Navy Calibration/Validation Protocols and Procedures for Visible and Thermal Satellites: Preparing for NPOESS

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14. ABSTRACT

We describe the issues associated with the calibration and validation of ocean satellite sensors and systems operating the VIIRS – Vis/IR Imager Radiometer Suite, which is designed as part of the National Polar-orbiting Operational Environmental Satellite System (NPOESS). Our objective is to develop a coordinated, integrated calibration/validation plan for Navy ocean satellite products, including the development of standard protocols and procedures to compare satellite retrievals with ground-truth measurements. We outline the measurements required, the collection and analysis protocols for the satellite and in situ data, satellite signal-to-noise constraints for ocean applications, and other important issues that must be addressed to reach the desired levels of accuracy. By building on our existing capabilities and a transition framework that is already in place between the Naval Research Laboratory Stennis Space Center (NRL-SSC) and the Naval Oceanographic Office (NAVOCEANO), we can develop and implement a plan now, using existing systems, in preparation for future systems. This approach will ensure that Navy-wide standards and consistency levels will be achieved for all ocean products across all platforms.

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CONTENTS

Executive Summary

New remote sensing satellites are under planning and design considerations. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) will replace the current military (Defense Meteorological Satellite Program (DMSP)) and civilian (NOAA Polar-orbiting Operational Environmental Satellites (POES)) satellites beginning in 2013. The four satellite mission should provide environmental information to civilian and military METOC users until approximately 2021. NPOESS will provide 38 parameters of interest to its users. Because a new set of sensors will fly on NPOESS, the NPOESS Preparatory Program (NPP) will fly some of the sensors in September 2009 as a risk reduction effort for NPOESS. While Northrop-Grumman Space Technology (NGST) is the contractor responsible for constructing NPOESS, program management for NPOESS and NPP are the responsibility of the tri-agency Integrated Program Office (IPO) of NPOESS. The Department of Defense (DoD), Department of Commerce (DoC), and NASA are represented in the IPO. Rather than use their own satellites, NASA is looking to NPP and NPOESS to provide the environmental data required to complete their earth science mission NASA will therefore provide calibration and validation activities on NPP. Each of the NPOESS satellites will also need to undergo calibration and validation of the sensors before they are declared operational. A blueprint for this latter calibration and validation is required for NPOESS. A portion of this blueprint is laid out in the following document for calibration and validation of NPP and NPOESS satellites.

In order to meet the rigid requirements for calibration and validation, it is in the interest of all agencies to provide key components that each has expertise. One emerging sensor suite to which the Navy can provide critical calibration and validation capabilities is in the Visible-Infrared (Thermal) Imager Radiometer Suite (VIIRS). This document sets forth a list of activities where the METOC community can play a vital role in calibration and validation activities. These efforts fall in line with past capabilities regarding calibration and validation of previous satellites such as SeaWiFS and MODIS. In both of these satellites NRLSSC, NAVOCEANO, and CNMOC have used VIIRS portions of the spectra to derive environmental data

records (products). These products include, 1) diver visibility, 2) optical properties for ASW and MCM system performance for the Master Environmental Data Library (MEDAL), 3) chlorophyll, and 4) sea surface temperature.

The calibration and validation efforts for satellite products includes efforts that span initial radiometric calibration with post-launch checks, atmospheric corrections, in-situ quality control and key parameter derivation, product generation, and finally validation and distribution of time critical Navy products. Within the calibration and validation framework of NPP and NPOESS the Navy can contribute to several calibration and validation efforts to exploit these satellites.

➢ *Adopt the calibration methods currently being used for SeaWiFS and MODIS (TERRA, AQUA), for the NPP and NPOESS satellite*

➢ *Adopt the calibration methods currently used for AVHRR and MODIS – thermal IR SST*

➢ *Establish and adopt a protocol for ocean observing instruments*

➢ *Provide an infra - structure that meets requirements of a database of in situ data and satellite match-ups that can be performed in real-time*

➢ *Develop both short-term and long-term coastal calibration monitoring sites for Navy products particularly in coastal regions*

The primary role of these efforts is to use methodology and resources that NRLSSC and NAVOCEANO have used to quickly implement new algorithms and calibration factors into products for Navy customers. The first three recommendations are necessary for consistency with past product delivery and quality control over present and future satellites. The last two are directed at short-term and longer-term validation efforts to ensure stable product delivery over the history of the satellite and over spatially and temporally changing environments. These require specific calibration monitoring capabilities and the infra-structure for databasing that are not available at the time-scale and spatial scales necessary to support mission needs.

The areas where improvements and necessary adjustments to standing protocols for consistency and support to Navy relevant activities such as those used during OPERATION IRAQI FREEDOM are laid out. These are based on NRLSSC automated processing and transitions already underway at NRLSSC via CNMOC and

NAVOCEANO. We develop a coordinated, integrated calibration/validation plan for Navy ocean satellite products, including the development of standard protocols and procedures to compare satellite retrievals with ground-truth measurements. These can be utilized in all future satellites for a continual product line that can start with the signal from the satellite to the delivery of a mission specific product at time scales not achievable under normal NPP and NPOESS calibration and validation activities.

Introduction:

New remote sensing satellites are under planning and design considerations. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) will replace the current military (Defense Meteorological Satellite Program (DMSP)) and civilian (NOAA Polar-orbiting Operational Environmental Satellites (POES)) satellites beginning in 2013. The six satellite mission should provide environmental information to civilian and military METOC users until approximately 2023. NPOESS will provide 38 products or product combinations of interest to its users. Because a new set of sensors will fly on NPOESS, the NPOESS Preparatory Program (NPP) will fly some of the sensors in September 2009 as a risk reduction effort for NPOESS. While Northrop-Grumman Space Technology (NGST) is the contractor responsible for constructing NPOESS, program management for NPOESS and NPP are the responsibility of the tri-agency Integrated Program Office (IPO) of NPOESS. The Department of Defense (DoD), Department of Commerce (DoC), and NASA are represented in the IPO. Rather than use their own satellites, NASA is looking to NPP and NPOESS to provide the environmental data required to complete their earth science mission. NASA will therefore provide calibration and validation activities on NPP. Each of the NPOESS satellites will also need to undergo calibration and validation of the sensors before they are declared operational. A blueprint for this latter calibration and validation is required for NPOESS. A portion of this blueprint is laid out in the following document for calibration and validation of NPP and NPOESS satellites.

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for the Master Environmental Data Library (MEDAL), 3) chlorophyll, and 4) sea surface temperature.

Abstract

We describe the issues associated with the calibration and validation (calibration and validation) of ocean satellite sensors and systems operating in the VIIRS – Vis/IR Imager Radiometer Suite which is designed as part of the National Polar-orbiting Operational Environmental Satellite System (NPOESS)). Our objective is to develop a coordinated, integrated calibration/validation plan for Navy ocean satellite products, including the development of standard protocols and procedures to compare satellite retrievals with ground-truth measurements. We outline the measurements required, the collection and analysis protocols for the satellite and *in sit*u data, satellite signal to noise constraints for ocean applications, and other important issues that must be addressed to reach the desired levels of accuracy. By building on our existing capabilities and a transition framework that is already in place between the Naval Research Laboratory Stennis Space Center (NRLSSC) and the Naval Oceanographic Office (NAVOCEANO), we can develop and implement a plan now, using existing systems, in preparation for future systems. This approach will ensure that Navy-wide standards and consistency levels will be achieved for all ocean products across all platforms.

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) will replace the current military (Defense Meteorological Satellite Program (DMSP)) and civilian (NOAA Polar-orbiting Operational Environmental Satellites (POES)) satellites beginning in 2013. The four satellite mission should provide environmental information to civilian and military METOC users until approximately 2021. NPOESS will provide 38 products or product suites of interest to its users. Because a new set of sensors will fly on NPOESS, the NPOESS Preparatory Program (NPP) will fly some of the sensors in September 2009 as a risk reduction effort for NPOESS. While Northrop-Grumman Space Technology (NGST) is the contractor responsible for constructing NPOESS, program management for NPOESS and NPP are the responsibility of the tri-agency Integrated Program Office (IPO) of NPOESS. The Department of Defense (DoD), Department of Commerce (DoC), and NASA are represented in the IPO.

NASA is looking to NPP and NPOESS to provide the environmental data required to continue their earth sciences mission, rather than fly their own satellites. The NPP and NPOESS Visible-Infrared Imager Radiometer Suite (VIIRS) will provide the data to continue that mission. NASA will therefore calibrate and validate NPP VIIRS sensor data. However, the missions of NASA and the Navy differ and the VIIRS data must be calibrated and validated to support the Navy-unique product line. A blueprint for calibration and validation of the VIIRS data is required for NPP. This blueprint will be extended to each of the VIIRS sensors on the NPOESS satellites which will also need to undergo calibration and validation before they are declared operational.

There are several ocean satellite sensors currently undergoing calibration and validation (Cal/Val) activities similar to those required for NPP, NPOESS, and GOES-R. These include: AVHRR, SeaWiFS, MODIS (TERRA, AQUA), Hyperion, EO1, ASTER, and classified systems. The Navy has been improving and expanding the ocean color operational products derived from these sensors to support the Navy warfighter (NRLSSC Report to NASA Applications Branch, 2003). Derived properties include sea-

surface temperature (SST) and bio-optical properties such as chlorophyll concentration, absorption, scattering, diffuse attenuation, and beam attenuation coefficients. These derived properties are subsequently converted into Navy products (such as diver visibility, which is based on the beam attenuation coefficient) by NRLSSC and evaluated and tested at NAVOCEANO. Feedback to NRLSSC provides additional validation and helps improve the product for operational use. The emerging satellites will provide an opportunity to further expand the number of ocean products. We are developing the Navy Calibration/Validation plan based on the present confirmation for the VIIRS – Vis/IR Imager Radiometer Suite which is designed as part of the National Polar-orbiting Operational Environmental Satellite Systems (NPOESS) sensors which is outlined in Table 1. The 13 spectral channels of prime interest in this report are: M1 (412 nm); M2(445 nm) ; M3 (488 nm); M4(555 nm) ; M5(672 nm); M6(746 nm); M7 (865 nm); I1(640 nm); I2(865 nm); M12(3700 nm); M13(4050 nm); M15(10763 nm); and M16(12013 nm).

To make the best use of existing and future systems, a coordinated, integrated calibration and validation plan that can be applied to all these sensors and products is required to ensure product quality and consistency. The calibration and validation plan should address issues including image reception (Raw Data Record, RDR to Sensor Data Record, SDR), data flow, processing, property derivation, product development (Environmental Data Record level, EDR), comparison with *in situ* measurements, transition protocols, and ultimate delivery to the end-user. Such a plan will ensure efficient development and product evaluation and guarantee an inter-comparison of sensors and algorithms for smooth transition of products from multiple sensors. Our intention is to build on the existing framework and current capabilities that are in place at the Naval Oceanographic Office (NAVOCEANO) and the Naval Research Laboratory at the Stennis Space Center (NRLSSC) for transition of satellite processing and product development.

