THE STATUS OF NASA OCEAN COLOR RESEARCH USING SeaWiFS, MODIS (Terra and Aqua) AND IMPLICATIONS FOR NPP/VIIRS

INDEPENDENT PANEL REVIEW
11-12 FEBRUARY 2004
Greenbelt, Maryland

EXECUTIVE SUMMARY

A Review Panel (Appendix A) met on 11-12 February 2004 to evaluate the status of NASA's ocean color remote sensing capabilities, as presented by key members of the MODIS Characterization Support (MCST), MODIS Oceans (Miami and NOAA), and the Ocean Color Discipline Processing (ex-SeaWiFS/SIMBIOS) Teams (Appendix B). The presentation materials are available through Dr. Vince Salomonson at GSFC .

The principal concerns motivating the review, to paraphrase Dr. Vince Salomonson, are troubling issues associated with ocean color observations from **MODIS-Terra** that have implications also for **MODIS-Aqua** and **NPP/VIIRS**. Despite progressive improvements in the MODIS-Terra ocean color products, the root causes of the relatively rapid variations over time (as compared to other sensors) of the instrument's radiometric characteristics remains unsettled, and unexplained differences persist in comparisons of its products with SeaWiFS at certain latitudes and/or times of year.

The panel was asked to evaluate – with fresh perspective -- what has been, and is being, done to address these issues, and offer suggestions as to what could be done better, or differently, that might resolve the issues and **improve the combined MODIS (Terra and Aqua) and SeaWiFS ocean color products to obtain time-series of Climate Data Record (CDR) quality**.

A ***"CDR-quality ocean color product"*** is one calculated using ***"exact normalized water-leaving radiances"*** $L_{WN}^{ex}(\lambda)$ (see pp22ff) having a ***combined standard uncertainty of ~5 %***;

1. ***The uncertainty of every other ocean color product derives directly from the uncertainty of*** $L_{WN}^{ex}(\lambda)$***;***
2. ***5 % uncertainty in*** $L_{WN}^{ex}(\lambda)$ ***implies < 0.5 % uncertainty in*** $L_T(\lambda;\theta,\phi,\theta_o,\phi_o)$ measured by the satellite sensor, a level that can effectively be realized only if ***Vicarious Calibration and On-Orbit Sensor Characterization are continued on a retrospective basis throughout each sensor's operating lifetime.***

Of concern also, therefore, are the status and prospectus of the ***ocean color infrastructure***, i.e. personnel, data sources and other resources, required to maintain sensor calibration and characterization at the level needed to achieve and maintain CDR-quality ocean color time-series products throughout the operating lifetime of each satellite ocean color sensor.

MODIS: Status and Prospectus

A model expressing ***MODIS-Terra*** calibration coefficients (m1) as a function of time was recently developed by MCST through retrospective analyses and modeling of data from views of the solar diffuser, moon and SRCA (Xiong). When combined with the RADCOR corrections developed by the U. of Miami (Evans), the smoothed m1 coefficients appear to improve many of the artifacts observed in comparisons between SeaWiFS and MODIS-Terra, and between MODIS-Terra and MODIS-Aqua, but significant challenges remain to be addressed (Evans/Xiong). Remaining issues include "Earth-shine" illumination of the solar diffuser, changes in polarization sensitivity, possible illumination of the focal plane by stray light passing around the primary mirror, unexplained time and latitude dependent differences in pair-wise comparisons of normalized water-leaving radiances between MODIS-Terra, SeaWiFS and MODIS-Aqua, and anomalous cross scan patterns (Xiong/Evans/Waluschka/Wolfe). Uncertainties associated with models of aerosol scattering (phase functions and optical thickness) and ocean bi-directional reflectance are also of concern in this regard.

The Panel believes that both MODIS-Terra and -Aqua on-orbit characterization and processing should be continued with the expectation that Terra will be reprocessed as part of the combined ocean color CDR record. By abandoning Terra at this point in time, the ability to go back to complete the retrospective characterization of this sensor will be made more difficult and the effort less likely to occur. The combined use of Terra and Aqua would provide information critical to near-real-time ocean science and operations, and at the same time contribute to the continuing on-orbit characterization of MODIS-Aqua, SeaWiFS and other ocean color sensors.

MODIS-Aqua is still early in its mission. So far, its degradation modes appear to be better behaved (i.e. smoother trends) than those observed with MODIS-Terra, but it is too soon to draw firm conclusions.

The ***out-of-band (spectral) stray light*** functions of MODIS (Terra and Aqua) must be used to determine ***total-band (in-band + out-of-band)*** radiances over oceans in global imagery, even though the ***in-band*** (1 % level) response functions are adequate for determining m1 reflectance calibration coefficients. The m1 related radiance calibration coefficients are adequate for calibrating land and atmospheric spectral radiance measurements, which have approximately the same spectral shape as the solar diffuser and other radiance sources used to derive m1. Spectral distribution of radiance above the ocean, on the other hand, is very different from that of the calibration source used to derive m1. Therefore, the m1 coefficients incorrectly scale the integrated out-of-band spectral stray light responses in each channel, and MODIS in-band and total-band radiances above the atmosphere over oceans differ significantly from each other. If the above-ocean out-of-band stray light were a fixed bias in each channel, the effect would be removed by the vicarious calibration using MOBY. However, the spectral shape of exoatmospheric radiance over the ocean varies globally, and so too does the out-of-band stray light effect in some channels. The relative magnitudes of out-of-band to in-band differences in each channel have <u>histogram widths</u> as low as < 0.5 % in some MODIS channels (vicarious calibration is effective by itself) and as high as > 2 % in others (full out-of-band response must be taken into account) (Voss). The direct and indirect consequences of neglecting out-of-band stray light seem not yet to have been thoroughly investigated, and clearly they should be. A uniform procedure must be adopted for treating spectral out-of-band effects in all three aspects of ocean color research (bio-optical algorithm development, vicarious calibration, satellite measurements).

The ***MODIS Point Spread Function (PSF)*** is similar to the SeaWiFS PSF, and magnitudes in tails of both are large enough to cause significant artifacts in radiances $L_T(\lambda)$ measured within 5 to 10 Km of bright and/or large extents of clouds or land. Note the pre-flight characterization data did not measure "out of plane" in the sense that in the along track direction, no information is known about what is the effect of a cloud or bright target either ahead of, or behind, the present scan line. It would be plausible to assume that the shapes of the PSF in this dimension are similar in shape and magnitude to the measured within-scan PSF, and to apply a 2-dimensional correction (or data rejection screen). PSF artifacts would be interpreted as part of aerosol radiance, which would tend to reduce the direct effects on $L_{WN}^{ex}(\lambda)$, but it is not clear how spectral variations in PSF-cloud/land/glint effects would interact with aerosol models and the atmospheric correction. This could be important in SeaWiFS/MODIS $L_{WN}^{ex}(\lambda)$ comparisons at different times of day, viewing/sun geometry, and cloud conditions. A simple test of the sensitivity of SeaWiFS/MODIS $L_{WN}^{ex}(\lambda)$ comparisons to PSF-cloud artifacts would be to mask each pair of scenes at progressively increasing distances from cloud (bright target) area boundaries, and compare only the areas unmasked in both scenes.

SeaWiFS: Status and Prospectus

SeaWiFS radiometric performance is well documented, its rates of degradation in radiometric sensitivity, as determined by monthly views of the moon, are well behaved and reasonably predictable, and its data products are widely accepted as reliable. The standard uncertainty of its Vicarious Calibration using MOBY is ~5 % in $L_{WN}^{ex}(\lambda)$, following its initial Vicarious Calibration (during the first 2 to 3 years of operation). Since the initialization, lunar determinations of changes have generally been indistinguishable from subsequent MOBY comparisons, and only infrequent small adjustments to the degradation prediction models have been needed over the past several years.

1. NASA has extended the SeaWiFS data purchase contract for 1 year, and has not currently budgeted to extend it further.
2. SeaWiFS is beyond its life expectancy, albeit there is hope it will continue to function for a few more years.
3. It is important to maintain the viability of SeaWiFS until the large seasonal and latitudinal differences with MODIS are understood and can be corrected for. The possibility should not be excluded that removal of these differences may require corrections to SeaWiFS, as well as MODIS, data.

Ocean Color Infrastructure: Status and Prospectus

The support infrastructure needed to determine CDR-quality ocean color time-series products includes a NASA comprehensive support team, one or more *in situ* time-series sources of "vicarious calibration quality $L_{WN}^{ex}(\lambda)$", and additional *in situ* sources of $L_{WN}^{ex}(\lambda)$ and bio-optical data for satellite ocean color sensor and product validation. The NASA Ocean Color program appears to have reached a critical juncture in the sense that some resources and/or activities that are critical to maintaining CDR-quality ocean color products have been, or will in the near future be, discontinued, and no firm plans to replace all of them have been put forward (at least to the Panel). In this section we outline the elements we regard as "essential infrastructure" and point out some of those that appear to be phasing out, as background for our recommendations that these (or equivalent) activities and resources be somehow maintained, or replaced, if CDR-quality ocean color data products are to be sustained.

