Inter-Satellite Comparison and Evaluation of Navy SNPP-VIIRS and MODIS-Aqua Ocean Color Properties

S. D. Ladner[1], R. Arnone[2], R. Vandermeulen[2],
P. Martinolich[3], A. Lawson[1], J. Bowers[3], R. Crout[1], M. Ondrusek[4]

[1]Naval Research Laboratory, Stennis Space Center, Mississippi, MS 39529
[2]Dept. of Marine Science, University of Southern Mississippi, Stennis Space Center, MS 39529
[3]QinetiQ North America, Stennis Space Center, Mississippi, MS 39529
[4]NOAA NESDIS, College Park, MD 20740

ABSTRACT

Navy operational ocean color products of inherent optical properties and radiances are evaluated for the Suomi–NPP VIIRS and MODIS-Aqua sensors. Statistical comparisons with shipboard measurements were determined in a wide variety of coastal, shelf and offshore locations in the Northern Gulf of Mexico during two cruises in 2013. Product consistency between MODIS-Aqua, nearing its end-of-life expectancy, and Suomi-NPP VIIRS is being evaluated for the Navy to retrieve accurate ocean color properties operationally from VIIRS in a variety of water types. Currently, the existence, accuracy and consistency of multiple ocean color sensors (VIIRS, MODIS-Aqua) provides multiple looks per day for monitoring the temporal and spatial variability of coastal waters. Consistent processing methods and algorithms are used in the Navy's Automated Processing System (APS) for both sensors for this evaluation. The inherent optical properties from both sensors are derived using a coupled ocean-atmosphere NIR correction extending well into the bays and estuaries where high sediment and CDOM absorption dominate the optical signature. Coastal optical properties are more complex and vary from chlorophyll-dominated waters offshore. The in-water optical properties were derived using vicariously calibrated remote sensing reflectances and the Quasi Analytical Algorithm (QAA) to derive the Inherent Optical Properties (IOP's). The Naval Research Laboratory (NRL) and the JPSS program have been actively engaged in calibration/validation activities for Visible Infrared Imager Radiometer Suite (VIIRS) ocean color products.

Keywords: Satellite, SNPP VIIRS, Ocean Color, Optics, Validation, Vicarious Calibration

1. INTRODUCTION

The Navy exploits current and future polar-orbiting ocean color sensors to provide optical properties to obtain a picture of the operational environmental conditions of the battlespace. The current suite of Navy ocean color sensors includes MODIS-Aqua, NPP VIIRS and Korea's Geo-stationary Ocean Color Imagery (GOCI). Here we will evaluate the accuracy and inter-sensor consistency between satellite derived and insitu remote sensing reflectances (Rrs) and inherent optical properties (IOP's) between NPP VIIRS and MODIS Aqua only in the Northern Gulf of Mexico. The existence, accuracy and consistency of multiple ocean color sensors provide multiple looks per day for monitoring the temporal and spatial variability of coastal waters. Sensor characterization is critical in order to use the derived products to support Navy operations or ecosystem monitoring because the ocean color signal represents only ten percent of the total radiance signal at the top of the atmosphere (TOA). Errors in sensor calibration, out of spectral band response issues, polarization and atmospheric correction must be accounted for so that operational products can be accurate and provide consistency with existing ocean color products. In addition to providing a common environmental picture, the products can be used for validation of or assimilation into ocean forecast models. Ocean optical products are used to predict the impact of the environment on navy systems used in communication, mine detection and target detection.

The Navy is currently actively engaged with the JPSS program in ocean color calibration and validation activities. The ocean color calibration and validation team, led by NOAA STAR, is composed of leading personnel from the US government, universities and international collaborators who have expertise in sensor characterization, ocean color processing, atmospheric correction, vicarious adjustment and calibration, in-water algorithm development, and in situ

data collection from ship and AERONET-OC sites. The JPSS ocean calibration and validation program for VIIRS has established methods and procedures to insure the accuracy of the retrieved ocean satellite products and to provide methods to improve algorithms and characterize the product uncertainty. A Navy global monitoring network has been established and integrates in situ data collected at coastal (Aeronet Ocean Color – AOC) and open ocean (MOBY, Gyres) sites with satellite retrieved water leaving radiance values from ocean color satellites including MODIS and VIIRS. The global network provides a real-time monitoring capability to evaluate the quality of current ocean color sensors in different areas around the world and enables evaluation and validation of the products with in situ data. This evaluation is performed by tracking the nLw's and the "gain" at the Top of the Atmosphere (TOA). Real time coastal sites, though of lower quality, have been successfully used to monitor sensor stability and provide sufficient "matchups" in real time to perform more routine updates of the vicarious calibration. Because the MODIS sensor is aging, the satellite oceanography community is working to have the VIIRS mission be operational as soon as possible. VIIRS can provide a follow-on to heritage sensors such as SeaWIFS, MODIS and MERIS ocean color products for operational monitoring of water quality and support to Navy missions if sufficient sensor characterization and calibration are performed, including assessing the stability and consistency of ocean products. This effort includes continual validation of the VIIRS color products in a wide variety of ocean conditions and assessing the accuracy of ocean color processing. VIIRS ocean color products are compared with MODIS retrieved nLw's, chlorophyll and IOP's and have been shown to provide similar quality. New calibration updates are expected for VIIRS in the near future and will be addressed. Both VIIRS and MODIS Aqua have been vicariously calibrated by NASA (MODIS Aqua) and NRL (VIIRS) using the Marine Optical Buoy (MOBY) located off the Hawaii coast in a blue water stable environment with minimal natural variability (oceanic and atmospheric). Vicarious adjustments administered for VIIRS by the Navy follow the methodology developed by the NASA Ocean Biology Processing Group (OBPG) to do near real time cal/val activities.

The Joint Polar Satellite System (JPSS) launched the Suomi National Polar-Orbiting Partnership (NPP) satellite including the Visible Infrared Sensor (VIIRS) on November 28, 2011 containing five visible channels that are used to characterize spectral ocean color and two NIR channels for atmospheric correction at 750m spatial resolution. MODIS-Aqua was launched in May of 2002 and contains six visible channels and two NIR channels at 1200m spatial resolution. Both sensors provide repeat daily coverage. Satellite ocean color is used to characterize water quality properties requiring that the sensors are well characterized and calibrated, and that processing addresses atmospheric correction to derive radiometric water leaving radiance (nLw). These radiometric properties are used to retrieve bio-optical products that are essential for Navy operational support and ecosystem monitoring. The accuracy of the ocean color properties and inter-sensor consistency is also important.

Using the Naval Research Laboratory's Automated Processing System (APS) software (an extension to NASA's l2gen – http://www7333.nrlssc.navy.mil/docs/aps_v4.2/html/api/index.html), The Level 1B files (SDR's) for VIIRS and MODIS Aqua were obtained from the Navy IDPS and NOAA CLASS and processed from Level-1B (calibrated and geo-located Top of Atmosphere radiances) to Level-3 (fully calibrated, atmospherically corrected and mapped) to obtain Rrs at all visible sensor wavelengths and using bio-optical algorithms provide ocean color / water quality products. APS has the ability to process data and generate ocean products from multiple satellite sensors (SeaWiFS, MODIS, SNPP VIIRS, MERIS, GOCI, and HICO) and uses an improved atmospheric correction for coastal waters. Remote sensing ocean color algorithms are based on relationships between remote sensing reflectance (Rrs) and inherent optical properties of absorption and backscattering. In this study, relationships between vicariously calibrated MODIS Aqua and VIIRS Rrs' and IOP's are validated against insitu measurements. We assess the uncertainty between measured and satellite-derived properties (Rrs, absorption, backscattering and beam attenuation) for both VIIRS and MODIS Aqua using the Navy's Automated Processing System (APS) along with inter-sensor comparisons by using data collected during two field campaigns in the Northern Gulf of Mexico during September and November of 201. The objective of these field events where to collect data in support of the NASA GEOstationary Coastal and Air Pollution Events (GEO-CAPE) mission and Navy and JPSS program calibration and validation activities.

2. BACKGROUND

VIIRS and MODIS Aqua Level 1B files (SDR's) coincident with shipboard measurements were obtained from NOAA CLASS and processed from Level-1B (calibrated and geo-located Top of Atmosphere radiances) to Level-3 (fully calibrated, atmospherically corrected and mapped) using the Navy's Automated Processing System (APS) to obtain Rrs at all visible sensor wavelengths and using bio-optical algorithms provide ocean color / water quality products. The standard atmospheric correction was applied using the Gordon/Wang (1994) approach with a NIR iteration (Stumpf ????) to improve retrievals in the coastal ocean by iteratively estimating the NIR contribution replacing the standard black water assumption (little or no radiance leaving the water in the NIR) that occasionally results in negative nLw's in the coastal waters with high suspended sediment loads. The NIR iteration enables us to extend estimates of satellite-derived optical properties well into the bays and estuaries where high sediments and CDOM absorption dominate the optical signature. Inherent optical properties were derived from the VIIRS and MODIS Aqua remote sensing reflectances using the Quasi Analytical Algorithm – QAA (Lee et al). Figure 1 illustrates a comparison between VIIRS and MODIS Aqua derived total backscatter QAA @ 551nm (VIIRS) and 547nm (MODIS Aqua) product for November 20, 2013 covering the Mississippi Sound in the Northern Gulf of Mexico. It is important to note that IOP retrievals are difficult and can reflect the limitations of the algorithms rather than stand as a statement regarding satellite performance. A thorough discussion of deriving IOPS from remote sensing can be found in the IOCCG Report 5, 2006. As a baseline, literature suggests that mean relative errors ranging from 30 – 70% for IOP retrievals are not uncommon in coastal waters (Chang and Gould, 2006, Ladner, et al 2002).