Table 1: Spectral, Spatial, & Radiometric Attributes of 22 VIIRS Bands For NPP/ NPOESS

	Band No.	Wave-length (µm)	Horiz Sample Interval (km Downtrack x Crosstrack) Nadir	End of Scan	Driving EDRs	Radiance Range	Ltyp or Ttyp	Signal to Noise Ratio (dimensionless) or NEΔT (Kelvins) Required	Predicted	Margin
VIS/NIR FPA / Silicon PIN Diodes	M1	0.412	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	44.9	352	441	25%
					Aerosols	High	155	316	807	155%
	M2	0.445	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	40	380	524	38%
					Aerosols	High	146	409	926	126%
	M3	0.488	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	32	416	542	30%
					Aerosols	High	123	414	730	76%
	M4	0.555	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	21	362	455	26%
					Aerosols	High	90	315	638	102%
	I1	0.640	0.371 x 0.387	0.80 x 0.789	Imagery	Single	22	119	146	23%
	M5	0.672	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	10	242	298	23%
					Aerosols	High	68	360	522	45%
	M6	0.746	0.742 x 0.776	1.60 x 1.58	Atmospheric Corr'n	Single	9.6	199	239	20%
	I2	0.865	0.371 x 0.387	0.80 x 0.789	NDVI	Single	25	150	225	50%
	M7	0.865	0.742 x 0.259	1.60 x 1.58	Ocean Color	Low	6.4	215	388	81%
					Aerosols	High	33.4	340	494	45%
CCD	DNB	0.7	0.742 x 0.742	0.742 x 0.742	Imagery	Var.	6.70E-05	6	5.7	-5%
S/MWIR / PV HgCdTe (HCT)	M8	1.24	0.742 x 0.776	1.60 x 1.58	Cloud Particle Size	Single	5.4	74	98	32%
	M9	1.378	0.742 x 0.776	1.60 x 1.58	Cirrus/Cloud Cover	Single	6	83	155	88%
	I3	1.61	0.371 x 0.387	0.80 x 0.789	Binary Snow Map	Single	7.3	6.0	97	1523%
	M10	1.61	0.742 x 0.776	1.60 x 1.58	Snow Fraction	Single	7.3	342	439	28%
	M11	2.25	0.742 x 0.776	1.60 x 1.58	Clouds	Single	0.12	10	17	66%
	I4	3.74	0.371 x 0.387	0.80 x 0.789	Imagery Clouds	Single	270 K	2.500	0.486	415%
	M12	3.70	0.742 x 0.776	1.60 x 1.58	SST	Single	270 K	0.396	0.218	82%
	M13	4.05	0.742 x 0.259	1.60 x 1.58	SST	Low	300 K	0.107	0.063	69%
					Fires	High	380 K	0.423	0.334	27%
LWIR / PV HCT	M14	8.55	0.742 x 0.776	1.60 x 1.58	Cloud Top Properties	Single	270 K	0.091	0.075	22%
	M15	10.763	0.742 x 0.776	1.60 x 1.58	SST	Single	300 K	0.070	0.038	85%
	I5	11.450	0.371 x 0.387	0.80 x 0.789	Cloud Imagery	Single	210 K	1.500	0.789	90%
	M16	12.013	0.742 x 0.776	1.60 x 1.58	SST	Single	300 K	0.072	0.051	42%

The present satellite data stream planned for NPOESS has been identified into various levels of processing and data delivery (Table 2). We have identified how these data records applied to the existing Navy satellite data structure to provide a baseline for integration with our present architecture.

Table 2: NPOESS Data records

- RDR – Raw Data Record – Similar to the NASA level 1a - Digital Counts produced on board the spacecraft with appended information for calibration and geolocation.

- SDR – Sensor Data Record- Similar to NASA level 1b – Calibrated, geo-located data in radiance/reflectance and radiance/BB temperature.

- EDR – Environmental Data Record - Similar to NASA level 2 – environmental algorithms and atmospheric correction applied to the digital counts and geophysical data values derived.

- CDR – Climate Data Records – Binning and compositing of ocean environmental data into long term trends.

Currently the Navy is planning to obtain SDRs from the NPOESS sensors via the Integrated Data Processor (IDP) to be located at NAVOCEANO and will integrate their level 2 and level 3 processing described below to generate Navy ocean products. Our effort will include "tuning" the calibration coefficients supplied during the SDR as described below. .

Ocean color products require high radiometric accuracy and calibration at the sensor level (SDR for example) through the final end-user product (EDR level). These high standards are achievable with current technology, but consistent protocols and coordination among agencies and data providers is required to maintain the current product line for ocean products. A consistent calibration/validation activity establishes limitations of algorithms and ocean products and defines the accuracy of operational satellite ocean products. An integrated and complete plan will not only permit optimal utilization of existing satellites but will also provide a template for the new suite of ocean-sensing satellites.

The plan presented in this document is limited to ocean products derived from passive visible and thermal infrared satellite sensors. It is applicable to current systems already in use by the Navy, as well as planned systems under development. Currently, the ocean products have been developed using the NOAA 12 through 17 polar orbiters, SeaWiFS, MODIS – Terra /AQUA, and GOES series of satellites. These sensors are similar to the NPP and NPOESS VIIRS.

In preparation for NPP and NPOESS, it is necessary to establish the calibration and validation protocols and organizational infrastructure for future operational satellite systems. Our objective is to summarize the requirements and issues that must be addressed to develop an integrated calibration/validation plan for satellite ocean sensors. We outline a plan whereby the methods and data collected as part of Navy operations (NAVOCEANO) and naval research (NRLSSC), in addition to ongoing NOAA and

NASA programs, can be used as a focal point for calibration and validation efforts for NPP.

II. The Navy Perspective on Calibration and Validation Requirements

The initial issue for the Navy is to define what entry point into the calibration and validation procedure is appropriate for Navy capabilities and assets. The Navy calibration and validation plan identifies three stages of development in direct line with satellite data processing levels:

1) *Level 0*: Pre-launch calibration and sensor characterization.
2) *Level 1*: On-orbit sensor calibration and sensor precision– application of internal sensors for calibration and stability analysis (solar diffusers, thermisters, and lunar viewing to provide sensor calibration; RDRs to SDRs)
3) *Level 2*: Vicarious calibration where *in situ* observations are "matched-up" with satellite measurements to adjust and optimize the end products (SDRs to EDRs).
4) *Level 3*: Geometric registration and re-sampling (binning) of the satellite ocean product into standard Navy formats for integration into real-time data bases. This is similar to the CDR but will be for Navy ocean products.
5) *Level 4* : (We will not address Level 4 products in this document.)

From this document's perspective, Level 0 and *Level 1* calibration activities fall primarily on additional agencies responsible for specific sensor development and launch and the maintenance and control of the sensor systems which provide direct input to the developing the *Level 1* data stream. These outside activities are not addressed here. Although not totally inclusive, these calibration and validation effort include,

1) Pre-launch sensor calibration and characterization (polarization, stray light etc.)

2) On- board sensor calibration systems (stability and maintenance of solar diffusers, black body thermisters etc.)

3) Maintenance of sensor stabilization and calibration schedule of periodic sensor viewing targets such as Lunar views, space looks etc.

The Navy's primary contribution to calibration and validation is best integrated with *Level 2* as defined above. However, many of the results of *Level 2* calibration and validation will result in a re-evaluation of the calibration and sensor precision determined through the on-orbit calibration effort. Because ocean color and sea surface temperature use different parts of the solar spectrum, the best calibration and validation protocols are not identical. However, as will be pointed out below, there are several similarities so that the infrastructure and capabilities provided by NRLSSC and NAVOCEANO for ocean color and sea surface temperature (SST) complement one another and can be integrated into a common effort.

A. *Ocean Color calibration and validation*

The Navy's evolution   process of generating products derived from the ocean color satellite data is illustrated in Figure 1. Foremost is the requirement that products be based on highly accurate radiometric controls and checks. The process outlined ensures the delivery of an accurate Navy product with global applications even in areas where no *in situ* observations are available. Briefly, Figure 1 shows the progression from characterization and calibration of the satellite radiometry to a Navy product. The steps include:

1. reception of accurately calibrated radiances from the satellite,
2. the application of reliable atmospheric correction procedures,
3. the derivation of spectral water leaving reflectivity (i.e. ocean color), (feedback to the sensor calibration)
4. application of the algorithms to retrieve the ocean optical properties, and
5. production and delivery of specific Navy products for applications.

Calibration and validation of the intermediate data and products are required at each step of the product development process to ensure a high-quality end-product. Otherwise, errors in the intermediate products will propagate and amplify through the development chain and it will not be possible to meet required accuracy constraints for the final product.

For NPP and NPOESS, the onboard sensor calibration (through *Level 1*) must meet or exceed the sensor specifications outlined for the MODIS and SeaWiFS satellites.

(The sensor specifications of the NPP/ NPOESS outlined in Table 1, while similar are not identical to the MODIS sensor specifications presented in Table 3 (Appendix A). Note, in particular, the higher Signal to Noise ratio (SNR) in MODIS as compared to that in the NPP sensor.

{Note: The impact of these differences in the VIIRS specification between MODIS and NPP may significantly impact the derived Navy ocean color products. However, the magnitude of the impact caused by these differences is beyond the scope of this white paper.}

As demonstrated in the MODIS specifications, which are currently used for several Navy products, there are extremely rigid radiometric standards required to meet the accuracy for Navy products. Although strict, procedures (calibration and validation activities) are being successfully applied to SeaWiFS and MODIS satellites to generate high quality products. The process is closely aligned with NASA and NOAA product development, but there are some differences. The Navy requires calibration and validation procedures within a framework based on requirements for real-time processing and dissemination of products, whereas the NASA-NOAA mission requires protocols dedicated to longer time periods and establishing Climate Data Records. This suggests several differences in ocean product development and subsequent calibration and validation issues that arise between agencies in order to meet their respective mission requirements. Our intention, within the Navy, is to coordinate Navy calibration and validation procedures as much as possible, taking advantage of an interagency collaboration and asset sharing. However there will be times, such as updated algorithm data reprocessing, quick sensor performance and calibration deviations, and rapid Navy response needs, where the Navy's real-time requirements will "over take, or take precedence over" long term monitoring requirements.

A primary Navy calibration issue is to "accelerate" calibration and validation procedures to provide for real-time processing and updates. This is accomplished by integrating calibration and validation procedures into automated "real-time" product development (explained later). The Navy's existing calibration and validation procedure and template for future work is illustrated in Figure 1 which is used for the MODIS and SeaWIFS satellites. Our intention is to extend this calibration and validation effort for

follow-on sensors to ensure consistency of Navy products and to permit generation of new algorithms and expanded product line. Navy Research and Development programs have a strong presence in the operational transition of new algorithms into the next generation of Navy products. Our plans are to make these products rapidly available to NAVOCEANO operations as these products are developed, tested, and validated in a joint NRLSSC/ NAVOCEANO effort. The roadmap to rapidly get an operational product to the fleet is embedded into the calibration and validation process. These Navy calibration and validation steps are expanded below.

Steps in the Navy Ocean Color Product Development Process:

Sensor Calibration - The initial step (Fig. 1) involves the pre- and post-launch on-board sensor calibration and characterization. This step is typically the most difficult but it determines the long-term stability of the sensor. This step includes sensor drift (spectral response) and spectral (channel) accuracy over time. Once on orbit, *Level 1* calibrations are applied to the data. (Liao et al., 2003). These are determined through on-board internal radiometric checks for sensor stability that include viewing a solar diffuser and/or periodic views of the moon (Lunar calibration). The corrections for spectral drift are critical precursors for subsequent processing steps, but it may be necessary to further modify the calibration coefficients if follow-on steps indicate that adjustment is necessary to produce an accurate product. This adjustment uses optimization schemes designed to minimize the error associated with the final product. However, our first step in the process is to use the *Level 2* sensor calibration information provided by the designer and the NPOESS project. This use of the SDR level data permits error analysis between the raw sensor data and the operational product. The mid-level science data record is used in algorithm development and product formation. It is only after we have gone through the remaining steps that sensor calibration is refined to optimize the final Navy product.

