Ocean Color Data Product Quality Assessment Report for NPP VIIRS

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Table of Contents

1. Introduction

This document provides a concise summary of the NASA/Goddard Space Flight Center (GSFC) NPP VIIRS Ocean Science Team's (VOST) assessment of the VIIRS sensor performance and related recommendations to best achieve science and climate quality data from VIIRS. This assessment represents several years of participation in NPP and evaluation of algorithms and VIIRS performance by members of the NASA/GSFC Ocean Ecology Branch (Code 614.2), with support from other members of the Ocean Data Processing Group (OBPG). This team's involvement in NPP/VIIRS began with the VIIRS Critical Design Review (February 2002) that C. McClain attended at the invitation of Robert Murphy, the NPP Project Scientist at that time. In 2003, the group's participation in NPP was formalized when the group's proposal for membership on the first NASA NPP science team was selected. The group has had the role of NASA NPP ocean team lead since then.

The role of the NPP science team, as stated in all three NASA Research Announcements, is to evaluate the Environmental Data Records (EDR) for suitability in Ocean Color climate research. This group has conducted extensive evaluations of the operational calibration, bio-optical, and atmospheric correction algorithms, which were forwarded to the Integrated Program Office (IPO) via the NASA Project Scientist (initially R. Murphy; currently James Gleason). The evaluation showed that these algorithms were years behind those developed by NASA/GSFC and would not be adequate to either produce science quality data or provide the consistency needed to continue the current climate data record (CDR). The VOST evaluations also incorporated recommendations to improve these algorithms and make them more consistent with those being employed in the NASA SeaWiFS and MODIS processing, however the cost and effort needed by the contractor to reproduce NASA's capabilities in the operational processing stream seemed prohibitive.

Over time, the group has also gotten involved in assessing the sensor design, performance attributes, and satellite operational issues and how these influence the EDRs. In fact, much more time has been dedicated to these evaluations than to the algorithms because Ocean Color measurements are strongly limited by prelaunch characterization knowledge. Improvements in the EDR data quality require a detailed understanding of sensor characteristics like crosstalk, out-of-band (OOB) response, stray light, and polarization sensitivity. The VIIRS performance improved through the group's recommendation of a redesign of the solar diffuser assembly to reduce contamination by Earthshine and reflections off spacecraft structures. Another example was the group's early recommendation that the National Institute of Standards and Technology (NIST) conduct calibrations using a portable version of the Spectral Irradiance and Radiance responsivity Calibrations using Uniform Sources (SIRCUS), or Traveling SIRCUS (T-SIRCUS), which was eventually approved and executed in 2010. A third notable contribution was the recommendation to conduct lunar calibrations via the space view port and analyses on how the lunar calibrations could be optimized with modest roll maneuvers.

The group has done extensive analyses of the pre-launch data and coordinated its efforts with the NASA/GSFC NPP Instrument Characterization Science Team (NICST). This collaboration with NICST has included reviews of almost all of the innumerable NICST technical evaluation documents on engineering design unit and flight unit test data. The group has also presented its analyses at many informal meetings at GSFC and the IPO and more formal presentations at NPP VIIRS Operational Algorithm Team (VOAT) and NASA NPP science team meetings.

The assessments and recommendations presented here do not guarantee that VIIRS products will achieve a level of accuracy and consistency presently derived from SeaWiFS and MODIS data, which would be required for NPP Ocean Color EDR products to meet NASA objectives for climate and Earth System Science research, as well as Earth Observing System (EOS) CDR data continuity. **It must be understood, that for climate research using satellite ocean CDRs, an on-orbit calibration stability of 0.1% over the mission lifetime is required as has been achieved by SeaWiFS. However, long-term instrument performance is only one requirement towards meeting NASA science and climate objectives.** To continue Earth System Science and climate research at NASA, minimum scientific requirements also include, but are not limited to:

- Sensor data quality comparable to heritage EOS-era instruments,
- State of the art data product algorithms consistent with those currently employed by EOS instruments,
- Inter-agency investment in post-launch vicarious and on-board calibration and validation (Cal/Val) activities (e.g., field sites), including approving spacecraft lunar maneuvers as executed by heritage missions, and
- The capability for mission-level data reprocessing.

As described in the following document, some concerns regarding these requirements currently exist or, as in the case of the algorithms and reprocessing capability, not being met at all.

Section 2 discusses briefly the need for reprocessing to meet NASA objectives and to support the research community in particular. Section 3 covers issues concerning the operational algorithms. An evaluation of instrument performance and characterization is covered in Section 4 of this the document. 4.1 looks at the major issues with the spectral response characteristics, 4.2 and 4.3 cover other radiometric behavior that are scan dependent or independent, respectively, and 4.4 discusses the spatial response of VIIRS. Section 5 discusses calibration issues and the need for further evaluation and monitoring of on-orbit performance. Conclusions are provided in Section 6.

2. Reprocessing

A recommended minimum requirement for a consistent Ocean Color CDR, *or most any CDR*, is mission-level data reprocessing. As was the case for MODIS Aqua, VIIRS will have a sun-glinted swath and a single calibration buoy. Because of those constraints, it took MODIS Aqua about three years to accumulate enough data to converge on stable vicarious calibration corrections (Franz 2007). Once these corrections were obtained, the previous three years of data needed to be reprocessed to provide a consistent data record. Similarly, any changes to instrument behavior on-orbit, or deviation from prelaunch understanding of known anomalies, would require either new corrections or modification to existing ones. For heritage instruments, this process can require a lengthy time series, as was the experience with MODIS Aqua (Meister et al. 2005) and Terra (Kwiatkowska et al. 2008) in determining the polarization response on-orbit. To produce a consistent data record, any new or revised correction will need to be applied retrospectively. ***An Ocean Color CDR cannot be produced without mission-level reprocessing.***

Currently, NASA/GSFC has the expertise to perform both forward processing, with algorithms that are consistent with the present CDR record, and mission-level reprocessing (sometimes referred to in operational organizations as re-analysis). Moreover, NASA/GSFC has the existing infrastructure to support both forward processing and reprocessing, requiring only a relatively minor expansion to existing hardware. The OBPG currently distributes algorithms and data products for heritage missions, and although not formally mandated with the task, could easily and inexpensively extend that distribution to include software and data for NPP VIIRS. NASA/GSFC will also need to distribute a complete reprocessed data record to leverage its strong collaborative relationship with the research community in evaluating and improving the Ocean Color EDR and CDR products. Therefore, it is recommended that an OBPG mission-level reprocessing capability be supported.

3. Algorithms

Data product consistency is another fundamental CDR requirement. Currently, the NPP operational algorithms are outdated from those currently used by NASA (e.g., MODIS, SeaWiFS) to generate its Ocean Color CDR products. The NPP algorithm for atmospheric correction over the ocean is fundamentally based on the same theory, but is several years behind the current NASA algorithm. The NPP algorithm is expected to yield results that are neither consistent with nor of the same level of quality as those found in current NASA production software. In addition, the NPP algorithm for chlorophyll *a* concentration is not only completely inconsistent with the one used by NASA to produce its climate data record, it has been demonstrated using validation data that it simply will not perform as well, especially in coastal regions (Signorini et al. 2005). Thus the current operational NPP algorithm for chlorophyll *a* also cannot be expected to produce data of the quality that are commensurate or even compatible with the current climate data record. ***Given the current operational NPP/NPOESS Ocean Color EDR algorithms, it is clear that the Ocean Color CDRs cannot be continued with the operational NPP EDRs.***

The theoretical basis and implementation of the NPP operational algorithms for Ocean Color were done in 1999. The initial science code was largely based on a late 1990's version of the NASA/GSFC SeaDAS software package (Baith et al. 2001). When the VOST evaluated the Algorithm Theoretical Basis Document (ATBD) and science algorithms in 2004 and 2005, it was found that no change had been made in over a half a decade, while NASA/GSFC had continued its development for SeaWiFS, and then later for MODIS Aqua. NASA/GSFC provided the NPP contractor with code to support sun glint correction. The implementation of that single software module was projected to cost the NPP project $900K. After that, the Ocean Color software was frozen by the NPP contractor for a few more years, while GSFC continued improvement of the Ocean Color algorithms. In 2009 and 2010, the NPP contractor announced a few upgrades to the Ocean Color algorithm, but these changes are limited, are not consistent with the state of research algorithms, and have not been validated or even tested with real data.

Table 1 - Listed are key developments to the Ocean Color processing. The R column indicates the status of the research algorithm or methodology developed at NASA/GSFC. The O column refers to the status of the NPP operational algorithm. Green indicates that the capability is fully tested and vetted. Yellow means that the capability is still under development, exists but has not benefitted from developments at NASA/GSFC, or has not been consistently developed to the NASA standard. Red indicates that the capability is missing or completely deficient.

	Development	Description	R	O
1	NIR Correction	Important for turbid and productive waters (e.g., coastal waters). This is an iterative process that may impact latency requirements for the operational stream.		
2	Aerosol Models	GSFC improved aerosol correction using relative humidity based aerosol selection scheme of 80 AeroNET-band aerosol models. These improvements are not in the operational algorithms.		
3	Polarization Correction	This is crucial to account for variation in the instrument response to TOA polarization. Both operational and research streams have this correction.		
4	Trace Gas Absorption	NO2 Corrections; updated source spectra for O3 cross-section; other gaseous absorption included for SeaWiFS. Operational version is not tested; proper and consistent use of ancillary data is not clear.		
5	Sun Glint Correction	Crucial to improve data coverage; Wang-Bailey (2001) algorithm provided to contractor in 2005 for operational algorithm (testing status is unknown).		

	Development	Description	R	O
6	Updated Rayleigh Model	Updated tables, pressure corrections, and source spectra. VIIRS version may require additional corrections (e.g., detector-to-detector or crosstalk specific relative spectral response) and both operational and research teams are looking at this.		
7	Revised Whitecap Algorithm	This calculation of the reflectance from whitecaps was improved over the version still found in the operational version.		
8	VIIRS Crosstalk Correction	A method was developed by the operational team, but has not been tested and could have significant limitations. However, the method is simple to implement in the research processing stream.		
9	OOB Correction	Based on best relative spectral response (RSR) curves available, band-pass correction and Rayleigh tables are adjusted for OOB light leaks.		
10	Band-Pass Corrections	Necessary to account for differences between ground and space sensor band-passes. Lw band-pass corrections based on latest Morel bio-optical model.		
11	BRDF Corrections	Necessary correction to account for geometric effects of in-water reflectance. Changes included upwelling/ downwelling reflection/refraction and f/Q.		
12	New K490 Algorithm	The extinction coefficient at 490nm was revised and tuned with the NOMAD V2 dataset.		
13	Tuned Chl *a* Algorithm	Algorithm is tuned using NOMAD V2 dataset developed by GSFC. Operational team has added research algorithm, but has not tuned it.		
14	Produce POC and PIC	Particular organic carbon and particular inorganic carbon are now standard products in the GSFC research processing stream.		
15	Report Rrs instead of nLw	Remote sensing reflectance is now reported as a standard product instead of nLw to support community needs.		
16	Angstrom Exponent and AOT	Angstrom exponent and aerosol optical thickness are now standard products of the GSFC research processing stream.		
17	Produce PAR	Photosynthetically available radiation is now a standard product of the GSFC research processing stream.		
18	Research Products	Numerous other data products, such as semi-analytic models of chlorophyll and inherent optical properties (IOP), are available through GSFC software. Operational processing stream provides Carder Chl a and IOP parameters as standard EDR products.		

	Development	Description	R	O
19	Vicarious Calibration Methodology	Considerable research was done to develop the techniques to use calibration buoy measurements and atmospheric correction models to determine static gain biases. It is not clear whether this is being applied properly for the operational product.		

Table 1 compares capabilities that are found in the research processing stream at NASA/GSFC to the NPP operational processing stream. Many corrections are missing from the NPP operational processing stream, such as the NIR correction. It is suspected that this correction, which is iterative, might be viewed as prohibitive for the operational use as it can be computationally expensive. In addition, a correction for gaseous absorption was presumably added recently to the NPP operational processing stream, though it is not clear whether it will work as effectively as the heritage correction, which has been validated with flight data. Items 12-17 include data products that are now standard for research processing stream at NASA/GSFC, which are not included in the operational Ocean Color EDR product suite. For both the NASA research algorithms and NPP operational algorithms, the methods for addressing the idiosyncratic spectral and crosstalk characteristics of NPP VIIRS (items 6, 8, and 9) are based on the techniques used for heritage missions. But, in either case, these remain largely untested and are marked as still being under development.

The OC chlorophyll algorithm (O'Reilly et al 1998) has been inserted into the NPP operational stream, but this has not yet been tuned to the VIIRS band-pass and there are currently no plans to do so using the second and most recent version of the standard NASA dataset known as the NASA bio-Optical Marine Algorithm Dataset (NOMAD V2). Moreover, the OC algorithm has only been placed in the operational processing for further study and there is no current plan to generate chlorophyll concentrations with this algorithm on a regular basis. Therefore, there is no indication that the operational algorithm will ever be consistent with the current climate data record for chlorophyll *a* concentration.

4. Instrument Performance and Characterization

To produce a CDR requires the highest quality data with well quantified and understood uncertainties. Many VIIRS instrument characteristics, or their analyses by other teams, were reviewed and it was determined that no corresponding adverse affects were expected for the data quality. However, a number of issues were identified that still could preclude applicability of VIIRS to climate research. This section provides a review of all these instrument characteristics, divided into the categories of radiometric, spatial, and spectral performance. Radiometric characteristics are further distinguished as being notably scan angle dependent or not. For each instrument behavior, the relationship to the Ocean Color data product quality is discussed.

In general, most radiometric characteristics were found to have little to no significant impact to data quality. But, special attention was given for the issue of a moderate signal-to-noise ratio (SNR) and the existence of radiometric response anomalies for radiance levels near the gain switch point for dual gain bands. Neither of these issues alone will preclude VIIRS as a viable Ocean Color sensor with a potential for CDR production, but they will likely prevent achieving data quality comparable to MODIS Aqua. In addition, the instrument response verses scan (RVS) was also found to be adequately characterized for the visible and NIR bands.

Detector-to-detector differences for radiometric and spectral response are expected to produce significant striping. The analyses for several spatial performance areas were also reviewed, including band-to-band registration, near-field response, and the spatial effects of crosstalk. In general, none of the spatial effects were expected to cause significant issues, although further analysis of the spatial characteristics of crosstalk may be warranted.

The area that may present the greatest challenge for VIIRS as an Ocean Color instrument is its spectral performance; specifically its ability to get the same measurement for two identical radiance values in a given band when the two target spectra are different at other wavelengths. The current VIIRS FU1 Integrated Filter Assembly (IFA) has spectral performance issues that could affect the ability to consistently calibrate the instrument to a level commensurate with heritage performance. This challenge can be overcome only if the IFA is rigorously characterized. Effort continues toward that end, but estimation of characterization uncertainties remains incomplete. These uncertainties are a crucial issue for on-orbit correction. Furthermore, polarization sensitivity of spectral response and aspects of crosstalk are not included in the spectral response curves, which compound uncertainty for an on-orbit correction. There have also been notable discrepancies in the characterization results amongst NASA and IPO analysts of the Government Data Analysis Working Group (Gvt-DAWG) and between two contractor teams. Unresolved, these uncertainties could amount to an ambiguity in the spectral characterization that could also hamper an on-orbit correction.

Some progress continues to be made to reduce these differences. Analyst teams continue their efforts to quantify or at least bound spectral characterization uncertainty. ***However, given the state of instrument characterization uncertainty, it is believed that any current prediction of instrument capabilities to deliver climate quality data, for good or bad, remains limited.***

4.1 IFA Quality Issues

The primary performance issues with the IFA are optical crosstalk and OOB light leaks. Optical crosstalk is defined as any detector's reception of photons of any wavelength that originated from some other part of the Focal Plan Assembly (FPA). When such photons originate from the IFA over one or more detectors in the same band, the phenomenon has been termed *intra-band* crosstalk. If the photons came from some other part of the FPA, it has been called *inter-band* crosstalk. OOB light leaks are the extraneous transmittance of photons through the IFA directly over a given detector but are at wavelengths outside of the nominal band-pass. There were no tests devised during the test program that adequately differentiate between intra-band crosstalk and OOB light leaks, and thus are included together in the characterization data.

4.1.1 Optical Crosstalk

Static crosstalk produces a radiometric bias that varies with the spectrum of the target being measured. To understand its general affect on Ocean Color EDR quality and NASA's science needs, the effects of optical crosstalk on the Ocean Color algorithm were estimated through a numerical experiment that used MODIS data as a proxy for VIIRS. The experiment was designed to answer the simple question of how much impact would occur to MODIS Ocean Color data products if that sensor had uncorrected optical crosstalk similar to VIIRS. The approach is viewed as sufficient to provide an overall assessment of the expected EDR data quality impact based on available test data.