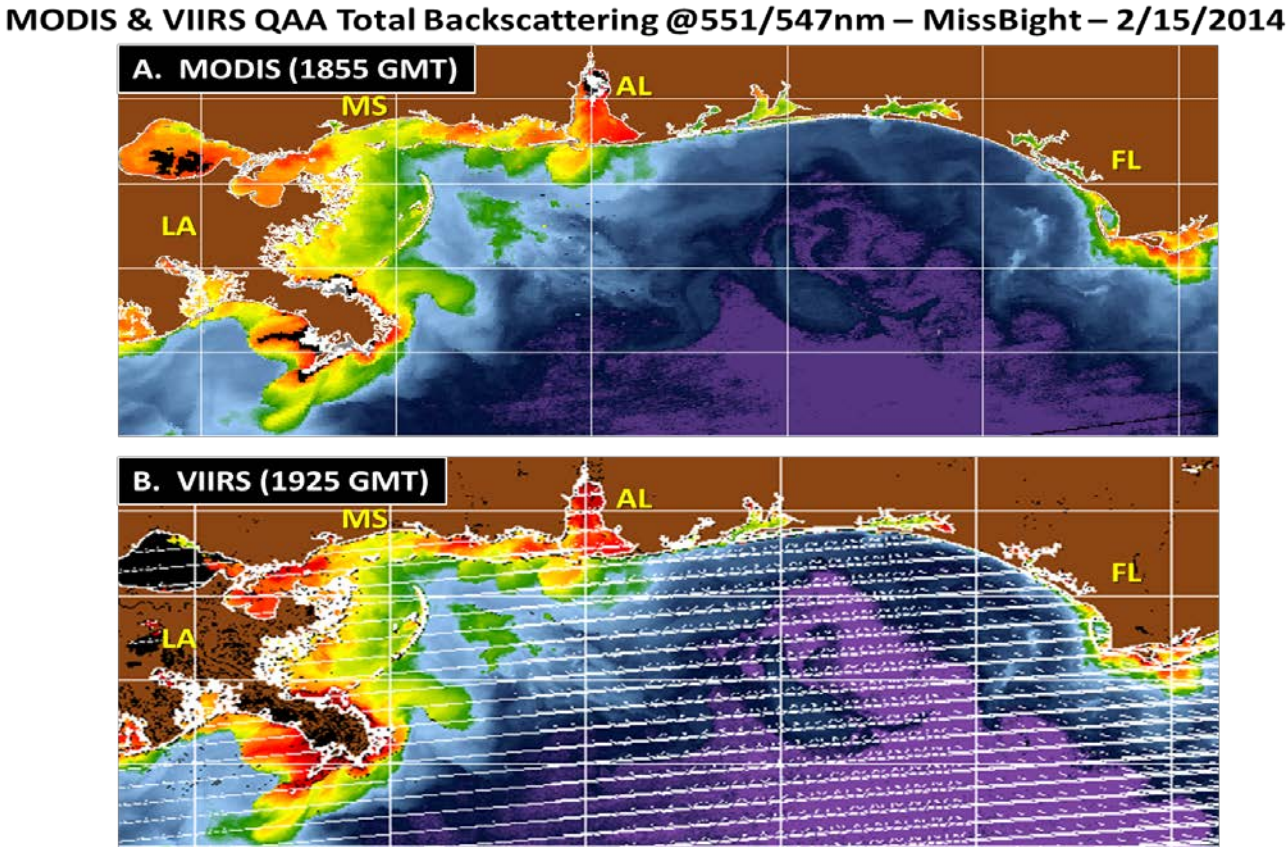


Figure 1 shows a comparison between VIIRS and MODIS Aqua derived total backscatter QAA @ 551nm (VIIRS) and 547nm (MODIS Aqua) product for November 20, 2013 covering the Mississippi Sound in the Northern Gulf of Mexico. Note that the derived total backscattering for both sensors is very similar and a small resolution improvement for VIIRS at 750m as compared to MODIS Aqua is at 1 kilometer. Blue dots represent flowthru data sample locations and red dots above water rrs.

Comparison Between MODIS and VIIRS - November 20, 2013
Mississippi Sound
QAA Total Backscattering (551nm for VIIRS & 547nm for MODIS Aqua)

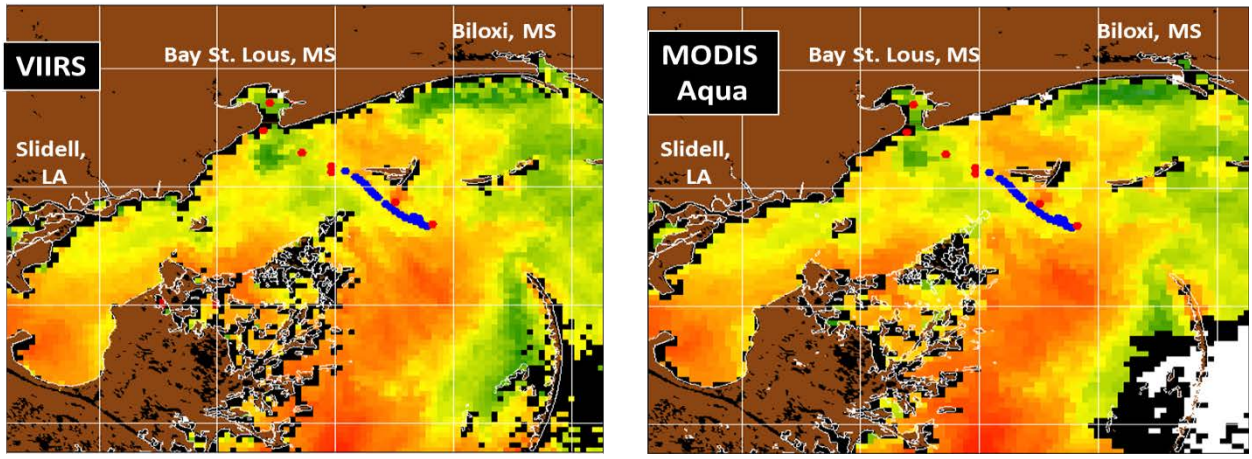


Figure 1 shows a comparison between VIIRS and MODIS Aqua derived total backscatter QAA @ 551nm (VIIRS) and 547nm (MODIS Aqua) product for November 20, 2013 covering the Mississippi Sound in the Northern Gulf of Mexico. Note that the derived total backscattering for both sensors is very similar and a small resolution improvement for VIIRS at 750m as compared to MODIS Aqua is at 1 kilometer. Blue dots represent flowthru data sample locations and red dots above water rrs.

Insitu Rrs and IOP's were collected during two field campaigns in the Northern Gulf of Mexico in September and November of 2013 in support for the NASA GEOstationary Coastal and Air Pollution Events (GEO-CAPE) mission and Navy and JPSS calibration and validation activities. The GEO-CAPE cruise took place between September 9 and September 19, 2013 in the Northern Gulf of Mexico off the Louisiana and Texas coast. The insitu was collected in a wide variety of coastal, shelf and offshore locations and measurements of above and below surface radiances and inherent optical properties and provided to NRL courtesy of Mike Ondrusek (NOAA NESDIS) and Zhongping Lee (University of Massachusetts). Insitu Rrs data were collected using a Satlantic free-falling hyperspectral optical profiler (HyperPro) and a Satlantic above water hyperspectral radiometer (HyperOCR) using a skylight-blocked approach for Rrs. IOP's were collected using a WetLabs Hyperspectral absorption and attenuation meter (ACS) for absorption and beam attenuation and WetLabs ECOPUC for backscattering. Figure 2 shows the VIIRS derived total backscatter product derived using the Quasi Analytical Algorithm (QAA) and station locations to support the NASA/NOAA GEOCAPE. Station locations are dotted in blue. Total number of valid matchups between insitu and satellite rrs was 25.