Vicarious calibration provides for continuous monitoring and adjustment of sensor performance. It also minimizes the error in the final product since results from every step in calibration and validation are compared to ancillary information. NASA and Navy have used a similar procedure based on the radiometric measurements from the in-water MOBY buoy (Hawaii) to optimize the retrieved radiance for this open ocean,

relatively stable site (Harring et al., 1997, Clark et al., 2001). For many spectral channels this adjustment to calibration has been important for ocean open waters. For Navy applications in coastal waters, however, the vicarious calibration requires additional protocols to deal with the variable environment. This may include vicarious calibration of spectral channels not often used or even needed for open ocean applications. Therefore an important aspect of calibration and validation is the establishment of one or more coastal calibration sites. For NPP and NPOESS this requirement is critical in order to calibrate and validate the SDR and EDR obtained in coastal environments.   The protocol for coastal operational application requires special consideration.
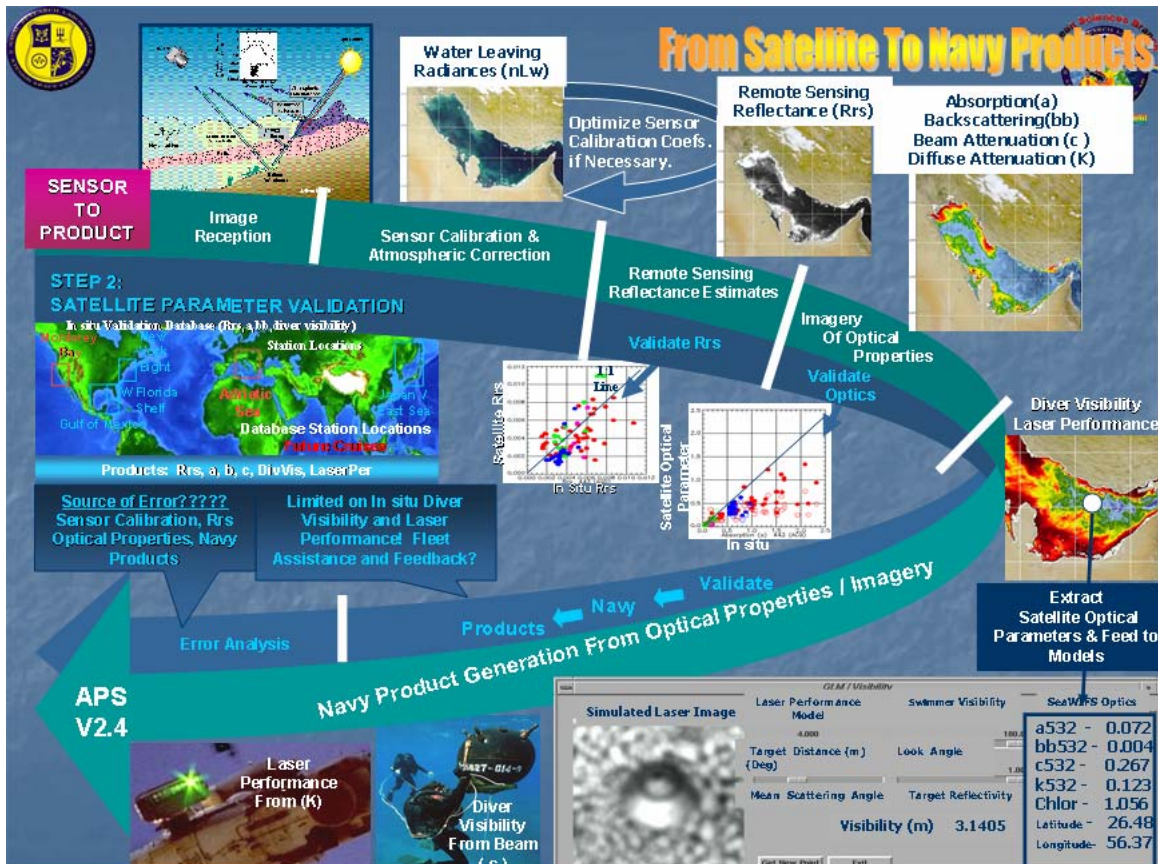
Figure 1- Illustrated steps from Sensor to Product calibration and validation used by Navy for Ocean Color

While vicarious calibration in coastal waters is difficult it still remains a necessity for validation of Navy products. There are several identifiable problems that affect vicarious calibration and validation procedures in this environment and include:

1. high spatial variability of coastal waters that make individual pixel match-ups with *in situ* data difficult,

2. high temporal variability that creates uncertainty in data consistency for the match–ups,

3. high variability of the vertical light field that causes difficulty in the *in situ* measurement of remote sensing reflectance and optical properties, and

4. low reflectance signals in blue wavelengths (400-450 nm) due to increased levels of dissolved and particulate materials that absorb light at these wavelengths and therefore requiring higher accuracy and precision in this spectral range, relative to open-ocean measurements, and

15

5. non-uniform aerosol distribution in the coastal environment that causes unit correction problems.

Atmospheric Correction - Because the atmosphere can contribute as much as 90% of the total signal measured in space, atmospheric correction is an extremely important step in calibration and validation for ocean products. The atmospheric signal (noise from an ocean perspective) can be partitioned into Rayleigh (molecular) and aerosol scattering components. The correction for the Rayleigh component is based on the sun-sensor-pixel geometry and the aerosol component is modeled using several near-infrared spectral channels. Therefore errors in the radiometric calibration (RDR and SDR level in NPP) and atmospheric correction procedures lead to major errors and uncertainty in the water-leaving radiances (ocean reflectivity). To generate Navy products, ocean reflectivity must be accurate to 2-5%. Such accuracies require tight measurement protocols and measurement specifications.

The standard NASA atmospheric correction algorithms were originally developed for open-ocean regions and use only the near-infrared (NIR) spectral channels to estimate the atmospheric contribution. To limit errors, highly accurate and precise calibration is required for these channels. However, there are problems with the NIR atmospheric correction when applied to coastal waters due to scattering by suspended sediment impacting the NIR channels. Different methods are required to atmospherically correct satellite imagery over coastal waters.

To meet this challenge the Navy has developed a coupled ocean/atmosphere (radiative transfer?) model to improve atmospheric correction in coastal waters (Stumpf et al., 2002). By applying an iterative solution between the initial atmospheric correction step and subsequent steps (i.e. deriving the ocean water reflectivity), an optimal solution to separate the atmospheric and oceanic signals is obtained. The method is based on determining the water reflectance in the NIR channels to separate the surface and atmospheric radiance before removing the atmospheric signal from the visible spectrum; this increases the reflectance in the blue channels. This approach was required to eliminate the negative radiances obtained using standard atmospheric correction techniques for the open ocean water. This methodology also accounts for reflectivity of

the sea surface (sky reflectance) and includes radiance corrections for white foam on the surface. In calibration and validation this type of consistency check is required for derivation of accurate EDRs.

Water reflectivity – Remote sensing reflectance (RRS; or spectral water reflectivity) is the ratio of the water-leaving radiance to incident irradiance (the total sunlight and skylight striking the sea surface). The satellite sensor measures the total radiance, including contributions from the water, the water surface, and the atmosphere, and it is dependent on solar and viewing angles. The RRS can be measured at the sea surface and therefore is a primary property of satellite validation. Measurement of RRS is very difficult, especially in coastal waters, and requires exact (and tested) protocols. Changes of 10 – 15 % between instruments and protocols can occur and these errors cascade into other calibration and validation efforts. The spectral RRS are used by algorithms to derive the bio-optical properties of the near-surface waters. This property is commonly used in the match-ups of the SDR's from the satellite and that measured at the ocean surface (ground-truth data) prior to incorporation into algorithms.

In-water optical properties - The spectral RRS is used to estimate bio-optical properties using a suite of inversion techniques and algorithms. These algorithms range from simple empirical algorithms (the NASA OC3 chlorophyll 3 channel ratio method) to complex semi-analytical algorithms such as those used to retrieve the inherent optical properties (spectral absorption, backscattering, colored dissolved organic matter absorption, and phytoplankton absorption). Most Navy products are tightly linked to the inherent optical properties of the waters and the Navy currently uses approximately 10 RRS algorithms to develop Navy products. These algorithms and bio-optical products undergo continuous validation, including match-ups with the in-water optical properties.

Match-ups between satellite-retrieved optical properties and *in situ* measurements are an important step in the calibration and validation of the bio-optical algorithms. Furthermore, the optical properties can be coupled with radiative transfer models to help validate the remote sensing reflectance expected at the surface. Recent advances in optical instrumentation allow *in situ* measurement of the inherent water optical properties. The measurements are difficult, however, particularly in the rapidly-changing coastal environment. In this environment instrumentation methodology and protocols are

definitely required to permit cross-comparisons between cruises and investigators. Ongoing validation efforts of the Navy ocean optical products have demonstrated good agreement with observations (Ladner et al., 2002, Moline et al., 2003, Saha et al., 2003).

To assist in this effort, Navy research has an advanced set of optical instruments and has established exact procedures for measuring the in-water optical properties. This calibration and validation step helps determine the accuracy of the derived satellite properties. This step is also where most algorithms are developed and where satellite ocean research is linked to the ocean processes. Navy products are associated directly with the retrieved water optical properties; this is a slightly different approach from NASA or NOAA who are interested in biological properties such as chlorophyll as the EDR. It is usually easier (and more accurate) to quantify the relationships between RRS and optical properties than it is to link RRS with biological properties, because of the difficulties of cell physiology, structure, and adaptation.

Navy Ocean Products - The last step in the Navy ocean color product generation is to use the optical properties such as absorption and scattering to develop Navy-relevant products, such as diver visibility or laser-penetration depth. These EDR type products are often difficult to validate, since they may or may not have direct methods of measurement. This last step often requires a suite of algorithms that may be based on system-specific performance and are linked to ocean processes that influence system performance directly. Therefore this step is difficult to validate because these products deal with 1) classified systems and their particular responses to the optical properties, 2) non–quantitative metrics such as diver eyesight, and 3) have multi-parameter effects that are often not described by a linear set of optical measurements. Consequently calibration and validation requires direct feedback and interaction between the operational customer and the product developer. The use and interpretation of the operational product by the "customer" is often the key in the validation of the product. Recent efforts with Navy operational products using MODIS satellite imagery for diver visibility are outlined in Arnone et al., 2003 demonstrating this feedback. Adjustment of calibration coefficients based on user input allows for a rapid improvement of the operational Navy product and real-time capabilities which are critical for Navy EDRs.

Calibration and validation activities are required at each step in the development process outlined above. A simple "match-up" of the end product with the observations is not sufficient. Each step contributes to errors and uncertainty in the accuracy of the end product. There is not just one algorithm, but a number of algorithms applied sequentially and each can contribute error to the final product. Therefore, it is important to track the errors at each step. Understanding the propagation of errors, and the accuracy and limitations of each step is critical to the understanding of the accuracy and reliability of the final product. As outlined above these include the errors associated with:

1) sensor calibration coefficients for application to the radiance levels,
2) atmospheric correction algorithms,
3) remote sensing reflectance algorithm,
4) in water bio-optical algorithms, and
5) Navy product algorithms.

In the Navy's calibration and validation plan vicarious calibration procedures will be used initially to minimize the error in satellite RRS based on the *in situ* observations (Ladner et al, 2002). The sensor calibrations will be adjusted to optimize the match between the retrieved RRS and the measured values. Likewise, the error in the optical properties (absorption, backscattering) is minimized based on the *in situ* observations by adjusting the calibration and validation via the water bio-optical algorithms. To improve this capability NAVO and NRLSSC are establishing and merging coastal data sets of optical property match-ups to improve the calibration of satellite sensors. For ocean color products this iterative procedure assures the highest quality of end-product with internally consistent radiometric quantities and derived optical properties.

B. Sea Surface Temperature

The present NAVOCEANO SST operational product (EDR) is calculated from either AVHRR or GOES satellite data (May et al, 1998; May and Osterman, 1998). SST retrieval production follows the fundamental theory that differential absorption of surface emitted infrared radiation from multiple wavelength channels can be utilized to estimate

atmospheric absorption corrections to obtain absolute SST. AVHRR and GOES SST algorithms use either 2 or 3 infrared channels.

Several forms of algorithms exist to derive SST from satellite data. The most popular methods include either regressing satellite channel brightness temperatures against atmospheric transmission model radiances to generate theoretical algorithms or else regressing satellite channel brightness temperatures against in situ SST measurements to generate empirical algorithms. The Navy satellite SST products are produced using empirical algorithms obtained by matching satellite data to accurate drifting buoy and moored buoy SST measurements. The procedures that have been developed for deriving and validating the accuracy of the satellite SST products are easily modified to fit into the NPP and NPOESS calibration and validation protocols.