An aggregate Ocean Color Support "Team" of scientists and engineers must be tasked and supported to:

- Maintain close engineering liaison with each sensor manufacturer to assure that each sensor's pre-launch characterization is complete and documented at a level that will permit retrospective modeling of changes in critical characteristics as the sensor ages and degrades on orbit. For ocean color, the completeness of the sensor characterization is more important than its pre-launch calibration. A sensor's characterization is typically done by the sensor manufacturer and/or the responsible mission office, but often not at the level of detail and completeness needed for CDR-quality ocean color analyses. Therefore, the "Team" must maintain close engineering liaison with each sensor manufacturer to assure that sufficient characterization information is available
- Sustain ongoing retrospective vicarious calibration analyses and on-orbit characterization of performance changes and degradation of each satellite ocean color sensor throughout its lifetime. These analyses combine:
  - Time-series match-up comparisons of $L_{WN}^{ex}(\lambda)$ pairs derived from the sensor and an *in situ* Vicarious Calibration Observatory, such as MOBY, to provide on-orbit traceability to an absolute (NIST) standard of spectral radiance with well-understood and minimal uncertainty. The stringent radiometric and environmental requirements for vicarious calibration observations are summarized in the "Fundamental Background" section of the Panel Report (pp23ff). At present these data are provided by the MOBY Observatory, which became operational in 1997 and has provided $L_{WN}^{ex}(\lambda)$ data for the consistent Vicarious Calibration of every satellite ocean color sensor in operation since that date.
  - Additional sensor-derived $L_{WN}^{ex}(\lambda)$ match-up comparisons with $L_{WN}^{ex}(\lambda)$ from other satellites and *in situ* sources, to allow global validation and on-orbit characterization of sensor measurement anomalies that may correlate with latitude, orbit-phase (e.g. thermal cycling and/or battery charging), solar zenith angles, Rayleigh polarization, etc. These data consist of radiometric and bio-optical measurements, made from ships, buoys and towers, by members of NASA ocean color science teams and the international ocean color community at large, following protocols established and documented under the former SeaWiFS and SIMBIOS Projects.
  - Time-series records of system responses to on-board LED or lamp sources, solar diffuse (SD) reflectance assemblies, and lunar reflectance to determine the rates and patterns of trends over time of degradation in the sensor's spectral radiance responsivity. Because SD readings are only available once per orbit, reference to an onboard lamp of some type would seem to be essential. On the other hand, on-board lamp sources contribute uncertainties of their own that are difficult to track,

and an instrument that fluctuates in calibration on an hourly basis is seriously deficient.
    - Characterization studies to evaluate system changes – e.g. in polarization sensitivity, degradation of solar diffusers, mirror surfaces, other optical surfaces/elements -- using a ray-trace model of the sensor, which was validated during its pre-launch characterization.
- Validate non-radiometric ocean color algorithms and products, such as chlorophyll *a* concentration, and maintain the validation data archives and distribution infrastructure (e.g. SeaBASS) necessary to support this effort and assure that these products are also of CDR-quality.
- Periodically reprocess the entire data stream for each sensor to reflect improved knowledge of its performance changes.

The newly formed Ocean Color Discipline-based Processing Team (OCDPT) at GSFC has been tasked to assume responsibility for processing SeaWiFS and MODIS-Aqua data (initially), thus absorbing functions of the former SeaWiFS/SIMBIOS Projects plus elements of the original MODIS Science (Oceans) Team at the Univ. of Miami (Evans) and GSFC/MODAPS (Esaias). The MODIS Science (Oceans) Team has recently been completely restructured, and it is not yet clear to what extent its new membership will contribute to the supporting infrastructure, in contrast to ocean science applications of ocean color products. The UM oceans group (Evans) has provided vital MODIS sensor characterization contributions up to the present; its continuing participation in independent on-orbit characterization analyses provides an important means of validating the results of future MODIS characterization analyses by the OCDPT.

At present, the OCDPT is relying on MCST for most engineering aspects of the on-orbit characterization of MODIS-Aqua, and MODIS-Terra (when its data are re-incorporated into the CDR-quality ocean color time series analysis). The MCST task planning has entered a "ramp-down" phase and its engineering support for retrospective on-orbit characterization of MODIS degradation will correspondingly decline in the immediate future. Some part of the "Team" should be tasked, and provided adequate resources, to maintain these critical on-orbit characterization activities that are vital to maintaining ocean color data of CDR-quality with MODIS and SeaWiFS.

The hyperspectral MOBY *in situ* $L_{WN}(\lambda)$ Observatory for Vicarious Calibration is regarded by the ocean color community as an essential facility for deriving CDR-quality ocean color products from MODIS (Terra and Aqua), SeaWiFS, VIIRS (NPP and NPOESS) and other satellite ocean color sensors. Currently available aggregate funding for MOBY will allow its continued operation through late 2004. If nothing changes, MOBY will be pulled out of the water, and MOBY and its support site in Honolulu will be decommissioned in November 2004. The Panel is not aware of alternative sources, and/or methods, for acquiring *in situ* $L_{WN}^{ex}(\lambda)$ that meet the stringent radiometric and environmental constraints, and have established the detailed uncertainty budgets, that are needed for Vicarious Calibration (see below, "Panel Report", pp23ff).

The fundamental objective of vicarious calibration is to isolate the effects of a satellite sensor's systematic gain offset on the difference in a matched pair of $L_{WN}^{ex}(\lambda)$ derived from satellite and *in* *situ* measurements. This is accomplished by combining complete characterization of both sensors with constraints on the measurement conditions to minimize all other components of the combined uncertainty of the two measurements. In an ensemble of vicarious calibration $L_{WN}^{ex}(\lambda)$ matched pairs, the combined uncertainty of individual pairs will vary, and it is important to estimate the absolute uncertainty of each one, either as a basis for generalized weighted Least-Squares analysis, or for excluding data points with excessive uncertainty. Assuming that both sensors are well characterized for all viewing geometries, variations in the magnitude of combined uncertainty of a matched $L_{WN}^{ex}(\lambda)$ pair arise from the atmospheric correction (uncertainty varies with aerosol optical thickness, cloudiness near the site, and with viewing and solar zenith angles), ocean BRDF corrections (uncertainty varies with wind speed, viewing zenith angle, solar zenith angle, and water-mass turbidity), environmental effects on *in situ* L_W determination (uncertainty varies with near-surface turbidity, surface wave conditions, and cloud conditions), and the different effects of spatial heterogeneity of ocean optical properties on the *in situ* (single point) and satellite (area integral) measurements. These factors motivate the specifications for a Vicarious Calibration Observatory, which are outlined under "Fundamental Background" in "Panel Report" (pp23ff) and include:

- *in situ* radiometric instrument uncertainties, including traceability of all aspects of radiance responsivity calibration directly to NIST, hyperspectral resolution to allow reconstruction of each satellite in-band function, full spectral response characterization to allow out-of-band stray light corrections to in-band radiances within $\sim 10^{-6}$, and other specific factors outlined below (Panel Report, Fundamental Background, pp23ff);
- uncertainties in atmospheric corrections to < 5 %, which is accomplished by accepting data only when the aerosol optical thicknesses are < 0.1 at visible wavelengths, and by excluding also data with excessive sun glint and/or local cloud conditions that may introduce significant uncertainties in the modeled downward radiance distribution incident on the sea surface;
- uncertainties in vertical extrapolation of upwelled radiance to and through the interface, which are minimized by restricting measurements to clear Case I waters ($Chl < 0.25$ mg m^{-3}); and
- uncertainties due to horizontal heterogeneity in optical properties when matching point measurements with ~1 Km^2, accomplished by using measurements only when horizontal spatial variations within ~10 Km of the *in situ* site are < 0.05 mg m^{-3}.

If MOBY is decommissioned, and not replaced, a likely prognosis is that the quality of ocean color products will gradually decline (i.e. uncertainties will increase) and no longer meet the CDR-quality standard.

IMPLICATIONS FOR VIIRS (NPP AND NPOESS)

Looking ahead to VIIRS, neither MCST, nor OCDPT, is currently tasked, or staffed, to maintain collaborative engineering liaison with the VIIRS manufacturer during its pre-launch characterization; the contractual requirements for VIIRS characterization are unlikely to provide the complete information needed for timely on-orbit vicarious calibration and characterization and production of CDR-quality ocean color products. VIIRS characterization is happening now.

The fabrication and characterization of the NPP/VIIRS instrument is already in progress.

1. NASA does not currently provide support for engineering liaison and cooperative oversight of the NPP/VIIRS pre-launch sensor characterization that is comparable to the activities provided for SeaWiFS and MODIS characterizations. If this omission is not corrected, it will be extremely difficult, if not impossible, to successfully carry out the ongoing on-orbit characterization of NPP/VIIRS.
2. There is no contractual requirement for the vendor to develop and provide a validated ray-trace model of NPP/VIIRS, for use in either pre-flight, or on-orbit characterization.
3. VIIRS is based on a different design concept than either SeaWiFS or MODIS.

The prospects for deriving CDR-quality ocean color time-series products from NPP/VIIRS will be seriously diminished if this situation continues.