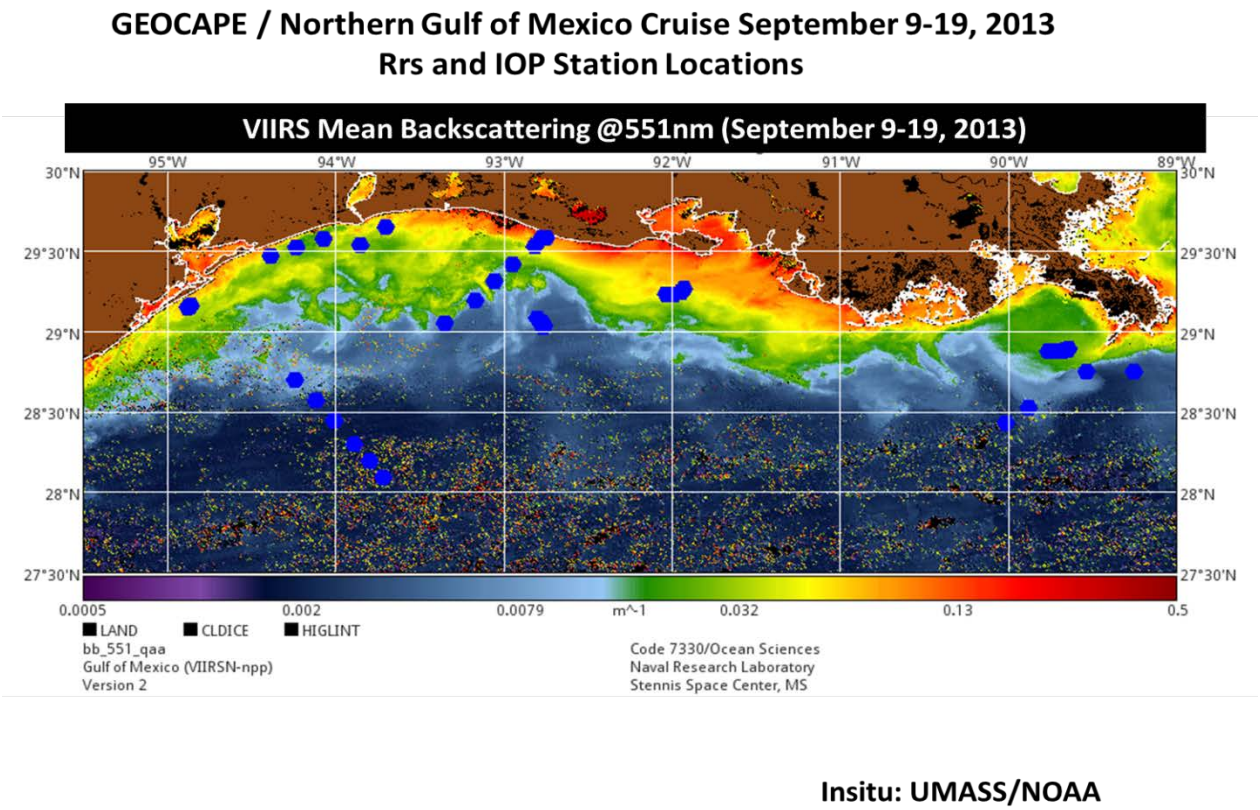


Figure 2 shows the VIIRS derived total backscatter product to support the NASA/NOAA GEOCAPE cruise that took place in the Northern Gulf of Mexico from July 9 to the 19, 2013. Station locations are dotted in blue.

A second cruise aboard the Navy's RV Ocean Color was conducted on Nov 20, 2013 in which stations and flow-through system data were collected. The flow through data included ac-9 (absorption and beam attenuation) along a path from Bay St Louis out to the Gulf of Mexico past Horn Island. These data were spatially bin averaged to the resolution of the VIIRS and MODIS Aqua sensors to matchup with the retrieved satellite ocean products. The rrs data was collected at 7 station locations using a Analytical Spectral Devices (ASD) handheld hyperspectral radiometer. Figure 3 shows the location of transect data taken from A to B off the coast of Mississippi.

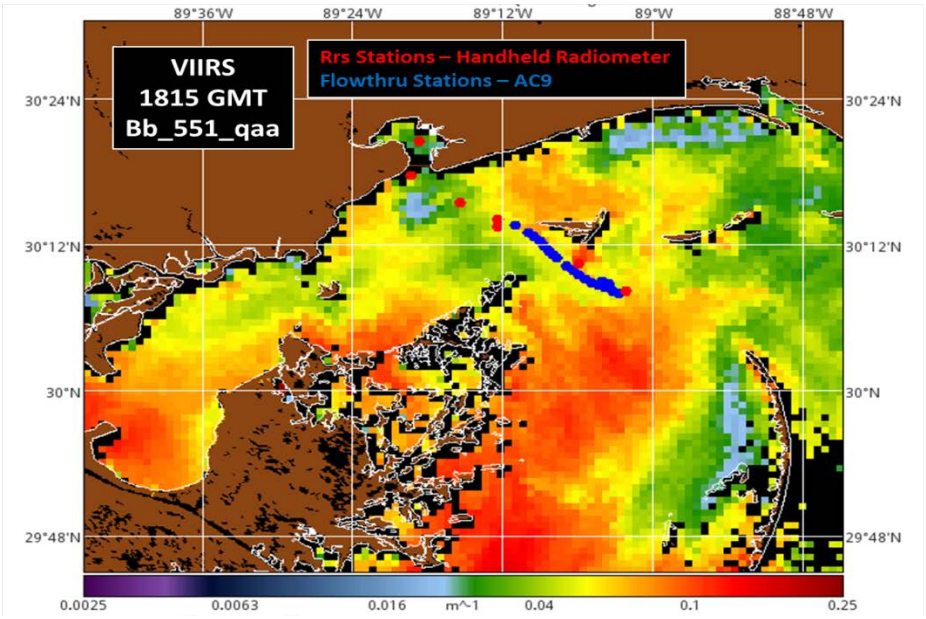
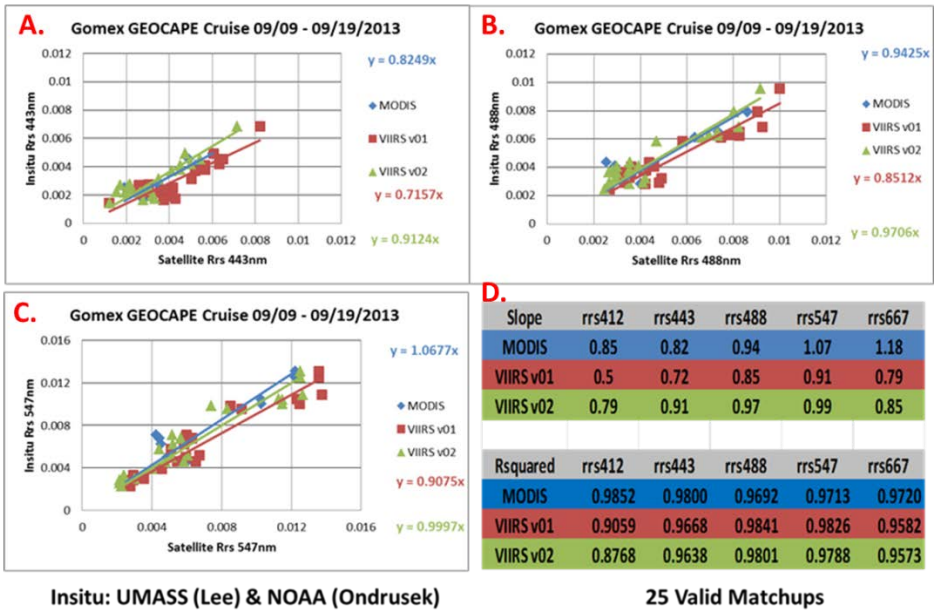


Figure 2 shows the VIIRS derived total backscattering product from the Quasi Analytical Algorithm (QAA) and the location of Flowthru (blue) and Rrs (red dots) data taken off the coast of Mississippi during the Navy R/V Ocean Color Cruise.