There are several methods available to validate SST products. These include methods for both the Bulk temperature and the Skin temperature. Bulk temperature measurements can be made with several instruments. However, the skin temperature can be measured by ships at sea and/or moored buoys using only a select set of radiometer instruments. Hence only a limited set of Skin Temperature data is available to ensure proper calibration and maintenance of the radiometer during operation. Unfortunately only a handful of academic and international agencies today can provide these high quality radiometer instruments that meet the specifications needed to validate satellite skin SST retrievals. Various other less accurate radiometric instruments have been deployed and utilized in specified locations around the world to validate satellite skin SST measurements.

The validation process for Sea Surface Temperature (SST) is very similar to that used for ocean color with numerous steps taken in the calibration and validation of remotely sensed channel data. Like ocean color, a critical requirement is the availability of extremely accurate onboard radiometric measurements and monitoring of sensor characteristics. The SST product is extremely sensitive to deviations in sensor calibration consistency, and therefore a buoy (*in situ*) monitoring program is required to assure product accuracy over time (described below). The steps for calibration and validation include:

1. pre-launch and post-launch characterization and radiometric verification,

2. application of cloud detection and removal algorithms,

3. monitoring of sensor drift and stability with co-located *in-situ* buoys,

4. minimization of error between retrieved and measured temperatures and cloud detection capabilities,

5. secondary tuning of coefficients minimizing error in SST retrievals (i.e. optimization of the algorithm).

Pre-launch and Post-launch Characterization- The Navy's initial SST product, using NPP and NPOESS, will incorporate the sensor channel calibration coefficients provided by the NPOESS project for the level 2 data stream. It is important that spectral channel accuracy and sensor drift are accounted for properly in the calibration process. The initial sensor calibration will be determined through on-board internal radiometric control and sensor stability. Sensor stability and drift has significant impact on the resulting SST product generated. Because of the sensitivity to radiometric accuracy, the sensor pre-launch characterization is an important part of sensor performance verification. A thorough pre-launch sensor performance and characterization process must be undertaken to verify that the instrument is adequate and can be precisely calibrated when placed in orbit. After launch, the stability and performance of the sensor channels must be closely monitored to ensure that on-board calibration methods are performing to specified standards and requirements.

Cloud Contamination Removal- The quality of the SST product is highly dependent upon the efficiency of the cloud detection process. The calibrated satellite channel radiances are utilized to perform extensive cloud detection tests. This is critical to ensure that SST products do not include cloud contaminated data. This process ensures that satellite SSTs are derived from only high quality, cloud-free pixels. The steps for cloud contamination removal include- multiple channel inter-comparisons for channel consistency, examination of spatial coherence across the image and among channels, and channel threshold testing. Understanding the accuracy and limitations of each step is critical to the accuracy of the SST product. NAVOCEANO uses the cloud detection tests documented in (May et al, 1998).

Temperature Algorithm Stability and Calibration Monitoring- SST equation coefficients are continuously monitored (and updated if necessary) using a variety of methods. The initial procedure minimizes the error in the satellite SST retrievals by comparing retrieved SST to co-located buoy SSTs, historical SST data fields, and other satellite derived SST values for the region. An SST match-up database containing drifting and moored buoy SSTs and satellite SSTs that are matched within specified time and distance constraints is used. The database is updated each day by matching new satellite retrievals to the latest buoy SST measurements received. The NAVOCEANO match-up database receives information from several hundred buoys each day worldwide.

The major steps in the buoy data match-up are outlined in Figure 2. The steps of the procedure are: a) the ingest of buoy temperature measurements, b) update of daily and historical data information, c) match-ups of SST buoy and SST satellite derived temperatures, and d) calculation of statistical deviations and anomalies in the data.
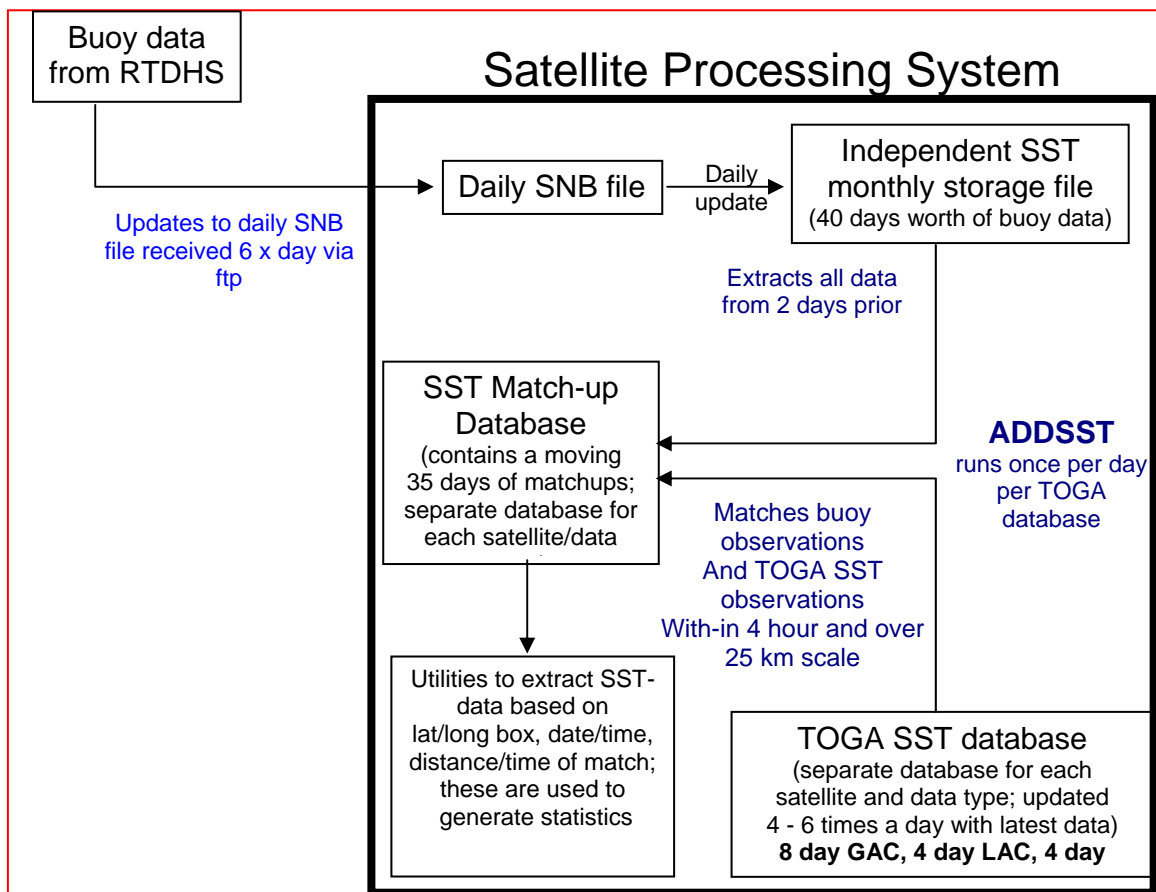

Figure 2   NAVOCEANO Operational SST Satellite Processing System calibration

The NAVOCEANO match-up database provides information needed to track and validate the SST equation performance. Figure 3 illustrates the location of sea surface temperature in situ data for the month of January, 2004. The plot represents locations from drifting buoys and moored TOGA TAO and PIRATA buoy arrays. The in situ buoy measurements are obtained via the real time GTS data feed. These data come from sources such as 1) Navy platforms and drifting buoys, 2) NOAA platforms (ships and buoys), 3) university platforms and moorings, and 4) international agency or university platforms and moorings.

Bulk SSTs are matched up with the satellite data to calculate weekly statistics of bias and variance. These statistics are monitored over time to determine if sensor drift, cloud contamination, and/or SST algorithm error is occurring. Based on these statistics, more detailed investigations can be undertaken to identify the cause of algorithm error and what corrections need to be made.
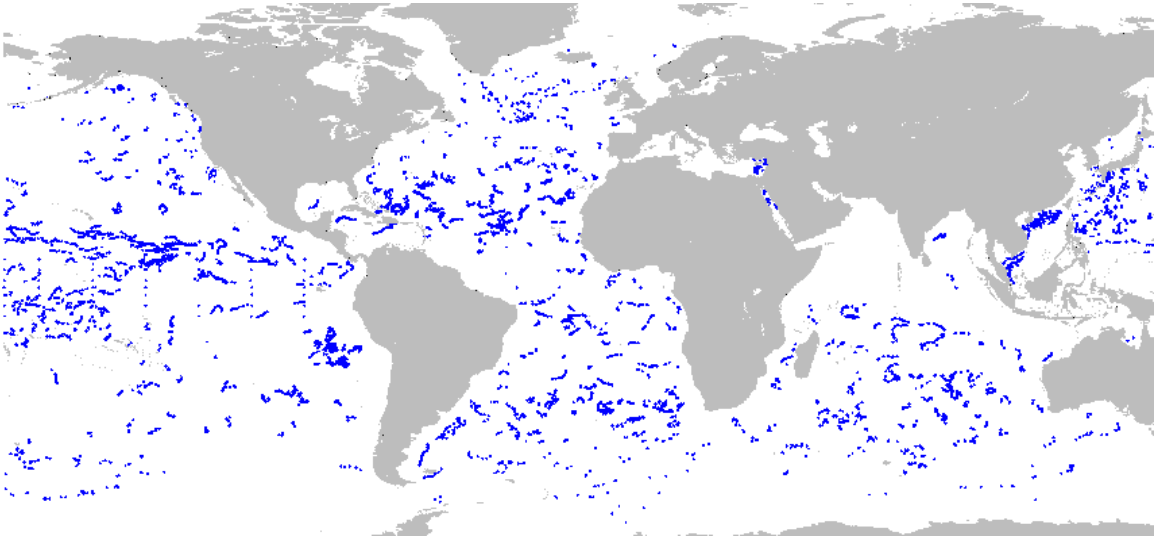
Figure 3. NAVOCEANO Buoy match-ups for the month of January 2004.

Minimization of SST error and secondary adjustments - The historical time series record of algorithm error statistics provides the information needed for accurate SST production. By minimizing the error in the cloud detection schemes, we are also minimizing the error in the resulting satellite SST retrievals. This helps constrain the validation issue by removing cloud interference as much as possible. SST match-ups from the historical record (30 day period (JD 332 – 361) are presented in Figure 4) are

examined on a monthly basis to provide for the best calibration and validation. These differences in SST in Figure 4 are shown as a function of the temperature. Note that the majority of the match-up differences are clustered about 0 deg. C with greater variances at ~ 24 degree. The errors are tied to the individual temperatures.

When a satellite is first launched, satellite SSTs are first generated using a theoretical SST equation or else an equation from a previous satellite. The matchup information described above is then collected for two months and examined for accuracy. New SST equations are regressed from half of the data and then independently tested for accuracy against the other half of data. The resulting equations are typically accurate for a few years, but are monitored continuously in case changes are necessary. If required, such changes typically occur within weeks of the match up examination. By continuously monitoring these differences, the health of the satellite, the sensor channel calibration coefficients, cloud detection methods, and SST equation algorithm can be monitored.

Buoy SST Type 152 Julian Days 332 - 361
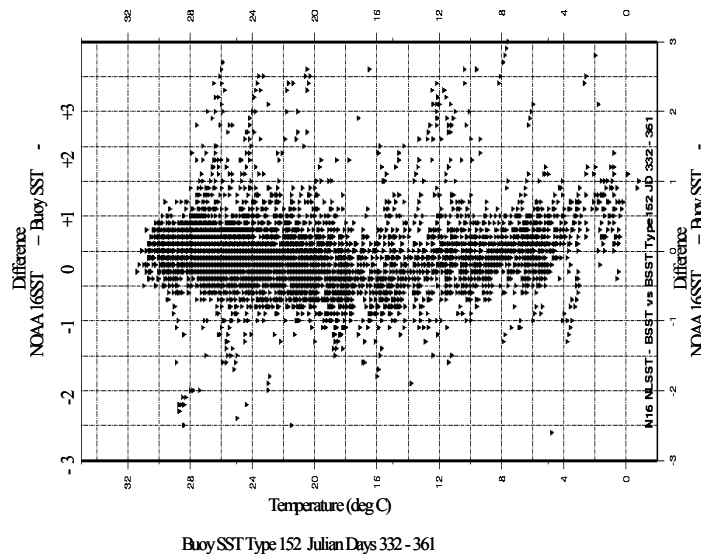
Figure 4. SST match-ups showing statistical deviations.