This current experiment excludes the OOB influence from the crosstalk model, unlike earlier studies that leaned toward a worst-case scenario over concern that the OOB light leaks could not be adequately separated from inter-band crosstalk. Out-of-band effects are more difficult to evaluate since their characterization are an integral part of the Ocean Color algorithm and calibration, as will be further discussed in the next section. As a result, this evaluation presents a smaller total effect from what was reported in earlier assessments.

Currently no validated correction for optical crosstalk exists for the visible and NIR VIIRS bands, so crosstalk mitigation was not included in this assessment. To properly evaluate any potential crosstalk correction would involve simulating the effects of several key steps in retrieving in-water apparent optical properties, including atmospheric correction with full-band processing and OOB correction, and possibly including vicarious calibration procedures. Furthermore, crosstalk characterization uncertainty, which is not well understood, would also need to be adequately modeled.

More information continues to come to the project regarding crosstalk characterization uncertainty. Approaches are being considered for assessing proposed crosstalk corrections; approaches that look at the entire process behind generating science quality Ocean Color products, including vicarious calibration. These developments may lead to a more complete analysis of the effect of crosstalk on EDR quality. Ultimately, the best understanding of impact to the Ocean Color product will only be clear with a postlaunch evaluation using real VIIRS data.

Collaborative work over three years by Northrop Grumman, Raytheon, MIT Lincoln Labs, Aerospace and NASA have contributed to understanding the behavior of crosstalk in NPP VIIRS, leading to a largely empirical model that is highly dependent on characterization data. As key component is a table of crosstalk influence coefficients (often called a crosstalk map), which are derived from the FP-15 and FP-16 spectral characterization tests. Measurements from these tests record the VIIRS response between channels at wavelengths that span the blue edge of the visible range to about one micron, in steps of about five or six nanometers (each with a band width that is comparable to the step size). Influence coefficients are then defined for each test wavelength as the ratio of the signal that reaches a single receiver band detector to the average signal present across all detectors of a sender band. The band-to-point influence coefficients derived by groups outside of NASA were similar to those developed and applied by NICST.

The ETP-655 test was specially designed to characterize the point-to-point propagation of the crosstalk signal, albeit in a limited fashion. The resulting filter spread function (FSF), similar to a point spread function, provided a basis for extending the band-to-point empirical model to MODIS imagery. However, to save critical development time, NICST did not apply this information for this version of experiment, but instead used an earlier rendition of the FSF involving a simple weighting scheme across detectors in the scan direction. Therefore, this study only considers a very crude representation of the spatial nature of optical crosstalk. This is not expected to significantly affect evaluation of open ocean regions. However, this may not be sufficient for evaluation of scenes where water features are highly structured spatially, which will require a different experiment.

To apply the influence coefficients to MODIS scenes, some assumptions must be made. First it is important that optical crosstalk behave linearly before applying influence coefficients as factors for predicting crosstalk levels. For that reason, a band-to-point influence coefficient map cannot predict point-to-point behavior for a two-dimensional, heterogeneous scene. Therefore spatial effects must be accounted for when applying the influence coefficient map to two-dimensional scenes. It is also known that the directional shape of the FSF is sensitive to polarization and that all crosstalk data was derived using a polarized source. Furthermore, the model assumes that signals from two or more sources add, which is known as the *superposition assumption*. Finally, there are limitations (<10%) in predicting the total effect of optical crosstalk because of the existence of static electronic crosstalk, which can be difficult to distinguish from optical crosstalk. Thus, electronic crosstalk is considered a systematic uncertainty in predicting the effects of optical crosstalk. The uncertainty that stems from these effects are not handled in this experiment, but would have to be accounted for when assessing a crosstalk correction.

For open ocean observations, the primary concern is the radiometric bias caused by crosstalk when viewing a uniform scene. Although some spatial effects could contribute to the results in the analysis using MODIS data, the dominant effect is driven by differences between target and solar diffuser spectra over predominantly uniform scenes. Furthermore, the most prominent spatial effects from crosstalk would not be included in either the NASA level 3 products or used for vicarious calibration or validation. High contrast boundaries, such as water near cloud edges and shorelines, would be masked out for most science applications and thus these regions are excluded in this study.

Regions where the marine spectrum is highly variable spatially, such as waters near coasts, would require further analysis. Because the MODIS sensor would naturally blur sharp features to a courser resolution than VIIRS, it is probably not the best choice to study spatial/spectral effects of crosstalk when viewing these stressing targets. Instead, such a study would be based on real or simulated hyperspectral data that have a spatial resolution that is comparable or finer than VIIRS (e.g., data from the Hyperspectral Imager for the Coastal Ocean or HICO).

In order for the NICST crosstalk model to be applied to MODIS L1B products (i.e., calibrated, geolocated TOA radiance), the influence coefficient map was restructured spectrally by NICST to match MODIS bands, so that the true radiance in these bands can be used to predict the amount of extraneous signal that would occur. Crosstalk occurs at wavelengths that fall between MODIS bands. For each inter-band region, a weighted interpolation is applied to the MODIS data to estimate the average radiance level and this is multiplied by the sum of influence coefficients over the corresponding inter-band region. Crosstalk influence coefficients pertaining to the in-band region of the sender band (where the in-band region is defined by the 1% of peak points of the band's relative spectral response or RSR) were excluded from the study as being static electronic crosstalk, while influence coefficients that were associated with the in-band region for a receiver band were excluded as a NFR effect (or stray light in the test). NICST excluded these influence coefficients from the study with the intention of providing only the effects of optical crosstalk. It is worth noting that some small quantity of optical crosstalk may have been masked by this exclusion.

Finally, these effects were applied to the MODIS scenes prior to the application of vicarious calibration coefficients, which in the modeling for this study did not include any crosstalk information. In practice, vicarious calibration coefficients would include biases from crosstalk given the typical conditions when viewing the calibration site. Given this, it is expected that vicarious calibration will remove some of the bias caused by crosstalk. However, it is sufficient for assessing the raw impact of the crosstalk phenomenon to not model crosstalk in the vicarious calibration. A more detailed analysis of this process may be considered, especially in support of evaluating the effectiveness of crosstalk mitigation schemes. A likely approach might be applying the crosstalk model to the MODIS match-up data for vicarious calibration and producing crosstalk-affected gain corrections.

The NASA standard Ocean Color production software was used to run the Gordon-Wang atmospheric correction (Gordon and Wang 1994), the original NPP algorithm for Chlorophyll *a* concentration (Carder et al 1999, Hommel et al, 2005, Northrop Grumman Corp 2010), and the standard NASA chlorophyll *a* concentration algorithm (O'Reilly et al 1998), the version applied to MODIS being known as OCM3. The VOST processed pairs of scenes, each pair consisting of one scene with crosstalk, as modeled by NICST, and one scene without, and the difference between each pair was taken. Statistics were taken from the relative differences as a measure of impact. Difference images were mapped to identify how the crosstalk effects were distributed regionally. This was particularly important for coastal scenes, which showed the greatest regional variability. For instance, it can be seen in Figure 1 that although the effect of crosstalk to the OCM chlorophyll *a* algorithm overall is relatively small, an unacceptable amount of impact can still can be seen for small, but significant regions. Further quantitative analysis is forthcoming involving bathymetric or other stratifications to better isolate and quantify the impact of crosstalk on coastal aquatic features.

Three representative MODIS Aqua scene pairs were selected for the numerical experiment, including the open ocean surrounding the tradition vicarious calibration site, a coastal scene at mid-latitudes, and a coastal scene at higher latitudes. Statistics of relative differences of each pair were computed for two cases: 1) exclusion of flags for high radiance, cloud, and land and 2) for exclusion for conditions defined by the entire suite of flags that is used to as criteria for selecting satellite data for vicarious calibration. In addition, evaluation was performed on only the middle two thirds of the scan to avoid geometric complexity of the MODIS bow-tie effect.

Table 2 and Table 3 show the summary regional statistics for the relevant ocean products. Table 2 shows the median relative difference taken for the first flag case. Order statistics were used to filter out large outliers. Table 3 is the difference of the 95th and 5th percentile divided by four, providing a value slightly less than a standard deviation for a normal distribution. Data products for coastal and in-land water showed the greatest impact. In all three scenes, significant crosstalk effects were observed in TOA radiance in the 443nm and 869nm channels of the MODIS data (~0.3% and ~0.4%, respectively). In the experiment, crosstalk also was seen to produce biases and extraneous variation in normalized water-leaving radiance (nLw) and Chlorophyll *a* concentration. The 7% bias in nLw for the 443nm band in the Argentinian waters scene is rather significant, as it is greater than the heritage objective of 5% uncertainty in nLw. This high value was possibly caused by a higher percentage of coastal pixels in the Argentinian water scene, due to the fact that most of the open ocean is under cloud cover, and this was born out in the difference maps for the waters off the coast of Argentina. All three scenes showed crosstalk impact that often met NPP EDR performance requirements, while the impact

Table 3 – The regional variation (5-95% inter-percentile difference) for same products in Table 1.

REGIONAL VARIATION

	A20031711810	A20040332355	A20051071815
	Argentina	Hawaii	East USA
Chl a			
OCM3	2.86%	2.85%	2.41%
NPP	11.36%	2.81%	**87.33%**
nLw			
412 nm	1.21%	0.27%	**9.23%**
443 nm	2.40%	0.32%	3.43%
488 nm	0.83%	0.31%	2.30%
547 nm	0.92%	1.25%	2.20%
667 nm	2.38%	**10.00%**	**10.33%**
Lt			
412 nm	0.01%	0.01%	0.01%
443 nm	0.04%	0.04%	0.04%
488 nm	0.02%	0.02%	0.02%
547 nm	0.01%	0.01%	0.01%
667 nm	0.01%	0.02%	0.01%
748 nm	0.02%	0.03%	0.02%
869 nm	0.12%	0.12%	0.10%

Table 2 – Regional bias (median relative difference) for Chl a (NASA-selected algorithm OCM3, and NPP operational algorithm), normalized water-leaving radiance (nLw), and TOA radiance (Lt).

REGIONAL BIAS

	A20031711810	A20040332355	A20051071815
	Argentina	Hawaii	East USA
Chl a			
OCM3	3.7%	8.8%	2.8%
NPP	16.6%	11.0%	21.1%
nLw			
412 nm	-1.9%	0.2%	3.3%
443 nm	-7.0%	-1.1%	-1.7%
488 nm	-1.7%	0.0%	0.8%
547 nm	0.2%	2.8%	1.9%
667 nm	3.2%	**14.2%**	9.8%
Lt			
412 nm	-0.1%	-0.1%	-0.1%
443 nm	**-0.3%**	**-0.3%**	**-0.3%**
488 nm	-0.1%	-0.1%	-0.1%
547 nm	0.0%	0.0%	0.0%
667 nm	0.1%	0.1%	0.1%
748 nm	0.1%	0.1%	0.1%
869 nm	**0.5%**	**0.4%**	**0.5%**

from crosstalk consumed a large amount of the error budget. Interestingly, the NASA Chlorophyll *a* concentration algorithm (OCM3) was more robust in the presence of crosstalk than the NPP operational algorithm, especially in coastal waters (see Figure 1). This underscores the need to use NASA selected algorithms for VIIRS. In general, the crosstalk impact appears significantly smaller for Ocean Color data quality than the impacts stemming from OOB light leaks seen in VIIRS (or heritage missions) for some bands. Thus, based on current data, optical crosstalk alone produces a significant, but not necessarily overwhelming impact to Ocean Color products, pending development of a viable means to correct the effects.

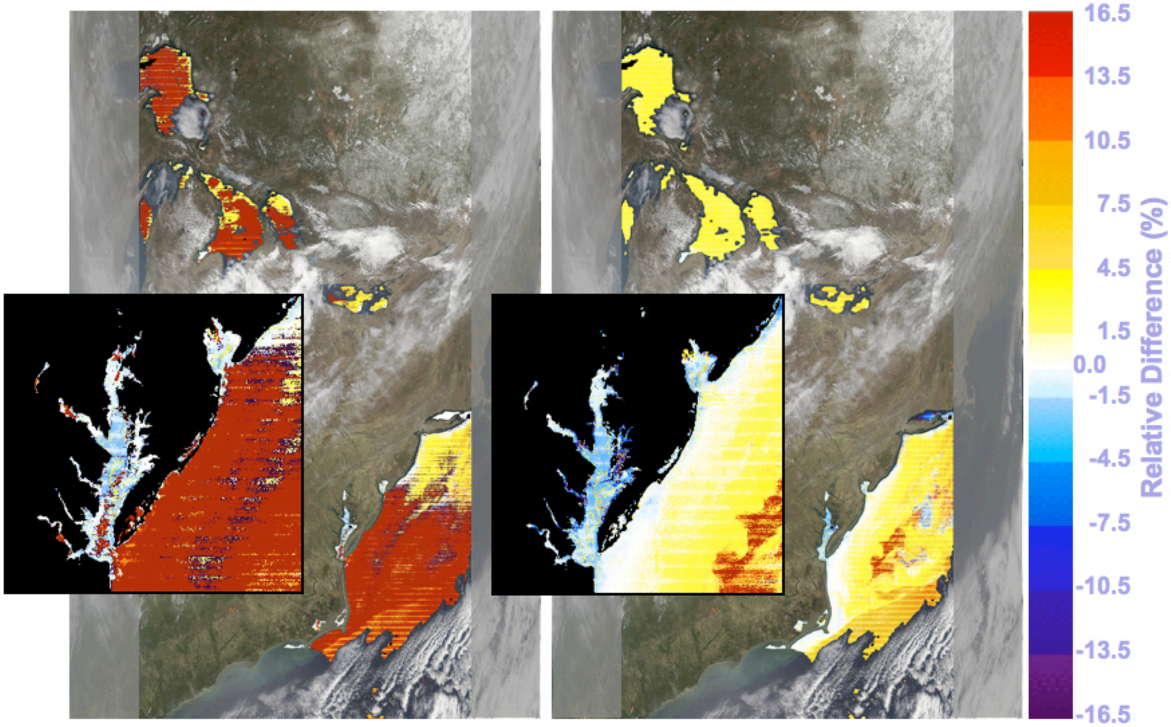

Figure 1 – the spatial distribution of the effects to the NPP operational chlorophyll algorithm (left) and the NASA-selected operational algorithm (OCM3) (right) in the presence of optical crosstalk. Data were assessed along the East Coast of the USA, as derived from measurements taken MODIS Aqua on 17 April 2005, at 1815 GMT. For this scene,. Featured in the inset is the Chesapeake and Delaware Bays. Note the near zero crosstalk impact along the coast outside the mouth of the Chesapeake Bay.

4.1.2 OOB Light Leaks

An analysis was performed to assess the overall impact of out-of-band (OOB) light leaks in VIIRS Flight Unit 1 (FU1) for the Ocean Color environmental data record (EDR). This analysis and the conclusions of this assessment are based on what is known at present about the relative spectral response (RSR) of FU1 ocean bands, which should not be viewed as definitive until analysis of spacecraft-level testing is complete. It is concluded that the size of the OOB response in the VIIRS bands M1, M3, M4, M5 and M6 is comparable to the more significant OOB light leaks seen in MODIS and SeaWiFS. MODIS Aqua had significant effects for only its 412nm and 750nm ocean bands. SeaWiFS had large leaks in multiple bands, but did not have the benefit of a system-level characterization of its band filters and does not use its solar diffuser for a reflectance-based calibration, which could reduce the impact of OOB light leaks. In either case, the NASA team was successfully able to apply techniques that compensated for these effects over the open ocean (McClain et al 2004). How effective these methods are for more stressing conditions, such as turbid coastal waters, is largely unknown.

The OOB error defined by Equation 1 represents a bias in the TOA reflectance. The calibration of TOA spectra using the solar diffuser partially mitigates the OOB error, since the solar-illuminated diffuser measurements also incorporates the OOB error, though with a different source spectrum. The error in the calibrated TOA spectrum is the difference between the errors in the blue ocean TOA spectrum and the solar diffuser spectrum:

$$Error_{OOB} = \frac{\int_{TB} L_{Ocean}(\lambda) \cdot RSR(\lambda) d\lambda}{\int_{IB} L_{Ocean}(\lambda) \cdot RSR(\lambda) d\lambda} - \frac{\int_{TB} L_{Solar}(\lambda) \cdot RSR(\lambda) d\lambda}{\int_{IB} L_{Solar}(\lambda) \cdot RSR(\lambda) d\lambda} \qquad \text{Equation 1}$$

where TB denotes the total-band region of the spectral response (the union of the in-band and out-of-band regions) and IB refers to the in-band region alone. $L_{Ocean}(\lambda)$ is defined as the TOA radiance spectrum over the ocean and $L_{Solar}(\lambda)$ is the spectrum of the solar diffuser.