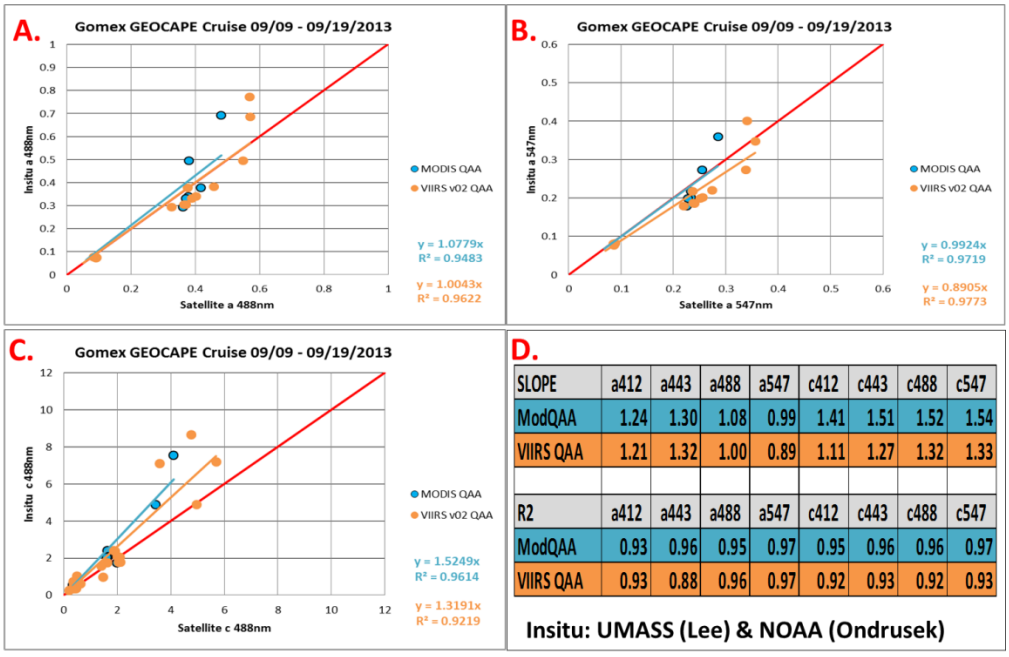
3. RESULTS



Slope	rrs412	rrs443	rrs488	rrs547	rrs667
MODIS	0.85	0.82	0.94	1.07	1.18
VIIRS v01	0.5	0.72	0.85	0.91	0.79
VIIRS v02	0.79	0.91	0.97	0.99	0.85

Rsquared	rrs412	rrs443	rrs488	rrs547	rrs667
MODIS	0.9852	0.9800	0.9692	0.9713	0.9720
VIIRS v01	0.9059	0.9668	0.9841	0.9826	0.9582
VIIRS v02	0.8768	0.9638	0.9801	0.9788	0.9573

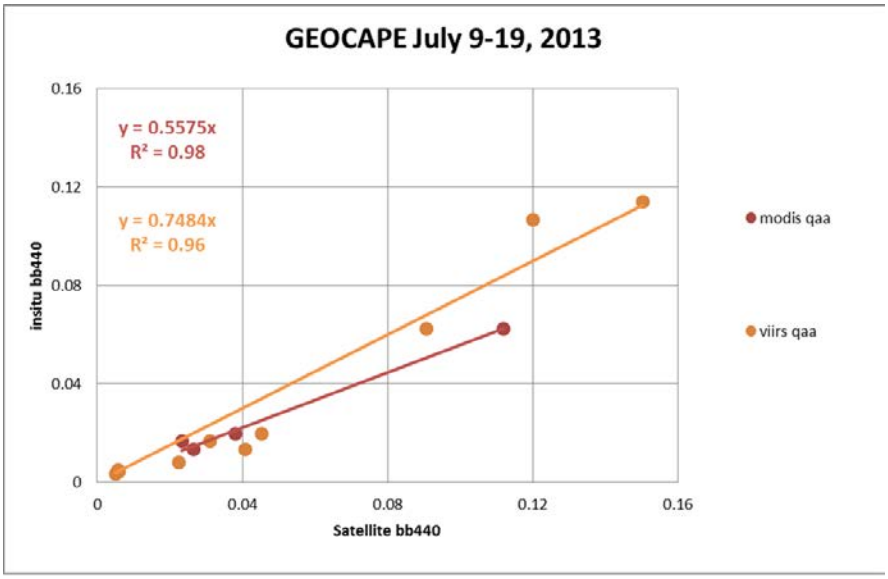
Figure 30 shows the location of transect data taken from A to B off the coast of Mississippi. The left plot shows the matchup along the track for the IOP – 443 nm absorption products from MODIS and VIIRS using AOPS, VOCCO, and the ac-9 in situ measurement. The right plot shows the regression of satellite products against the in situ 443 nm products. Note the VOCCO product (using Carter algorithm) has data gaps because of non-retrievals (negative nLw's) of the EDR product. The MODIS retrievals (red) were above the one to one line. The VIIRS AOPS retrievals (purple) used the QAA algorithm and NIR processing, all falling close the one to one line (slope = 1.05). Notably, the VIIRS ocean color products are doing better than MODIS in this comparison. This supports arguments for upgrading the IDPS to support coastal ocean products.



SLOPE	a412	a443	a488	a547	c412	c443	c488	c547
ModQAA	1.24	1.30	1.08	0.99	1.41	1.51	1.52	1.54
VIIRS QAA	1.21	1.32	1.00	0.89	1.11	1.27	1.32	1.33

R2	a412	a443	a488	a547	c412	c443	c488	c547
ModQAA	0.93	0.96	0.95	0.97	0.95	0.96	0.96	0.97
VIIRS QAA	0.93	0.88	0.96	0.97	0.92	0.93	0.92	0.93

Figure 30 shows the location of transect data taken from A to B off the coast of Mississippi. The left plot shows the matchup along the track for the IOP – 443 nm absorption products from MODIS and VIIRS using AOPS, VOCCO, and the ac-9 in situ measurement. The right plot shows the regression of satellite products against the in situ 443 nm products. Note the VOCCO product (using Carter algorithm) has data gaps because of non-retrievals (negative nLw's) of the EDR product. The MODIS retrievals (red) were above the one to one line. The VIIRS AOPS retrievals (purple) used the QAA algorithm and NIR processing, all falling close the one to one line (slope = 1.05). Notably, the VIIRS ocean color products are doing better than MODIS in this comparison. This supports arguments for upgrading the IDPS to support coastal ocean products.



NOAA ECOPUC Data
(Ondrusek)

bb440	Rsquared	Slope
modis qaa	0.9895	0.5600
viirs qaa	0.9586	0.7500

Figure 30 shows the location of transect data taken from A to B off the coast of Mississippi. The left plot shows the matchup along the track for the IOP – 443 nm absorption products from MODIS and VIIRS using AOPS, VOCCO, and the ac-9 in situ measurement. The right plot shows the regression of satellite products against the in situ 443 nm products. Note the VOCCO product (using Carter algorithm) has data gaps because of non-retrievals (negative nLw's) of the EDR product. The MODIS retrievals (red) were above the one to one line. The VIIRS AOPS retrievals (purple) used the QAA algorithm and NIR processing, all falling close the one to one line (slope = 1.05). Notably, the VIIRS ocean color products are doing better than MODIS in this comparison. This supports arguments for upgrading the IDPS to support coastal ocean products.