Another issue related to deriving CDR-quality ocean color products from NPP/VIIRS, is the current lack of a definite plan, and associated budget, within either NASA or NOAA to provide full-resolution Level-1A (earth-located, scan-format, uncalibrated digital counts, together with satellite and sensor engineering metadata) to the OCDPT in a timely way. As is explained in this report, it is not possible to derive CDR-quality ocean color products from the real-time ocean color sensor-data records that will be produced and distributed by the NPP/VIIRS contractors, under the oversight of the Interagency Program Office. The Level-1A data stream is the Fundamental Climate Data Record needed as input for retrospective vicarious calibration, on-orbit characterization of VIIRS, and derivation of Exact Normalized Water-Leaving Radiances and other Thematic CDR's to be calculated from them.

RECOMMENDATIONS

1. Assure that the ***NASA ocean color team infrastructure***, as currently represented by the Ocean Color Discipline-oriented Processing Team (OCDPT), MCST, and the MODIS Science (Oceans) Team, provides adequate long term capabilities for carrying out the continuing engineering and scientific tasks described above. These tasks and capabilities include engineering liaison during pre-launch calibration of future satellite ocean color sensors (e.g. VIIRS), continuing retrospective vicarious calibration and on-orbit characterization over the operating lifetime of each sensor, sensor and algorithm validation resources (e.g. SeaBASS archive, linkage to AERONET, etc.), and reprocessing the data stream from each sensor at intervals indicated by its on-orbit vicarious calibration and characterization.
2. Recognizing that the NPP VIIRS characterization and preflight testing are already in progress, immediate action should be taken to improve NASA liaison with the VIIRS project. A concise "ocean color lessons learned" document should be prepared, perhaps by the OCDPT at GSFC, to communicate to those responsible for VIIRS the perceived requirements that must be met to derive CDR-quality ocean color products from NPP/VIIRS. A proactive effort should also be quickly put in place, perhaps by MCST or OCDPT, to establish close, cooperative engineering liaison with the sensor manufacturer in the preflight characterization of the VIIRS instrument.
3. Together with other agencies, provide for the continuing, long-term operation and maintenance of an ***$L_{WN}(\lambda)$ Vicarious Calibration Observatory*** as an essential international facility to provide data for vicarious calibrations needed to maintain CDR-quality ocean color time series products from each sensor. In this context, it should be

recognized that, irrespective of funding considerations, the expected time frame for developing a new observatory with capabilities comparable to the existing MOBY observatory will be at least 2 to 3 years.

4. SeaWiFS data should be acquired until the large seasonal and latitudinal differences with MODIS have been reconciled using the results of studies suggested above. CDR-quality data sets are not obtained if differences in $L_{WN}^{ex}(\lambda)$ between sensors are not ~5 %.
5. The ongoing work, currently by MCST, to characterize degradation in MODIS-Terra polarization sensitivity, and possible stray-light pathways, should be continued to completion.
6. Re-evaluate normalized water leaving radiance comparisons between MODIS-Terra, SeaWiFS and MODIS-Aqua. Previous such comparison results are **out of date** and potentially misleading, because the MODIS-Terra ocean products were not based on the smoothed m1 model, and in some cases, did not apply MODIS (Terra or Aqua) out-of-band stray light functions to determine corrected in-band radiances.
7. MODIS Terra characterization and data processing should be continued jointly with Aqua processing. Continued on-orbit characterization of Terra provides advanced understanding of how Aqua will respond in the future. Terra and Aqua are both providing high quality ocean information to ocean research. Although the unsettled Terra characterization is difficult to maintain, the satellite is providing high quality science data and should be maintained. Expect that reprocessing will be required for MODIS (Terra and Aqua) as was done for SeaWIFS reprocessing. Reprocessing is expected in order to provide CDR-quality.
8. Together with NOAA, implement a concrete plan for timely archival of the NPP/VIIRS Level-1A data stream, which comprises the Fundamental CDR basis for retrospective vicarious calibration, on-orbit sensor characterization, and determination of CDR-quality ocean color products from NPP/VIIRS.
9. The out-of-band stray light function of each MODIS band should be used to determine total-band radiances, or alternatively used to correct the in-band radiances for this artifact, for all measurements over oceans. This recommendation would also apply to SeaWiFS, if out-of-band stray light is not taken into account in current algorithms (this was not discussed during the presentations). Moreover, a uniform procedure must be adopted for treating spectral out-of-band effects in all three aspects of ocean color research (bio-optical algorithm development, vicarious calibration, satellite measurements).
10. The spectral out of band response should be measured over the entire spectral range corresponding to finite detector responsivity, using a full aperture unpolarized source, such as tunable laser-illuminated integrating sphere sources, for example the NIST facility for Spectral Irradiance and Radiance responsivity Calibration using Uniform Sources (SIRCUS). For filter radiometers, adequate characterization of out-of-band spectral response may possibly be done using a double-monochromator and source, if sufficient signal-to-noise ratios and uncertainties are demonstrated.
11. The possible influences on $L_{WN}^{ex}(\lambda)$ of artifacts by bright clouds, or land, outside the instantaneous field-of-view, but within the significant tails of the PSF, should be re-evaluated for SeaWiFS, MODIS-Terra and MODIS-Aqua. Note the pre-flight characterization data did not measure “out of plane”, in the sense that in the along track direction, no information is known about what is the effect of a cloud or bright target

either ahead of, or behind, the present scan line. It would be plausible to assume that the shapes of the PSF in this dimension are similar in shape and magnitude to the measured within-scan PSF, and to apply a 2-dimensional correction (or data rejection screen). A possible first approach might be to evaluate the changes in statistics of differences in global $L_{WN}^{ex}(\lambda)$ match-ups between the satellites, for successively increased masks (ranging from 0 to 20 Km) are applied near clouds and land (as determined by brightness criteria, which would include sun glint in some latitudes). Were differences to increase statistically as the masked areas were decreased, that would suggest that the PSF cloud/land artifacts should be examined more critically to consider possible correction algorithms. If, on the other hand, this did not occur, the PSF effects would be thus shown to be insignificant.

12. To comply with the CDR-quality definition (above), the primary comparisons between satellite sensors, and between satellite sensors and *in situ* data, should be based on matched pairs of same-day exact normalized water-leaving radiance $L_{WN}^{ex}(\lambda)$. In making such comparisons, the same, consistent algorithms and methods should be used to derive $L_{WN}^{ex}(\lambda)$ from each sensor, with appropriate adjustments for differences in time of day and/or exact wavelengths. It is essential that the same values of $\bar{F}_o(\lambda)$, the mean solar irradiance above the atmosphere, be used for all comparisons between $L_{WN}^{ex}(\lambda)$ derived from different sensors. Until analysis of data from different sensors routinely determines $L_{WN}^{ex}(\lambda)$ to within ~5% at the same location, CDR-quality data sets are not being obtained.
13. The SeaWiFS Solar Diffuser (SD) measurements should be analyzed quantitatively and compared to the lunar and MOBY-based estimates of degradation. Issues to investigate include Earthshine and the relative merits of YB-71 vs Spectralon. There is a paper by the University of Arizona group that references space related degradation of diffuse reflectance standards, and in their view YB-71 was the best overall performer. Therefore, the SeaWiFS SD data may be very interesting, even though there is not a Solar Diffuser Stability Monitor (SDSM) on the spacecraft.
14. In planning for new satellite sensor systems, e.g. NPOESS VIIRS, allow sufficient time for adequate pre-flight characterization. Start the sensor design, build and characterization phases of a mission early enough to avoid pressure to proceed to launch before a sensor is proved ready for satisfactory operation on orbit.

PANEL REPORT

INTRODUCTION

At the request of Dr. Vincent Salomonson and Dr. Paula Bontempi, an "independent" panel met to briefly review the status of, and near-term directions in, NASA's satellite ocean color research program. The panel members, together with their affiliations and contact information, are tabulated in Appendix A. The panel members are "independent" in the sense that none of them are more than peripherally active in current efforts to derive long-term time series of ocean color Climate Data Records (CDR) from SeaWiFS, MODIS-Terra, and MODIS-Aqua, and in the future from NPP/VIIRS.

Dr. Salomonson requested that the panel review

> "*the procedures being applied to the MODIS instrument on the NASA Earth Observing System (EOS) Terra satellite as they pertain to getting climate-data-record quality observations of ocean color and subsequent derived products like chlorophyll concentrations.*" Of primary concern, he went on, are "*troubling issues that are associated with ocean color observations from the MODIS instrument on the NASA Earth Observing System (EOS) Terra spacecraft. These same issues have implications also for the MODIS instrument on the EOS* [Aqua] *spacecraft and potentially for the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument that will* [be] *flown on the NASA Preparatory Project starting sometime around 2006 and on the National Polar Orbiting Environmental Satellite Series (NPOESS) later in that same decade. A considerable amount of effort over many months has been put into trying to resolve the issues by the MODIS Calibration and Characterization Support Team (MCST--Dr. Jack Xiong, Dr. William Barnes, et al.) and by University of Miami folks (e.g., Robert Evans, et al.) plus SeaWiFS personnel (Bryan Franz, Chuck McClain, et al.). Much has been accomplished in improving the Terra MODIS ocean color observations and their consistency over time. Nevertheless, the root-cause for the relatively (as compared to other instruments) rapid variations over time in the performance/calibration characteristics (e.g. gain characteristics) of MODIS remains unsettled. In addition, the significant lack of agreement over time and in selected regions in comparison with comparable SeaWiFS observations remains unsettled.*
>
> "*Because of the issues just described, It has become very clear to me as the MODIS Science Team Leader and others (e.g., with complete encouragement and concurrence of Dr. Bontempi) that we need to have knowledgeable people with a fresh perspective take a look at what has been and is being done to ascertain what is being missed in the present approaches, or whether some alternative approach needs to be taken to reach the generic and nominal potential of the MODIS instrument particularly as it pertains to providing climate date record (CDR)-quality observations of ocean color and its derivatives such as chlorophyll concentration, etc.*
>
> "*So, to reiterate, it is with the background and perspective above that I am now approaching you to see if we could receive your help and knowledge as*

part of a review team constituted to do what the previous paragraph describes; i.e., evaluate and offer suggestions as to what can be done better or differently that would resolve the issues alluded to and improve the climate data record ocean color observation consistency and agreement obtainable from SeaWiFS and MODIS."