The NASA Ocean Color algorithm includes RSR characterization curves in the atmospheric correction algorithm (Gordan and Wang 1994) to correct for OOB light leaks and an OOB correction to reconcile ground and spaceborne instrument band pass differences. Residual biases from these corrections should be partially absorbed by vicarious calibration. The chain of interactions with the spectral response is complicated and hence it was not appropriate to assess the potential impact using the same type of numerical experiment that was applied for optical crosstalk (see section 4.1.1). Instead, the OOB light leaks are assessed for MODIS Aqua and SeaWiFS using the effective reflectance calibration bias, as defined in Equation 1. The hypothesis is that if the VIIRS spectral OOB response is comparable to heritage, then provided the appropriate Cal/Val infrastructure is in place, VIIRS could potentially be a viable Ocean Color instrument and

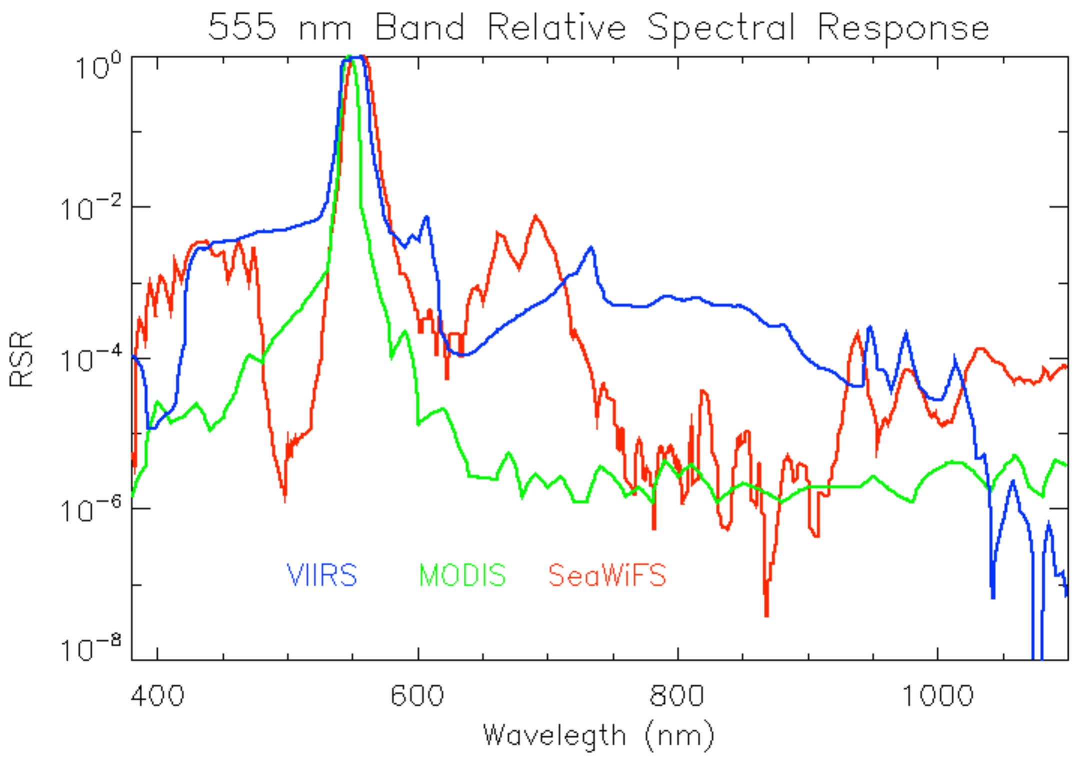

Figure 2 - 555 nm Band Relative Spectral Responses.

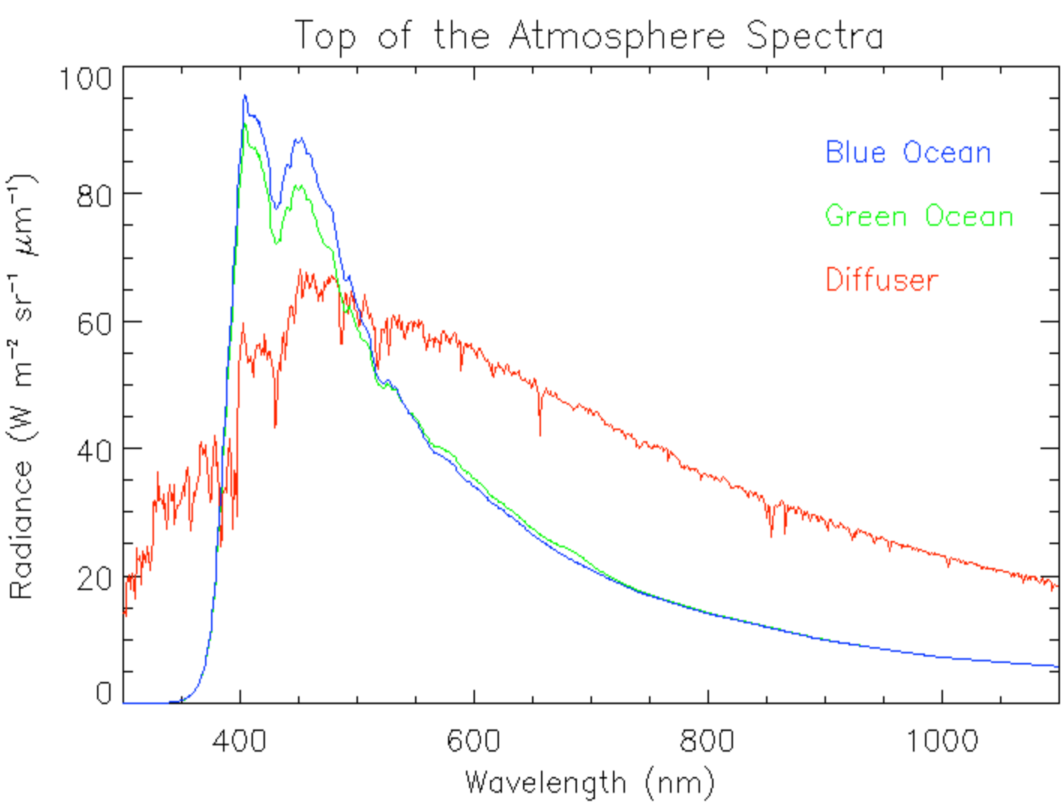

Figure 3 - Top of the Atmosphere Spectra.

perhaps meet NASA requirements for climate and earth science research.

The OOB light-leak analysis compared the calibrated top-of-the-atmosphere (TOA) reflectance for blue and green ocean spectra, as would be observed by VIIRS, MODIS Aqua and SeaWiFS. The metric of comparison for this analysis is the fractional reflectance error in the in-band spectrum due to OOB signal, where the in-band RSR is defined by the 1% of peak points. Representative RSR curves for VIIRS band M4 (555 nm) and the corresponding MODIS Aqua (band 12) and SeaWiFS (band 5) bands are shown in Figure 2. The TOA spectra for a blue ocean, a green ocean, and sunlight reflected by a solar diffuser are shown in Figure 3. The OOB light analysis involves using the RSR curves to derive the TOA spectra as would be observed by the instruments.

For VIIRS, the tabulated results for the analysis are shown in Table 4. Because there are uncertainties in the magnitudes of the OOB for the RSR curves due to the in-band/out-of-band stitching process, this analysis was performed with two sets of RSR curves: the baseline RSR curves, and a set of RSR curves where the magnitudes of the OOB RSR curves were increased by 50%. The results of this same analysis applied to MODIS Aqua are shown in Table 5. Unlike MODIS or VIIRS, the solar diffuser is not used in the direct calibration of the TOA spectra for SeaWiFS, so that sensor does not benefit from the resulting cancellation of biases. The analysis results for SeaWiFS are shown for the blue ocean spectrum in Table 6.

Table 4 - VIIRS Out-of-Band Biases. The TOA out-of-band biases for a blue ocean spectrum, a solar diffuser spectrum, and the calibrated spectrum are shown for the baseline RSRs and for the RSRs with the out-of-band increased by 50% (*). The biases are given in percent.

Band	Wavelength (nm)	Blue Ocean	Solar Diffuser	Calibrated Spectrum	Blue Ocean *	Solar Diffuser *	Calibrated Spectrum *
M1	412	0.329	0.961	-0.632	0.494	1.441	-0.948
M2	445	0.339	0.388	-0.049	0.509	0.582	-0.073
M3	488	0.374	0.676	-0.302	0.561	1.014	-0.453
M4	555	4.891	3.967	0.924	7.337	5.95	1.387
M5	672	0.648	0.496	0.153	0.973	0.743	0.229
M6	746	2.351	1.652	0.699	3.327	2.478	1.049
M7	865	1.016	0.629	0.388	1.525	0.943	0.581

Table 5 - MODIS Aqua Out-of-Band Biases. The TOA out-of-bands biases for a blue ocean spectrum, a solar diffuser spectrum, and the calibrated spectrum are shown for the baseline RSRs and for the RSRs with the out-of-band increased by 50% (*). The biases are given in percent.

Band	Wavelength (nm)	Blue Ocean	Solar Diffuser	Calibrated Spectrum	Blue Ocean *	Solar Diffuser *	Calibrated Spectrum *
B8	412	2.037	3.364	-1.460	3.056	5.056	-1.990
B9	443	0.617	0.763	-0.161	0.925	1.145	-0.220
B10	488	1.387	1.380	0.007	2.080	2.070	0.010
B11	531	0.911	0.915	-0.004	1.366	1.372	-0.006
B12	551	1.088	1.029	0.065	1.632	1.543	0.089
B13	667	0.933	1.004	-0.078	1.399	1.506	-0.107
B14	678	1.140	1.184	-0.049	1.710	1.776	-0.066
B15	748	3.794	3.154	0.704	5.691	4.730	0.961
B16	869	1.072	1.003	0.077	1.608	1.504	0.104

Table 6 - SeaWiFS Out-of-Band Biases. The TOA out-of-band biases for a blue ocean spectrum are shown for the baseline RSRs and for the RSRs with the out-of-band increased by 50% {*}. The biases are given in percent.

Band	Wavelength (nm)	Blue Ocean	Blue Ocean *
B1	412	0.518	0.777
B2	443	0.369	0.554
B3	490	0.608	0.912
B4	510	0.656	0.983
B5	555	2.861	4.291
B6	670	1.566	2.349
B7	765	1.432	2.148
B8	865	5.665	8.497

An examination of the VIIRS results in Table 4 shows that Band M4 (555nm) is the worst case with an OOB calibration bias of ~1%, with other bands showing 2/3 or less of the effect. Only band M2 shows a bias of less than 0.1%. Furthermore, the magnitude of the calibration bias is proportional to the size of the OOB signal: a 50% increase in the OOB signal results in a 50% increase in the calibration bias.

The MODIS Aqua results in Table 5 shows a 1.5% bias for band 8 (412 nm) and a 0.7% bias for band 15 (748 nm), but the other MODIS bands have a bias of 0.1% or less. The SeaWiFS results in Table 6 also help demonstrate the advantage of using a reflectance-based calibration in mitigating the OOB bias in the TOA spectra: the residual SeaWiFS biases ranging from 0.4% in band 2 (443 nm) up to 5% in band 8 (865 nm) must be removed by more complex means (e.g., vicarious calibration).

The comparison of the VIIRS, MODIS Aqua, and SeaWiFS OOB calibration biases show that the expected performance of VIIRS on orbit should be worse than that of MODIS Aqua, though comparable to that of SeaWiFS. Six of seven VIIRS bands show biases of more than 0.1%, while only two MODIS bands do. The VIIRS on-orbit performance, due to the OOB calibration biases alone, is comparable to that of SeaWiFS for the shorter wavelengths and is better than that of SeaWiFS for the longer wavelengths. If the VIIRS OOB calibration biases are not adversely complicated by the crosstalk, the heritage OOB mitigation approaches that were developed for SeaWiFS and MODIS Aqua should work for VIIRS. These approaches incorporate the out-of-band response into the Rayleigh and aerosol tables through the RSRs as the primary correction for the OOB bias in the calibrated TOA radiances, then use direct OOB corrections of the water-leaving radiances to remove residual OOB biases

4.1.3 Sources of Spectral Response and Crosstalk Characterization Uncertainty

The correction of sensor radiometry to support most Ocean Color applications requires a highly accurate characterization of the instrument behavior. For VIIRS, there is a concern that uncertainty in the spectral response characterization could adversely impact such an on-orbit correction. For instance, one of the fundamental problems with crosstalk characterization is the difficulty in separating crosstalk effects from other instrument characteristics (e.g., near-field response or out-of-band response) and from effects caused by the characterization test equipment. Government and contractor analysts have identified a number of error sources during and following the spectral characterization of NPP VIIRS. Further discussion and analyses of these sources and their net effect on the characterization quality continues.

Detector-to-detector differences were observed for both crosstalk and spectral response. The net result of these instrument variations and test limitations will likely be striping in the Ocean Color products. Because this potential source of striping will depend on the spectrum that is seen by VIIRS, it will be difficult to remove. It is recommended that detector specific corrections be considered for on-orbit use, provided it can be verified that the observed along-track variation was not a testing artifact.

Much of the along-track variation could be attributed to the behavior of the instrument itself. For crosstalk, the theoretical model for optical crosstalk implies that there will be less extraneous light propagating to receiver detectors that are close to the along-track edge. Furthermore, testing of electronic crosstalk demonstrated that it was highly dependent on the relative position of the sending and receiving detectors. For spectral response, it was suggested that an inherent instrument "smile," which stems from the non-telecentric design of the optics, was accurately measured using the T-SIRCUS in tests carried out by NIST. Analysis of the variation in the nominal band center for each band, however, implied that there would be little impact to the Ocean Color EDR, given that there was less than 0.2% maximum variation in reflectance. Nonetheless, contractor analysts suggest performing a per detector adjustment based on a Rayleigh spectrum.

Testing artifacts may also have introduced detector-to-detector differences, which if present would induce variability in the characterization of the instrument that does represent real instrument behavior. For instance, it is known that detector-to-detector differences in illumination were caused by a non-uniform slit image during the characterization of spectral response and crosstalk. Likewise, the alignment of the slit image on the detector array could also produce along-track variation. For tests using the same apparatus, additional variation might have been caused by variation of polarization along track, but the source was never tested for polarization uniformity. Contractor analysts also identified the possibility that the color temperature of the bulb filament may not have been uniform and hence induced further detector-to-detector variation, especially at the blue end of the spectral range.

Source instability may have had an effect in the characterization of the spectral response of band M1 (412nm). Repeated measurements between two bulbs using bands M1 and M4 (551nm) indicated that bulb age appeared to cause a difference in the relative spectral output of the source. The instrument tester reported that burn-in time might not have been adequate to achieve stability at the blue end of the spectral range. This issue was exacerbated by the fact that the source was only characterized once during the bulb's life, usually after many hours of measurement. Also, the bulbs were originally from the MODIS-era and quite old, and tended to burn out well before the manufacturer's expected lifetime. In addition to concern about source instability, there was a need to replace bulbs three times during the characterization tests. For the third bulb, a burnout was experienced before there was chance to perform a characterization. Fortunately, of the three ocean bands that were characterized with this bulb, i.e., bands M1, M4, and M7, only M7 was not repeated with a characterized bulb for the OOB region (M4 was not repeated for its in-band region). Moreover, most of the differences between bulbs (and hence their instabilities) were observed to be in the blue region, and M7 was demonstrated to have very little OOB response at visible wavelengths. Therefore, the lack of the third bulb characterization is not considered an issue for Ocean Color.