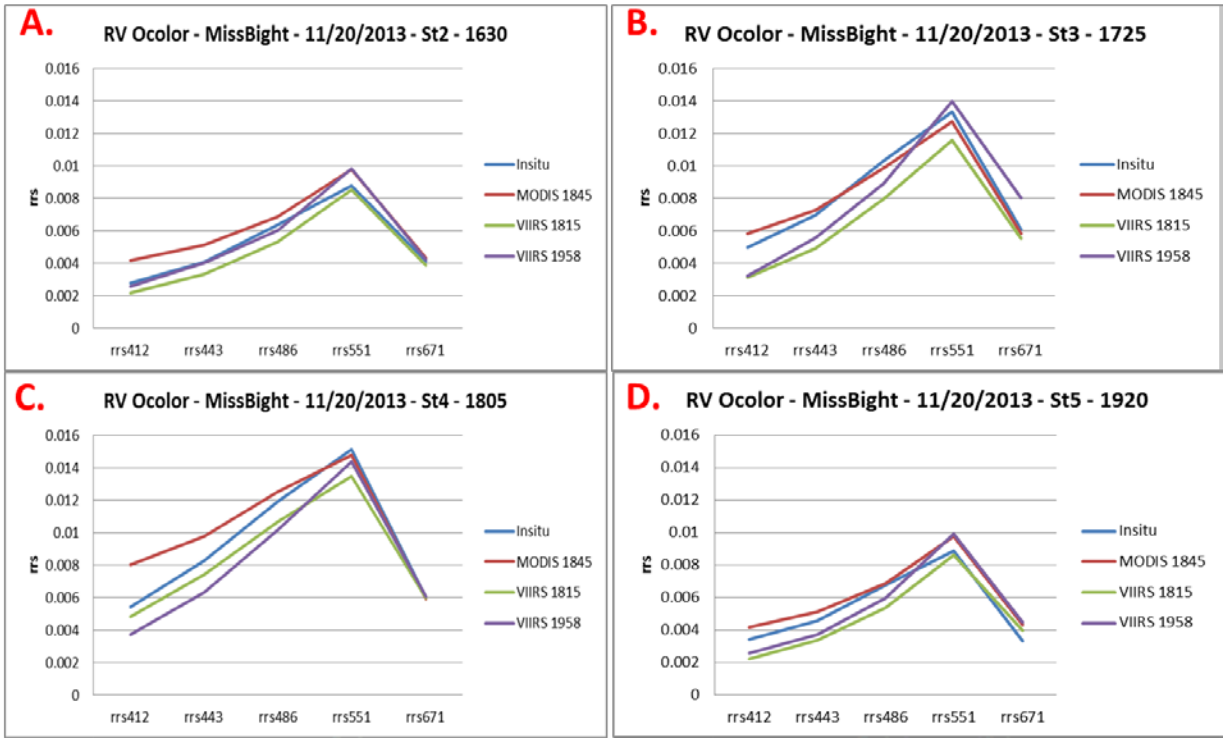
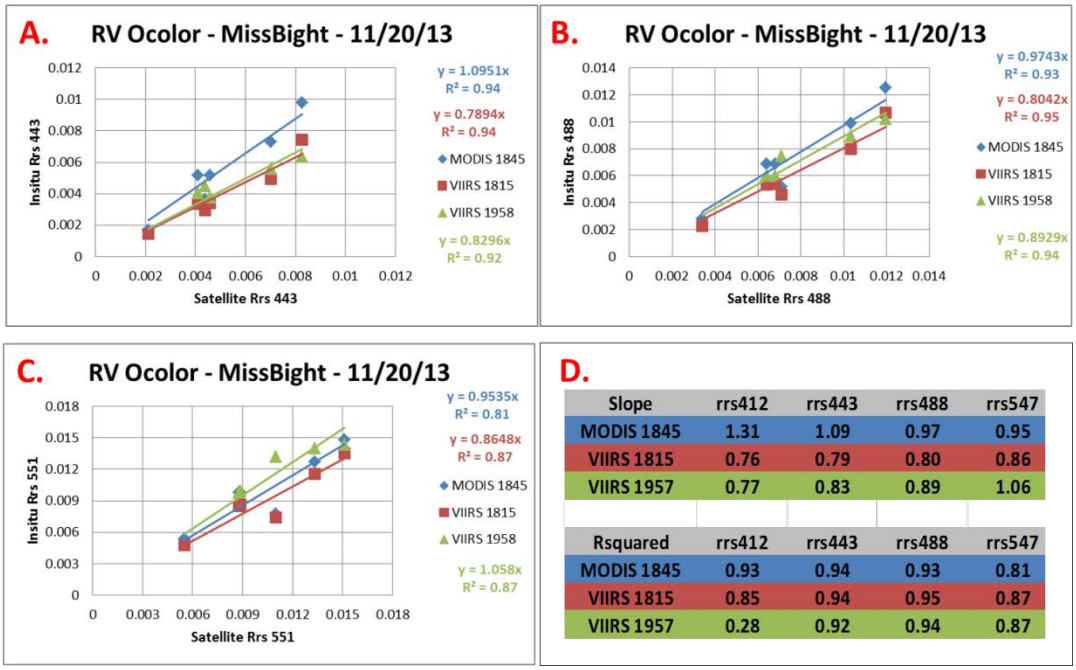


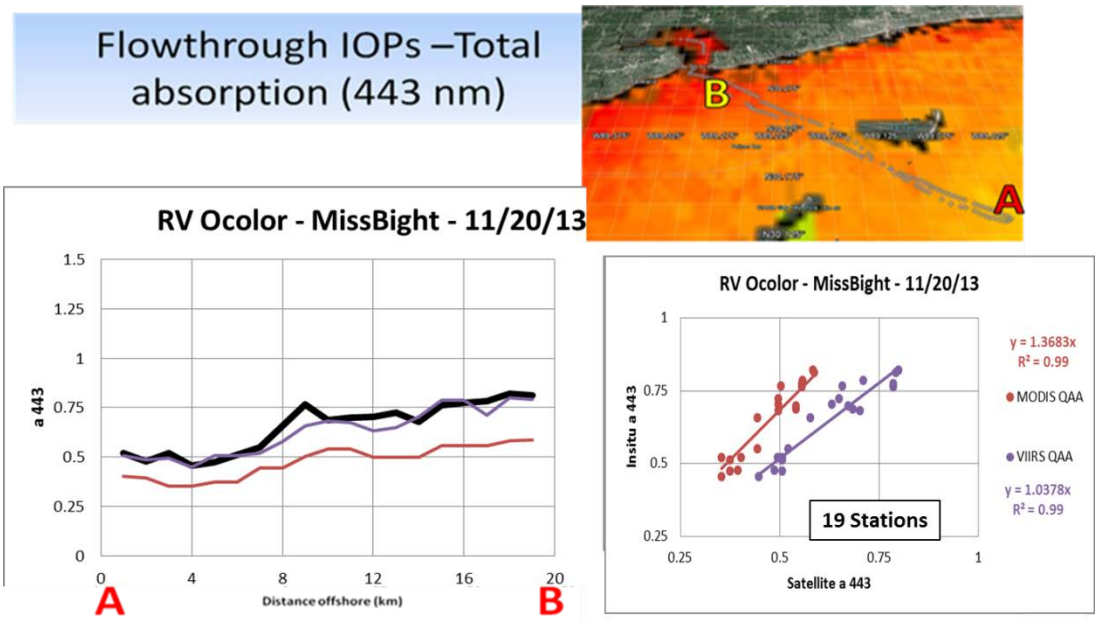
Figure 30 shows the location of transect data taken from A to B off the coast of Mississippi. The left plot shows the matchup along the track for the IOP – 443 nm absorption products from MODIS and VIIRS using AOPS, VOCCO, and the ac-9 in situ measurement. The right plot shows the regression of satellite products against the in situ 443 nm products. Note the VOCCO product (using Carter algorithm) has data gaps because of non-retrievals (negative nLw's) of the EDR product. The MODIS retrievals (red) were above the one to one line. The VIIRS AOPS retrievals (purple) used the QAA algorithm and NIR processing, all falling close the one to one line (slope = 1.05). Notably, the VIIRS ocean color products are doing better than MODIS in this comparison. This supports arguments for upgrading the IDPS to support coastal ocean products.



Slope	rrs412	rrs443	rrs488	rrs547
MODIS 1845	1.31	1.09	0.97	0.95
VIIRS 1815	0.76	0.79	0.80	0.86
VIIRS 1957	0.77	0.83	0.89	1.06

Rsquared	rrs412	rrs443	rrs488	rrs547
MODIS 1845	0.93	0.94	0.93	0.81
VIIRS 1815	0.85	0.94	0.95	0.87
VIIRS 1957	0.28	0.92	0.94	0.87

Figure 30 shows the location of transect data taken from A to B off the coast of Mississippi. The left plot shows the matchup along the track for the IOP – 443 nm absorption products from MODIS and VIIRS using AOPS, VOCCO, and the ac-9 in situ measurement. The right plot shows the regression of satellite products against the in situ 443 nm products. Note the VOCCO product (using Carter algorithm) has data gaps because of non-retrievals (negative nLw's) of the EDR product. The MODIS retrievals (red) were above the one to one line. The VIIRS AOPS retrievals (purple) used the QAA algorithm and NIR processing, all falling close the one to one line (slope = 1.05). Notably, the VIIRS ocean color products are doing better than MODIS in this comparison. This supports arguments for upgrading the IDPS to support coastal ocean products.



SLOPE	a412	a443	a488	a547	c412	c443	c488	c547
ModQAA	1.4719	1.3683	1.1459	0.8762	1.3836	1.4048	1.4270	1.4263
VIIRS QAA	0.8398	1.0374	0.9853	0.8244	1.3357	1.4410	1.4748	1.4678

R2	a412	a443	a488	a547	c412	c443	c488	c547
ModQAA	0.9968	0.9966	0.9961	0.9974	0.9875	0.9872	0.9871	0.9873
VIIRS QAA	0.9929	0.9966	0.9958	0.9965	0.9915	0.9914	0.9908	0.9909

Figure 30 shows the location of transect data taken from A to B off the coast of Mississippi. The left plot shows the matchup along the track for the IOP – 443 nm absorption products from MODIS and VIIRS using AOPS, VOCCO, and the ac-9 in situ measurement. The right plot shows the regression of satellite products against the in situ 443 nm products. Note the VOCCO product (using Carter algorithm) has data gaps because of non-retrievals (negative nLw's) of the EDR product. The MODIS retrievals (red) were above the one to one line. The VIIRS AOPS retrievals (purple) used the QAA algorithm and NIR processing, all falling close the one to one line (slope = 1.05). Notably, the VIIRS ocean color products are doing better than MODIS in this comparison. This supports arguments for upgrading the IDPS to support coastal ocean products.

4. CONCLUSIONS

The Navy's assessment of the Visible Infrared Imager Radiometer Suite (VIIRS) on Suomi National Polar-orbiting Partnership (NPP) indicates ocean color products are of high quality. Evaluations to date indicate the sensor meets Navy requirements for operational ocean optical products as demonstrated by comparison to both in situ data and as compared to current operational products derived from Moderate Resolution Imaging Spectroradiometer (MODIS Aqua). In both cases, VIIRS maintains a linear relationship with other accepted measurement techniques.

