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

INDEPENDENT PANEL REVIEW

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Greenbelt, Maryland

PANEL MEMBERS

Dr. James L. Mueller
(Chairperson)
Center for Hydro-Optics and
Remote Sensing
San Diego State University

Dr. Robert A. Arnone
Naval Research Laboratory
Stennis Space Center, MS

Dr. Stuart Biggar
Remote Sensing Group
Optical Sciences Center
University of Arizona, Tucson

Dr. Alan Holmes
Santa Barbara Instrument Group
Santa Barbara, CA

Dr. Carol Johnson
NIST
Gaithersburg, MD

Dr. Ron Zaneveld
WETLabs Inc.
Philomath, OR

Panel Terms of Reference

- The Review Panel was convened at the joint request of Drs. Vince Salomonson and Paula Bontempi
- 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**.

TECHNICAL PRESENTATIONS

- SeaWiFS calibration/characterization procedures leading to ocean color products--SeaWiFS team (C. McClain, B. Franz, Feldman, et al./GSFC)
- MOBY Overview--Steve Brown/NIST & D. Clark/NOAA
- MODIS/MCST calibration/characterization procedures for Level 1 products -- J. Xiong, et al./GSFC
- MODIS ocean color product radiation corrections ("radcorr") procedures for ocean color products, etc.-- R. Evans, et al./Univ. of Miami
- Ocean Color atmospheric corrections (polarization, BRDF, out-of-band stray light) -- K. Voss/H. Gordon/Univ. of Miami
- Modeling of MODIS performance/ray tracing--E. Waluschka/GSFC
- Solar diffuser/"Earthshine" effects--Robert Wolfe/SSAI-GSFC

MODIS & SeaWiFS Point Spread Functions (PSF)

- The SeaWiFS and MODIS ***Point Spread Functions (PSF)*** were not discussed in any of the presentations, but came up at the end of Panel discussions. We were provided with PSF info after the meeting.
- The PSFs of MODIS and SeaWiFS are similar, with tails typically decreasing to 10^{-3} at ~3 Km, 10^{-4} at 6 to 8 Km, and 10^{-5} at 10 - 20 Km.
- These tails are big enough to cause significant artifacts in L_W. At 7 Km, a 1 Km^2 cloud with radiance ~100Lw would produce a positive artifact of ~0.01Lw, and if its area was 10 Km^2 an artifact ~0.1Lw. The artifacts will treated as "aerosol radiance" & reduced, but what does that do to aerosol model selection in atmospheric corrections?
- The Panel suggests that a closer look at PSF-related bright target effects is in order. Perhaps the significance of the effect could be evaluated through a simple screening experiment to determine if statistics of, e.g., MODIS/SeaWiFS exact-L_{WN} differences change when the "rejection distance" to cloud boundaries is increased.

EXACT NORMALIZED WATER-LEAVING RADIANCE

- "Exact-L_{WN}" is **defined** as water-leaving radiance that would be viewed at nadir, with the sun at zenith and at mean earth-sun distance, and with no intervening atmosphere. It is obtained:
  - from **satellite** $\boldsymbol{L_T(\lambda;\theta,\phi,\theta_o,\phi_o)}$ 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 $L_W(\lambda;\theta,\phi,\theta_o,\phi_o)$.
  - from **nadir-viewing, *in situ*** $\boldsymbol{L_W(\lambda;0,.,\theta_o,\phi_o)}$ by removing atmospheric effects on incident surface irradiance, scaling the earth-sun distance, and applying the Ocean BRDF.
- $L_W(\lambda;\theta,\phi,\theta_o,\phi_o)$ 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 "exact-L_{WN}".

CDR-quality Ocean Color Products

- A ***"CDR-quality ocean color product"*** is one calculated using ***"exact normalized water-leaving radiances"*** **"exact-$L_{WN}(\lambda)$"** having a ***combined standard uncertainty of ~5 %***;
  - ***1. The uncertainty of every other ocean color product derives directly from the uncertainty of*** **"exact-$L_{WN}(\lambda)$"*;***
  - ***2. 5 % uncertainty in*** **"exact-$L_{WN}(\lambda)$"** ***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.

- A ~5 % combined standard uncertainty in "exact-L_{WN}" can be attained, or at least closely approached, through:
    - ***Complete Radiometric Characterization of the Sensor before Launch***.
    - ***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.
    - ***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.