During the course of exploration of crosstalk behavior it was determined that crosstalk, and to a lesser degree out-of-band spectral response, was sensitive to the polarization state of the light incident on the filter array. This presented a problem with the characterization because the test source was found to be highly polarized, especially at longer wavelengths. Some effort was made to characterize the test source polarization, but this was not repeated to verify temporal stability, nor was the polarization measured along the output slit to verify uniformity. The ETP-655 test for characterizing the VIIRS crosstalk response to polarization only looked at a few wavelengths, for a few bands, and at only four polarization angles (0, 45, 90, and 135 degrees). This was potentially problematic as it was observed in tests with filter witness samples that the angular response of crosstalk propagation could be asymmetric across quadrants. Moreover, the shape of the response profiles were not consistent with wavelength or position on the FPA, which undermined the ability to extend the observed behavior to the rest of the unmeasured wavelengths, bands, and polarization states. T-SIRCUS provided an opportunity to observe the VIIRS response to a uniform, unpolarized source. Using the limited knowledge obtained with ETP-655, contractor analysts did successfully predict some of the difference between the T-SIRCUS test and the results from the test with a polarized source, but there were also significant discrepancies. In general it appears that the polarization response of crosstalk or spectral response is poorly understood and the prediction of this effect on orbit given the polarization state of light entering VIIRS is considered infeasible. The result of this uncertainty could play a significant role in the viability of any crosstalk mitigation strategy.

During characterization of crosstalk and spectral response, the process of measuring and reducing the data yielded sources of uncertainty. Naturally, some measurement noise is expected and was evaluated by contractor analysts in detail. Furthermore, in cases where tests were repeated, some inconsistency was observed. In producing RSR curves, in-band response is joined to OOB response measurements through a process called "stitching," which initially produced significantly different results for different test data analysis teams. For instance, our analysis of RSR curves from several analyst teams have yielded significant differences in the integrated OOB response. A careful examination of these curves indicated differences in the application of filters and weighting. Thus, although the same data is being used, there is apparently significant uncertainty in the processing that could propagate through to an on-orbit correction. With hope, understanding of these discrepancies will continue to develop, and eventually be resolved.

4.2 Radiometric Response – Scan Dependent Behavior

Certain instrument characteristics are dependent on viewing geometry, e.g., polarization response, response versus scan (RVS), and in the case of VIIRS, signal-to-noise ratio (SNR). Careful characterization of polarization response and RVS on the ground is important because these two effects are difficult to distinguish on orbit. The SNR is also of importance as it governs what can be retrieved on finer scales, but has a lesser effect on climatology products.

4.2.1 Polarization Response

The polarization characterization of VIIRS was initially done with a rotating Ahrens prism and a collimator; this setup is called the Polarization Source Assembly (PSA). NASA scientists repeatedly pointed out weaknesses of this design. The resulting measurements did not produce the expected cosine curve as a function of twice the polarization angle. These effects were notably worse than what was observed when the PSA was used to characterize MODIS. Most likely, Raytheon abandoned the use of the PSA setup when it was found to produce inconsistent results depending on which part of the VIIRS focal plane was illuminated.

The test was completely redesigned, this time using polarization filters that were rotated around their transmission axis. A first version of this test suffered from inadequate baffling and significant out-of-band contamination in band M1. In a second version (ETP-679, the final test configuration), baffling was adequate, and a band-pass filter was used to eliminate wavelengths above 600nm for the measurements of M1-M3.

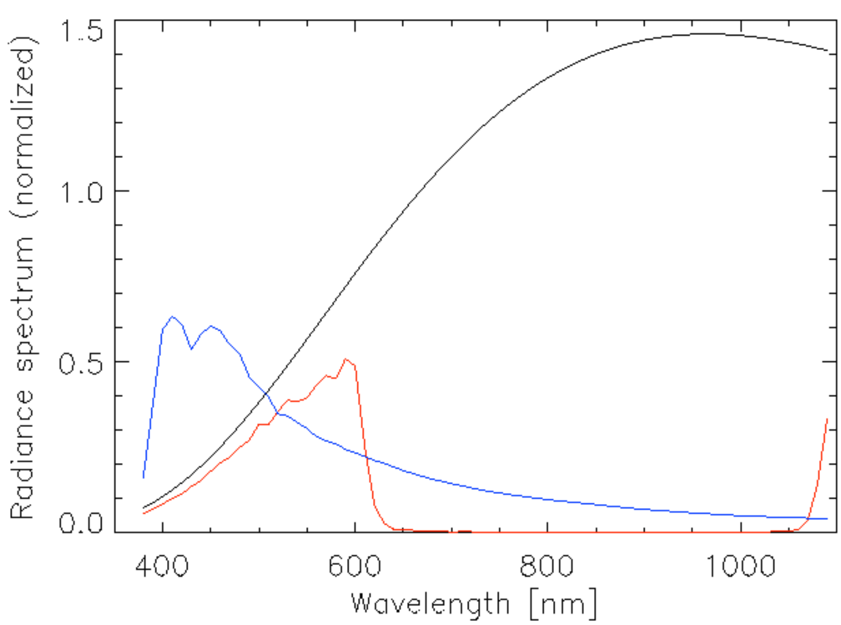

Figure 4 - Normalized radiance spectra of SIS (black), SIS after 600nm bandpass filter (red) and typical blue-ocean top-of-atmosphere (blue).

Figure 4 shows that the addition of this filter produced a source spectrum (red line) that is much closer to the spectrum that will be seen on-orbit (blue line) than the initial SIS spectrum (black line); however, it is still significantly different, peaking at about 600nm, and producing an out-of-band contribution above 600nm that is much lower than on-orbit. The expected uncertainty due to this effect should be less than about 0.5%. Since all other uncertainty sources for this test are smaller than 0.3%, the total uncertainty of the VIIRS polarization characterization is better than that of the MODIS Aqua polarization characterization (Meister et al. 2005).

One surprising result of the VIIRS polarization characterization is the strong detector dependence of the polarization sensitivity, in fact, up to 1.5% absolute (see Figure 5). An erroneous detector dependence of this magnitude would lead to significant striping in the Ocean Color products, but there is evidence that the measured detector dependence of VIIRS is correct. Originally, the NASA VOST had expressed concern about whether the along-track variation actually stemmed from instrument behavior or was an external artifact of the characterization experiment instead. A special test was done where VIIRS was shifted relative to the light source (in the track direction) to determine whether the illumination of the focal plane is the reason for the detector dependence. The results indicated that the along track shift of VIIRS did not cause any change in the variation,

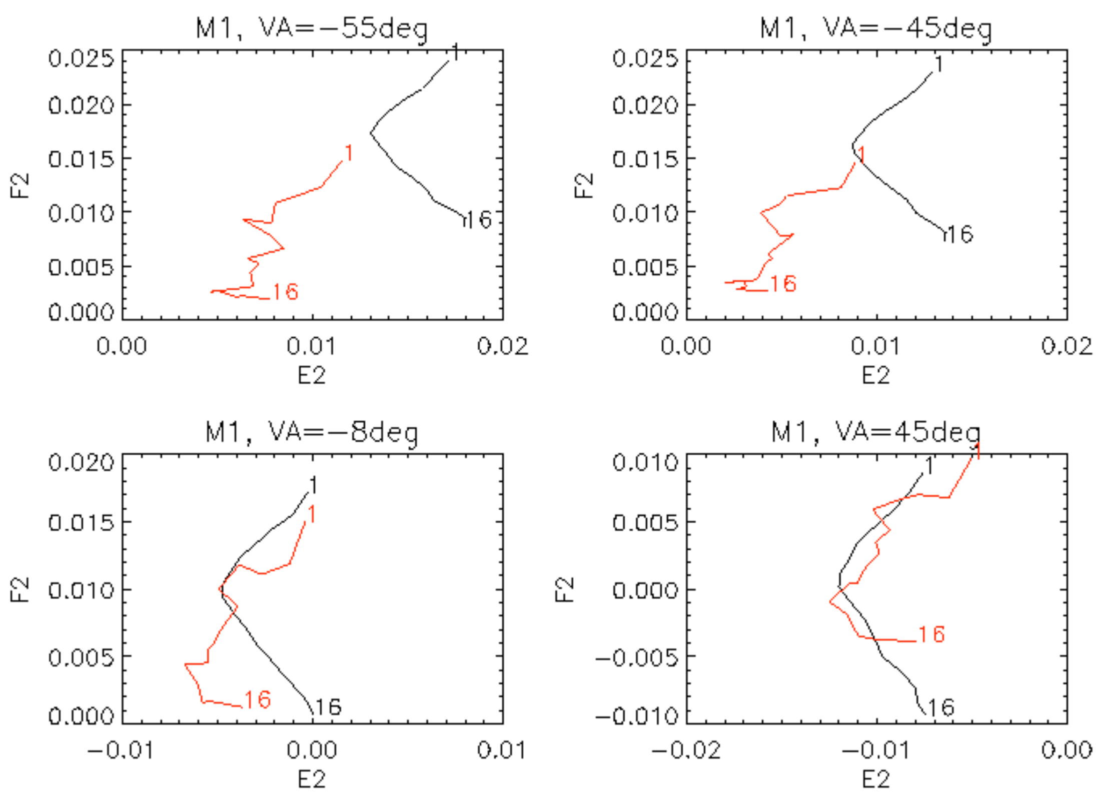

Figure 5 - E_2 and F_2 are the second-order Fourier coefficients (sine and cosine) derived from the VIIRS band M1 polarization characterization measurements (black: with bandpass filter, red: without; lines connect detectors 1 to 16).

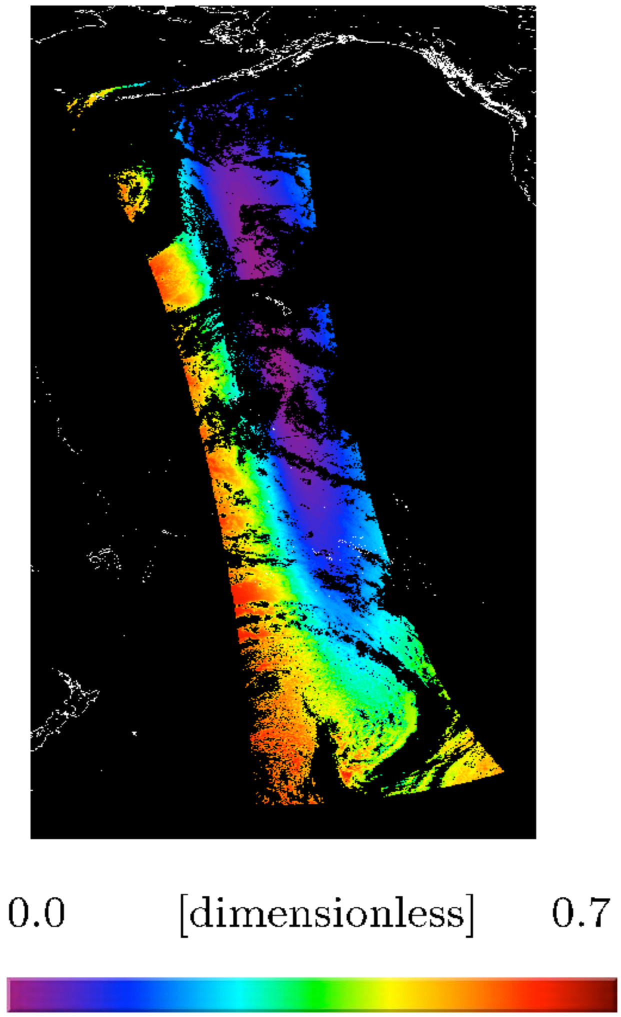

Figure 6 – Degree of linear polarization of the top-of-atmosphere radiance for a MODIS Aqua orbit over the pacific. The beginning of the MODIS Aqua scan is in the east, the end in the west.

thus supporting the hypothesis that the detector dependence was a property of the instrument and not caused by the test.

Since a raytracing model of VIIRS did not predict a detector dependence, and because the MODIS prelaunch polarization characterization has a detector dependence that produced significant striping, it will certainly be appropriate to investigate if a polarization dependence averaged over detectors reduces striping, once on-orbit data is available.

For the MODIS polarization correction, two facts combined in an unfortunate way: the polarization sensitivity of MODIS increases towards the end of the scan, and the degree of polarization of the top-of-atmosphere increases towards the end of the scan as well, see Figure 6. VIIRS will be in the same orbit as MODIS Aqua, so the later is true for VIIRS as well. Fortunately, the VIIRS polarization sensitivity decreases towards the end of the scan (see Figure 7). So for VIIRS, the impact of small polarization characterization inaccuracies is expected to be small in the first half of the scan (because the degree of polarization of the incoming radiance is low) and in the second half of the scan as well (because the VIIRS polarization sensitivity is low). In addition, the average sensitivity of VIIRS to polarization is lower than that of MODIS (see Figure 7), so it is expected that the VIIRS Ocean Color products will be much less affected by polarization than those of MODIS.

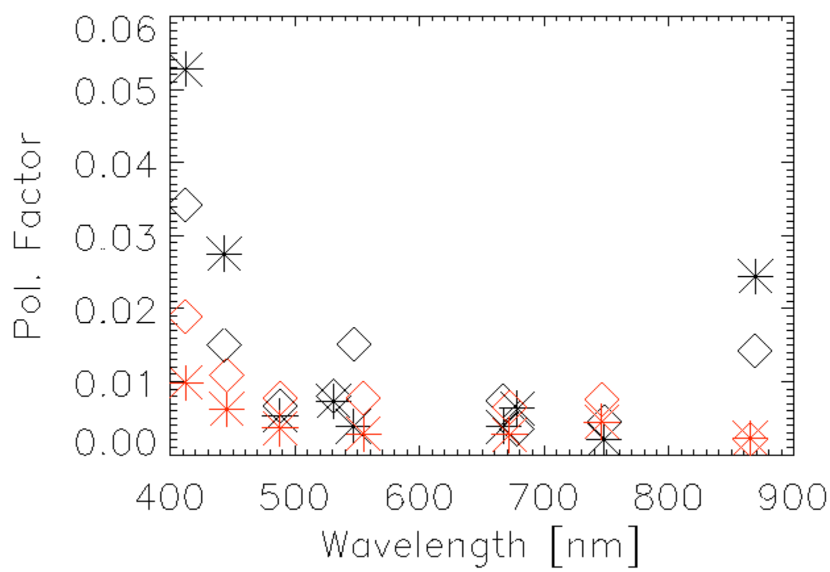

Figure 7 – Sensor polarization sensitivity (polarization amplitude) of MODIS Aqua (black) and VIIRS FU1 (red). Stars are for +45° view angle, diamonds for -45°.

4.2.2 Response vs Scan Angle

The response-versus-scan (RVS) characterization of VIIRS is achieved by having VIIRS look at a constant light source (the spherical integrating source SIS) from different scan angles by rotating VIIRS relative to the light source.

The EDU measurements of the VIIRS RVS were hardly usable, because the SIS stability was not adequately monitored. As suggested by the NASA VOST, Raytheon significantly improved its monitoring of the SIS radiance output. This was done by using a dedicated SIS internal radiance monitor, and by repeating the VIIRS measurements at a scan angle of -8° several times during the test. The VIIRS RVS measurements were made at 11 scan angles (from -55° to +55°), compared to the 11 scan angles (from -53° to +53°) used for the prelaunch characterization of MODIS Aqua and the 7 scan angles (from -58° to + 58°) used for the prelaunch characterization for SeaWiFS.