Spatial and temporal variability of bio-optical properties combined with differences in measurement techniques contribute to inconsistencies between remotely sensed and in situ measurements. We provide ground truth measurement for two ocean color sensors, VIIRS and MODIS, for two exercises in the Northern Gulf of Mexico during September and November 2013. Comparisons are shown between satellite and in situ measurements of remote sensing reflectance, total absorption, total backscattering and beam attenuation using standard bio-optical algorithms. Discrepancies are attributed

to imperfect atmospheric corrections, uncertainties originating from sampling errors (including pixel to point matchups and including sea surface variations), natural bio-optical variability and common errors in coastal bio-optical algorithms (30 – 70%). Normalized water-leaving radiances and remote sensing reflectances are within requirements for both the VIIRS and MODIS Aqua sensors.

Results indicate the VIIRS sensor will provide a continuous data stream to support operational navy products. VIIRS appears well characterized and is generating quality ocean color products as compared to existing ocean sensing satellites. The VIIRS sensor is capable of generating scientific research quality data in addition to meeting operational demands. Continued Cal/Val procedures are required to monitor ocean color product data stream for global trends and evaluate possible sensor degradation. As the JPSS Cal/Val Team (NASA, NOAA, and NRL) continues to better characterize the sensor and monitor the trends of the sensor's calibration tables, improvements to the generated ocean products are expected.

Based on previous and current (this study) validation results, the Navy will continue to use the VIIRS sensor data operationally using the Navy's Automated Processing System, which is based on L2gen for ocean color products. Although continued monitoring and analyses will be required, the products should provide an adequate follow-on and replacement to MODIS to support Navy operations. The Navy sees no reason that the VIIRS sensor should not provide scientific research quality data for new algorithm development and the capability to produce operational products to support the fleet as well as perform ecological monitoring.

5. ACKNOWLEDGEMENTS

We greatly appreciate the support we have received from our Navy and NOAA sponsors. Wesley Goode (NRL), Mike Ondrusek (NOAA) and ZhongPing Lee (UMASS) is recognized for collecting and providing in situ cruise data. We thank NAVO (VIIRS SDR AFWA) and NOAA CLASS for providing VIIRS and MODIS Aqua data and the JPSS SDR team for contribution of the VIIRS weekly LUTS.

6. REFERENCES

[1] Mahoney K., R. Arnone, P. Flynn, B. Casey and S. Ladner, "Ocean Optical Forecasting in Support of MCM Operations," 8th Int. Symposium on Technology of the Mine Problems, Proceedings, May 2008.

[2] Giddings, T. E. and J. J. Shirron. "Performance Prediction for Underwater Electro-Optical Mine Identification Systems". Ocean Optics XIX. 2008.

[3] Ladner, S. D., J. Sandidge, P. E. Lyon, R. A. Arnone, R. W. Gould, Z. P. Lee, and P. M. Martinolich. "Development of Finer Spatial Resolution Optical Properties from MODIS", Proceedings of SPIE Optics and Photonics Meeting, August 2007.

[4] Martinolich, P.M., "The Automated Satellite Data Processing System", NRL Website, URL http://www7333.nrlssc.navy.mil/docs/aps_v4.0/user/aps/, Version 4.0, 2006

[5] Lee, Z. P., A. Weidemann, J. Kindle, R. Arnone, K. Carder and C. Davis, "Euphotic Zone Depth: Its Derivation and Implication to Ocean Color Remote Sensing", Journal of Geophysical Research, Vol. 112, C03009, 2007.

[6] Martin, P. J., "Description of the Navy Coastal Ocean Model Version 1.0", NRL Report #NRL/FR/7322/00/9962, 45 pp. [Available from NRL Code 7322, Bldg. 1009, Stennis Space Center, MS 39529-5004, USA, 2000.

[7] Cummings, J. A., "Operational Multivariate Ocean Data Assimilation," Q.J.R Meteorology Society, 131, pp. 3583-3604, doi 10.1256/qj.05.105, 2005

[8] Arnone, R.A., B. Casey, S. Ladner, P. Flynn, D.S. Ko, I. Shulmann, K. Mahoney, "New Capabilities for Defining the Coastal 3D Ecosystems Based on Uncertainty of Physical-bio-optical Relationships," Oral Presentation. SPIE Denfense, Security and Sensing Conference, Conference 7317, Ocean Sensing and Monitoring Session, 2009.

[9] Casey, B. C., R. Arnone and P. Flynn, "Simple and Efficient Technique for Spatial/Temporal Composite Imagery," Proceeding of SPIE Optics and Photonics, 2007.

[10] Leachtenauer, J.C., W. Malila, J. Irvine, L. Colburn, and N. Slavaggio. “General Image-Quality Equation: GIQE”. Applied Optics, volume 36, no. 32, 1997

[1] Zibordi, G., Holben B., Slutsker I., Giles D., D’Alimonte D., Mélin F., Berthon J.F., Vandemark D., Feng H., Schuster H., Fabbri B.E., Kaitala S., and Seppälä J., “AERONET-OC: A Network for the Validation of Ocean Color Primary Products”, J. Atmos. Oceanic Technol., 26, 1634–1651, (2009).

[2] Clark D., et al., “MOBY: A Radiometric Buoy for Performance Monitoring and Vicarious Calibration of Satellite Ocean Color Sensors: Measurements and Data Analyses Protocols”, Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 4, Part VI, NASA Tech. Memo. 2003-210004/Rev 4./Vol. VI, NASA Goddard Space Flight, Greenbelt, Maryland, 3-34, (2003).

[3] Fargion, G., Arnone R., et al., “Real Time VIIRS Cal/Val With Satellite Validation Navy Tool (SAVANT)”, 2012 Ocean Sciences Meeting, Session 121, B1294, (2012).

[4] Werdell, P.J. and S.W. Bailey, “An improved bio-optical data set for ocea0n color algorithm development and satellite data product validation”, Remote Sensing of Environment , 98(1), 122-140, (2005).

[5] Hooker S., McClain C. and Mannino A., “A Comprehensive Plan for the Long-Term Calibration and Validation of Oceanic Biogeochemical Satellite Data”, NASA/SP-2007-214152, 1-40, (2007).

[6] D'Alimonte, D., Zibordi, G, “Statistical assessment of radiometric measurements from autonomous systems”, IEEE Geosci. Remote Sens., 44, 719-728, (2006).

[7] Pennucci, G., Fargion, G., Alvarez, A., Trees C., Arnone, R, “A methodology for calibration of hyperspectral and multispectral satellite data in coastal areas”, SPIE # 8372, ?? (2012).

[8]Martinolich, P., et. al, “The automated processing system, Version 4.2.0,” Naval Research Laboratory, Stennis Space Center, MS: http://www7333.nrlssc.navy.mil/docs/aps_v4.2/html/user/aps/aps.xhtml, (2011).

[9] Werdell, P., McClain, C. , “Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry”, Applied Optics, Vol. 46, Issue 22, pp. 5068-5082 (2007).

[10] Arnone, R., Fargion, G., Lawson, A., Martinolich, P., Lee, Z., Davis, C., Ladner, S., Bowers, J., Zibordi, G., “ Monitoring and Validation of Ocean Water Leaving Radiance and inter - satellite continuity.” 2012 Ocean Sciences Meeting, Session 121, Salt Lake , UT. Feb 2012

[11] Lee, Z.P, K. L. Carder . R.A. Arnone, “Deriving inherent optical properties from water color: a multiband quas-analytical algorithm for optically deep waters”, Applied Optics, Vol. 41, no 27, 5755 -577, (2002).

[12] Arnone, R.A. and A. R. Parsons, “Real-time use of ocean color remote sensing for coastal monitoring”, Chapter 14 in Remote Sensing of the Coastal Environment, pages 317-335, Springer Publishing – Editors R. Miller, C. De Costello and B. McKee, (2004).

[13] Zibordi, G., Berthon, J.-F., Mélin, F., D'Alimonte, D, “Cross-site consistent in situ measurements for satellite ocean color applications: The BiOMaP radiometric dataset”, Remote Sensing of Environment 115 (8) , 2104-2115, (2011).

Arnone,R., R. Vandermeulen, S. Ladner, H. Yang, P. Donaghay, G. Fargion, P. Martinolich, M. Wang “ Characterizing physical and ecological exchange processes in coastal and open waters using the VIIRS – Suomi NPP sensors” . AGU- Ocean Sciences Meeting – Hawaii Feb 2014

Arnone, R., S. Ladner, G. Fargion, P. Martinolich, R. Vandermeulen, J. Bowers, and A. Lawson, “Monitoring bio-optical processes using NPP-VIIRS and MODIS-Aqua ocean color products,” Proc. SPIE 8724, Ocean Sensing and Monitoring V, 87240Q (June 3, 2013), http://dx.doi.org/10.1117/12.2018180.