The validation and adjustment of satellite SST products from buoy derived data uses appropriate *in situ* measurements for satellite data match-ups. In-water buoys can measure bulk temperature (T_b) while above-water thermal radiometers measure only surface skin temperature (T_s). While still being debated, NAVOCEANO has found very good agreement between the buoy-derived "bulk" SST and the satellite derived values.

The protocols for these modeled relationships require careful assessment of potential errors.

Remote sensing only measures surface temperature. Therefore a key issue in SST product formation is the relationship required to get an accurate SST using both Skin Temperature and Bulk Temperatures. Thus, in order to calibrate and validate the SST values, information on the transfer of temperature across the air-sea interface is required. The air-sea interface fluxes are highly dependent upon accurate knowledge of the skin temperature. Thus it is important that accurate skin SSTs are obtained. These temperatures are used together with coupled ocean-atmosphere models to improve SST retrieval accuracies. The modeled skin temperatures are validated using the accurate, but sparse, shipboard radiometric measurements.

By continuously monitoring the differences in SST throughout areas, a statistical record of the algorithm performance can be adopted. This supplies information on both the health of the satellite and the SST generation process. The statistical temperature differences can be used to adjust the SST algorithms and cloud detection tests. However, the statistical differences have also been very useful in identifying sensor channel calibration problems associated both with AVHRR and GOES sensor systems. The most notable cases whereby SST algorithm examinations revealed satellite sensor problems are the midnight calibration effect present with GOES, and the AVHRR calibration problems at the terminator (when the spacecraft crosses from nighttime into daytime). The complexity of the SST approach requires a well characterized calibration and validation approach for the NPP and NPOESS satellites. This must include approaches to measure and validate both skin and bulk temperatures and are therefore steps that are included in the Navy's overall SST planned calibration and validation activity.

As part of the Navy's proposed NPP/NPOESS calibration and validation effort a suite of SST buoys will be needed. These SST measurements will be used for primary calibration and validation for satellite SST retrievals. This buoy suite will supplement that already in use for the NAVOCEANO SST algorithm calibration and validation procedures. Measurements from these buoys must be supplemented with radiometric measurements using shipboard skin SST radiometers in order to provide the most reliable retrieval of SST products.

III. Ongoing Ocean Calibration/Validation Activities within the NAVY

There is no long-term ocean calibration and validation activity for remote sensing within the Navy that is specifically identified and funded. Most calibration and validation efforts are off-shoots of other programs that require, to varying degrees, the calibration and validation of remote sensing products. Most of these calibration and validation efforts take place either in the transition of algorithms or in the basic research associated with oceanographic process studies.

The primary Navy ocean color effort is located at NRLSSC. NRLSSC conducts basic and applied Navy research aimed at ocean color algorithm and software development, with ultimate transition to NAVOCEANO for fleet support. The primary focus has been the algorithm development for coastal waters. This effort has been built on years of field measurements and close cooperation and coordination with other members of the ocean color community, including NASA, NOAA, and universities.

While not specifically identified as calibration and validation efforts, activities within the Navy (NRLSSC/NAVOCEANO) still continue. Embedded in Navy activities include the comparison of the *in situ* and satellite values. This is a long-term effort that must be performed regularly to characterize sensor drift in order for the Navy to utilize satellite products. The ongoing comparisons lead to time-varying calibration coefficients and corrections. This results in continuous corrections that require constant evaluation and testing of the algorithms. This methodology is the only way to determine whether the modifications and refinements lead to an improved product, or if new algorithms are needed to provide a more reliable product.

An inter-comparison of products derived from different sensors is critical for Navy operations, and is a component of on-going activities. Through ancillary activities in algorithm development the Navy must be confident that an optical coefficient derived for a given area will be accurate and consistent, regardless of the satellite sensor that collected the data. But such efforts to characterize the sensors rely heavily on the calibration procedures which is not a fundamental component of the Navy's present satellite program. Differences between sensors, including spectral wavelengths,

bandwidths, sensor response and sensitivity, must be thoroughly characterized. These factors must be accounted for with the calibration maintenance and the algorithms development. Even though a full calibration/validation effort is required for customer use of satellite products, this is beyond the on-going Navy's activities thus far. The strongest component of the Navy's ongoing calibration and validation program lies in the rapid ability to process satellite data, integrate new algorithms, and then test the products with match-up data bases. This is accomplished using the Automated Processing System software (APS, detailed below) developed by NRLSSC and a strong NASA/Navy/NOAA collaboration. The APS software is used to generate Navy ocean color products and has been transitioned to NAVOCEANO for operational product formation. The satellite calibration and validation is linked with APS software and is part of the transition processes between NRLSSC and NAVOCEANO.

The SST calibration and validation effort is more standardized in the Navy than the ocean color. While much of the ocean color validation and calibration takes place within the research and development community, the majority of the SST validation is performed at NAVOCEANO. This is in part due to long existence of the NOAA AVHRR satellite network and the number of ocean temperature measurements and *in situ* buoys continuously deployed. These buoys and their role in the calibration and validation of the SST have been previously discussed. As new algorithms are developed for current and planned satellites (i.e. MODIS and then NPP and NPOESS) they can be incorporated into the APS for transition. The validation match-ups and the coefficient upgrades needed for the SST products from these satellites (currently with MODIS) can be integrated into the NAVOCEANO SST calibration program using APS. This will be similar to the present AVHRR program with buoy match-ups however linked to the ocean color procedures in a more direct manner.

The Navy activities in calibration and validation outlined in section III.C could not be accomplished without the interaction with other agencies. The largest collaborations take place with NASA and NOAA for ocean color and SST respectively. The ocean color requires the largest interaction since algorithms and protocols are being continuously developed and tested for coastal applications.

A. NRLSSC, NAVOCEANO and NASA interaction

The Navy has a strong interaction with NASA. Through NRLSSC, the Navy participates on the NASA SeaWiFS and MODIS Science Teams, as well as the Sensor Inter-comparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) Program. Whereas NASA has focused primarily on open-ocean waters, Navy interests extend the atmospheric correction and optical algorithms into coastal areas. The NRLSSC remote sensing algorithm development with its associated calibration and validation efforts target products specific to Navy applications in these coastal environments. From the operational perspective, NAVOCEANO tests and evaluates optical products and provides feedback to NRLSSC, allowing refinement and improvement of the algorithms and products. Through interaction with NRLSSC, NAVOCEANO stays abreast of updates in algorithms and calibration and validation efforts for the SeaWiFS and MODIS satellites.

Due to the requirement of highly accurate radiometric data, the Navy works closely with NASA to establish consistent protocols that provide for accurate *in situ* radiometric measurements. This data is then used for calibration of ocean color sensors (Mueller et al, 2002). Much of the color protocols have been a joint effort and the Navy has adopted these protocols for data collection and sensor calibration. This effort was initiated with the SeaWiFS satellite due to the identifiable problems of previous satellites and their long-term calibration and validation. The calibration protocols and stringent measurement procedures have continued with the MODIS sensors. Currently these procedures are being extended to other satellites such as EO-1 Hyperion and Advanced LANDSAT Imager and are expected to be a key component of the NPP and NPOESS calibration and validation procedures. As noted above in both ocean color and SST product formation the radiometric accuracies significantly impact the final product's data quality.

For SeaWiFS and MODIS, the NRLSSC calibration and validation procedures are initially based on the Level 0 and Level 1 calibrations provided by NASA (RDR to SDR for NPP). But *the in situ* data match-ups from SIMBIOS and other Navy field programs helps "re-calibrate" the satellite sensors and atmospheric correction processing for coastal applications. For NASA, substantial radiometric correction of SeaWiFS and MODIS in

the open ocean are a result of the MOBY open-ocean calibration site off Hawaii. These ongoing checks, comparisons, and corrections to the sensor data are critical for the long-term stability and accuracy of the ocean color sensors. The Navy's implementation of the NASA protocols allows for some Navy data to be submitted to the NASA *in situ* data bases (SEABASS). It is the Navy's desire to continue this cooperative exchange.

The Navy has adopted many of the procedures implemented by the NASA satellite programs for calibration and validation. In particular has been the establishment of guidelines for calibration and database match-ups for developing inter-sensor comparisons. For the coastal waters the Navy has taken the lead role in these data match-ups. NRLSSC has created a match-up data base based on the SIMBIOS data formats for the Navy in coastal waters. This facilitates mechanisms to interlink NASA and Navy efforts and leverage off of *in situ* observations collected by various agencies. The data match-up is one of the key mechanisms by which calibration and validation takes place. However, due to spatial and temporal constraints it is also the most difficult. The Navy envisions this as a thrust area in the NPP and NPOESS calibration and validation efforts. There are efforts underway to optimize data match-ups and minimize errors associated with spatial and temporal issues.

Towards the data match-ups, NRLSSC is currently developing web-based, interactive tools that will facilitate calibration and validation activities for many sensors including NPP and NPOESS. The tools are being developed to more easily match-up satellite retrievals with *in situ* ship observations of optical properties and SST. As ocean color and thermal satellite imagery is processed at NRLSSC, the data files are automatically archived in an SQL data base, enabling rapid browse and search capabilities on the data. Similarly, an SQL data base is under development for the *in situ* ship data. Metafiles are created for each station with pertinent information concerning date, time, location, properties measured, etc. To perform calibration and validation of the sensors and algorithms, the user enters a region of interest, a time period, and a property (optical or SST). The software "matches-up" the station information with the corresponding satellite imagery and retrieves the satellite estimates. Options are available for plotting the data or exporting ASCII data files to external spreadsheet software for subsequent analysis.

The automatic processing capability (via APS below) of these routines greatly simplify the *Level 2 (SDR)* calibration efforts since both imagery and *in situ* data are easily added to their respective data bases. These data bases and programs are being created with the flexibility to be extended to include future satellite sensors. The ability to "match-up" areas over various pixel areas allows for error analysis in both the measured (*in situ*) and satellite retrieved properties. The transition of this data base is targeted toward NAVOCEANO where additional match-up and real-time calibration can be performed. Currently, NAVOCEANO optical data is being linked into the match-up validation data bases.

In order to have the best possible match-up data, NRLSSC and NAVOCEANO are devoting considerable effort in developing protocols for instrument measurement techniques, in situ data processing, and spatial and temporal data analysis. The instruments and measurements needed for calibration and validation are listed in Section V. The NASA/Navy interaction has helped define the measurement protocols and the data processing required to give accurate in situ data. This includes the remote sensing reflectance and inherent optical properties used at the SDR level and the EDR level. The instruments and measurement techniques are transitioned to NAVOCEANO via NRLSSC/ONR/NASA for implementation in their survey program. This effort between NRLSSC/NAVOCEANO, and NASA provides a match-up data base that can be utilized for NPP and NPOESS satellite and algorithm calibration and validation efforts.

B. Calibration/Validation activities within the Automated Processing System (APS)

One aspect of Cal/Val that has plagued many efforts is the ability to rapidly process imagery, ingest new calibration coefficients, implement new algorithms, and then validate results. To overcome this problem NRLSSC and NAVOCEANO have developed the Automated Processing System (APS) for operational processing of satellite imagery (Martinolich et al, 2002). This software ingests, processes, and archives satellite imagery from multiple sensors. This software is established as the Navy's operational software for ocean color, with plans for MODIS SST products as well. The software's concept and basic structure is applicable to satellites such as NPP and NPOESS.

The basic task of this software is to process 1000's of scenes automatically and to establish a regional area (target location) where automatic real-time products can be generated. The process is set up to easily move files into a series of directories and then using a set of scripts produces specific customized products. One of the advantages of the software is that it provides a method to very easily re-process data with new calibration and new algorithms by simply moving files into the input directories. This allows for comparisons of new algorithms, new calibration coefficients for sensors, and new spatial and temporal match-up data sets; it facilitates all calibration and validation efforts.