The resulting RVS is a smooth function of angle of incidence on the HAM, and the variations are limited to a maximum of 1.1% over the whole scan angle range. These results are similar to the MODIS Aqua prelaunch characterization. This is not expected

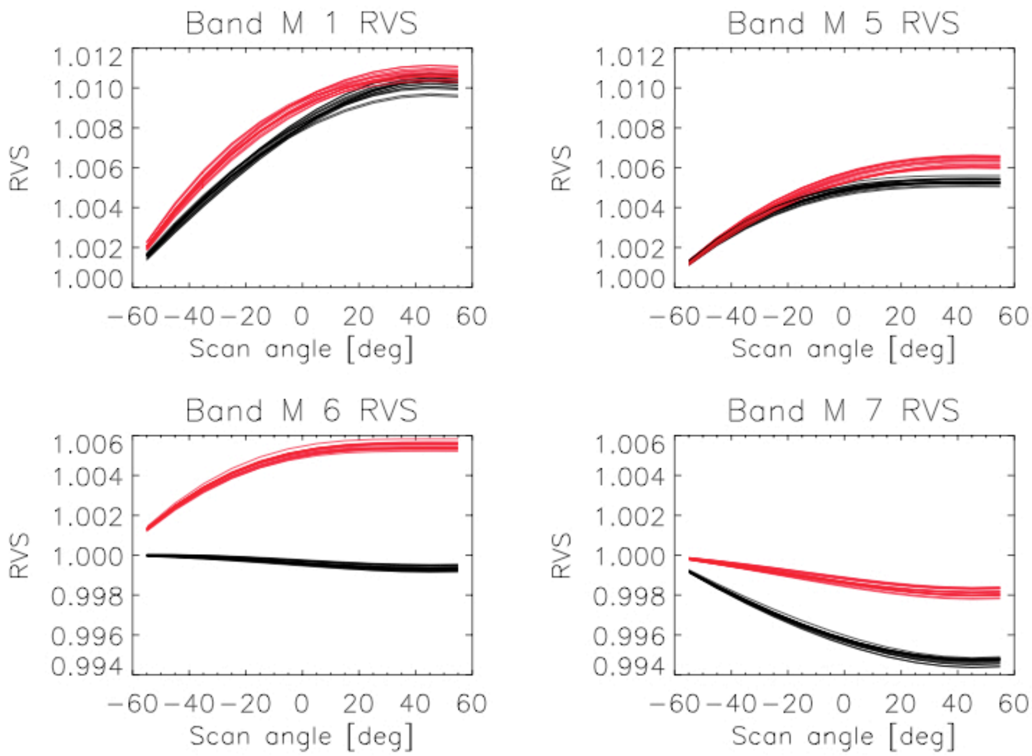

Figure 8 - VIIRS FU1 RVS for HAM sides A (black) and B (red). Each line corresponds to one of the 16 detectors. RVS is defined as the ratio of the response as a function of scan angle to the response at the SD scan angle (not shown because it is outside of the earth view range). Data provided by NICST.

to be a problem for VIIRS Ocean Color processing unless the RVS changes on-orbit. The RVS did change significantly on-orbit for both MODIS Aqua and Terra, but insignificantly for SeaWiFS. It is hoped that the VIIRS RVS will follow the SeaWiFS example, because the VIIRS telescope design should protect the mirror, as it does for SeaWiFS (the MODIS scan mirror is much less protected than the VIIRS HAM). Unlike MODIS, there is no mechanism to monitor changes in the VIIRS RVS on-orbit (e.g., comparing the solar diffuser and lunar measurements, see Section 5). Once on-orbit, the VIIRS Ocean Color radiances will be trended as a function of scan angle (as is the current practice of the OBPG for MODIS) to determine possible VIIRS RVS changes.

The VIIRS RVS is shown in Figure 8 for four bands. The RVS for bands M2 through M4 is very similar to that of bands M1 and M5, so only the later are shown. M6 and M7 have a different RVS shape from the other bands, and they have significant differences between the two HAM sides. M6 is the band with the largest difference between the two HAM sides. The variation with detector is very small for all bands.

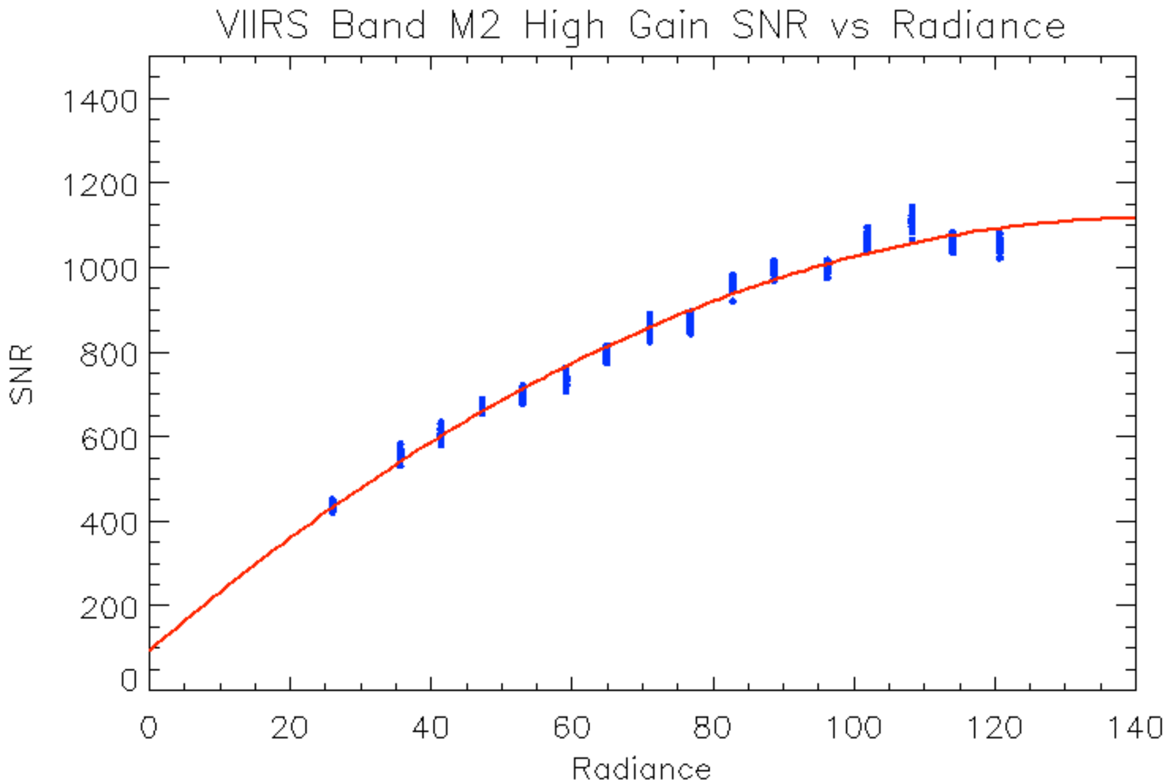

Figure 9 - Band M2 SNR vs Radiance fits.

4.2.3 Signal-to-Noise Ratios

The high-gain SNR characterization data used in this analysis is summarized in Table 7 and were provided by NICST; the radiances used in the analysis have been corrected for the out-of-band bias. An SNR model was developed for each band by fitting a quadratic function to the measured SNR vs radiance data. The data and fit for band M2 are shown

Table 7- SNR vs Radiance Measurements. The number of measurements, number of radiances, radiance range, and measured SNR range for the VIIRS SNR characterization. The radiance units are W m^{-2} sr^{-1} μm^{-1}.

Band	Num of Points	Num of Levels	Minimum Radiance	Minimum SNR	Maximum Radiance	Maximum SNR
M1	735	23	44	543	183	1438
M2	505	16	26	420	121	1142
M3	341	10	25	519	91	1276
M4	320	10	18	479	72	1251
M5	193	7	10	338	57	1209
M6	254	8	6	295	23	704
M7	288	9	4	414	26	1369

Table 8 - VIIRS Signal-to-Noise by Aggregation Zone. The VIIRS SNRs, measured prelaunch for typical ocean radiances (W m-2 sr-1 µm-1), are compared for the 1:1, 2:1, and 3:1 pixel aggregation zones.

Band	Ltypical Ocean	1:1 Agg Zone	2:1 Agg Zone	3:1 Agg Zone
M1	78.6	826	1169	1431
M2	70.2	853	1207	1478
M3	53.1	887	1254	1536
M4	33.9	762	1078	1320
M5	16	512	725	887
M6	9.3	387	547	670
M7	4.6	426	603	739

in Figure. 9. These fits were then used to compute the SNRs at the revised typical ocean radiances used in the MODIS characterization analysis. Initially, the VIIRS SNRs are computed on the basis of a single instrument IFOV rather than on the basis of comparable pixel areas, since the data is processed at the IFOV level. Since VIIRS has three pixel aggregation zones across the scan, the SNRs for the three zones are provided in Table 8.

Table 9 - Signal-to-Noise Comparison. The SNRs, measured prelaunch for typical ocean radiances (W m^{-2} sr^{-1} μm^{-1}), are compared for VIIRS, SeaWiFS, and MODIS Aqua.

Band	Ltypical Ocean	VIIRS Prelaunch	SeaWiFS Prelaunch	MODIS Aqua Prelaunch
M1	78.6	1155	897	1633
M2	70.2	1193	967	2219
M3	53.1	1239	1010	2164
M4	33.9	1065	870	1799
M5	16	716	570	1958
M6	9.3	540	522	876
M7	4.6	596	364	726

For comparing with corresponding prelaunch SeaWiFS and Aqua MODIS SNRs at the typical ocean radiances, a weighted scan-averaged SNR is computed for eacn VIIRS band, where the SNRs from the six aggregation zones are weighted by the number of pixels in each zone. This comparison is shown in Table 9 and shown graphically in Figure 10. The VIIRS performance exceeds that of SeaWiFS for all bands in the 2:1 and 3:1 aggregation zones and for band M7 in the 1:1 aggregation zone with the scan-averaged SNRs exceeding the SeaWiFS values by 20% or more for all bands except M6. Overall, the VIIRS SNR performance is better than that of SeaWiFS but less than that of MODIS.

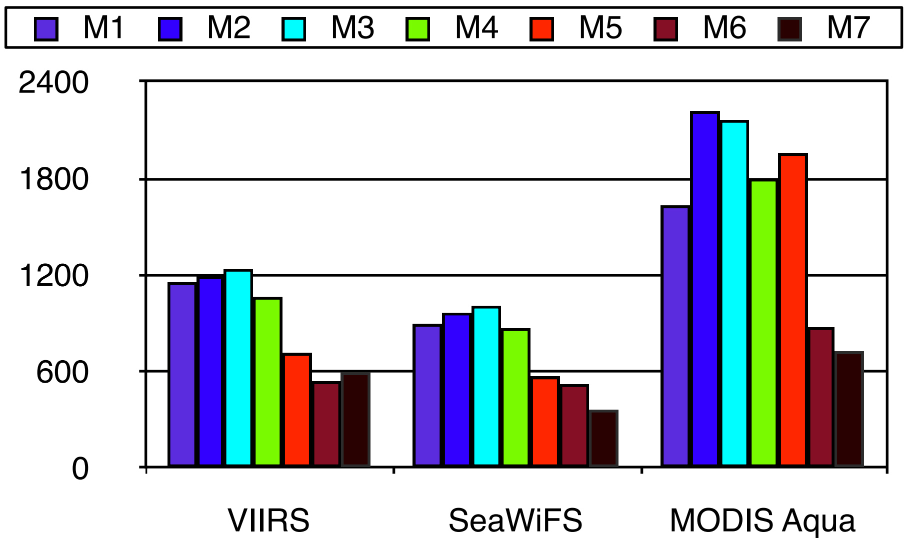

Figure 10 - This bar chart is a graphical representation of Table 9, where effective prelaunch SNR levels for the VIIRS ocean bands (M1-M7) are visualized aside the levels for corresponding SeaWiFS and MODIS bands.

4.3 Radiometric Response – Scan Independent Behavior

4.3.1 Radiometric Resolution

Experience with SeaWiFS showed that quantizer step size in the NIR is important for quality Ocean Color retrievals (Hu et al 2000). In particular, the stepwise variation that result can cause adverse fluctuations in the aerosol model selection. VOST analysis of VIIRS spectral range and resolution in 2005 raised concerns with the 865 nm band, i.e., band M7 on VIIRS. The proposed quantization step size was thought to be as much as twice that of MODIS in the corresponding band. However, the step size of VIIRS is significantly smaller than SeaWiFS, and more importantly, it is less than the noise for band M7. Therefore, the round-off error should decrease by a factor of 1.7 in the 3:1 aggregation zones and 1.4 in the 2:1 aggregation zones, putting the error at 17% and 40% larger than MODIS, respectively. In general, quantization error is not expected to adversely affect the Ocean Color EDR product quality.

4.3.2 Dynamic Range

Early in the characterization of VIIRS, there was a concern that band M1 switches from high to low gain at a radiance of 10% below the specified L_{max} for high gain. The specification for L_{max} is 135 ($W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$), the measured L_{max} appeared to be ~120, and L_{typ} for band M1 in the open ocean is considered to be 78 from our analysis of heritage data. We concluded at the time that this lower gain switch point was still well above the L_{typ} value for the ocean data. Later, it was discovered that the lower values were a result of the OOB light leak on the long-ward side of the bandpass for band M1 and the fact that the calibration source is fairly red spectrally. After correcting for the OOB response, L_{max} for band M1 was found to be actually 173 ($W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$), which still does not appear to present a problem for Ocean Color.

4.3.3 Linearity

The overall linearity for the reflective solar bands is within 0.25% of the response at L_{max}. The VIIRS reflective bands show a non-linear response in the vicinity of the gain transition points in the form of additional noise. This non-linearity is about 4 times larger than the overall non-linearity (about 1%) and affects a range of radiances that is detector-dependent over a radiance range of 0.9 – 0.912 L_{max}. The effect of this non-linearity on typical Ocean Color scenes and significant ocean features was examined to determine if it is a significant impact on Ocean Color data.

SeaWiFS High Resolution Picture Transmission (HRPT) data was examined as a proxy for VIIRS data to assess the amount of impact of non-linear radiances. Total radiances were examined from general ocean conditions as well as from a range of conditions having brighter radiances to determine the rate at which these phenomena are affected by the non-linear range.

In the general global case, band M1 at 412nm was found to have up to 2.5% of ocean radiances in the non-linear range while the other bands showed little impact. The affected pixels were near the scan edge, but mostly inside of the SeaWiFS Level-3 sensor zenith exclusion limit of 60 degrees, especially at lower latitudes. If the noise in this range is significant, it would limit the unaffected amount of VIIRS data available. Other bright ocean cases, such as coccolithophores, bottom reflectance, or coastal regions, showed occasional impacts up to the 2.5% level in band M1, and up to 2% in bands M2 to M4 in regions affected by the phenomena. Products, like chlorophyll concentration, which rely on visible band combinations could be affected to a greater extent by the non-linear range. However, good chlorophyll estimates under these conditions are already difficult due to the complex water type. Although the impact is relatively low in most cases, it should be remembered as a possible noise source for these special conditions.

4.3.4 Thermal Response

All of the VIIRS reflective solar bands are insensitive to focal plane temperature variations to the extent that they are not expected to impact the Ocean Color EDR quality. Proposed test plan reductions that would have led to the removal of one radiometric response characterization plateau temperature raised the possibility of a bias in the thermal response correction. However, three were measured and thus there are no adverse effects to Ocean Color EDR quality.

4.3.5 Uniformity

The response uniformity requirement for VIIRS states that the sensor response at a given radiance, on average, should vary on a detector-by-detector basis by less than the noise at that radiance. In other words, the uniformity requirement is 1 NEdL, which implies that near the peak of the radiance ranges for each VIIRS band the variation in response across the detectors should be less than 0.1%. The dual-gain ocean bands at high gain and band M6 meet this uniformity requirement of 1 NEdL. However, the applicability of these results to Ocean Color data retrievals is questionable because of the uncertainty in the uniformity of the integrating sphere output in the along-track direction. Thus the test is probably not sensitive enough to detect striping at the levels set by the specifications. Moreover, other instrument behavior is expected to generate striping in the satellite swath. Striping was seen with both MODIS instruments and is an inherent artifact with this instrument design. Any impact to Earth science applications is unavoidable, but is not anticipated to cause a major issue.

One aspect of uniformity can be explored using data from a test performed by NIST to measure the RSR curves of VIIRS using its T-SIRCUS instrument after VIIRS had been integrated onto the NPP spacecraft at Ball Aerospace. Variations along track of the bandpass were interpreted as an actual instrument characteristic, called the *instrument spectral smile*, which stems from the non-telecentric design of the optics. For the blue bands the signal levels for the test were insufficient to characterize the out-of-band response of the instrument beyond what had been done during the thermal vacuum

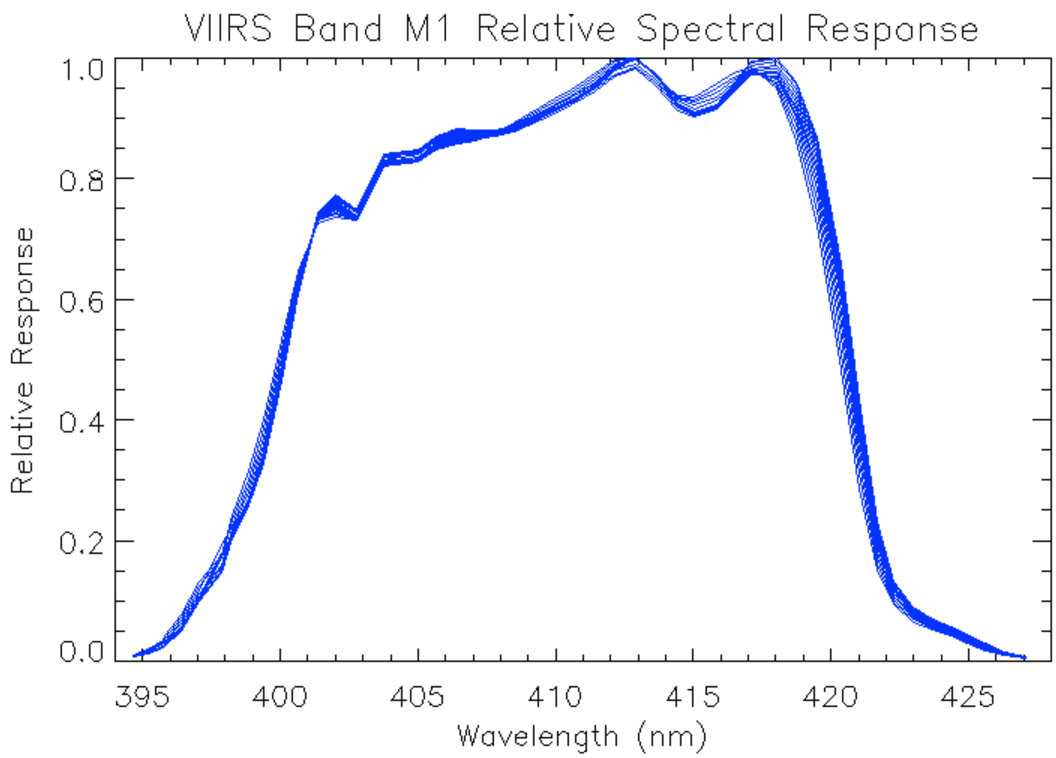

Figure 11 - In-Band Relative Spectral Responses for each detector of band M1.

testing. However, the in-band response of the instrument was measured on a detector-by-detector basis. To assess the uniformity of the RSR for the blue bands, the in-band detector-specific RSRs for band M1 have been examined in a manner analogous to the out-of-band analysis discussed in Section 4.2.2.

