low sensor/solar zenith angle and AOT(869)<0.15) around MOBY site locations. Then a preliminary match-up is performed to exclude outliers beyond 1.5 standard deviations (288 images selected).
2. Set the gains of the three SWIR bands to be 1.0 and process the selected images using SWIR method. Each vicarious gain of the NIR bands were individually adjusted using an **iterative method** so that the final nLw is zero in the averaged sense with respect to the specific averaging method. The derived NIR gains were then used for NIR processing.
3. For both the SWIR and NIR ocean color data processing, each of the visible gains were individually adjusted so that in the averaged sense:
   - the ratio of the final nLw to the MOBY site in-situ value is one or
   - the difference between them is zero
4. The averaging methods involve taking the medians of the 11x11 pixels for each of the 288 images, and using mean or median of those 288 median values.
5. The criteria for MOBY-satellite match-up is to require satellite passing time to be within three hours of MOBY measurement time.
6. In addition to the (1) **iterative gain-adjusting method**, (2) **non-iterative inverse method** (forward RTE TOA radiance computations) that computes the ratio from the **TOA radiances** was also performed for comparison.

Vicarious Gains Derived from Three Different Averaging Methods

SWIR and NIR VC Gains Derived from MOBY In Situ						
Wavelength (nm)	*Ratio based: **Mean** of 11x11-Box-Median*		*Difference based: **Mean** of 11x11-Box-Median (baseline)*		*Ratio/Diff based: **Median** of 11x11-Box-Median*	
	SWIR	NIR	SWIR	NIR	SWIR	NIR
412	0.9650	0.9643	0.9649	0.9645	0.9645	0.9639
443	0.9745	0.9738	0.9745	0.9740	0.9745	0.9750
469	0.9964	0.9957	0.9964	0.9959	0.9965	0.9962
488	0.9713	0.9707	0.9714	0.9710	0.9720	0.9710
531	0.9798	0.9794	0.9799	0.9796	0.9807	0.9792
551	0.9788	0.9785	0.9790	0.9787	0.9793	0.9787
555	0.9837	0.9835	0.9838	0.9836	0.9845	0.9839
645	0.9933	0.9937	0.9936	0.9937	0.9920	0.9940
667	0.9790	0.9790	0.9792	0.9790	0.9784	0.9789
678	0.9774	0.9774	0.9776	0.9774	0.9774	0.9767
748	0.9777	–	0.9777	–	0.9777	–
859	0.9918	–	0.9918	–	0.9918	–
869	0.9867	–	0.9867	–	0.9867	–

Note: The highlighted gains were used to process all 1164 match-up images at the MOBY site for validation for both NIR & SWIR

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Vicarious Gains Derived from Iterative and Non-iterative Methods

SWIR and NIR VC Gains Derived from MOBY In Situ						
Wavelength (nm)	*Baseline: Median-Mean-Diff*		*Non-iterative NOAA-MSL12 Inverse Method*		*Non-iterative: NIR nLw = [0.0018,0.00097,0.00089]*	
	SWIR	NIR	SWIR	NIR	SWIR	NIR
412	0.9649	0.9645	0.9640	0.9633	0.9600	0.9596
443	0.9745	0.9740	0.9737	0.9729	0.9809	0.9804
469	0.9964	0.9959	0.9958	0.9950	0.9978	0.9976
488	0.9714	0.9710	0.9711	0.9703	0.9709	0.9706
531	0.9799	0.9796	0.9789	0.9781	0.9814	0.9816
551	0.9790	0.9787	0.9776	0.9770	0.9845	0.9850
555	0.9838	0.9836	0.9822	0.9818	0.9819	0.9825
645	0.9936	0.9937	0.9918	0.9918	0.9924	0.9938
667	0.9792	0.9790	0.9782	0.9778	0.9788	0.9799
678	0.9776	0.9774	0.9768	0.9765	0.9773	0.9785
748	0.9777	–	0.9774	–	0.9793	–
859	0.9918	–	0.9936	–	0.9956	–
869	0.9867	–	0.9894	–	0.9913	–

As expected, NIR gains increase with including the NIR nLw at the MOBY site.