Navy satellite requirements are driven by real-time aspects where many ocean products are required routinely. The volume of satellite imagery provided daily amounts to significant processing. The APS software provides NAVOCEANO and potentially other agencies with the ability to address many different ocean regions around the world for Cal/Val efforts. The ability to modify algorithms quickly then reprocess data makes APS extremely valuable in calibration and validation efforts.

Figure 5. Web site of operation satellite ocean products. Red dot locations indicate the real-time ocean products are being tested and evaluated.　　　　　**www7333.nrlssc.navy.mil**

Testing and improvements to the APS are done at NRLSSC who uses the APS for testing R&D algorithms and improving the data handling architecture; processing approximately 5- 8 gigabytes of data from around the world on a daily basis. Daily pre-operational products are accessed through a website (http:www7333.nrlssc.navy.mil, Figure 5) which also contains links to the match-up data base. This provides for quick assessment of on-going calibration and validation activities.

Currently, APS handles AVHRR, SeaWiFS, MODIS, OCM and MERIS imagery and it is flexible so the code can be modified to accommodate new sensors. Processing within APS includes atmospheric correction, geo-rectification (warping to a Mercator projection), derivation of geophysical parameters, and compositing. This process, in effect, goes from the RDR to the EDR for the NPP and NPOESS systems. The geophysical parameters are estimated through the application of the thermal and bio-optical algorithms. Weekly and monthly composites are generated to reduce the number of cloud-contaminated pixels. NRLSSC works closely with NASA, NOAA, and the University of Miami to ensure that the latest coefficients and algorithms are implemented in the software.

New versions of APS are distributed routinely as new capabilities are implemented. Whereas new research versions of APS that reside at NRLSSC are constantly undergoing upgrades and improvements (to the algorithms and processing flow), the operational version at NAVOCEANO has undergoes extensive operational testing and evaluation. (OPTEST and OPEVAL). As new versions are developed at NRLSSC and tested for stability and robustness, they are released to NAVOCEANO. This ensures that the software meets operational standards in accordance with NAVOCEANO guidelines. As part of a calibration and validation procedure this incorporates customer requirements at the EDR level with the RDR to SDR to EDR calibration and validation. This also assures quality control and quality assurance. This quality control and assurance is an aspect of calibration and validation that must be maintained for the NPP and NPOESS system data processing and algorithm testing.

C. Coordinated Navy projects with ancillary calibration and validation efforts
As indicated previously there are several ongoing activities and Navy programs that address different calibration and validation aspects. These include possible resources that an integrated Navy/IPO program could leverage from for future NPOESS:

1) *SPAWAR – "Ocean Optical Products" –*

This is one of the primary Navy R&D activities that impacts calibration and validation efforts. Through this program NRLSSC transitions MODIS and SeaWiFS processing software and algorithms to NAVOCEANO. This program provides the infrastructure to develop and transfer new algorithms from research to Navy operational mode. The standard algorithms, procedures, and methods are quality controlled for product quality assurance. The calibration and validation activities conducted under the NASA MODIS and SeaWiFS programs are also linked to, and coordinated with, this program. As new sensors are launched and new algorithms are developed, this program incorporates the required modifications into APS when the new satellite systems are targeted as potential operational resources for Navy applications. NAVOCEANO and NRLSSC have established a working group to facilitate implementation of algorithms and sensors into operations, and the changes made to APS (new versions) are eventually transitioned to NAVOCEANO through this program.

This program has helped establish a data base of *in situ* optical properties which have been collected by NRLSSC from research programs over the last 5 years. The data base was required for the algorithm development, calibration and validation. The *in situ* data base uses formats consistent with the SIMBIOS NASA Program, to maintain compatibility with ongoing NASA programs and sensors. This extensive data base is the source of future algorithm initial development. NAVOCEANO conducts extensive field programs in support of fleet planning operations and is also contributing to this *in situ* data base.

As previously presented this optical data base is continually updated with new measurements and is used to provide calibration and validation information for transition products and the algorithms. An effort is underway to automate the process whereby the *in situ* observations and satellite imagery is matched in space and time to provide improved calibration coefficients. This will help track and characterize the improvements to the bio-optical algorithms and atmospheric correction procedures for multiple sensors.

NRL – Hyperspectral Characterization of the Coastal Zone

One of NRLSSC's basic research efforts is developing ocean color algorithms and Navy products using high spectral resolution satellites. This program (Hyperspectral

Characterization of the Coastal Zone) is a core NRLSSC program that is collaborative and leverages off of the ONR Code 32 (Environmental Optics, Hyperspectral Coastal Ocean Dynamics Experiment (HYCODE) program). This programs goal is to develop an understanding of the hyperspectral signature of coastal waters and to exploit these signatures beyond the current ocean color algorithms based on multispectral capabilities. This NRLSSC program is assessing the utility of applying hyperspectral data (such as will be collected by the GOES-R and other experimental hyperspectral sensors (Coastal Ocean Carbon Observations and Applications sensors) to coastal processes and applications. Many of the new algorithms developed under these programs are considered candidates for transition to NAVOCEANO as operational Navy products. The programs also offer a method by which optimal waveband selection can be evaluated. A suite of *in situ* observations collected by these programs is used for calibration and validation efforts of the MODIS and SeaWiFS satellites. These basic research efforts provide new *in situ* measurement techniques using state-of-the-art instrumentation, as well as atmospheric correction methods that are integrated into the APS transition program. The data base and methods developed are already setting the stage for future requirements for NPP/NPOESS.

2) NASA – Hyperion Calibration/Validation –

The hyperspectral Hyperion sensor and the Advanced LANDSAT Imager (ALI) were launched in November 2000 on the EO-1 satellite. These sensors were developed with a focus on land applications and their utility for water applications was largely ignored. Consequently, NRLSSC is conducting a calibration/validation program to characterize these sensors and demonstrate the utility of hyperspectral data for ocean applications. As mentioned above, tighter radiometric controls and greater signal:noise are required over water targets. Specifically, a field campaign is underway with a suite of *in situ* optical measurements being collected concurrently with satellite overpasses, in both open-ocean and coastal waters. The data/imagery match-ups are being used to test optimization algorithms to derive water optical properties, bottom reflectance, bottom type, and bottom depth from Hyperion ocean color imagery. Procedures and protocols developed for SeaWiFS and MODIS are being followed. In some cases other satellites

(i.e. SeaWiFS) which has been well characterized is used to help calibrate and validate the sensors signal. This has lead to an extension of the satellites capabilities beyond what was originally believed possible. This program will provide *in situ* optical and thermal observations that can be used for the calibration/validation program. The techniques used in this inter-sensor calibration/validation are directly related to those necessary to assure proper calibration and validation of the NPP and NPOESS sensors.

3) *NASA/NOAA/NRL Integrated Ocean Products for the Gulf of Mexico –*

Calibration and validation is enhanced when numerical models and satellite imagery are integrated so that ocean variability and spatial/temporal trends can be used as "gap fillers". Currently such near-real-time integrated satellite/numerical modeling products are under development for the Gulf of Mexico. These products link model-derived currents, temperature, and salinity fields with satellite optical properties, within 1-2 hours of the satellite overpass. These Navy pre-operational research products are being coupled with NOAA applications, including detection and monitoring of harmful algal blooms (HABs) and river discharge/hypoxia events. This program is designed to demonstrate the utility of satellite and numerical modeling products for monitoring the coastal oceans and to provide decision support to NOAA coastal programs. Under this program, we can monitor oceanographic processes in the entire Gulf of Mexico using multiple satellites and numerical circulation models. This work can be used to identify any calibration problems that arise with these satellites over time, and permit adjustments to the calibration coefficients and algorithms as required. The real-time nature of this work has the advantage of using the APS system to make adjustments in near-real-time, rather than months later, as has been done with past satellite reprocessing schemes.

4) *NAVOCEANO Field Programs –*

NAVOCEANO ocean optics group conducts multiple surveys throughout the year in strategic areas around the world. These surveys make daily collection of bio-optical and physical oceanographic properties. This is a rich data source provides substantial calibration and validation measurements in a data base covering a wide variety of open-ocean and coastal locations, seasons, and ocean conditions. The wide variety of oceanic

environments makes such data extremely useful in the calibration and validation of NPP and NPOESS type satellites. All data is stored in an internal data warehouse from which NAVOCEANO (and approved researchers such as NRLSSC) can draw upon to investigate sensor performance. One issue that is evident is that both NRLSSC and NAVOCEANO use slightly different data collection procedures. For accurate calibration and validation programs these differences must be compared and any differences reconciled. However, through the standardization of measurement techniques and instrumentation this data base can be integrated with the calibration and validation efforts of the larger research community. Currently, some NAVOCEANO *in situ* data are being used for validation, and the protocols for data transfer between NAVOCEANO and NRLSSC have been established.

IV. Potential Collaboration Opportunities for Calibration/Validation

A. *Observatory networks*

There is a unique opportunity for the calibration and validation of satellite systems to take advantage of new coastal monitoring networks which are under development in the USA and throughout the world. These are long-term ocean observatories being established under sponsorship of Ocean US, the National Science Foundation, NOAA, and the Navy with additional support among the international community. These coastal observing systems throughout the USA are linked through the Integrated Ocean Observing System (IOOS) via the Ocean US program; and through NSF via the Ocean Observatories Initiative (OOI) and the Ocean Research Interactive Observatory Network (ORION). The intent of these programs is to provide an infrastructure and equipment capability for monitoring the coastal ocean through a series of networks over long time series. While this network of observatories is not specifically oriented toward satellite coastal calibration, their development and establishment of the infrastructure for ocean observations provides an asset that calibration and validation activities can leverage and exploit. In addition, the timeline for development and initiation of these large ocean observatories is parallel to the proposed NPP and NPOESS satellite systems.

Since these programs are not designed with bio-optical and remote sensing as their primary mission, they do not have calibration and validation activities at the heart of their monitoring programs. However numerous ancillary data and long-term measurement of several bio-optical properties important to environmental monitoring are embedded in these programs. These measurements offer methods to track anomalies which are often over looked in the sparse field measurements normally conducted as part of calibration and validation. This is because the anomalies may represent extremes and boundary conditions in the calibration and validation which are suspect in short-term measurement programs. Because the programs are in their infancy there is also considerable leverage that the Navy can use to insure that as many calibration and validation measurements and protocols are included in the operation of these ocean observatories. These large national observatories are building upon the emergence of numerous new coastal observing systems over the past 3-5 years within the United States (see http://www.csc.noaa.gov/coos/). These smaller observatory efforts cover 9 major areas of the USA (see Appendix B). Each of these coastal observatories is focused on a particular region; however, they all are working toward a common environmental network across the USA. Using these observing systems and their resources can provide an extended calibration and validation capability that is not otherwise possible due to the expense and the complexity of calibration and validation of ocean optical properties and remote sensing. Several examples of current efforts include:

LEO – 15 – Rutgers University – the original intent was to demonstrate the utility of real-time monitoring of coastal New Jersey with physical, optical and mooring and models and to act as a test-bed for Autonomous Underwater Vehicles. It has grown into a demonstration of continuous (5 year operation) of a coastal ocean research center. With a two moorings, an extensive summer field program and the AUV testing this project has measured the temporal response of bio-optical and physical properties in the near-shore environment. The summer program measures numerous bio-optical properties that are consistent with those required for calibration and validation. http://marine.rutgers.edu/mrs/LEO/LEO15.html

MBARI (Monterey Bay) Ocean Observing System (MOOS) – the project monitors a coastal system that has a deep canyon with distinct layers at depth. The area

has subsurface layers that can be important in some remote sensing applications (or the lack of satellite to detect these layers). There are concurrent physical, optical, and modeling programs with measurements of optical properties and occasional hyperspectral system. The program deploys ship surveys, moorings, and aircraft overflights. http://www.mbari.org/bog/NOPP/default.htm

Gulf of Maine Ocean Observing System (GMOOS) – This is an extensive ocean mooring , satellite, and ship measurement and modeling effort in the Gulf of Maine. It is directly linked with the commercial fisheries and the University of Maine. The program collects biological, optical, and physical oceanographic data; however little effort at this time is directed toward satellite calibration and validation efforts. Data is available in real time. http://www.gomoos.org

Martha's Vineyard Observing System – This is a new project and facility that is planned for ocean observations. Proposed efforts include specific ocean optics and physical ocean physical oceanographic studies. The project has identified calibration and validation of MODIS and coastal properties as one of its primary objects. This observation project is viewed as a test-bed for calibration and validation activities.

http://www.whoi.edu/mvco/oceans2000.pdf

While the summarized programs above have calibration and validation potential in the past, there are few that (except Martha's Vineyard program) that have specifically identified calibration and validation as a primary objective. In order for NPP and NPOESS to be successful, the Navy (via NRLSSC and NAVOCEANO) must play a strong role in either identifying and participating in coastal observing programs that support calibration and validations activities in line with Navy needs, or invest in a coastal observation capability that is consistent with the application of NPP and NPOESS for Navy operations.