To assess the calibration bias across the band due to the detector-dependent RSR, the in-band bias in the blue ocean TOA spectrum has been assessed on a per-detector basis. The in-band RSR is defined by the 1% of peak data points; for band M1, the in-band response is over the wavelength range of 395-427 nm. Figure 11 shows the in-band RSRs for band M1 for all 16 detectors. The envelope of the responses shows the size of the calibration biases between the detectors.

The radiance reflectance in the calibrated TOA spectrum for the i^{th} detector is the ratio between the band-averaged blue ocean TOA spectrum and the band-averaged solar diffuser spectrum:

$$R_i = \frac{\int_\Lambda L_{Ocean}(\lambda) \cdot RSR(\lambda, j, i) \cdot d\lambda}{\int_\Lambda L_{Solar}(\lambda) \cdot RSR(\lambda, j, i) \cdot d\lambda} \qquad \text{Equation 2}$$

where $RSR(\lambda)$ is the relative spectral response of the j^{th} band, $L_{Ocean}(\lambda)$ is the TOA spectrum over the ocean, $L_{Solar}(\lambda)$ is the solar spectrum measured when the instrument views the solar diffuser, Λ is the total spectral range of the instrument with wavelength $\lambda \in \Lambda$.

In order to assess the size of the bias over the band, the bias relative to detector 8 was computed using the relation:

$$B_{i,8} = \frac{R_i}{R_8} \qquad \text{Equation 3}$$

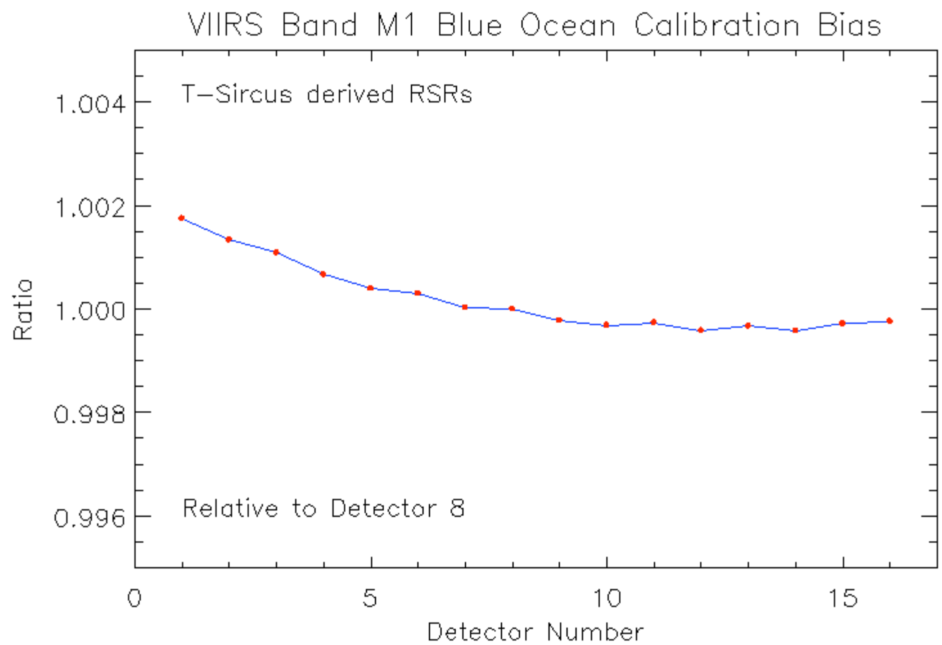

Figure 12 - Band M1 In-Band Calibration Biases Relative to Detector 8.

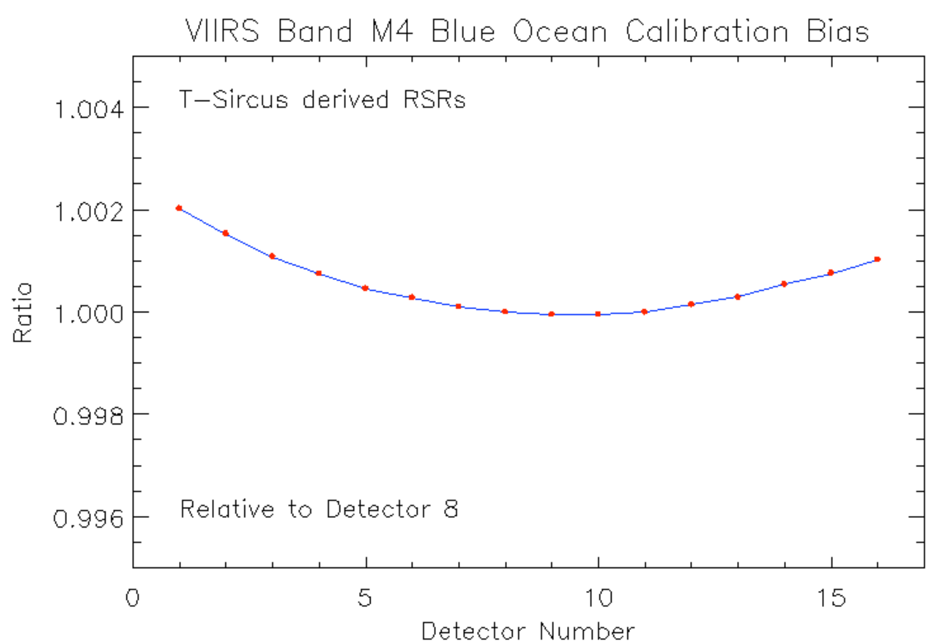

Figure 13 - Band M4 In-Band Calibration Biases Relative to Detector 8.

The calibration biases relative to detector 8 are shown for band M1 in Figure 12 and for Band M4 in Figure 13. The calibration bias results for all 7 Ocean Color bands are shown in Table 10. The biases across the bands are typically ~0.2%, with the outer detectors generally having a higher bias then the inner detectors; the trends in the bias are generally not symmetric across the band. These across-band calibration biases are a significant source of the band non-uniformities. Based on this analysis, only band M7 meets the uniformity requirement of 0.1%. The need for detector-specific RSRs or for detector-corrected RSRs for Ocean Color retrievals is an ongoing topic of investigation.

Table 10 - Across-Band Calibration Bias - The calibration biases are computed for the individual detectors in each band relative to detector 8.

Band	Minimum Bias	Maximum Bias	Range of Bias
M1	0.999579	1.001747	0.22%
M2	0.999912	1.001714	0.18%
M3	1.000000	1.001462	0.15%
M4	0.999950	1.002019	0.21%
M5	0.999960	1.001403	0.14%
M6	0.999831	1.001941	0.21%
M7	0.999995	1.000581	0.06%

4.3.6 Radiometric Stability

Short-term stability of the reflective solar bands is within the specified limits (0.3%) and is less than 0.1% for most bands over the period of one orbit (100 minutes). The long-term stability of VIIRS has not been assessed, and will be assessed as part of the the long-term monitoring phase of the mission on-orbit.

4.4 Spatial Performance

Generally speaking, the band-to-band registration and pointing knowledge seem quite good for the moderate resolution bands and thus are adequate for producing a science quality Ocean Color EDR. However, there are concerns regarding spatial response that require monitoring. First, the Near-Field Response (NFR) is important as it governs how close to the edge of a bright target (e.g., a cloud) data can be retrieved. Changes as much as one or two pixels can dramatically reduce the amount of data coverage. Furthermore, the frequency of obtaining vicarious calibration match-ups is directly related to the amount of coverage, and so NFR can affect the time required for the instrument to be properly calibrated for Ocean Color applications. This is also true of other effects, such as crosstalk, that could affect measurement of the ocean near bright targets or for scenes with high contrast. Finally, the spectrally driven spatial effects, such as crosstalk, can adversely affect the quality of retrievals in highly variable coastal waters or over bright algal blooms.

4.4.1 Crosstalk Spatial Effects

Crosstalk is not expected to have a significant effect on the retrieval of good quality ocean measurements further than three pixels from bright target edges in the 3:1 aggregation zones. This is based on analyses performed on MODIS scenes and from the results from ETP-655. Still, most characterization and analyses of crosstalk have been focused on propagation along the scan direction. Given that the upstream side of filter array was inverted to face the detectors, the Flight Unit 1 could have considerable scatter along track (e.g., *intra-band* crosstalk) that is both polarization and spectrally dependent. There was no general testing of this effect outside of the limited measurements made during ETP-655 and FP-13. Therefore, this along-track effect should be expected and evaluated on-orbit.

No conclusive studies have been done of the impact of crosstalk spatial effects in highly structured scenes, such as very turbid coastal waters or highly reflective blooms (e.g., coccolithophore blooms). Although this does not directly concern the quality of NASA's current climate data records, it does affect biogeochemical cycling questions that are being researched by the Ocean Color community (e.g., calcite concentrations, particulate organic carbon, and total suspended sediment). However, as mentioned in Section 4.1, evaluation of the spatial effect of crosstalk would require analyzing the impact using either real or simulated data that is at least at the resolution of the VIIRS unaggregated pixels, and ideally, that data would include hyperspectral information to better capture optical crosstalk effects that stem from wavelengths between bands.

4.4.2 Near-Field Response (NFR)

The instrument NFR is characterized through an experiment where VIIRS scans across a bright slit. The slit is very bright, so that signals of only one part in one million of the peak intensity can be detected, which is necessary to characterize the response of VIIRS

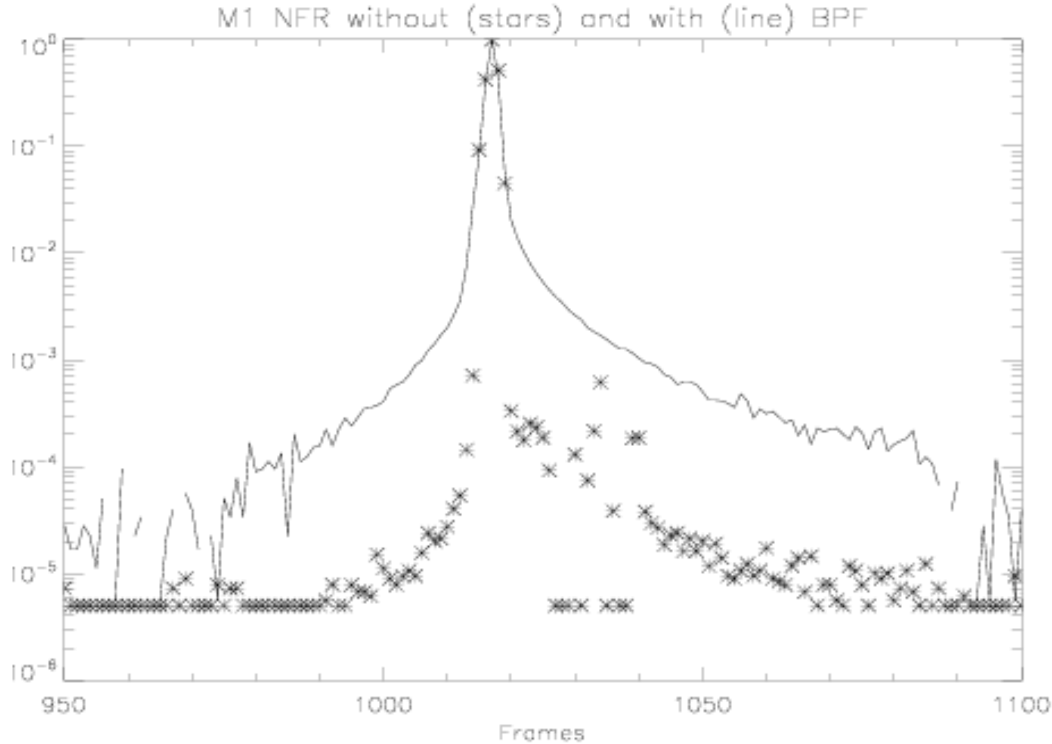

Figure 14 - NFR measurements for M1 normalized to central peak, with and without BPF (preliminary processing). The frames correspond to unaggregated samples.

when it measures ocean regions that are 10km or more away from clouds or coast lines. In order to relate the low signal measurements to the intensity of the peak (which saturates VIIRS), additional measurements are made with neutral density filters.

The NFR test was conducted without any band pass filter (BPF), and with a BPF for each band. BPF measurements were taken to test whether spurious features that appeared on the NFR profile were caused by crosstalk from other wavelengths. An analysis of the data showed a large difference in the measurements with and without the use of a BPF, as can be seen in Figure 14 for band M1. The measurements with BPF were repeated, and the difference disappeared. Figure 14 also shows that there are several sharp peaks near the central peak in the measurements without BPF, but not in the measurements with BPF. Since the BPF measurements eliminate optical and electronic crosstalk, these sharp peaks are due to crosstalk. In order to separate crosstalk from stray light effects, the measurements with BPF (from the second run, not shown here) were used by NICST to model the VIIRS NFR with Harvey-Shack functions for the structured scene spec. VIIRS passes the specification, but the specification is not directly relevant for determining the required size for a stray light mask for Ocean Color products.

A qualitative evaluation of the VIIRS NFR can be made by comparing it to the NFR measurements of MODIS Aqua, which is shown in Figure 15. It can be seen that the NFR of all three instruments (VIIRS EDU and FU1 and MODIS Aqua) are relatively similar. This result is surprising, because it was expected that the VIIRS telescope design would provide better stray light rejection than the MODIS scan mirror, which is relatively

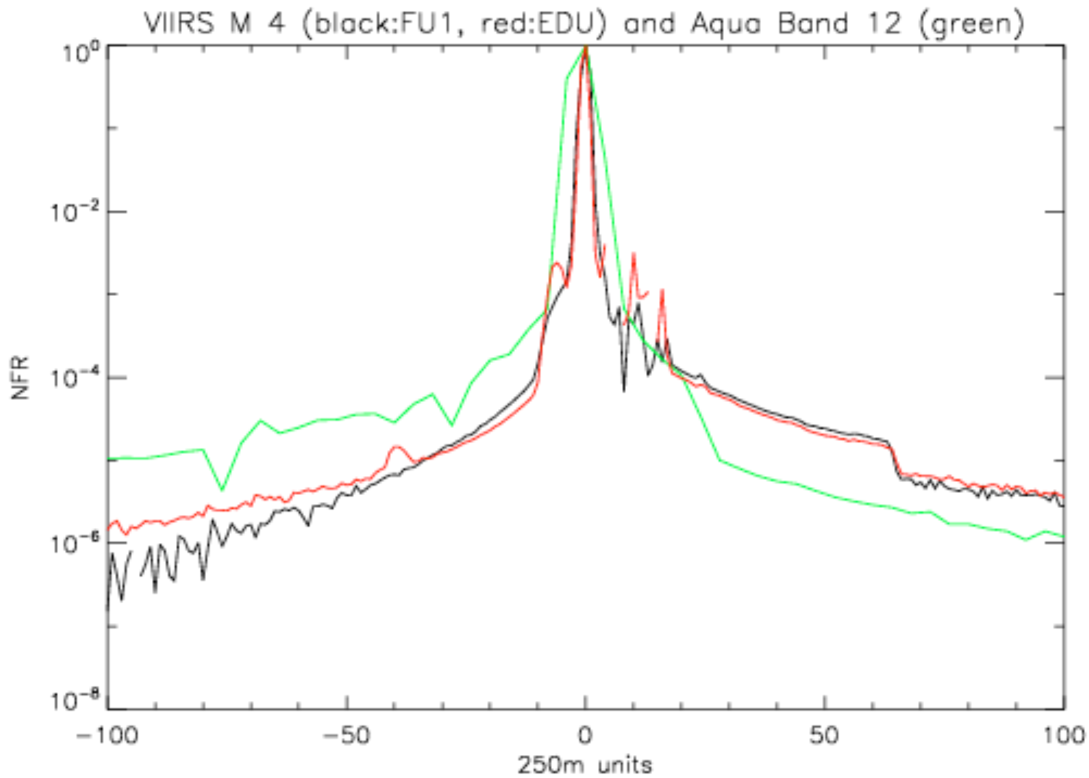

Figure 15 - NFR measurements normalized to central peak for 555nm band (VIIRS FU1: black, VIIRS EDU: red, MODIS Aqua: green)

unprotected. In any case, these comparisons (the results are comparable for all Ocean Color bands, M1-M7) leads to the conclusion that the impact of stray light contamination for both MODIS and VIIRS will be similar, so that the VIIRS Ocean Color processing can use a similar cloud mask as the MODIS Ocean Color processing. However, a limitation of this comparison is that the slits used for the MODIS and VIIRS NFR measurements are not identical. Therefore, these comparisons are purely qualitative.