There being no currently accepted definition of a "CDR-quality ocean color product," the Panel proposes the following working definition.

An "***Ocean Color Product of CDR-Quality***" is one determined from ***Exact Normalized Water-Leaving Radiances***, $L_{WN}^{ex}(\lambda)$ (see pp22ff), that are derived from a satellite ocean color sensor and meet, or approach, the long established goal of ***5% uncertainty***.

The uncertainty of every other ocean data product stems directly from the uncertainty of $L_{WN}^{ex}(\lambda)$, with additional uncertainty associated with its algorithm.

PANEL OBJECTIVES

As a basis for its considerations of the material presented during the meeting, the Panel adopted as its specific objectives to identify requirements for the production of ocean color products of Climate Data Record (CDR) Quality using existing and future satellite missions. These requirements include identification and consideration of:

- Key elements of pre-launch characterization, on-orbit responsivity tracking and vicarious calibration of satellite ocean color radiometers;
- The implementations of these elements as applied to SeaWiFS and MODIS, especially in the context of ongoing difficulties in deriving water-leaving radiances, from Terra and Aqua MODIS data,
- Lessons learned and to be applied in pre-launch and on-orbit characterizations of future ocean color satellite missions, including VIIRS on NPP and NPOESS.

FINDINGS

To specifically answer the questions, raised by Dr. Vince Salomonson, concerning the efforts by MCST, the original MODIS Oceans Team, and the planned activities of the new Ocean Color Processing (ex-SeaWiFS/SIMBIOS) Team to characterize MODIS-Terra (and Aqua) and thereby derive CDR quality ocean color products from that sensor, the Panel's impressions are that:

- The activities described by the MCST, MODIS Oceans (Miami) and Ocean Color Processing Teams are highly professional, thorough and are making promising progress towards the desired goal.
- The panel did not identify any major shortcomings in the approach and methods. Unresolved questions and issues certainly remain, but the approaches planned to address these areas seem appropriate and well considered.
- ***Based on the briefing information presented to the panel, there is good reason to expect that CDR-quality Ocean Color data records may be successfully derived from MODIS-Terra, MODIS-Aqua and SeaWiFS***.

- ***SeaWiFS*** radiometric performance is well documented, its rates of degradation in radiometric sensitivity as determined by monthly views of the moon are well behaved and reasonably predictable, and its data products are widely accepted as reliable.
    - The SeaWiFS vicarious calibration (standard uncertainty ~5 %), using data from MOBY, was used to initially adjust the sensor's responsivity calibration. Lunar determination of subsequent changes in responsivity have generally been indistinguishable from those obtained from MOBY, and only a few small adjustments to the degradation prediction models have been needed over the past several years.
    - NASA has extended the SeaWiFS data purchase contract for 1 year, and has not currently budgeted to extend it further.
    - SeaWiFS is beyond its life expectancy, albeit there is hope it will continue to function for a few more years. It is important to maintain the viability of SeaWiFS until the large seasonal and latitudinal differences with MODIS are understood and can be corrected for.
- ***MODIS-Terra***, in terms of ocean color data, has a history of difficult to explain, abrupt changes in radiometric responsivity that have been notoriously difficult to characterize. From information presented at the review panel meeting, the panel has formed the impressions that:
    - Many of the changes, and certainly the abrupt shifts following periods when the instrument was turned off, and then back on, appear to be associated with the system electronics.
    - Apparent degradation of the Solar Diffuser target assembly, mirror reflectance at different scan angles (differing on the two - M1 & M2 - sides of the mirror), and apparent changes in the system polarization sensitivity need to be quantified.
    - The MODIS Oceans Discipline Group, in particular Univ. of Miami researchers, addressed the on-orbit stability of MODIS using comparisons of selected Earth scenes, in particular those collected over the MOBY site (see below); this has led to successive improvement in the description of the sensor's characterization functions. The procedure is difficult because of the requirement to correct for the atmospheric radiance, the presence of sun glint, and the natural radiance distribution in the oceans, all of which must be considered. With the acquisition of a sufficient number of images, which takes from 6 m to 1 yr over the MOBY site, Evans reported that the effect of cross-scan variations were reduced about a factor of 30 using images from adjacent orbits. In addition, the effect of detector dependence within a band was reduced a factor of 2 to 3 by observations of striping and cross-scan variations, and the mirror side correction was improved a factor of between 6 and 15 by consideration of solar zenith angle.
    - The semi-empirical approach used by UM relies on the current values in the MODIS LUT, which takes time to implement as the necessary SD, Lunar, and SRCA images are acquired. If the MODIS characteristics changed but are not reflected in the current LUT, the UM efforts are based on incorrect values and their analysis must be repeated once the MODIS results are corrected by the MCST. The approach was changed in early 2003, with MCST updating the LUT at least monthly, based on the SD measurements. The result is that the effect of unanticipated (and unpredictable) changes in the radiometric responsivity of

MODIS-Terra is less severe regarding ocean color products. This in turn facilitated the UM refinements on the MODIS characterization functions using the selected Earth images.

- Very recent progress has been made by MCST in smoothing the MODIS-Terra system calibration coefficients (m1) and has developed a model giving calibration coefficients (m1) as a function of time for the entire operating life (to date). This was accomplished through retrospective analyses and modeling of data from views of the solar diffuser, monthly views of the moon through the deep-space port, and views of the SRCA; these independent on-orbit calibration signals are viewed by each detector at 3 different mirror incidence angles. The smoothed m1 coefficient, when combined with the additional RADiance calibration CORrections (RADCOR) developed at the Univ. of Miami (UM/Evans), appear to improve many of the artifacts observed in $L_{WN}^{ex}(\lambda)$ comparisons between SeaWiFS and MODIS-Terra, and between MODIS-Terra and MODIS-Aqua.
    - The resulting m1 model is "epochal" in that sense that it accounts for abrupt shifts in system gain, associated with known events (power cycling, etc.), superimposed on smoothed trends in m1 associated with degradation of the Solar Diffuser (SD), temperature variations, and changes in the response-vs-scan angle (RVS) due to degradation of the scan mirrors. (Xiong)
    - Vicarious calibrations of MODIS-Terra at the Marine Optical Buoy (MOBY) site, using the smoothed m1-model and RADCOR, have a standard uncertainty of ~5 % in $L_{WN}^{ex}(\lambda)$ (Evans).
    - Preliminary analyses comparing MODIS-Terra (using the new m1-model and RADCOR) and SeaWiFS $L_{WN}^{ex}(\lambda)$ show closer agreement than was obtained in previous such comparisons (Evans).
- Significant challenges remain to be addressed. Those issues on which work is currently in progress include:
    - "Earth-shine" illumination of the solar diffuser when viewing the sun (Wolfe)
    - Illumination of the focal plane area by stray light entering the earth view port and passing around the primary mirror (Waluschka).
    - Polarization sensitivity and on-orbit changes, using a Monte Carlo ray trace model (Waluschka).
        - The polarization sensitivity modeling is made more complicated because the properties of optical surface coatings are proprietary secrets, and it is therefore difficult to understand how their polarization properties may change on-orbit.
    - Unexplained significant time and latitude dependent differences persist in pair-wise comparisons between MODIS-Terra, SeaWiFS and MODIS-Aqua (Evans). These anomalies may correlate with the orbit-phase (e.g. thermal cycling or battery charging), solar zenith angle, or Rayleigh polarization variations.
    - Anomalous cross-scan patterns, seen as patterns of departure from SeaWiFS and as discrepancies in $L_{WN}^{ex}(\lambda)$ from overlapping adjacent orbit

swaths, remain to be understood and fully corrected. These pattern anomalies vary with latitude and correlate with solar zenith angle and Rayleigh polarization (Evans).