B. Current long-term calibration sites

In addition to emerging observational capabilities there are several satellite calibration and validation sites that are already routinely used for calibration. The Marine Optical Buoy (MOBY) effort in Lani, Hawaii is a coordinated NOAA- NASA effort that offers a stable environment to provide a satellite long-term satellite stability and radiometric assurance for the "blue water". This type of monitoring effort is required to

insure that sensor drift can be monitored. But while important to sensor drift in a stable blue water condition, such calibration and validation sites are only part of the requirements for Navy operational systems.

For any future operational Navy system the need for coastal calibration and validation sites is critical. There is one coastal calibration site; the Venice tower in the Northern Adriatic which is supported by the IOCCG (International Ocean Color Coordinating Group) through Italian ocean color research efforts. Such coastal sites provide information on the calibration and validation in environments that have high signals due to backscattering, but are also high in absorption. This combination potentially can impact system performance and may alter a sensors operational utility in a coastal application as compared to the open ocean. On-the-other-hand, the increased signal and high concentrations in the coastal environment often allows a sensor that has low open ocean utility to have reasonable performance in the coastal environment. It is through these coastal monitoring programs that such information on the sensitivity of the senor to varying optical conditions is evaluated. This is particularly important in calibration and validation, and in algorithm testing, since variable data can be problematic. The Navy must be cognizant of this requirement for NPP and NPOESS calibration and validation.

V. Primary Measurements for a Calibration and Validation Programs

As indicated previously, calibration and validation of a satellite requires high quality *in situ* measurements. From a Navy perspective these must include coastal and open ocean environments. There are several measurements that are essential to establish a calibration and validation data base for satellite calibration. Foremost among these is the remote sensing reflectance and atmospheric properties. In addition, the bio-optical properties of the water offer a means to assess algorithm performance and to validate the way remote sensing reflectance are derived, and in some instances, provide the corrections needed to the remote sensing reflectances. There have been substantial improvements in the measurement of these *in situ* properties over the last 5 years. These advancements have increased the confidence that the measured properties can be significant for calibration and validation even in coastal environments (using moorings, observational networks, and data match-ups).

A. Optical properties

Past satellite efforts demonstrated the absolute requirement for radiometric accuracy and consistent protocols for calibration and validation. In response, NASA sponsored the Sensor Inter-comparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) workshops to establish a common set of protocols and instrument requirements for calibration and validation. Such a set of common protocols must be established by the Navy for NPP and NPOESS. As previously noted, these established procedures and protocols provide a means to follow radiometric response of the satellite and algorithm performance. The program demonstrated the inter-calibration of sensors that is required in order to maintain the accuracy needed for calibration such as for NPP and NPOESS consistency. SIMBIOS demonstrated how the inconsistency in instrument measurements and protocols for measurement could impact calibration and validation efforts. NRLSSC was involved with this sensor inter-comparison to provide the validation that is built into Navy products. All instruments used were linked to NIST standards as well as inter-compared amongst other key calibration and validation measurements.

SIMBIOS identified several key areas and issues that must be addressed for a proper calibration and validation effort to be initiated and useful. These key areas carry over into the NPP and NPOESS efforts as well. They include:

1) the proper calibration and maintenance of ocean instrument used for data collection with continuous recalibration and control with respect to NIST standards (this includes inter-sensor comparisons)

2) use of established and common protocols in how instruments are deployed for data collection (including in-water and above water data collection), and

3) application of common methods for post analyses procedures (software etc) of the data into geophysical units and the spatial and temporal averaging that is implemented in the data analyses

There have been several protocols for ocean optical measurements which have been outlined by NASA which the Navy has adopted. These protocols form the basis for the data collection used by the Navy for calibration and validation of satellite sensors.

In order to meet Navy needs for the NPP and NPOESS satellites, NAVOCEANO and NRLSSC have identified several specific bio-optical properties that are necessary for the validation and calibration efforts. This list, while not all inclusive, includes the primary parameters for radiometric and algorithm calibration and validation. These measurements include:

- Remote sensing reflectance (Rrs, Spectral (λ))- measured both above and below the water surface with concurrent measurement of incident solar light for normalization and atmospheric contribution

  Necessary for tracking radiometric accuracy and to fine tune either calibration coefficients or algorithm discrepancies in various environments (SDR level Cal/Val)

- Aerosol Optical Depth – measured under a variety of sky conditions and during all measurements of Rrs.

  Measurement is required for atmospheric correction which is critical in the Cal/Val effort when trying to compare in situ data with satellite RDR level data.

- Spectral absorption- (a, λ) measured in the water as a function of depth which division into "total", phytoplankton, detritus, mineral, and colored dissolved material fractions

  A property used in satellite algorithms for retrieval of Navy relevant products, also used for inversion to check Rrs for consistency; total absorption is the most critical. With spectral backscattering and scattering distribution it represents one of the primary factors contributing to ocean color.

- Spectral backscattering coefficient (b_b, λ) – measured as a function of water depth and commonly done at only one angle with expansion over the angular range of 90 to 180 degrees; new instrumentation may allow more accurate measurement

  Together with absorption the backscattering represents the major contribution of signal received by a satellite that originates from the ocean. The property is essential in inversion methods but its measurement is very difficult.

- Total beam attenuation coefficient (c, spectral (λ)) – a parameter that adds validity to the absorption and backscattering measurements and is required for

many of the Navy operational products such as diver visibility, diver vulnerability, and imaging system performance

There is no direct method to retrieve total beam attenuation from only remote sensing information without assumptions about the scattering function. Its measurement can add confidence in other measurements as relationships between optical properties often involve 'c' as a required property.

Spectral downwelled irradiance (E_d, λ) – commonly measured with a cosine corrected device to correct for angular effects on a detector including immersion coefficients for in water measurements; the quantity is the incident light impinging on the water's surface and must include sky and solar conditions; for in-water measurements this is a quantity that is extremely difficult to measure accurately for remote sensing purposes since wave focusing can change the magnitude of E_d by factors of five at a given depth in milliseconds. For moorings this measurement is also effected by significant biofouling or sedimentation and therefore special consideration is required for these factors.

The measurement of E_d above the water's surface is affected by the changing sky conditions and any movement in the measurement platform. As such care must be taken to insure adequate measurement time has been achieved. The in-water measurements are subject to wave focusing from which natural logarithmic transforms must be done to help analyze the data. The in-water values are also subject to Raman scattering, surface reflectance, and ship shadow.

- Spectral diffuse attenuation coefficient (K_d, λ) – can not be measured but rather is derived from E_d and is a property that describes the vertical extinction of solar light and is effected by solar conditions, angle, and measurement scenario; the rate of descent of the instrument package, ship shadow or package conditions, and surface effects

  This measurement has been often used over long distances to describe the rate of attenuation of light. The difficulty has come in the fact that this is a derived property from the spectral downwelling irradiance E_d and is a rate of change over the depth interval. Hence the value will change as the radiance field

changes. Due to wave focusing measurement of K_d is often made by holding an irradiance sensor at specific depths over long periods of time then normalizing to incident light.

- Spectral upwelled radiance (L_u, λ) – measured with either hyperspectral or multispectral devices and either above water or below the water with narrow field of view radiometers; above the surface can must be taken for surface films, foam, bubbles, wave conditions, and ship wake; below the water surface extraction to near the surface and bottom influences must be considered. As a measurement with the proper orientation this property can be done well below the surface, however, it is extremely difficult above the surface and requires several measurements either spatially or temporally.

  The upwelled radiance is the portion of the incident light that is going to contribute to the remote sensing reflectance and as such is an extremely important property. It is often measured just below the surface and at depth so that radiative transfer techniques can be used to show consistency with remote sensing reflectance, retrieved optical properties, or bottom depths. Because of the orientation of the sensor it is generally less susceptible to bio-fouling (McLean, personal communication). The difficulty in its measurement is how to transform the property into one that is easily used for remote sensing applications. Instrument shadow has long been recognized as a source of error in measurement of L_u.

In the above list several of the measurements are made with either one instrument or are coupled together for either ease or to normalize one against the other. For the inherent optical properties (absorption and total attenuation) the standard accepted instrument is the WetLab's Inc., ac-9, with a higher resolution spectral instrument in final testing phase. The backscattering measurement can be made with a host of instruments using one to three angles and individual spectral filters. New instrumentation will allow more spectral and angular information and is under procurement by NRLSSC. The apparent optical properties (E_d, L_u, and derived K_d) are measured using commercial radiometers that were designed to meet the stringent radiance accuracies for the SeaWiFS

program. The first company to meet these requirements and the most widely accepted instrumentation is from Satlantic Incorporated. Lastly the remote sensing reflectance (above water) is measured with several instruments (NRLSSC uses instruments from Analytical Spectral Devices, and a custom built instrument) that each have gone through extensive testing. All the measurement devices have specific protocols and all of the inherent property measurement devices have gone through inter-comparison procedures in the SIMBIOS program. The Navy (both NRLSSC and NAVOCEANO) have been at the forefront in the use and testing of the optical instrumentation used in ocean color calibration and validation and have pushed for state-of-the-art optical instrumentation that meets the specifications necessary for calibration and validation activities.

B. Sea Surface Temperature

As previously presented, there are two measurements that are critical for SST calibration and validation. These are the Bulk temperature and the Skin temperature. Both have several specific measurement capabilities, but by far the easiest and most robust is the bulk temperature.

Bulk temperatures are measured using many common commercial sensitive and "fast response" thermistors. These thermistors are mounted on buoys and deployed throughout the world as previously described. NAVOCEANO uses these commercial thermistors from drifting and moored buoys to improve the temperature data base. These data have provided reliable measurements for determining SST algorithm validation for more than a decade. Use of stable and reliable drifting and moored buoy measurements should be a high priority within SST validation for NPP and NPOESS.

The satellite observations are a measure of the surface emitted energy. Thus the bulk temperature from buoys is not exactly what the satellite measures. However, the bulk and skin are highly correlated and within a few tenths of a degree except for a range of conditions that depend upon wind speed, solar insolation, and air/sea temperature difference. In addition, the disadvantage with skin temperature is that the dynamic ocean models require bulk temperature information associated with ocean features rather than skin layer information. Conversion of skin to bulk using models that incorporate wind speed, insolation, and air temperature information is still a work in progress. At present,

each of theses inputs to the models often introduces more error to the bulk SST estimate than what can be obtained from simple regression of satellite channels to buoy SSTs.

To precisely match what the satellite senses, the skin temperature must be measured. However, the skin temperature can only be measured by a select set of instruments which are operated by the University of Miami and the University of Wisconsin. The Marine-Atmosphere Emitted Radiance Interferometer (M-AERI) is a specialized instrument used to measure the skin radiation temperature of the ocean and is required for calibration of the Thermal IR satellites. But with only a select number of M-AERI instruments available and with a high cost, these measurements are limited to only a select number of locations (http://www.rsmas.miami.edu/ir/maeri/maeri.html).