A comparison of the red and black line in Figure 15 shows that the variations near the peak are larger in the EDU than in FU1, which means that Raytheon has successfully reduced the impact of dynamic crosstalk. The peak in the green line is broader than the peak in the red or black line because the VIIRS data were taken in diagnostic mode, without sample aggregation.

4.4.3 Band-to-Band Registration

The band-to-band registration refers to how well detectors in different bands can be co-registered. The performance for VIIRS is within specification thresholds for all Ocean Color bands, and so this characteristic is not expected to adversely affect the Ocean Color EDR or CDR product quality. This is especially true in the case for the 3:1 aggregated pixels, where the maximum misalignment is expected to be only a few percent or less at the end of scan.

5. On-Orbit Calibration/Validation

To achieve Ocean Color comparable to heritage, the instrument calibration must be stable to 0.1%, as was achieved with SeaWiFS (see Sun et al. 2008 and Eplee et al. 2010). However, there are currently significant issues concerning the on-orbit calibration of VIIRS. For instance, although work to analyze results continues, system-level functional tests of the reflective band calibration system remain inconclusive, and this fact poses a risk for on-orbit sensor performance. A detailed argument for this risk reduction step was carefully laid out in a VOST memorandum that was submitted last spring (Turpie 2009). Furthermore, cross-comparison with SeaWiFS data proved essential for assessing and correcting on-orbit behavior of MODIS Aqua and Terra (Kwiatkowska et al., 2008). There is a risk that there will be no reliable U.S. sensor assets in orbit to accommodate such an independent check for VIIRS. Finally, it is a minimal requirement that a spacecraft roll maneuver be done monthly to collect adequate and consistent lunar measurements to check radiometric stability, and a set of yaw maneuvers be done once or twice during the mission to measure the calibration system response on orbit. ***It is vital that NASA approve these maneuvers, and urges its partners to approve these maneuvers throughout the mission, to assure that NASA climate and Earth System science data continuity requirements are met.***

The draft Integrated Program Office (IPO) Ocean Calibration/Validation (Cal/Val) program plan currently defines fairly conventional tasks, although the implied interagency agreements need to be defined and negotiated. Unfortunately, the draft's mostly traditional approach assumes that VIIRS will behave like heritage sensors. Given the instrument's performance risks, the plan could lack the extra measures or innovations that may be needed to, if possible, deal with any idiosyncrasies. Therefore, a gap analysis (i.e., determining whether the technology and resources available are sufficient to support required steps for Cal/Val) is needed to determine whether the current plan will be adequate given what is being learned now about the sensor and its characterization. Furthermore, that analysis needs to be done imminently, ideally in parallel with instrument performance assessment, in order to give time for any additional Cal/Val resources to be identified and ready prior to launch. ***Thus, it is crucial that such analysis be supported in advance of launch in order to assure that the intensive Cal/Val phase and long-term monitoring are adequately scoped.***

VIIRS will pursue a very similar calibration approach as MODIS:

- A solar diffuser (SD) will be the primary calibration source.
- A Solar Diffuser Stability Monitor (SDSM) will track the degradation of the reflectance of the solar diffuser.
- Presumably, lunar roll maneuvers will allow additional measurements of the lunar irradiance through the space view port, which is needed to detrend response changes in the instrument.
- Vicarious calibration is needed to address biases for Ocean Color.

However, differences in the design of VIIRS and MODIS will have a profound impact on how these calibration sources can be used, as discussed in the following subsections. It is not clear whether any of the problems described above will occur for VIIRS. However, there is a (presumably small) possibility that one (or all) of them will degrade the radiometric quality of VIIRS data.

5.1 Solar Diffuser Calibration

5.1.1 AOI Dependent Degradation

MODIS views the SD at an angle of incidence (AOI) on the primary scan mirror equivalent to the start of the second half of the earth view scan, and it views the moon at an AOI equivalent to the very beginning of the earth view scan. VIIRS views both the SD and the moon at an AOI on its half-angle mirror slightly outside the AOIs of the earth view. The AOI is identical for the lunar and SD view. Therefore, it will not be possible to use the lunar and SD measurements to correct for response versus scan angle variations. This has been critical for the MODIS visible bands (e.g. a 20% effect on the MODIS Aqua 412nm band). The VIIRS telescope design is similar to the SeaWiFS design, where the HAM is well protected and has not shown a significant AOI dependent degradation. Therefore, the assumption is that the VIIRS HAM will not show any AOI dependent degradation either. It is not clear how much confidence can be put into this assumption, but the assumption is not unreasonable. Conversely, if such degradation occurs, then there is no on-board calibration mechanism to correct for such effects. It may be possible to correct such effects, e.g., with the methods presented by Kwiatkowska et al (2008), but it is not clear what truth data will be available for VIIRS (neither SeaWiFS nor MODIS Aqua may be available at the end of the VIIRS mission), and such corrections are very difficult to implement for an operational mission (due to the need to predict the corrections into the future using data acquired in the past).

5.1.2 Solar Diffuser Reflectance Degradation

The MODIS design protects the SD from solar illumination with a door that is only opened for the actual calibration events (approximately every two weeks). VIIRS calibration events occur every orbit, so there is no door to protect the SD. This means that the reflectance of the SD will degrade much faster than on MODIS. The SDSM looks at the SD at a different angle than the VIIRS telescope. As long as the degradation of the reflectance of the SD is not angularly dependent, this is not a problem. If the change of reflectance measured by the SDSM is small, it is reasonable to assume that the effects with Bidirectional Reflectance Distribution Function (BRDF) are small as well. However, if the degradation measured by the SDSM is large, it is likely that the SD reflectance for the VIIRS telescope view angle is significantly different. These effects could be responsible for the corrections that need to be applied to the MODIS Terra SD measurements (see Kwiatkowska et al. 2008). In that case, the MODIS Terra SD door became stuck open due to a mechanism malfunction in May 2003, leading to a large increase in the rate of degradation of the SD reflectance; both the SD reflectance degradation and the required corrections are largest at 412nm.

5.1.3 Solar Diffuser Screen Characterization

MODIS has two different sets of bands in the visible and NIR, one for the oceans, one for land (and atmosphere) applications. The ocean bands are more sensitive than the land bands and saturate at high radiances. VIIRS uses a dual gain approach for most of its VIS and NIR bands, i.e. the same detectors are used for ocean and land processing, but the gain state is different, depending on the measured radiance. So, for MODIS it was necessary to view the SD both fully illuminated (for the land bands, to achieve good SNR) and at reduced illumination (for the ocean bands, to avoid saturation), which was achieved by moving a SD screen (SDS) between the SD and the sun. VIIRS has the SDS permanently in the light path. The problem with this approach is that the vignetting function of the SDS cannot be determined from on-orbit measurements (as it was done for MODIS by simply taking measurements with and without the SDS). The VIIRS vignetting function was measured prelaunch, but it remains to be seen whether these measurements are of sufficient quality. This concern stems from the fact that it is very challenging to accurately simulate solar-like illumination in the laboratory; attempts to illuminate the SD with solar-like illumination using NIST laser sources during the space craft level testing at Ball Aerospace in Spring 2010 were at best moderately successful.

5.2 Lunar Calibration

Lunar calibration is necessary to detrend changes in the instrument response over the course of the mission. As was pointed out in Section 5.1.1, the on-orbit solar diffuser and lunar observations by VIIRS will be made at the same AOI on the HAM. The lunar calibration and solar diffuser time series will provide complementary data sets for monitoring the instrument's on-orbit radiometric performance. The overall on-orbit calibration of the instrument will require the development of analysis techniques to combine these two data sets, as was done for SeaWiFS early in its mission (Barnes et al., 1999). While the VIIRS calibration team is proceeding in the development of routines to analyze the VIIRS solar diffuser data, a similar development effort is required to extend the USGS RObotic Lunar Observatory (ROLO) photometric model of the Moon to work with VIIRS lunar data. The VIIRS RSR curves need to be incorporated into the ROLO model to adapt the model output to the VIIRS bands. Additionally, an oversampling correction scheme for the VIIRS lunar images needs to be developed. Finally, the mission planning software required to predict the lunar calibration opportunities needs to be implemented. The current planning for on-orbit calibration of VIIRS does not address these development efforts.

5.3 Vicarious Calibration

Vicarious calibration removes static biases in the radiometry, after being detrended via lunar and solar calibration. This includes biases in both the instrument calibration and the atmospheric correction algorithm. The vicarious calibration process depends on matching up best quality satellite TOA radiance measurements with radiances derived from surface data that was taken at one or more calibration buoys and then subsequently converted into TOA radiance (using atmospheric radiance calculated by the radiative transfer algorithms used in the Ocean Color atmospheric correction).

Convergence of the vicarious calibration gain corrections to stable quantities is a function of overall data quality, and the number of data match-ups acquired. The number of usable data match-ups acquired for a given match-up protocol is a function of time and number of independent calibration sites in operation. Anomalies in the instrument performance for VIIRS that change from one match-up data pair to another, despite detrending with lunar calibration, will increase the number of data match-ups required to achieve convergence. Furthermore, biases that change as one moves away from the calibration site(s) (e.g., crosstalk) could decrease the effectiveness of the gain corrections in global applications.

Given the postlaunch plans for NPP VIIRS, one-year data data collection time would be ideal, and it would certainly be undesirable for the data collection time to exceed the projected operational lifetime of the instrument. However, with a single calibration site and NASA/GSFC vicarious calibration protocols, no heritage mission has achieved optimal stability for vicarious gain corrections for a given band in less than two years, and for MODIS Aqua some bands took as many as three years (Franz et al. 2007). It is expected that the number of data match-ups for NPP VIIRS, like MODIS Aqua, will have less coverage of the ocean then SeaWiFS, because it is also a nadir pointing instrument that is subject to a substantially large sun glint pattern. Therefore, if a single calibration site is used, as it was for heritage missions and as described in current Cal/Val plans, the rate of convergence under NASA/GSFC protocols should not expected to be any faster.

Furthermore, there are instrument performance issues that could impact the vicarious calibration convergence rate. VIIRS SNR levels are comparable to SeaWiFS and, as experienced with heritage instrument, instrument noise could also affect the convergence rate for vicarious gain corrections. To address this, special aggregation protocols may needed to be developed to improve the convergence rate, if possible. Likewise, spectrally driven anomalies for NPP VIIRS (e.g., crosstalk) could affect the global effectiveness of gain corrections, depending on how well these effects can be removed. This would require further study to better quantify.

In addition, even a slight increase in the expected amount of data over the ocean that are significantly degraded or excluded around bright clouds can greatly reduce the amount of data available to perform a vicarious calibration. This relationship was studied by looking at the number of vicarious calibration data pairs for MODIS Aqua were acquired

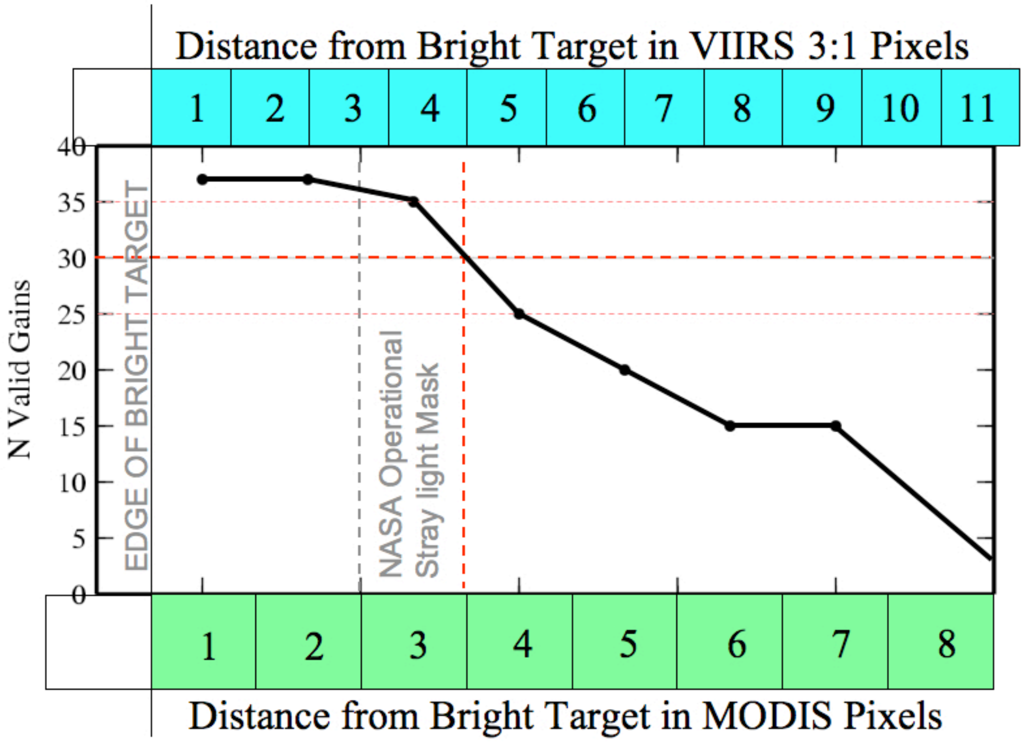

Figure 16 - The broken line indicates the number of valid match-up pairs of satellite and calibration site data that were acquired for MODIS Aqua when the number of pixels (given by the green boxes along the bottom of the plot) were masked from cloud edges. The blue boxes given the equivalent in VIIRS 3:1 aggregation pixels. The dashed vertical lines indicate a range of mask sizes comparable to the 5x7 cloud pixel mask applied routinely by NASA/GSFC. The dashed horizontal lines indicate the number of match-up data pairs needed to achieve convergence of the gain corrections to stable quantities. The amount of available satellite data drop rapidly beyond seven MODIS pixels.

as pixels of an increasing distance from clouds were masked (see Figure 16). For VIIRS, this will also require an active investigation of the how much data is mask for stray light contamination versus possible correction strategies for crosstalk or NFR effects for the VIIRS data. Part of the trade analysis involves the number of match-up data required to perform a preliminary vicarious calibration and the further number of match-up data required to refine that calibration to achieve climate data records.

In general, it is recommended that further study be done to develop protocols for how data is selected for either vicarious calibration or validation. The NASA/GSFC protocols have the considerable experience of heritage mission which would make it an ideal starting point for VIIRS. However, as mentioned, a number of VIIRS specific issues should be considered.