- The on-orbit characterization of ***MODIS-Aqua*** has not yet reached a point where its modes and rates of change and degradation have been well established. Thus far, its vicarious calibration using MOBY data has a standard uncertainty ~5 %, and power cycling has not introduced the abrupt gain shifts that are so troublesome with MODIS-Terra. MODIS-Aqua data also show latitude-dependent cross-scan pattern anomalies and differences in comparisons with SeaWiFS with magnitudes similar to those seen in MODIS-Terra data (Evans). MODIS-Terra on-orbit characterization has provided enormous insight toward understanding on-orbit MODIS-Aqua degradation. In this context, continued MODIS-Terra operations will help prepare for characterizing an aging MODIS-Aqua!
- Vicarious calibrations based on normalized water-leaving radiance "match-ups" with MOBY yield Type-A standard uncertainties of approximately 5% for SeaWiFS, MODIS-Terra and MODIS-Aqua.
- Significant, unexplained disagreements in SeaWiFS/MODIS-Terra, SeaWiFS/MODIS-Aqua and/or MODIS-Terra/MODIS-Aqua occur in global normalized water-leaving radiances, and other products, that are geographically removed from MOBY.
    - The viewing and solar incidence geometries differ significantly between SeaWiFS, MODIS-Terra and MODIS-Aqua at any normalized water-leaving radiance "match-up" pair location, and the ranges of viewing and solar angles for each satellite vary strongly with latitude. Wide variations in view-sun geometries place strong demands on the uncertainties of the aerosol phase function and ocean BRDF models, which are respectively used for atmospheric correction and conversion from water-leaving radiance to normalized water leaving radiance. Uncertainties in polarization corrections are also sensitive to such geometric variations and differences. The global ranges of geometric variations experienced by the MODIS instruments are greater than those experienced by SeaWiFS, due to orbit and scan characteristics, but all ocean color sensors are affected by these factors (Voss).
    - In some ocean ecosystems, such as near the sub-Antarctic Front, diurnal variability in near surface optical properties may be large enough to cause >10 % changes in remote sensing reflectance, and thus in water-leaving radiance, between ocean color observations at 1030 (MODIS-Terra), 1200 (SeaWiFS) and 1330 (MODIS-Aqua).
    - No mention was made, during the review, of including ocean color data from non-U.S. satellite ocean color sensors, such as MERIS, in the production of CDR-quality ocean color product time-series. Given the importance of the cross-sensor comparisons and merging analyses in the generation and validation of global CDR-quality ocean color time-series products, the addition of these data into the mix would seem to be invaluable. MERIS and other non-US ocean color satellites share a 10:30 orbit that overlaps with MODIS-Terra, and they are a natural place to look for additional comparisons. The successful comparison of MODIS-Terra and MISR data is another source of relevant information (Xiong).

- The Panel has the sense that continued processing and on-orbit characterization of MODIS-Terra data, and its on-orbit characterization, will add, rather than detract from the effort to understand the disagreements between different ocean color satellite $L_{WN}^{ex}(\lambda)$ products.

The influence of spectral-out-of band on the measurements is not being considered uniformly within the ocean color community. For example, the MODIS bio-optical algorithms developed by Clark and the MOBY products are total-band and have been corrected for the effect of the different spectral distributions of the calibration and the in-water sources. MODIS L1B products reported by MCST are in terms of "in-band" (defined at the 1% of maximum RSR) and no correction is made for the difference in the relative spectral shape of the calibration source (Solar) and the exoatmospheric radiance (primarily Rayleigh); SeaWiFS uses total band and applies a correction for spectral out-of-band, but this is to L_{WN}, not to the exoatmospheric radiance.

The vicarious calibration procedure using MOBY "corrects" for the spectral out-of-band for any ocean color sensor to the extent that the exoatmospheric radiance for the match-up data and the *in situ* water-leaving radiances *have the same* relative spectral shape. However:

- Voss presented preliminary results that indicate the MODIS results are sensitive to geolocation, and by inference to the relative spectral shape of the exoatmospheric radiance. This work should be continued, as it impacts the ocean color products directly and indirectly (via the near infrared bands and the atmospheric correction algorithms).
- A uniform procedure must be adopted for treating spectral out-of-band effects in all three aspects of ocean color research (bio-optical algorithm development, vicarious calibration, satellite measurements).
- The Relative Spectral Response (RSR) measurements of upcoming ocean color sensors (VIIRS) should be accurate, complete, and verified using tunable laser characterization, as was done with MOBY.

The observed variations in the global distributions of differences between in-band and total-band radiances are unique to each channel, and the histogram widths are particularly large in channels used to determine aerosol radiance. Out-of-band stray light artifacts in the near-IR channels, when propagated through the atmospheric correction, are likely to adversely impact the uncertainty of $L_{WN}^{ex}(\lambda)$ determined from in-band $L_T(\lambda;\theta,\phi,\theta_o,\phi_o)$ in all channels. It is also possible that propagated effects of uncorrected out-of-band stray light may vary systematically with solar zenith and/or scan angle. ***The direct and indirect consequences of neglecting out-of-band stray light seem not yet to have been thoroughly investigated, and clearly they should be***.

The SeaWiFS and MODIS ***Point Spread Functions (PSF)*** were not discussed in any of the presentations. In Panel discussions, one of the members (Dr. Stu Biggar) suggested that the amplitudes of the MODIS PSF tails may be large enough to cause significant artifacts in $L_T(\lambda;\theta,\phi,\theta_o,\phi_o)$ within several Km of land or clouds. Following the meeting, MCST provided the Panel members with a summary of the MODIS PSF studies, as presented originally in February 1997. From the information made available to the Panel, the PSF was apparently not measured in the along-track direction.

- The PSFs of MODIS and SeaWiFS are similar. Both instruments have significant amplitudes in the PSF tails of all channels, and the PSF shapes differ from channel to channel in each instrument.
- The PSFs typically drop to 10^{-3} at ~3 Km, 10^{-4} at 6 to 8 Km, and 10^{-5} at 10 to 20 Km.
- The MODIS-Terra PSFs are worse in the Near-IR channels due to high scatter in a particular optical element. This element was replaced in MODIS-Aqua, and it is assumed that the PSFs of the Near-IR channels would thereby be improved (from the information provided, it is unclear whether this assumption was tested during characterization). Because the Near-IR channels are used to determine aerosol radiance, PSF artifacts in these channels may act through the atmospheric correction to affect $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$ at all other wavelengths.
- The typical amplitudes of the PSF tails are large enough to introduce significant artifacts in radiances measured above the atmosphere when clouds or land are present. The magnitudes of these artifacts are determined as the integral of cloud/land radiances over the area covered by the extended tails of the PSF. For example, a single cloud having an area of ~1 Km^2 and a radiance ~100 $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$, would produce an artifact of magnitude ~0.01 $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$ in $L_{\mathrm{T}}(\lambda)$ at a pixel ~7 Km away (PSF ~ 10^{-4}). If the cloud covered 10 Km^2 at the same radial distance from the pixel, it would produce an artifact of magnitude ~0.1 $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$.
- If the PSF's of channels used to correct for aerosol radiance were nearly the same as PSF(λ) and the cloud/land radiance spectrum were white, then much of this artifact would be removed as aerosol radiance, but it is unclear how the resulting choice of aerosol type, etc., might lead to possible under-, or over-, corrections for aerosol radiance.
- The PSF-effects could cause differences between matched Level-2 SeaWiFS and MODIS determinations of $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$, simply because the observations are made a different times of day, with different view/sun geometry and possibly different nearby cloud conditions.
- A "simple" test of PSF sensitivity in SeaWiFS/MODIS comparisons would be to mask both images at progressively decreasing distances (20, 15, 10, 5, 3 Km) from a reasonable brightness threshold, and compare only match-ups passing each filter in both cases. If the differences between regional, or zonal, statistics of matched SeaWiFS/MODIS-T $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$ pairs do not increase significantly as the masking distance is decreased, the PSF would be shown to not be a problem. Conversely, should that not be the case, it would suggest that PSF-related effects need much closer examination.

In all cases, derivation of CDR-quality time series of ocean color products will require ***ongoing retrospective characterization of sensor changes and degradation in radiance responsivity on-orbit,*** followed by reprocessing of each data stream from Level-1A to account for changes in the system calibration and characterization model.

- In principle, the ***new discipline-based Ocean Color Processing Team***, vice sensor or mission-based processing team, approach is structured to deal with these requirements.
    - This is said with the caveat that the ocean color processing team is provided with enough ***mission specific engineering support to carry out the vicarious calibration and on-orbit characterization of changes and degradation in each sensor.***

  - Therefore, the sustained tasking, staffing and financial support for this "Processing Team" must also embrace all elements of on-orbit characterization and vicarious calibration of each ocean color sensor, and product validation. These vital functions are very unlikely to be supported within the baseline programs of multi-discipline sensor missions, like MODIS; the uncertainty requirements of the partner disciplines (atmospheric and terrestrial remote sensing) are an order of magnitude less demanding than those for ocean color remote sensing.
- The ***Marine Optical BuoY (MOBY) Normalized Water-Leaving Radiance Observatory***, or an equivalent replacement, is an essential facility for establishing and maintaining the vicarious calibration of all ocean color sensors.
  - MOBY has provided the normalized water-leaving radiance data used for the successful and consistent vicarious calibration of OCTS, SeaWiFS, MODIS-Terra, GLI, MODIS-Aqua, MERIS, and other satellite ocean color sensors.
  - Were the MOBY observatory to be decommissioned, the likely impact, over months to years, would be an increase in the uncertainty of data products from all present and future ocean color satellites. The on-orbit characterization efforts for each satellite sensor would no longer have a well-characterized absolute $L_{WN}^{ex}(\lambda)$ reference, and be forced to rely on *in situ* $L_{WN}^{ex}(\lambda)$ data of lower quality, trending sources such as solar diffusers and the moon, and intercomparisons between different satellite sensors.
  - The stringent radiometric and site environmental specifications for a Vicarious Calibration Observatory are briefly reviewed below under "Fundamental Background" (pp23ff).