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Vicarious Gains Derived from MOBY Assuming Non-zero NIR nLw

SWIR and NIR VC Gains Derived from MOBY In Situ						
Wavelength (nm)	*Iterative: NIR nLw = [0.0007,0.00039,0.00039]*		*Non-iterative: NIR nLw = [0.0007,0.00039,0.00039]*		*Non-iterative: NIR nLw = [0.0018,0.00097,0.00089]*	
	SWIR	NIR	SWIR	NIR	SWIR	NIR
412	–	–	–	–	0.9600	0.9596
443	–	–	–	–	0.9809	0.9804
469	–	–	–	–	0.9978	0.9976
488	–	–	–	–	0.9709	0.9706
531	–	–	–	–	0.9814	0.9816
551	–	–	–	–	0.9845	0.9850
555	–	–	–	–	0.9819	0.9825
645	–	–	–	–	0.9924	0.9938
667	–	–	–	–	0.9788	0.9799
678	–	–	–	–	0.9773	0.9785
748	0.9783	–	0.9783	–	0.9793	–
859	0.9925	–	0.9946	–	0.9956	–
869	0.9874	–	0.9905	–	0.9913	–

As expected, NIR gains increase with increase of the NIR nLw at the MOBY site.

The NIR Gains Accuracy

MODIS-Aqua NIR gains (for 748, 859, and 869 nm) derived from South Pacific Gyre (SPG):

- Iterative method: 1.0053, 1.0186, and 1.0197
- Inverse (forward): 1.0029, 1.0158, and 1.0180

Compared with the MOBY site (assume no NIR $nLw(\lambda)$):

- Iterative method: 0.9777, 0.9918, and 0.9867
- Inverse (forward): 0.9774, 0.9936, and 0.9894

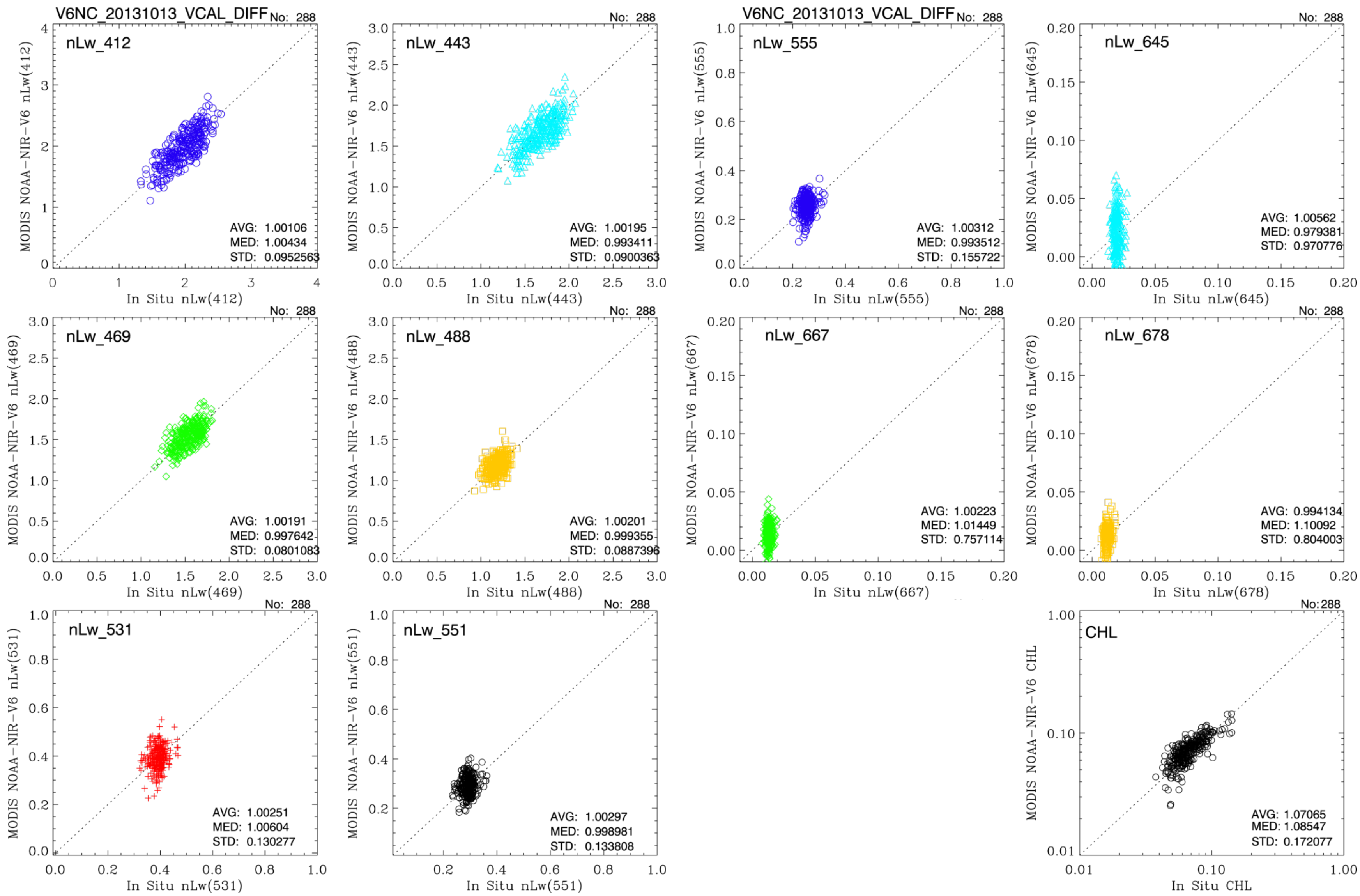
The NIR gain accuracy for the SWIR approach is <~3%.