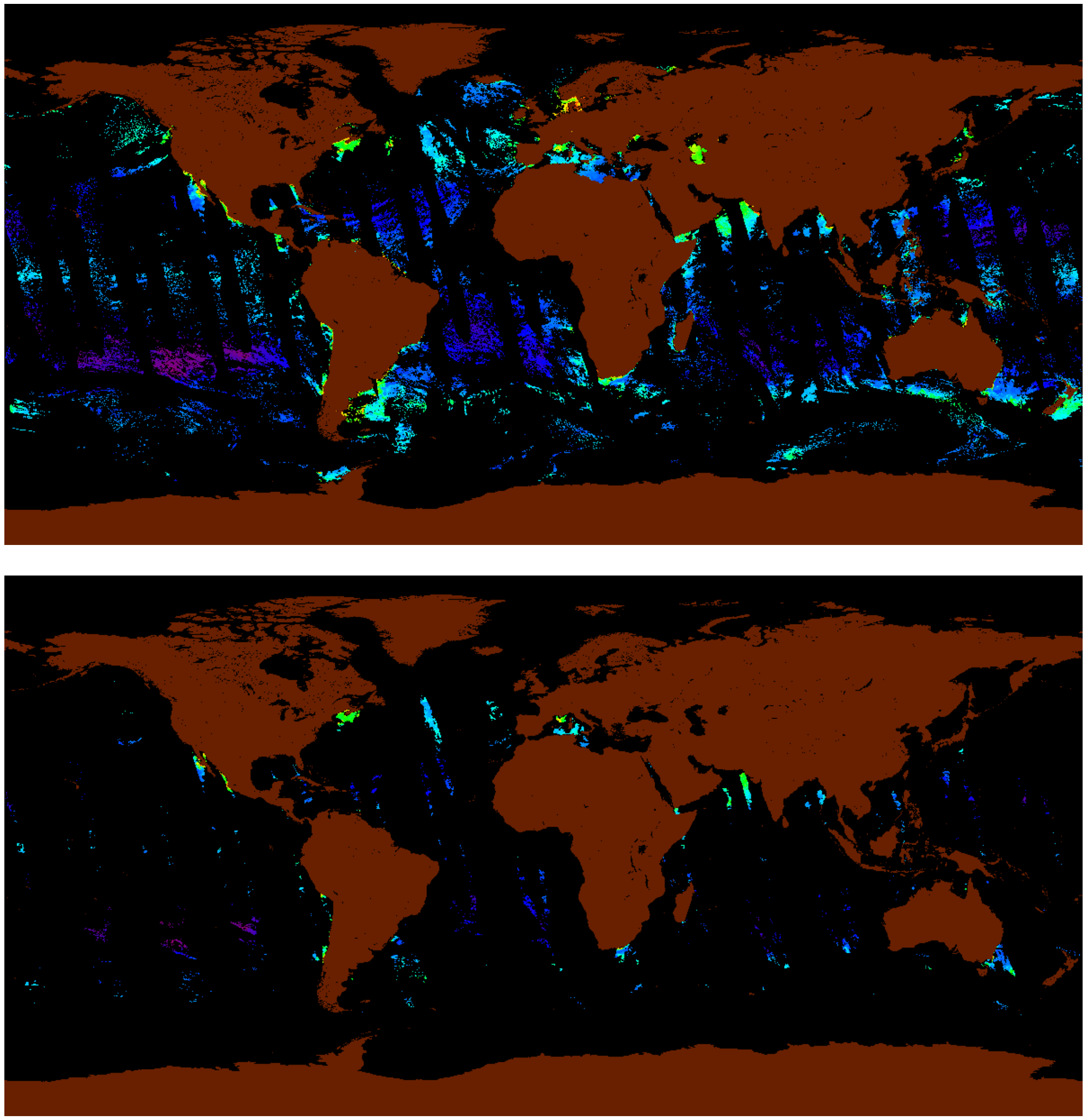

Figure 17 - Global coverage for a day of MODIS data (top) and the same MODIS data processed with VIIRS data exclusions (bottom). MODIS Aqua data from 18 March, 2008 was used in this study.

5.4 Validation Risks

The VIIRS data exclusion criteria for quality data (Northrop Grumman Corp. 2010) have some aspects that initially appeared to be significantly more restrictive than criteria used for standard NASA/GSFC Level-3 processing (i.e., generation of globally mapped data). At the time of this study of this situation, the most important of these were:

1) the 50 m shallow water depth exclusion, instead of the 30 m exclusion traditionally applied by NASA/GSFC,

2) the bright target mask of 12 mr, which roughly corresponds to a distance of 8 km from bright targets, instead of the NASA/GSFC stray light mask of 3 km along scan and 2 km along-track,

3) the exclusion of non-dark-pixel data, instead of using the NASA/GSFC NIR dark pixel iteration, and

4) the satellite zenith exclusion of 1700 km or 51.25 degrees, instead of the NASA/GSFC limit of 60 degrees.

The use of more restrictive criteria would significantly reduce the amount of usable data making validation of data performance increasingly less feasible.

The coverage of VIIRS was studied using the original NPP exclusions by taking a day of MODIS Aqua granules and processing them with the standard NASA/GSFC and the VIIRS exclusions (as best as possible using the software available). Figure 17 shows the global coverage attained under these two conditions.

The decrease of data coverage is significant: the areal coverage with the standard NASA/GSFC processing of 28% of the globe was reduced to only 3.5% when the stricter VIIRS exclusions were used. This amounts to a decrease in coverage of 87%, which would most likely lead to a longer time to obtain stable vicarious calibration and reasonable global coverage.

Since this early study, the contractor recognized that the exclusions defined for NPP would undermine performance validation. To address this problem, the excessively conservative data exclusions were modified by changing the bright target exclusion to be based on a stray light model that more realistically described the data degradation around bright targets and the shallow water exclusion was reclassified as a degradation condition, which allowed the inclusion of more coastal water in product validation without adding responsibility for performance in that region.

However, even given the changes made to NPP VIIRS exclusions, the estimates for coverage by the contractor still fall short of those current achieved for heritage missions, or 28% as mentioned above. This is surprising given that the VIIRS data coverage should be slightly larger than MODIS (see the box on the right). This is probably because of a more stringent Ocean

Is data coverage greater for VIIRS than MODIS?

The MODIS swath is ~2340 km, while VIIRS is ~3000, or about 28% larger. Given that Ocean Color is limited by the 60 degree sensor zenith angle, following NASA/GSFC exclusions, the effective swath widths are 1954 km for MODIS and 2217 km for VIIRS. In other words, this would lead to a 13.5% larger swath widths for VIIRS, provided both datasets were processed with standard NASA/GSFC algorithms (the current NPP operational software has a more stringent cutoff for swath width). In addition, the orbit period for NPP will be 101.6 minutes compared to 98.9 for Terra and Aqua, which means the swath centers are farther apart. Therefore, the daily coverage for VIIRS should be about 10% more than MODIS, barring a greater data loss around bright targets, like clouds and coastlines.

Color processing cutoff for scan angle in the current operational software for NPP, and possibly over estimation for cloud contamination. On-orbit operations will probably further reveal how exclusions should be defined to obtain an adequate sample set for validation. Thus, if required, the quality standards can be further reduced in early VIIRS mission operations in order to get more samples for validation (as was done in the early part of the SeaWiFS mission).

6. Conclusion

The operational Ocean Color EDR product, as currently configured, does not have sufficient quality to support NASA objectives for Earth System Science research, including Earth Observing System (EOS) CDR data continuity. The primary reasons are the use of outdated algorithms that are not consistent with the current CDR and a lack of support for mission-level reprocessing. There are also potential risks associated with instrument performance, characterization, and calibration. These programmatic and instrument issues are listed in Appendix A. It is suggested that NASA objectives might be met with a separate research processing stream that supports NASA selected algorithms and mission-level reprocessing, provided other risks regarding instrument performance or calibration do not present problems on-orbit. A full research processing capability is already largely supported at NASA/GSFC to facilitate production of heritage data products and the evaluation of operational NPP EDR products. Essentially, the expertise and most of the infrastructure that would potentially meet NASA data continuity and science objectives already exist, but are not being utilized.

In this assessment, considerable attention was given to VIIRS instrument performance because achieving high quality Ocean Color measurements was known to be a significant challenge in the development and characterization of heritage instruments. As with heritage instruments, many issues were identified and evaluated prelaunch for VIIRS. Just as with those heritage instruments, characterization test limitations and the potential of unforeseen changes in performance on-orbit limit the assessments and recommendations presented here. Any prelaunch assessment of VIIRS instrument performance does not guarantee that VIIRS data products will achieve a level of accuracy and consistency presently achieved with SeaWiFS and MODIS data. Therefore, the sensor should be carefully monitored on-orbit for changes in performance that would impact Ocean Color measurements. It is further recommended that this would be carried out collaboratively between an Ocean Color EDR team and SDR calibration team.

NASA has reason to be concerned with the performance of the poor quality IFA, given recent test data analyses and characterization uncertainty. However, the level of impact for IFA issues is less than was indicated by the Engineering Design Unit (EDU) or earlier FU1 tests. For FU1, a decision was made to flip the filter array to trade crosstalk effects with OOB light leaks, which may be easier to correct on-orbit. There are still some discrepancies between various test data analysis teams regarding the best representation of the instrument's spectral response. This presents an ambiguity that could possibly hamper on-orbit corrections of OOB light leaks. Work continues to reconcile or explain the differences seen between these various derivations of relative spectral response curves. In addition to quantifying characterization issues, such as polarization sensitivity, further effort should be made by an Ocean Color team to determine the best approach to handle spectral biases that could arise from the instrument's spectral smile. Finally, further work is recommended for: the evaluation of crosstalk and OOB light leak correction strategies, including the role of vicarious calibration; the stratification of the residual effects of crosstalk for conditions of interest; and a closer look at the spatial effects of crosstalk in coastal regions and bright algal blooms.

In addition to variation in detector gains, effects like crosstalk or instrument spectral response smile are expected to lead to striping in the Ocean Color EDR. Some corrections may reduce this problem, such as a point-to-point crosstalk correction or an along-track correction for instrument smile, but some residual striping will be inevitable and could be difficult to remove. However, striping is not expected to be unsurmountable for most applications of the Ocean Color EDR. NFR, crosstalk, and other sources of extraneous signal are expected to affect data coverage around cloud edges and coastlines. Although there is no clear evidence that this will be any worse than with heritage missions, it is recommend that the impact of cloud contaminated pixels be carefully evaluated on-orbit.

The instrument SNR is tolerable for most Ocean Color applications, especially in the 3:1 aggregation zone, but an aggregation scheme might be considered for raising the SNR to improve performance of the EDR algorithms, especially in the 1:1 aggregation zone. Furthermore, for NPP VIIRS, the margins above instrument specifications for SNR are very generous (i.e., 50-100% above specification thresholds). Unless the specifications are tightened for SNR, future VIIRS instruments are at considerable risk of being insufficient for most NASA Ocean Color research objectives.

As described in Section 5, a number of concerns also exist with the on-orbit calibration and validation. Prelaunch system-level testing of the solar diffuser calibration system is not yet conclusive, so like MODIS, the function of NPP VIIRS calibration system continues to carry a prelaunch risk. The lack of an approved plan for calibration maneuvers throughout the operational mission, including roll maneuvers for lunar calibration and yaw maneuvers to characterize the calibration system, is a programmatic risk to NASA science objectives. Other calibration system issues that are described in Section 5 will need to be monitored on-orbit, where possible. It is recommended that each of the issues enumerated in Section 5 be monitored during the Intensive Cal/Val (ICV) period of the mission, as feasible, by an Ocean Color EDR team. Furthermore, it is recommended that a gap analysis be done in advance of launch to determine whether the current Cal/Val program and infrastructure is sufficient given VIIRS performance characteristics and anomalies. In fact, an *immediate* assessment would be necessary to assure that required assets are deployed prior to launch for support of the ICV.

The NASA/GSFC OBPG has the expertise to perform on-orbit analysis of VIIRS Ocean Color EDR products and support both forward processing, using algorithms that are consistent with the present CDR record, and mission-level reprocessing (sometimes referred to in operational organizations as re-analysis). However, this will require clear direction from NASA to change the emphasis of the OBPG from evaluating the NOAA operational EDRs to producing research Ocean Color data products. The OBPG has the existing system infrastructure, requiring only a moderate expansion to existing hardware and technical staff to add VIIRS to the suite of national and international missions that are currently supported. The OBPG distribution of software and data products for heritage missions also could easily be extended to include software and data for NPP VIIRS. This would facilitate the existing collaborative relationship that the OBPG maintains with the research community and other agencies, which would strengthen further evaluation of VIIRS data products as a climate record. The application of OBPG capabilities and expertise would be a cost-effective avenue for meeting objectives of NASA and the Ocean Color research community that it supports, including: providing climate data continuity; identifying instrument issues on-orbit; and, where possible, developing and testing the necessary corrections to instrument anomalies. It is further suggested that OPBG and NOAA staff specializing in operational Ocean Color processing collaborate to facilitate growth of expertise on the operational side; to promote communication between Ocean Color research and operational groups; and to further streamline the operationalization of Ocean Color algorithms and their improvements.

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Appendix A: List of Key Watches, Concerns, and Issues

The table provided in this appendix contains a non-exhaustive list of watches, concerns, and issues regarding the ability to meet NASA Ocean Color objectives for EOS CDR data continuity and Earth System Science research, as of August, 2010. A watch is a situation or condition that could be associated with possible risk to these NASA objectives. A watch is monitored to be sure it does not become a concern. A concern is a situation or condition in which risk to NASA objectives are determined to be sufficient to require close analysis. Recommendations are given to proactively reduce the possibility that a concern become an issue. An issue is a problem where it is clear that there is substantial risk to NASA objectives. Issues warrant extensive analyses followed by clear warnings to management. Recommendations are given, when possible, in order to prevent issues from developing into unsolved problems or "*show stoppers*." Some issues in the table below are considered currently very detrimental to NASA objectives, including the lack of support for reprocessing and the reliance on outdated operational algorithms that are inconsistent with the NASA research CDR. A perceived precarious support for calibration maneuvers, the presence of crosstalk and OOB light leaks, and spectral characterization uncertainty are also high risk problems for which recommendations have been given, but the full impact of these situations will not be fully understood until flight data can be examined.

These definitions of watch, concern, and issue are specific the table below only and do not necessarily convey to the use of these terms elsewhere in this document. Their use here is intended to provide categories that are prioritized by perceived or determined level of risk and attention required.

CRITICAL AREAS FOR OCEAN COLOR SCIENCE	**MEASUREMENT ISSUES FOR NPP VIIRS** ■ **Watch** ■ **Concern** ■ **Issue**
1. Instrument Performance	■ **Crosstalk** - Significant impact on Ocean Color EDR. **(polarization sensitivity and static electronic crosstalk will limit characterization).** ■ **OOB light leaks** - Larger than most bands on MODIS; heritage solutions may be adequate. **(3-4% IOOB in M1 and 4-5% IOOB in M4 were noted).** ■ **Signal-to-Noise Ratio (SNR)** – Reasonable for algorithm in the 3:1 aggregation zone for bands M1, M6, and M7, but drops 20% in the 2:1 aggregation zone. Bands M2, M3, M4 are at best SeaWiFS quality, but below MODIS. Band M5 is very low. ■ **Polarization response** - Likely comparable or better than MODIS. ■ **Near-field response** - Likely comparable to MODIS, provide crosstalk is suppressed.

2. Instrument Characterization	**Relative spectral response (RSR) and crosstalk** - **Knowledge of characterization uncertainty is crucial!** Numerous technical challenges encountered during testing. **End-to-end calibrator test** Based on heritage experience this could be a significant risk if not done. **Polarization response characterization** – Much better than MODIS. Some detector-to-detector variation was observed.
3. Calibration	**Vicarious calibration infrastructure support**. Tasks in Ocean Cal/Val plans - inter-agency agreements need to be in place. **Data coverage and quality** - sensitive to unforeseen data loss around clouds and noise sources (outside 3:1 aggregation zone). **OC Cal/Val analysis team** - Dedicated team is critical to evaluate calibration data, including vicarious and lunar calibration data, and handle instrument calibration trends or anomalies to meet to minimum requirements. Tasks identified in Ocean Cal/Val Plan, but gap analysis needed.
4. Maneuvers	**Lunar roll maneuver** - A minimum requirement for NASA data continuity and is needed to track trends in detector degradation, prior to vicarious calibration. **Yaw maneuver** - Needed for characterizing SD panel/ screen system on orbit.
5. Validation	**Validation data collection**. Tasks and potential resources in Cal/Val plan, but gap analysis is needed. NASA SeaBASS possible repository for data. Interagency agreements need to be negotiated. **Independent assessment team** - Independent team to evaluate product quality. Tasks are identified in Ocean Cal/ Val Plan, but gap analysis is needed.
6. Algorithms	**Research algorithms** – Operational processing stream is inconsistent with NASA research processing stream. Operational algorithms are missing several years of corrections found in NASA/GSFC research algorithms. NASA/GSFC algorithms are required for CDR continuity and for support of NASA's Earth science research objectives. **Pathway to algorithm change long and slow** - future development of the operation processing stream will be dilatory. There are too many decision gates; working with the OC community for algorithm development is likely to be hampered.
7. Reprocessing	**Reprocessing** - **no support for mission-scale reprocessing!** This is a minimum critical requirement for the NASA Earth science and climate objectives. Recommend using NASA/GFSC OBPG systems to support reprocessing.