CONCERNS

1. Current funding support is inadequate to sustain essential infrastructure components that are necessary for successful continuation of CDR-Quality ocean color products beyond the next year or so.
   a. Current funding for the **MOBY $L_{WN}(\lambda)$ Vicarious Calibration Observatory** wil support its maintenance and operation until *circa* November 2004.
      i. Should MOBY be decommissioned, and not replaced, the lack of a well-characterized source of *in situ* normalized water leaving radiance for vicarious calibrations would be very likely to degrade the quality of ocean color data products from all satellite sensors, and to thus jeopardize the prospects for meeting CDR-quality standards.
      ii. It is questionable, and probably inappropriate, for NASA, a research agency, to remain the primary agency providing financial support for this essential operational facility that is relied on by other agencies (NOAA, NSF and DoD), as well as by many foreign satellite ocean color programs. This obvious disparity in distribution of the financial burden clearly complicates the problem of how this and other essential infrastructure facilities can be maintained indefinitely.
   b. The MCST task plan has entered a "ramp-down" phase and, at some point in the not too distant future, will be unable to continue the ongoing on-orbit

retrospective characterization of MODIS-Terra, or –Aqua, at the level-of-effort needed to adjust its calibration coefficients within "epochs" between rapid (abrupt) changes in system response that are apparently associated with the system electronics. If the degradation of MODIS-Aqua is better behaved, as has been the case with the relatively predictable decay patterns of the SeaWiFS channels, then the impact may not be as severe for that sensor. But if the patterns of degradation experienced by MODIS-Aqua are not well behaved, the On-Orbit Characterization and Cal/Val infrastructure may be hard pressed to cope with it in a timely fashion. Here, the main point is that one cannot predict in advance whether a sensor's modes of degradation will be smooth, or irregular, nor can it be assumed that a sensor will not abruptly change its degradation patterns at any time during a mission. Therefore, continuing on orbit characterization and vicarious calibration, including use of a MOBY-type facility (with all of its attributes), is needed to maintain each sensor's absolute calibration throughout its operating lifetime.

   c. Continuation of the overall infrastructure represented by the SeaWiFS and SIMBIOS Projects, which now transitions to the new Ocean Color Discipline-oriented Processing Team, is important and the long-term commitment to do that seems uncertain. This is especially critical given the reduction of the MODIS Oceans effort at Miami, and of MODAPS at GSFC, to be replaced by the Ocean Color Discipline-oriented Processing Team. When a community is addressing problems that are as multi-faceted and complex as those we consider here, it is vital to maintain intellectual diversity in the evaluation and validation of approach, methods and results.

2. The fabrication and characterization of the NPP/VIIRS instrument is already in progress.
   a. NASA does not currently provide support for an engineering liaison and cooperative oversight activity of the NPP/VIIRS pre-launch sensor characterization at a level comparable to that provided for SeaWiFS and MODIS characterizations. MCST does not have the resources to carry out this function, for example. If it continues, this omission is likely to make it extremely difficult, if not impossible, to successfully carry out the Ongoing On-Orbit Sensor Characterization of NPP/VIIRS.
   b. There is no contractual requirement for the vendor to develop and provide a model of NPP/VIIRS, for use in either pre-flight, or on-orbit characterization.
   c. VIIRS is based on a different design concept than either SeaWiFS or MODIS.
3. Another issue related to deriving CDR-quality ocean color products from NPP/VIIRS, is the current lack of a definite plan, and associated budget, within either NASA or NOAA to provide full-resolution Level-1A (earth-located, scan-format, uncalibrated digital counts, together with satellite and sensor engineering metadata) to the OCDPT in a timely way. As is explained in this report, it is not possible to derive CDR-quality ocean color products from the real-time ocean color sensor-data records that will be produced and distributed by the NPP/VIIRS contractors, under the oversight of the Interagency Program Office. The Level-1A data stream is the Fundamental Climate Data Record needed as input for retrospective vicarious calibration, on-orbit characterization of VIIRS, and derivation of Exact Normalized Water-Leaving Radiances and other Thematic CDR's to be calculated from them.

The prospects for deriving CDR-quality ocean color time-series products from NPP/VIIRS will be seriously diminished if this situation continues.

4. The panel found that in comparing SeaWIFS and MODIS results that there is some confusion whether identical processing methods were used. These processing methods, algorithms, subroutines, etc., should be as identical as possible to determine that differences in ocean radiance, or derived ocean properties, are the result of the sensor characterization and not the processing. Differences in the Miami code and the SeaWIFS code, for example, can have influence on the results.

RECOMMENDATIONS

1. Assure that the ***NASA ocean color team infrastructure***, as currently represented by the Ocean Color Discipline-oriented Processing Team (OCDPT), MCST, and the MODIS Science (Oceans) Team, provides adequate long term capabilities for carrying out the continuing engineering and scientific tasks described above. These tasks and capabilities include engineering liaison during pre-launch calibration of future satellite ocean color sensors (e.g. VIIRS), continuing retrospective vicarious calibration and on-orbit characterization over the operating lifetime of each sensor, sensor and algorithm validation resources (e.g. SeaBASS archive, linkage to AERONET, etc.), and reprocessing the data stream from each sensor at intervals indicated by its on-orbit vicarious calibration and characterization.
2. Recognizing that the NPP VIIRS characterization and preflight testing are already in progress, immediate action should be taken to improve NASA liaison with the VIIRS project. A concise “ocean color lessons learned” document should be prepared, perhaps by the OCDPT at GSFC, to communicate to those responsible for VIIRS the perceived requirements that must be met to derive CDR-quality ocean color products from NPP/VIIRS. A proactive effort should also be quickly put in place, perhaps by MCST or OCDPT, to establish close, cooperative engineering liaison with the sensor manufacturer in the preflight characterization of the VIIRS instrument.
3. Together with other agencies, provide for the continuing, long-term operation and maintenance of an ***$L_{WN}(\lambda)$ Vicarious Calibration Observatory*** as an essential international facility to provide data for vicarious calibrations needed to maintain CDR-quality ocean color time series products from each sensor. In this context, it should be recognized that, irrespective of funding considerations, the expected time frame for developing a new observatory with capabilities comparable to the existing MOBY observatory will be at least 2 to 3 years.
4. SeaWiFS data should be acquired until the large seasonal and latitudinal differences with MODIS have been reconciled using the results of studies suggested above. CDR-quality data sets are not obtained if differences in $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$ between sensors are not ~5 %.
5. The ongoing work, currently by MCST, to characterize degradation in MODIS-Terra polarization sensitivity, and possible stray-light pathways, should be continued to completion.
6. Re-evaluate normalized water leaving radiance comparisons between MODIS-Terra, SeaWiFS and MODIS-Aqua. Previous such comparison results are **out of date** and

potentially misleading, because the MODIS-Terra ocean products were not based on the smoothed m1 model, and in some cases, did not apply MODIS (Terra or Aqua) out-of-band stray light functions to determine corrected in-band radiances.

7. MODIS Terra characterization and data processing should be continued jointly with Aqua processing. Continued on-orbit characterization of Terra provides advanced understanding of how Aqua will respond in the future. Terra and Aqua are both providing high quality ocean information to ocean research. Although the unsettled Terra characterization is difficult to maintain, the satellite is providing high quality science data and should be maintained. Expect that reprocessing will be required for MODIS (Terra and Aqua) as was done for SeaWIFS reprocessing. Reprocessing is expected in order to provide CDR-quality.
8. Together with NOAA, implement a concrete plan for timely archival of the NPP/VIIRS Level-1A data stream, which comprises the Fundamental CDR basis for retrospective vicarious calibration, on-orbit sensor characterization, and determination of CDR-quality ocean color products from NPP/VIIRS.
9. The out-of-band stray light function of each MODIS band should be used to determine total-band radiances, or alternatively used to correct the in-band radiances for this artifact, for all measurements over oceans. This recommendation would also apply to SeaWiFS, if out-of-band stray light is not taken into account in current algorithms (this was not discussed during the presentations). Moreover, a uniform procedure must be adopted for treating spectral out-of-band effects in all three aspects of ocean color research (bio-optical algorithm development, vicarious calibration, satellite measurements).
10. The spectral out of band response should be measured over the entire spectral range corresponding to finite detector responsivity, using a full aperture unpolarized source, such as tunable laser-illuminated integrating sphere sources, for example the NIST facility for Spectral Irradiance and Radiance responsivity Calibration using Uniform Sources (SIRCUS). For filter radiometers, adequate characterization of out-of-band spectral response may possibly be done using a double-monochromator and source, if sufficient signal-to-noise ratios and uncertainties are demonstrated.
11. The possible influences on $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$ of artifacts by bright clouds, or land, outside the instantaneous field-of-view, but within the significant tails of the PSF, should be re-evaluated for SeaWiFS, MODIS-Terra and MODIS-Aqua. Note the pre-flight characterization data did not measure "out of plane", in the sense that in the along track direction, no information is known about what is the effect of a cloud or bright target either ahead of, or behind, the present scan line. It would be plausible to assume that the shapes of the PSF in this dimension are similar in shape and magnitude to the measured within-scan PSF, and to apply a 2-dimensional correction (or data rejection screen). A possible first approach might be to evaluate the changes in statistics of differences in global $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$ match-ups between the satellites, for successively increased masks (ranging from 0 to 20 Km) are applied near clouds and land (as determined by brightness criteria, which would include sun glint in some latitudes). Were differences to increase statistically as the masked areas were decreased, that would suggest that the PSF cloud/land artifacts should be examined more critically to consider possible correction algorithms. If, on the other hand, this did not occur, the PSF effects would be thus shown to be insignificant.
12. To comply with the CDR-quality definition (above), the primary comparisons between satellite sensors, and between satellite sensors and *in situ* data, should be based on matched pairs of same-day exact normalized water-leaving radiance $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$. In making such

comparisons, the same, consistent algorithms and methods should be used to derive $L_{WN}^{ex}(\lambda)$ from each sensor, with appropriate adjustments for differences in time of day and/or exact wavelengths. It is essential that the same values of $\overline{F}_o(\lambda)$, the mean solar irradiance above the atmosphere, be used for all comparisons between $L_{WN}^{ex}(\lambda)$ derived from different sensors. Until analysis of data from different sensors routinely determines $L_{WN}^{ex}(\lambda)$ to within ~5% at the same location, CDR-quality data sets are not being obtained.