PRE-FLIGHT CHARACTERIZATION

- For ocean color, ***complete characterization is more important than preflight radiometric calibration***. Sensor characteristics that critically influence 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.

CONTINUING ON-ORBIT CHARACTERIZATION

- Ongoing retrospective on-orbit characterization analyses of performance changes and degradation of each satellite ocean color sensor throughout its lifetime, combining:
- 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.
- "Exact-L_{WN}" match-up comparisons between 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 (including MOBY) 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.

VICARIOUS CALIBRATION

- 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 "exact-L_{WN}" derived from satellite and *in situ* measurements.
- This is accomplished by selective sampling to minimize uncertainties in:
  - *In situ* radiometric measurements: instrument related factors via thorough characterization, environmental factors by limiting measurements to clear waters and cloud-free sky conditions
  - Atmospheric corrections (aerosol optical thicknesses < 0.1)
  - Horizontal and vertical heterogeneity of water optical properties (spatial variability of Chl < 0.05 mg m-3 within ~10 Km of site)
- The MOBY Observatory was designed and implemented to frequently satisfy these conditions and has fulfilled this role successfully since 1997.

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.

MODIS-Terra

- 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 with "exact-L_{WN}" from other satellites.
- Significant challenges remain, and ongoing characterization work is addressing them appropriately
- **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.**
- 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 products.

MODIS-Aqua

- ***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.

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.
    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.

IMPLICATIONS FOR VIIRS

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

CONCERNS

- The MOBY Observatory may be decommissioned before the end of the year
- MCST funding is ramping down and its work on the engineering characterization of MODIS will decline and eventually disappear
- The new OCDPT at GSFC, while well-structured to address the continued processing, cal/val and analyses, is not currently tasked or staffed to replace MCST's role.
- The elimination of the independent analysis effort at the U. of Miami (Evans) is a significant loss to the program. Intellectual diversity in studying these types of problems is a huge plus.
- NPP VIIRS is marching forward and is unlikely to yield CDR-quality unless something changes.

RECOMMENDATIONS

- 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:
  - 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,
  - Providing 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.

RECOMMENDATIONS (CONT'D)

2. 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 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.

- 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.
   - 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.

RECOMMENDATIONS (CONT'D)

- 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 (e.g. MODIS-Terra ocean products were not based on the smoothed m1 model, or did not apply MODIS (Terra or Aqua) out-of-band stray light functions to determine corrected in-band radiances).
- The ongoing work, currently by MCST, to characterize degradation in MODIS-Terra polarization sensitivity, and possible stray-light pathways, should be continued to completion.
- The out-of-band stray light function of each MODIS band should be used to correct in-band radiances over oceans.
  - Applies to SeaWiFS too, if out-of-band stray light is not taken into account in current algorithms (this was not discussed during the presentations).
  - 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).

RECOMMENDATIONS (CONT'D)

- For all ocean color sensors, the spectral out of band response should be measured over the entire spectral range corresponding to finite detector responsivity.
    - One approach is to use full aperture, unpolarized sources, such as tunable laser-illuminated integrating sphere sources, such as the NIST SIRCUS facility.
    - For filter radiometers, characterization of out-of-band spectral response using a double-monochromator is sometimes adequate.
- Possible influences on "exact-L_{WN}" 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.
- For validating CDR-quality, 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.
    - Consistent algorithms and methods should be applied to each sensor
    - Use the same scale of exoatmospheric solar flux

RECOMMENDATIONS (CONT'D)

- 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 "exact-L_{WN}" are not ~5%.
- MODIS Terra characterization and data processing should be continued jointly with Aqua processing.
  - Although the retrospective MODIS-Terra characterization is difficult to maintain, the satellite is providing high quality science data and should be maintained.
  - It has yet to be established that differences between sensors are definitely artifacts associated with MODIS-Terra, or any of the other sensor's, characteristics. Other possibilities may include aerosol model and/or ocean BRDF discrepancies at differing solar/view geometry, or even diurnal variability in ocean optical properties in some oceanographic regimes.

RECOMMENDATIONS (CONT’D)

- 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” effects on SD measurements, and
  - the relative differences in on-orbit degradation of YB-71 vs Spectralon diffusers. In a previous study by the Univ. of Arizona group, YB-71 was the best overall performer.
- 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.