This should be good enough for ocean color data processing based on Wang and Gordon (2002).

Wang, M. and H. R. Gordon, "Calibration of ocean color scanners: How much error is acceptable in the near-infrared," *Remote Sens. Environ.*, **82**, 497-504, 2002.

The 288 match-ups at MOBY using the NIR processing

(Expecting Exact Matches)



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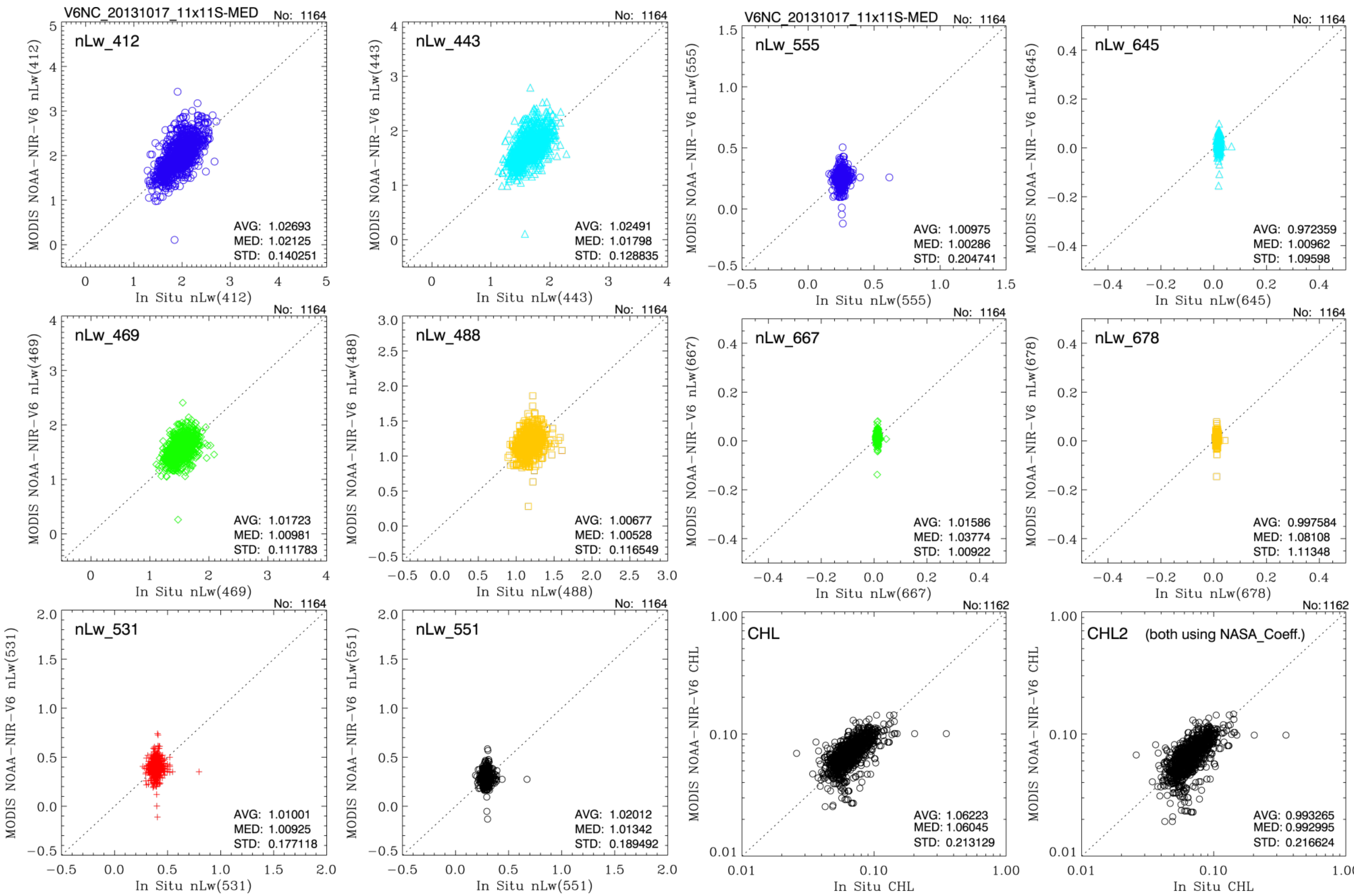
All 1164 match-ups at MOBY using the NIR data processing