13. The SeaWiFS Solar Diffuser (SD) measurements should be analyzed quantitatively and compared to the lunar and MOBY-based estimates of degradation. Issues to investigate include Earthshine and the relative merits of YB-71 vs Spectralon. There is a paper by the University of Arizona group that references space related degradation of diffuse reflectance standards, and in their view YB-71 was the best overall performer. Therefore, the SeaWiFS SD data may be very interesting, even though there is not a Solar Diffuser Stability Monitor (SDSM) on the spacecraft.
14. In planning for new satellite sensor systems, e.g. NPOESS VIIRS, allow sufficient time for adequate pre-flight characterization. Start the sensor design, build and characterization phases of a mission early enough to avoid pressure to proceed to launch before a sensor is proved ready for satisfactory operation on orbit.

FUNDAMENTAL BACKGROUND

Satellite ocean color remote sensing is unusually challenging, compared to, *e.g.*, atmospheric and terrestrial applications of remote sensing with the same or similar instruments. This is so, strictly because of the extremely low signal level associated with water-leaving radiance, compared to radiances reflected from land surfaces, clouds, aerosols, or even a pure molecular atmosphere.

We recall our working definition that an "***Ocean Color Product of CDR-Quality***" is one determined from ***Exact Normalized Water-Leaving Radiances***, $L_{WN}^{ex}(\lambda)$, that are derived from a satellite ocean color sensor and meet, or approach, the long established goal of ***5% uncertainty***.

The uncertainty of every other ocean data product stems directly from the uncertainty of $L_{WN}^{ex}(\lambda)$.

$L_{WN}^{ex}(\lambda)$ is **defined** as water-leaving radiance that would be viewed at nadir (θ=0), with the sun at zenith (θ_o=0) and at mean earth-sun distance, and with no intervening atmosphere.

1. $L_{WN}^{ex}(\lambda)$ is obtained from satellite $L_T(\lambda;\theta,\phi,\theta_o,\phi_o)$ by removing atmospheric effects, adjusting extraterrestrial solar flux for the actual earth-sun distance, and applying the Ocean Bidirectional Reflectance Distribution Function (BRDF) to the resulting $L_W(\lambda;\theta,\phi,\theta_o,\phi_o)$.
2. $L_{WN}^{ex}(\lambda)$ is similarly obtained from nadir-viewing, *in situ* $L_W(\lambda;0,.,\theta_o,\phi_o)$ by removing atmospheric effects on incident surface irradiance, scaling the earth-sun distance, and applying the Ocean BRDF.
3. $L_W(\lambda;\theta,\phi,\theta_o,\phi_o)$ measured with different viewing and/or solar angles, for a common location and identical in-water optical properties, are not equal. For valid comparison, each measurement must be converted to $L_{WN}^{ex}(\lambda)$.

The Ocean BRDF models combine in-water bidirectional scattering processes, which vary with the physical absorbing and scattering materials in seawater, with bidirectional surface reflection and transmittance processes that vary with wind speed. In clear Case-I waters, the uncertainty of the in-water BRDF is significantly less than 5 %. The uncertainty of the surface reflection and refraction correction depends primarily on the uncertainty of surface wind speed, and possibly also on wind direction if an anisotropic model is used to relate wind velocity to the sea surface slope distribution.

Over oceans, the water-leaving radiance $\boldsymbol{L_W(\theta,\phi,\theta_o,\phi_o,\lambda)}$ transmitted through the atmosphere is at most 10% of radiance $\boldsymbol{L_T(\theta,\phi,\theta_o,\phi_o,\lambda)}$ measured at the satellite. Therefore, a 1 % uncertainty in $\boldsymbol{L_T(\theta,\phi,\theta_o,\phi_o,\lambda)}$ yields a 10 % uncertainty in $\boldsymbol{L_W(\theta,\phi,\theta_o,\phi_o,\lambda)}$.

A 5 % combined standard uncertainty in $L_{WN}^{ex}(\lambda)$ would seem to imply requirements for < 0.5 % standard uncertainty in $\boldsymbol{L_T(\theta,\phi,\theta_o,\phi_o,\lambda)}$ measured at all scan angles for the entire mission life of each sensor, < 0.5 % standard uncertainty in atmospheric corrections, < 5 % uncertainty in extraterrestrial solar flux, and < 5 % uncertainty in the Ocean BRDF used to convert $\boldsymbol{L_W(\theta,\phi,\theta_o,\phi_o,\lambda)}$ to $\boldsymbol{L_{WN}(\lambda)}$.

- A 0.5% uncertainty in radiometric calibration and characterization is extremely challenging. It is not met with current methods for preflight calibration and characterization. Instruments drift and degrade over time, both in radiance responsivity and polarization sensitivity. The magnitudes of on-orbit, systematic effects in the radiometry must be very well understood to apply corrections and estimate their uncertainty.
- Atmospheric correction is also challenging. Aerosols have varying size distributions, composition and concentration, and therefore varying scattering phase functions. The polarization of atmospheric path radiance [~90% of $\boldsymbol{L_T(\theta,\phi,\theta_o,\phi_o,\lambda)}$] varies strongly, regionally and over each scan. The uncertainty of atmospheric correction increases markedly when sun glint is significant (varies with viewing and solar angles, wind speed and sea state). The uncertainty of atmospheric correction increases directly, but in general nonlinearly, with scan angle (viewing zenith angle) and solar zenith angle.
- Variations between published scales of mean extraterrestrial solar flux $\overline{F}_o(\lambda)$ vary from < 5 % through most of the visible spectrum and increase to approximately 8 % in the solar infrared region of the spectrum. Because $\overline{F}_o(\lambda)$ enters into the calculation of $L_{WN}^{ex}(\lambda)$, matched pairs of $L_{WN}^{ex}(\lambda)$ derived from two satellite sensors that use different values of $\overline{F}_o(\lambda)$ will differ systematically.
- The uncertainties of ocean BRDF models are currently under active investigation within the ocean color research community. It is thought that < 5% uncertainty is attainable in most open-ocean, Case-I waters, but there are currently unresolved issues and questions concerning the surface reflection and refraction terms (the "Gothic R" term in the most commonly used Ocean BRDF model); these difficulties may possibly result from uncertainty in determining instantaneous wind speed at each pixel. Research is also needed to characterize the volume scattering function and absorption coefficients as a basis for deriving BRDF models (and uncertainties) in turbid coastal and Case-II waters.

A 5 % combined standard uncertainty in $L_{WN}^{ex}(\lambda)$ can, nevertheless, be attained, or at least closely approached, through:

1. ***Complete Radiometric Characterization of the Sensor before Launch***.
2. ***Vicarious Calibration*** to obtain an internally consistent model of the Sensor/Sun/Atmosphere/Ocean System, and to maintain it throughout the operating life of the sensor in space.
3. ***On-Orbit Sensor Characterization to monitor, diagnose and correct for inevitable changes in system response***. This requires that a sustained effort be maintained throughout the mission lifetime of each ocean color sensor. Repeated, ongoing vicarious calibration comparison and analysis is one of the tools used in this process.

The 5 % uncertainty goal for $L_{WN}^{ex}(\lambda)$ is wholly inconsistent with the 5 % radiometric calibration uncertainties specified for SeaWiFS, MODIS and VIIRS. Therefore, the aforementioned CDRs from SeaWiFS and MODIS are made possible through the vicarious calibration using, e.g., the MOBY methodology (see below). We caution the reader that a vicarious calibration (see below) having an uncertainty of < 5 % in $L_{WN}^{ex}(\lambda)$ does not equate to a 0.5 % uncertainty in the absolute calibration, traceable to NIST, of the satellite sensor's measurements of radiance above the atmosphere. Nor does it mean that the same level of uncertainty applies to $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$ measurements with large scan angles, large aerosol optical thicknesses, significant sunglint, or turbid water-masses; the data used for vicarious calibration are selected to minimize uncertainty contributions from these factors as a basis for "correcting" apparent offsets in the sensor's radiance responsivity calibration (see below). The vicarious calibration uncertainty is only one part, albeit a vital part, of the uncertainty budget of satellite ocean color measurements under more general conditions, and additional methods and information must be used to determine the combined uncertainties of these.