Walton McBride, Bob A. Arnone, Jean-Francois P. Cayula, Improvements of Satellite SST Retrievals at Full Swath SPIE, Baltimore Security and Defense Conference DS211 Ocean Sensing and Monitoring V, April 2013

Ahmed, S., A. Gilerson, S. Hlaing, A. Weidemann, R. Arnone, and M. Wang, M., “Evaluation of ocean color data processing schemes for VIIRS sensor using in-situ data of coastal AERONET-OC sites,” Proc. the SPIE 8888, Remote Sensing of the Ocean, Sea Ice, Coastal Waters, and Large Water Regions, 88880H (October 16, 2013), http://dx.doi.org/10.1117/12.2028821.

Ahmed, S., A. Gilerson, S. Hlaing, I. Ioannou, M. Wang, A. Weidemann, and R. Arnone, “Evaluation of VIIRS ocean color data using measurements from the AERONET-OC sites,” Proc. SPIE 8724, Ocean Sensing and Monitoring V, 87240L (June 3, 2013), http://dx.doi.org/10.1117/12.2017756.

Pahlevan, N., Z. Lee, A. Lawson, R. Arnone, "Scene-based cross-comparison of SNPP-VIIRS and Aqua-MODIS over oceanic waters," Proc. SPIE 8866, Earth Observing Systems XVIII, 88660J (September 23, 2013), http://dx.doi.org/10.1117/12.2023423.
Nima Pahlevan, Zhongping Lee, Robert Arnone Investigating the Consistency between VIIRS and MODIS over the Oceans: The Sensor/Environmental Data Records (SDR/EDR) AMS- Austin Jan 2013
Alexander Ignatov1, Menghua Wang1, Peter Minnett2, Bob Arnone3, "S-NPP/VIIRS EDRS – OCEAN PRODUCTS," IGARRS, Melbourne, Aus, July, 2013
Bowers, J, R Arnone, G. S. Fargion., Ladner, S., Lawson., Martinolich, P. "Exploring Regional Adjustment Of Coastal VIIRS By Repurposing On-Orbit Vicarious Calibration Methodology", abstract AGU-San Francisco , Dec 8 – 2012 color
Arnone, B., G. S. Fargion, Wang, M.; Martinolich, P.; Davis, C.; Trees, C.; Ladner, S.; Lawson, A.; Zibordi, G.; Lee, Z.; Ondrusek, M. Ahmed, S. "Ocean Color Products From Visible Infrared Imager Radiometer Suite (VIIRS) ", IGARSS 2012, Munich, Germany. Color
Arnone R., G. S. Fargion., Lawson, A., , Paul Martinolich, Sherwin Ladner, Curtiss Davis, Charles Trees, Adam Lawson , Giuseppe Zibordi, ZongPing Lee, Michael Ondrusek, and Samuel Ahmed .: Validation of Ocean Color on VIIRS ", SPIE Defense Security and Sensing Conference 8372 April 2012 Paper # 83720K, Baltimore.
Arnone, R.A, G.S. Fargion., Ladner, S. Martinolich, P., Bowers, J., Lawson, A., Lee, A., Davis, C., Zibordi, G , "Monitoring Ocean Water Leaving Radiance for Inter-satellite Continuity, Abstract ID:12162, AGU, Ocean Sciences, Salt Lake City April; 2012 color
Arnone, Robert A., Sherwin Ladner, Ryan A. Vandermeulen,; Paul M. Martinolich, Giulietta S. Fargion, Jennifer Bowers, Adam Lawson, Monitoring bio-optical processes using VIIRS: NPP and MODIS ocean color products SPIE, Baltimore Security and Defense Conference DS211 Ocean Sensing and Monitoring V, April 2013
Ahmed, Sam, Alex Gilerson, Soe Hlaing, Ionnis Ioannou, ; Alberto Tonnizo, Menghua Wang, ; Alan Weidemann, ; Robert A. Arnone, Evaluation of VIIRS ocean color data using measurements from the AERONET-OC sites SPIE, Baltimore Security and Defense Conference DS211 Ocean Sensing and Monitoring V, April 2013

Arnone, R.A., R.W. Gould, Jr., A.D. Weidemann, S.C. Gallegos, and V.I. Haltrin. 2000. Using SeaWiFS ocean color absorption, backscattering properties to discriminate coastal waters. Proceedings, Ocean Optics XV, Monaco, 16-20 October, 2000.
Arnone, R.A., P. Martinolich, R.W. Gould, Jr., M. Sydor, R. Stumpf, and S. Ladner. 1998. Coastal optical properties using SeaWiFS. Proceedings, Ocean Optics XIV Meeting. Kona , HA, November.
Bricaud, A., A. Morel, M. Babin, K. Allali, and H. Claustre. 1998. Variations of light absorption by suspended particles with chlorophyll a concentration in oceanic (case 1) waters: analysis and implications for bio-optical models. J. Geophys. Res., 103(C13): 31,033-31,044.
Carder, K.L., F.R. Chen, Z.P. Lee, S.K. Hawes, and D. Kamykowski. 1999. Semianalytic Moderate-Resolution Imaging Spectrometer algorithms for chlorophyll a and absorption with bio-optical domains based on nitrate-depletion temperatures. J. Geophys. Res., 104(C3): 5403-5421.
Checkley, D.M., Jr., R.C. Dotson, and D.A. Griffith. 2000. Continuous, underway sampling of eggs of Pacific sardine (Sardinops sagax) and northern anchovy (Engraulis mordax) in spring 1996 and 1997 off southern and central California. Deep Sea Res. II, 47: 1139-1155.
Curcio, J. A, C.C. Petty. 1951. The Near Infrared Absorption Spectrum of Liquid Water. Journal of the Optical Society of America, 41(5):302-304.

Doney, S.C., I. Lima, K. Lindsay, J.K. Moore, S. Dutkiewicz, M.A.M. Friedrichs, and R.J. Matear. 2001. Marine biogeochemical modeling: Recent advances and future challenges. Oceanography, 14(4): 93-107.
Ducklow, H.W., D.K. Steinberg, and K.O. Buesseler. 2001. Upper ocean carbon export and the biological pump. Oceanography, 14(4): 50-67.
Feely, R.A., C.L. Sabine, T. Takahashi, and R. Wanninkhof. 2001. Uprake and storage of carbon dioxide in the ocean. Oceanography, 14(4): 18-32.
Garcia, S.M., A. Zerbi, T. Do Chi, and G. Lasserre. 2003. The ecosystem approach to fisheries. Issues, terminology, principles, institutional foundations, implementations and outlook. FAO Fisheries Technical Paper, 443. 81pp.
Garver, S.A. and D.A. Siegel. 1997. Inherent optical property inversion of ocean color spectra and its biogeochemical interpretation. 1. Time series from the Sargasso Sea. J. Geophys. Res., 102(C8): 18,607-18,625.