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MODIS NOAA NIR MOBY Match-ups

Product	The 288 Match-ups			1164 Match-ups	
	Mean Ratio ± STD	Median Ratio	Mean Diff ± STD	Mean Ratio ± STD	Median Ratio
$nL_w(412)$	1.0011 ± 0.0953	1.0043	7.39E-6 ± 0.1842	1.0269 ± 0.1425	1.0213
$nL_w(443)$	1.0020 ± 0.0900	0.9934	-3.37E-6 ± 0.1482	1.0249 ± 0.1288	1.0180
$nL_w(469)$	1.0019 ± 0.0801	0.9976	5.28E-6 ± 0.1209	1.0172 ± 0.1118	1.0098
$nL_w(488)$	1.0020 ± 0.0887	0.9994	-2.91E-7 ± 0.1040	1.0068 ± 0.1165	1.0053
$nL_w(531)$	1.0025 ± 0.1303	1.0060	1.71E-8 ± 0.0503	1.0100 ± 0.1771	1.0093
$nL_w(551)$	1.0030 ± 0.1338	0.9990	3.59E-7 ± 0.0386	1.0201 ± 0.1895	1.0134
$nL_w(555)$	1.0031 ± 0.1557	0.9935	-2.77E-6 ± 0.0386	1.0098 ± 0.2047	1.0029
$nL_w(645)$	1.0056 ± 0.9708	0.9794	-1.04E-6 ± 0.0182	0.9724 ± 1.0960	1.0096
$nL_w(667)$	1.0022 ± 0.7571	1.0145	1.39E-6 ± 0.0094	1.0159 ± 1.0092	1.0374
$nL_w(678)$	0.9941 ± 0.8040	1.1092	1.04E-6 ± 0.0092	0.9976 ± 1.1135	1.0811
Chl-a	1.0707 ± 0.1721	1.0855	- -	0.9933 ± 0.2166	0.9930

Computer accuracy

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MODIS NOAA SWIR MOBY Match-ups

Product	288 Match-ups			1164 Match-ups	
	Mean Ratio ± STD	Median Ratio	Mean Diff ± STD	Mean Ratio ± STD	Median Ratio
$nL_w(412)$	0.9990 ± 0.1268	1.0029	3.91E-6 ± 0.2436	1.0210 ± 0.1859	1.0177
$nL_w(443)$	0.9999 ± 0.1307	1.0001	-3.41E-6 ± 0.2150	1.0180 ± 0.1884	1.0098
$nL_w(469)$	1.0004 ± 0.1319	0.9997	5.28E-6 ± 0.2005	1.0108 ± 0.1855	1.0077
$nL_w(488)$	1.0061 ± 0.1443	0.9939	-2.93E-7 ± 0.1698	0.9996 ± 0.1995	1.0018
$nL_w(531)$	1.0015 ± 0.3408	0.9893	2.02E-8 ± 0.1321	1.0031 ± 0.4315	0.9962
$nL_w(551)$	1.0021 ± 0.4319	0.9921	3.66E-7 ± 0.1245	1.0133 ± 0.5370	1.0069
$nL_w(555)$	1.0023 ± 0.4787	0.9834	7.06E-7 ± 0.1197	1.0060 ± 0.5910	1.0000
$nL_w(645)$	1.0316 ± 4.1463	1.1574	2.43E-6 ± 0.0775	0.9194 ± 4.8848	1.0796
$nL_w(667)$	1.0393 ± 5.3983	1.1409	1.39E-6 ± 0.0675	0.7799 ± 6.4908	0.8442
$nL_w(678)$	1.0424 ± 5.4790	1.0656	1.04E-6 ± 0.0630	0.7139 ± 6.5792	0.8264
Chl-a	- -	- -	- -	1.0471 ± 0.6020	1.0089

Computer accuracy

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Conclusions

- It has been demonstrated that VC is necessary for producing accurate satellite ocean color products (e.g., from SeaWiFS, MODIS, MERIS, and VIIRS).
- The SWIR approach can derive the NIR gains with accuracy to < ~3%, which is accurate enough for ocean color data processing.
- Both the SWIR and NIR VC approaches can drive accurate and consistent VC gains for ocean color data processing. Thus, ocean color data can be derived consistently from both the SWIR and NIR ocean color data processing, e.g., with the NIR-SWIR approach to address the coastal and inland waters.
- In situ vicarious calibration facility for ocean color sensors, such as **MOBY**, to provide accurate $nL_w(\lambda)$ data is required and necessary. In particular, in situ NIR $nL_w(\lambda)$ measurements are useful/important.