For ocean color, ***complete characterization is more important than preflight radiometric calibration***. Sensor characteristics that critically influence $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$ uncertainty include:

- Radiance responsivity ***stability***, as affected by aging of electronics, optical surfaces and optical components;
- ***Out-of-band stray light***, which may be characterized using SIRCUS (see Recommendation 7, above);
- ***Scan and/or detector dependent variations in responsivity***, and possible (likely) sources of change in orbit;
- ***Polarization sensitivity***, both overall for the system, as well as the polarization characteristics of each "piece-part";
- The ***Point-Spread Function*** (PSF) of each sensor channel, and its possible variation with scan angle; and
- ***Systematic biases*** from other sources of stray radiation on-orbit, such as "earth-shine" on the solar diffuser, or other stray-light pathways that may not have been included in the sensors PSF characterization.

It is important that the team charged with On-Orbit Characterization validate the sensor vendor's methods and results during each phase of the pre-flight characterization, and that it conduct immediate, on-the-fly assessments of characterization test data for impact on ocean color products. Known problems discovered in this process should be fixed before launch. A ***Validated Instrument Ray-Trace Model*** should be developed and used to facilitate rapid analysis of test data in pre-flight characterization, and as a tool for assessing changes in instrument characteristics, and deriving corrections, on-orbit.

Vicarious Calibration essentially comprises minimizing the combined standard uncertainty of differences in ensembles of matched pairs of satellite and *in situ* $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$ by adjusting spectral radiance responsivity and other sensor characteristics, considering also data from the solar diffuse reflectance target, views of the moon and other on-board calibration sources as a basis for quantifying the rates and modes of change during the period considered for a particular vicarious calibration. Vicarious calibration amounts to an "internally consistent calibration" of the Sensor-Sun-Atmosphere-Ocean System. Vicarious calibration is required both for ***Sensor Initialization on-orbit***, and on a ***recurring basis*** throughout the sensor's mission life, as part of ongoing on-orbit sensor characterization.

The fundamental objective of vicarious calibration is to isolate the effects of a satellite sensor's systematic gain offset on the difference in a matched pair of $L_{\mathrm{WN}}^{\mathrm{ex}}(\lambda)$ derived from satellite and *in situ* measurements. This is accomplished by combining complete characterization of both sensors with constraints on the measurement conditions to minimize all other components of the combined uncertainty of the two measurements. In an ensemble of vicarious calibration $L_{WN}^{ex}(\lambda)$ matched pairs, the combined uncertainty of individual pairs will vary, and it is important to estimate the absolute uncertainty of each one, either as a basis for generalized weighted Least-Squares analysis, or for excluding data points with excessive uncertainty. Assuming that both sensors are well characterized for all viewing geometries, variations in the magnitude of combined uncertainty of a matched $L_{WN}^{ex}(\lambda)$ pair arise from the atmospheric correction (uncertainty varies with aerosol optical thickness, cloudiness near the site, and with viewing and solar zenith angles), ocean BRDF corrections (uncertainty varies with wind speed, viewing zenith angle, solar zenith angle, and water-mass turbidity), environmental effects on *in situ* L_W determination (uncertainty varies with near-surface turbidity, surface wave conditions, and cloud conditions), and the different effects of spatial heterogeneity of ocean optical properties on the *in situ* (single point) and satellite (area integral) measurements.

The ***in situ upwelled radiance measurements*** used to determine $L_{WN}^{ex}(\lambda)$ for ***vicarious calibration*** must have the lowest possible radiometric uncertainty. Uncertainty associated with extrapolating in-water profile measurements of upwelled radiance to, and transmitting it through, the wind roughened air-sea interface is estimated to range between 3 % and 5 % under ideal circumstances (i.e. in clear Case I waters). If ocean bio-optical properties vary significantly within a few Km of the calibration site, then significant uncertainties that are difficult to quantify will arise in the comparison of a matched pair of *in situ* $L_{WN}^{ex}(\lambda)$, representing a single point, and satellite $L_{WN}^{ex}(\lambda)$, representing the average over a Km^2 area. The radiometric and environmental requirements for Vicarious Calibration observations include:

- Hyperspectral (~1 nm) resolution to allow matching of radiances to the in-band and out-of-band radiance response functions of each individual satellite channel,
- Corrections for the in situ sensor's out-of-band stray light functions, as determinable using SIRCUS,
- Minimal platform and instrument shading, combined with validated corrections,
- Pre- and post-deployment radiometric responsivity calibrations, coupled with frequent validation of the direct traceability of the calibration sources to NIST scales of spectral irradiance and radiance,
- Tracking of the Observatories calibration sources using NIST-calibrated irradiance and radiance radiometers
- Frequent diver maintenance visits to clean all optical windows, preceded and followed by in-water measurements of each radiometer's response to an in-water stability monitoring source to verify the radiometric stability of the sensor and document the effects of bio-fouling.
- A site location removed from land by > 20 Km and characterized by low incidence of cloud cover in all seasons, and by aerosol optical depths that are typically small (< 0.1 in the visible) and spatially homogeneous (*i.e.* no nearby localized sources of aerosol plumes). Using only matched $L_{WN}^{ex}(\lambda)$ pairs observed when aerosol optical thicknesses at visible wavelengths are < 0.1 minimizes uncertainty associated with aerosol models in atmospheric corrections.

- Routine measurements of aerosol optical depth and sky radiance distributions, e.g. at a nearby AERONET site, or the equivalent are used to confirm aerosol optical thickness at time of individual comparison.

- A clear Case-I water mass, e.g. with chlorophyll *a* concentrations < 0.25 mg m^{-3}, and a range of horizontal variability over scales ~10 Km < 0.05 mg m^{-3}, in all seasons. Using only matched $L_{WN}^{ex}(\lambda)$ pairs observed in water masses where Chl < 0.25 mg m^{-3} and horizontal variability within ~20 Km in Chl is < 0.05 mg m^{-3} yields uncertainties significantly < 5 % in ocean BRDF adjustments to determine $L_{WN}^{ex}(\lambda)$.
- Frequent shipboard sampling of 3-dimensional radiometric and bio-optical variability near the site, as a basis for quantifying the resulting uncertainty when point observations at the buoy are matched with satellite radiance measurements integrated over 1 Km or larger scales.

The MOBY $L_{WN}(\lambda)$ Observatory was established in the lee of the island of Lanai to provide a long-term time-series of in situ $L_{WN}^{ex}(\lambda)$ measurements for the vicarious calibration of SeaWiFS, MODIS (Terra and Aqua), and other satellite ocean color sensors. This site was selected to meet the atmospheric and oceanic environmental specifications outlined above, while at the same time having access to nearby port facilities needed for logistic support. The MOBY system, including its specialized "optical bench" spar buoy design, hyperspectral (spectrograph) radiance and irradiance sensors, and supporting infrastructure, was developed by NOAA and NASA over the period from circa 1986 to 1997 at an approximate cost between $20M and $25M. Two MOBYs are used to provide continuous coverage. One MOBY is deployed off Lanai for approximately 3-months, while the other is refurbished and its radiometers are recalibrated at the MOBY Support Site in Honolulu, Hawaii. At monthly intervals during each deployment, divers visit MOBY to clean optical surfaces and windows and check system performance using an in-water stability-monitoring source of radiant flux. At the end of a 3-month deployment, the MOBYs are exchanged, using research vessels operated by the University of Hawaii. During each replacement cruise, a grid of ocean color validation stations is occupied to map the spatial distributions of $L_{WN}^{ex}(\lambda)$ and bio-optical variables within ~20 Km of the MOBY site. Since MOBY became operational in 1997, it has provided the primary basis for the vicarious calibration of SeaWiFS, MODIS (Terra and Aqua), OCTS, GLI, MERIS and several other satellite ocean color sensors.

APPENDIX A: PANEL MEMBERS

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APPENDIX B: AGENDA

MODIS Ocean Color Review
February 11 and 12, 2004

First Day (February 11)-Meeting start time: 8:00 A.M. at the Aerospace building with a continental breakfast available and coffee.

8:30 A.M. Welcoming remarks and Introductions

-V. Salomonson/MODIS Science Team Leader
-Paula Bontempi/Manager, Ocean Biology and Biochemistry Programs
-Jim Mueller/Chairperson for the Review Team -- Guidance for the Review Team, procedures to be followed, and introductions.

- SeaWiFS calibration/characterization procedures leading to ocean color products--SeaWiFS team (McClain, Franz, Feldman, et al./GSFC) (1 hour)

-MOBY Overview--Steve Brown/NIST (1 hour)

-MODIS/MCST calibration/characterization procedures for Level 1 products - J. Xiong, et al./GSFC (1 hour)

-MODIS ocean color product radiation corrections ("radcorr") procedures for ocean color products, etc.-- R. Evans, et al./Univ. of Miami (1 hour)

- Ocean Color atmospheric corrections (e.g., polarization, BRDF, etc.) -- K. Voss/H. Gordon/Univ. of Miami (1 hour)

-Modeling of MODIS performance/ray tracing--E. Waluschka/GSFC (1 hour)

-Solar diffuser/"Earthshine" effects--Robert Wolfe/SSAI-GSFC (1 hour)

Second Day--February 12

Start at 8:00 A.M.

8-10 A.M. Review Team Questions-further review/Participant Discussion

10 A.M. Review Team Caucus (discretion of Chairman)

By 3 P.M. Review Team Report--Summary of findings/suggestions