Gordon, H. R. and M. Wang. 1994. Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: a preliminary algorithm. Applied Optics Vol 33: 443-452.
Gordon, H.R. and A. Morel. 1983. Remote Assessment of ocean color for interpretation of satellite visible imagery: A review. Springer-Verlag, New York. 114 pp.
Gould, R.W., Jr., and R.A. Arnone. Submitted. Three-dimensional fields of salinity and total suspended solids derived from ocean color satellite imagery. Journal of Atmospeheric and Oceanic Technology.
Gould, R.W., Jr. and R.A. Arnone. 1997. Estimating the beam attenuation in coastal waters from AVHRR imagery. Continental Shelf Research, 17(11): 1375-1387.
Gould, R.W., Jr., R.A. Arnone, and P.M. Martinolich. 1999. Spectral dependence of the scattering coefficient in Case 1 and Case 2 waters. Applied Optics, 38(12): 2377-2383.
Gould, R.W., Jr., R.A. Arnone, and M. Sydor. 2001. Absorption, scattering, and particle size relationships in coastal waters: Testing a new reflectance algorithm. Journal of Coastal Research, 17(2): 328-341.
Gould, R.W., Jr., R.H. Stavn, M.S. Twardowski, and G.M. Lamela. 2002. Partitioning optical properties into organic and inorganic components from ocean color imagery. Proceedings, Ocean Optics XVI, Santa Fe, New Mexico, 18-22 November, 2002.
Haltrin, V.I., M.E. Lee, E.B. Shybanov, R.A. Arnone, A.D. Weidemann, V.I. Mankovsky, W.S. Pegau, and S.D. Ladner. 2002. Relationship between backscattering and beam scattering coefficients derived from new measurements of light scattering phase functions. Proceedings, Ocean Optics XVI, Santa Fe, New Mexico, 18-22 November, 2002.
Hansell, D.A. and C.A. Carlson. 2002. Biogeochemistry of Marine Dissolved Organic Matter. Academic Press, 774 pp.
Hansell, D.A., and C.A. Carlson. 2001. Marine dissolved organiv matter and the carbon cycle. Oceanography, 14(4): 41-49.
Jerlov, N.G. 1976. Marine Optics. Elsevier.
Kahru, M., and B.G. Mitchell. 2001. Seasonal and nonseasonal variability of satellite-derived chlorophyll and colored dissolved organic matter concentration in the California Current. J. Geophysical Research, 106(c2): 2517-2529.
Ladner, S., R. Arnone, R. Gould, A. Weidemann, V.I. Haltrin, Z. Lee, P. Martinolich, and T. Bergmann. 2002. Variability in the backscattering to scattering and F/Q ratios observed in natural waters. Proceedings, Ocean Optics XVI, Santa Fe, New Mexico, 18-22 November, 2002.
Ladner, S., R. Arnone, A. Lawson, G. Fargion, J. Bowers, P. Martinolich, M. Ondrusek, M. Wood. 2012. Evaluation of Recent VIIRS Sensor Performance in the Coastal Ocean. AGU Ocean Sciences Meeting, San Francisco, California, 3-7 December 2012.
Land, P.E., and J.D. Haigh. 1996. Atmospheric correction over case 2 waters with an iterative fitting algorithm. Applied Optics, 35(27): 5443-5451.
Land, P.E., and J.D. Haigh. 1997. Atmospheric correction over case 2 waters with an iterative fitting algorithm: relative humidity effects. Applied Optics, 36(36): 9448-9455.
Lee, Z., K.L. Carder, and R.A. Arnone. 2002. Deriving inherent optical properties from water color: a multiband quasi-analytical algorithm for optically deep waters. Applied Optics, 41(27): 5755-5772.
Loisel, H. and A. Morel. 1998. Light scattering and chlorophyll concentration in Case 1 waters: A reexamination. Limnol. Oceanogr., 43(5): 847-858.
Martinolich, P. 2012. The Naval Research Laboratories Automated Processing System – APS v4.10. http://www7333.nrlssc.navy.mil/docs/aps_v4.10/html/user/aps.xhtml
Mobley, C.D. 1999. Estimation of the remote sensing reflectance from above-surface measurements. Appl. Opt., 38(36): 7442-7455.
Moore, G.F., J. Aiken, and S.J. Lavender. 1999. The atmospheric correction of water colour and the quantitative retrieval of suspended particulate matter in Case II waters: application of MERIS. Int. J. Remote Sensing, 20(9): 1713-1733.
Morel, A. 1988. Optical modeling of the upper ocean in relation to its biogenous matter content (Case I Waters). J. Geophys. Res., 93(C9): 10749-10768.
Morel, A. and B. Gentili. 1993. Diffuse reflectance of oceanic waters. II. Bidirectional aspects. App. Opt., 32(33): 6864-6879.
Morel, A. and B. Gentili. 1996. Diffuse reflectance of oceanic waters. III. Implication of bidirectionality for the remote-sensing problem. Appl. Opt., 35(24): 4850-4862.
Morel, A. and L. Prieur. 1977. Analysis of variations in ocean color. Limnol. & Oceanogr., 22: 709-722.
Muhling, B. A., J.T. Lamkin, and M.A. Roffer. 2010. Predicting the occurrence of Atlantic bluefin tuna (Thunnus thynnus) larvae in the northern Gulf of Mexico: building a classification model from archival data. Fish. Oceanogr. 19(6): 526-539.

Petzold, T. J. 1972. Volume Scattering Functions for Selected Ocean Waters. SIO Ref: 72-78.
Pope, R.M. and E.S Fry. 1997. Absorption spectrum (380-700 nm) of pure water. II. Integrating cavity measurements. Appl. Opt., 36(33): 8710-8723.
Prieur, L. and S. Sathyendranath. 1981. An optical classification of coastal and oceanic waters based on the specific spectral absorption curves of phytoplankton pigments, dissolved organic matter, and other particulate materials. Limnol. Oceanogr., 26(4): 671-689.
Ruddick, K.G., F. Ovidio, and M. Rijkeboer. 2000. Atmospheric correction of SeaWiFS imagery for turbid coastal and inland waters. Appl. Opt., 39(6): 897-912.
Sarmiento, J.L., and N. Gruber. 2002. Sinks for anthropogenic carbon. Physics Today, August: 30-36.
Sathyendranath, S. 2000. General Introduction. In: Remote Sensing of Ocean Colour in Coastal, and Other Optically-Complex, Waters. Sathyendranath, S. (ed.), Reports of the International Ocean-Colour Coordinating Group, No. 3, IOCCG, Datmouth, Canada, pp5-21.
Siegel, D.A., M. Wang, S. Maritorena, and W. Robinson. 2000. Atmospheric correction of satellite ocean color imagery: the black pixel assumption. Applied Optics, 39(21): 3582-3591.
Smith, R.C. and K.S. Baker. 1978. Optical classification of natural waters. Limnol. Oceanogr., 23: 260-267.
Smith, R.C. and K.S. Baker. 1981. Optical properties of the clearest natural waters (200-800 nm). App. Opt., 20(2): 177-184.
Stramski, D., R.A. Reynolds, M. Kahru, and B.G. Mitchell. 1999. Estimation of particulate organic carbon in the ocean from satellite remote sensing. Science, 285:239-242.
Sydor, M. and R.A. Arnone. 1997. Effect of suspended particulate and dissolved organic matter on remote sensing of coastal and riverine waters. Applied Optics, 36(27): 6905-6912.
Sydor, M., R.A. Arnone, R.W. Gould, Jr., G.E. Terrie, S.D. Ladner, and C.G. Wood. 1998. A new remote sensing technique for determination of the volume absorption coefficient of turbid water. Applied Optics, 37(21): 4944-4950.
Stumpf, R.P., R.A Arnone, R.W. Gould, Jr., P. Martinolich, V. Ransibrahmanakul. 2003. A Partially_Coupled Ocean_Atmosphere Model for Retrieval of Water_Leaving Radiance from SeaWiFS in Coastal Waters: In: Patt, F.S., and et al.: Algorithm Updates for the Fourth SeaWiFS Data Reprocessing. NASA Tech. Memo. 2002__206892, Vol. 22, S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, (in press).
Toole, D.A., D.A. Siegel, D.W. Menzies, M.J. Neumann, and R.C. Smith. 2000. Remote-sensing reflectance determinations in the coastal environment: impact of instrumental characteristics and environmental variability. Appl. Opt., 39(3): 456-469.
Twardowski, M.S., R.A. Arnone, A.D. Weidemann, R. Gould, V. Haltrin, C. Davis, and W. Snyder. 2001. Progress in the development of a remote sensing algorithm for the determination of total suspended matter and its components. ASLO 2001 Aquatic Sciences Meeting, Albuquerque, NM, 12-16 February, 2001.
Williams, P.M., and E.R.M. Druffel. 1988. Dissolved organic matter in the ocean: Comments of a controversy. Oceanography, 1: 14-17.
Yan, B., K. Stamnes, M. Toratani, W. Li, and J.J. Stamnes. 2002. Evaluation of a reflectance model used in the SeaWiFS ocean color algorithm: implications for chlorophyll concentration retrievals. Applied Optics, 41(30): 6243-6259.

Petrenko, Boris, et al. "Evaluation and selection of SST regression algorithms for JPSS VIIRS." Journal of Geophysical Research, submitted (2013).

Wang, Menghua, et al. "Impacts of VIIRS SDR performance on ocean color products." Journal of Geophysical Research: Atmospheres 118.18 (2013): 10-347.

Behrenfeld, A. J., and P. G. Falkowski. 1997. A consumer's guide to phytoplankton primary productivity models. Limnology and Oceanography 42: 1479-1491.

Lee, Z. P., K. Du, and R. Arnone. 2005. A model for the diffuse attenuation coefficient of downwelling irrandiance. Journal of Geophysical Research 110: C02016 1-10.

Zibordi, Giuseppe, et al. "AERONET-OC: a network for the validation of ocean color primary products." Journal of Atmospheric & Oceanic Technology 26.8 (2009).

Holben, B. N., et al. "An emerging ground-based aerosol climatology: Aerosol optical depth from AERONET." Journal of Geophysical Research: Atmospheres (1984–2012) 106.D11 (2001): 12067-12097.

Bailey, Sean W., Bryan A. Franz, and P. Jeremy Werdell. "Estimation of near-infrared water-leaving reflectance for satellite ocean color data processing." Optics express 18.7 (2010): 7521-7527.

Vandermeulen, Ryan A., et al. "Improved monitoring of bio-optical processes in coastal and inland waters using high spatial resolution channels on SNPP-VIIRS sensor." SPIE Defense, Security, and Sensing. International Society for Optics and Photonics, 2013.

Cayula, J.F., May, D., Vandermeulen, R.A., Arnone, R. “Comparison of VIIRS SST Fields Obtained from Differing SST Equations Applied to a Region Covering the Northern Gulf of Mexico and Western North Atlantic.” SPIE Defense, Security, and Sensing. International Society for Optics and Photonics, 2014.

Yang, H., Arnone, R. Jolliff, J. “Estimating Advective Surface Currents from Ocean Color Satellite Images.” AGU-Ocean Sciences Meeting – Hawaii Feb 2014