In order to improve temperature calibrations, the skin temperature measurements and the bulk temperature measurements are made simultaneously and then many regression analyses are used with statistical data bases to help lessen the number of costly instruments. For sea surface temperature, the use of multiple satellites that inter-compare with one another and the large buoy record are the best capabilities for the global coverage. The protocols for SST retrieval have been documented at NAVOCEANO and used successfully. For NPP and NPOESS a similar protocol for measurement comparison of bulk and skin temperature using a combination of buoys, M-AERI radiometers, and satellite inter-comparisons is anticipated.

VI. Data collection Techniques

There are six primary methods of data collection that the Navy needs to address for calibration and validation of remote sensing products. These data collection methods include: a) normal and optics specific at-sea field collection programs, b) short-term moorings (< 6 weeks), c) optical/SST drifters, d) specific cross-sensor calibration exercises, e) autonomous unmanned vehicles, and f) long-term coastal calibration data.

A. Field data collection programs –

Collection of in-situ ocean optical and SST data from coastal and open ocean waters must always include a strong field program. Towards this end NAVOCEANO has extensive field programs that can provide unique data collection in diverse coastal environments, but these waters are usually limited to off-shore locations. NRLSSC research programs collect in-situ SST and optical measurements in unique and extreme

coastal areas such as river plumes, upwelling areas, surface salinity fronts, and areas with strong bottom resuspension. In addition, with NRLSSC's new suite of instrumentation, advanced algorithms and new relationships between SDR and EDRs can be formed. The difficulty that field data collections have is that they are often "too few", "too sparse", and "too time consuming" for many satellite programs. They do offer, however, a spatial coverage that can yield data match-ups if sampling is carried out in a timely fashion. But ship programs are costly and require cloud free match-ups for optimum use for calibration and validation. Thus while these are critical for calibration and validation efforts, they are not considered to be "good enough" for Navy needs with NPP and NPOESS. This was clearly demonstrated for the SeaWiFS and MODIS programs that have provided the Navy with its calibration and validation foundation.

B. Short-term moorings –

Short-term moorings provide the most optimum scenario for satellite and *in situ* match-ups of data. The short-term moorings have traditionally been expensive and subject to the same biofouling issues as longer term moorings. However there are now new instruments, such as that measuring RRS at the Venice tower (SeaPRISM), that do not biofoul and have the radiometric accuracy required for calibration and validation. A suite of coastal calibration sites that would deploy instruments, such as the SeaPRISM, would be invaluable to calibration and validation for the Navy. In addition, in situ measurements have new copper shutters and anti-biofouling materials that permit short term deployment with very little degradation in performance.

Short-term moorings have been tested that are "re-locatable" and can transmit data at regular intervals. These moorings have been established for work in the very shallow (<30 m) water where ship operations are sometimes limited and where variability in optical and physical properties is high. The moorings can measure absorption, scattering, conductivity, temperature, attenuation, upwelled radiance, and downwelled irradiance as a function of depth. These moorings can be co-located on the sea-floor bottom with Acoustic Doppler Current Profiler (ADCP) to provide relationships between the optical (remote) signature and physical properties. These moorings commonly are housed in anti-biofoulant cases and are deployed at "preset intervals". The rate of ascent can be adjusted between about 0.02 to 2.0 meters per second. This provides high

resolution measurements near the surface for both temperature and optical properties that are critical to remote sensing signals. These packages are small enough to be deployed from 20' fishing vessels and continue to decrease in size (Donaghay, personal communication).

The use of small portable moorings for approximately 30 days provides a continuous record of satellite and in-situ data match-ups in many environments. Because of its size and versatility and its real-time aspects, sensor problems can be easily identified. For calibration and validation work the mooring acts as a "tie-point" for the at-sea collection and calibration and is a point whereby the satellite will have at least one match-up each pass. One key in the moorings is the placement of these instrument packages to optimize calibration and validation in coastal waters. The Navy views a network of such calibration and validation sites as a unique opportunity to expand calibration and validation. The Navy views coastal moorings, such as the SeaPRISMS, as a necessity to accurately calibrate and validate emerging satellites. Through inter-agency cooperation with NASA and NOAA it is expected that such capabilities can be achieved. The Navy believes a calibration and validation site such as in the Gulf of Mexico will provide a unique site to test these autonomous (self-contained) portable moorings for calibration and validation efforts.

C. Ocean optical and SST drifters –

Recent developments in instrumentation have lead to much improved optic and SST drifter buoys which can relay data back in real-time for periods of months. Drifting buoys are the most valuable bulk SST data set available for validating satellite SST algorithms worldwide. It is imperative that a source of drifting buoy SST measurements continues to be readily available during the NPP and NPOESS program to validate satellite SST retrievals.

However, in the case of optics, these instruments are often expensive and are prone to bio-fouling. For the most part, drifting buoys are considered expendable instruments so that "value to cost" ratios have not been high to this point. Additionally they are typically applied in offshore water rather that coastal waters which is the focus of navy satellite optical product validation. This is due to the fact that many drifters located in such areas are quickly swept ashore. The optical buoys also have a tendency to

have salt deposition on above surface sensors and are subject to severe wind and wave fluctuations. However, advancements in the stability and utility of these instruments are emerging and there are new methods for sensors to "clean" and protect themselves when not in use. These lead to the potential for further use in planned calibration and validation activities. Within the Navy, the further development of these sensors was halted due to no explicit requirement for such data. The calibration and validation of future satellites such as NPP and NPOESS may require the Navy to reconsider these types of optics measurement methods. The constraints of these instruments will still include their surface wave interaction dependencies.

D. Continuous cross-calibration of satellites -

One often over-looked method of calibration and validation effort is the use of multiple satellites to provide statistics and information on each other. In certain ocean regions where there is stability in ocean color or temperature properties, we can use these match-ups of different satellites to provide a calibration and validation of the EDR level in particular. On multiple passes the trends in one satellite versus another that are either concurrent or within short time intervals can provide calibration and validation information on the stability and sensitivity of each sensor. This effort is very important since there will always be transition from one satellite to another. Sudden changes in the EDR products due to only changes in the satellite will be suspect for operational applications. Thus the METOC community promotes this effort as a required calibration and validation procedure. NRLSSC, using NASA funding, has conducted this type of inter-comparison between the Hyperion and SeaWiFS satellites where it was assumed that the SeaWiFS calibration in offshore water was more accurate due to the larger calibration effort associated with this sensor. The results were quite good; showing how such procedures can increase a sensors operational utility. These methods of calibration can insure constancy of the calibration and products. However, the methods may not account for all the differences between the sensors differences in their EDRs.

E. Autonomous unmanned vehicles –

Autonomous unmanned vehicles have emerged for both airborne and in-water METOC measurements. Small sized sensors, long-range power capabilities, and over-the-horizon communication technologies have made such devices promising for satellite

calibration and validation. At the present time, the instrument packages that are being considered include absorption via fluorescence, scattering, total attenuation, and chlorophyll sensors. While chlorophyll and absorption from fluorescence are used for frontal analysis they are complex biological properties that can not be used to asses product calibration or consistency. The extreme range (>50 km) of these unmanned devices and their ability to travel into coastal environments has lead the METOC community to consider how such systems can be effectively used in calibration and validation efforts. However, to date, no satellite calibration and validation program relies on such instrumentation without moorings or other reference measurements.

F. Long-term coastal moorings and monitoring -

A high priority measurement method is the establishment of a long-tern coastal monitoring/observation capability to compliment open-ocean calibration sites. For Navy applications and EDRs such a capability is essential to help distinguish statistical fluctuations in SDR and EDRs in a variable environment from algorithm and sensor performance degradation. There are several coastal observing systems that are part of the IOOS programs previously presented. It is important for the Navy METOC community to support and be an integral part of these programs for three reasons: 1) the EDRs that are specific for the Navy need to be calibrated and validated in coastal environments, 2) the Navy alone cannot bare the burden and cost of such a capability but certainly will gain significantly from a long-term calibration and validation effort, and 3) the environmental variability offers a good test for the robustness of algorithm and sensor performance. Therefore, based on a number of considerations, such as availability of coastal observing systems, cost of field programs, sensor advancements, and multiple satellites, it is felt that there are opportunities where specific coastal calibration and validation sites and efforts which can support and enhance Navy Cal/Val efforts. These include:

Possible Calibration – Validation Sites

Region	Unique region
Gulf of Mexico -	Northern Gulf - High river discharge areas, high CDOM , High suspended sediment areas
Chesapeake Bay	Coastal discharge areas – High CDOM and suspended sediment
Persian Gulf -	Foreign area of strategic interest – High river

	discharge, bottom reflectance issues -
Adriatic Sea / Mediterranean	- Navy Strategic area – Po River discharge
New England (Martha's Vineyard)	- High latitude area – coastal monitoring
Yellow Sea -	Navy Strategic area – high suspended sediment
Monterey Bay Ca.	– Upwelling area , Bioluminescence, biological processes

VII. Integrated Navy Efforts for Calibration and Validation (in-situ, moorings, and satellites)

Combining assets within the Navy will be a critical part of the calibration and validation effort for any satellite (e.g. NPP and NPOESS). Between NRLSSC and NAVOCEANO there is an extremely powerful background in past calibration and validation efforts for satellites such as SeaWiFS and MODIS. But these satellites have been primarily used for research and therefore many scientific communities have contributed to Cal/Val efforts. In order to meet objects of an operational satellite the Navy must have a well thought out calibration and validation program that extends from verification of signal at the RDR and SDR levels through the EDR level. This must include a fully integrated program that covers many aspects of calibration and validation including the rapid validation and transition of research and development into operational products.

This document has attempted to demonstrate the requirement that the METOC community foresees for the calibration and validation efforts of the NPP and NPOESS operational satellites. Our intention has been to provide an understanding of the Navy's present methods and future plans for calibration and validation of satellite ocean products. This document shows the procedures and protocols which are currently in place for calibration and validation activities in the Navy so that future efforts can leverage off these procedures and extend them to other satellites. From the beginning it has been shown that no one program can "do it all" and that only through an inter-agency collaborative effort can calibration and validation be accomplished; with the Navy playing an integral role.

The intent of this document is not to dictate calibration and validation efforts and procedures for the future NPP and NPOESS satellites. It is an effort to guide planning of calibration and validation efforts. Below are several recommendation and points that outline several issues that the METOC community feels are important for proper

calibration and validation and should be considered relevant to NPP and NPOESS efforts. This document should be viewed as one that evolves as the procedures, algorithms and methods for ocean satellite products change.

As presented the Navy currently has an active satellite oceanography research effort. New advances and algorithms and Navy products are currently under development. We have not presented the products which are in the Navy's satellite and optics roadmap and planned for the next five years. However, they are numerous and extend well beyond the current NPOESS product lines. We are anticipating that the NPP and NPOESS satellites will be used with these new algorithms and will enhance Navy products . Present research is focused on making these satellites part of the operational ocean constellation of the operational satellites.

The METOC community does feel it is important to recognize that the calibration and validation of these new products will be based on the current procedures and protocols which are in place today for SeaWiFS and MODIS satellites. The current plan is to extend and improve on these calibration and validations procedures for NPP and NPOESS; this document represents possible areas of improvement. More specifically the following is a list of items for consideration into an integrated calibration and validation plan in preparation of NPP and NPOESS.

- **Adopt the calibration methods currently being used for SeaWiFS and MODIS (TERRA, AQUA), for the NPP and NPOESS satellite.**
    - ❖ Sensor calibration and validation for Navy ocean products should be vicariously calibrated including use of an optimization method to reduce uncertainty in the product
    - ❖ Navy level 1 calibration/validation (RDR to SDR level) will be based on optimizing the RRS inter-mediate properties using in situ measurements from both an offshore ocean mooring and coastal ocean optical measurements.
    - ❖ Calibration will be conducted in both coastal and open ocean environments
    - ❖ Navy level 2 calibration/validation (SDR) will use the optical properties (e.g. absorption and backscattering) to determine the sensor calibration.
    - ❖ Part of the Navy level 3 calibration/validation (SDR to EDR) will be to implement cross calibration of both products and signals between sensors (RDR, SDR, and EDR levels)
- **Adopt the calibration methods currently used for AVHRR and MODIS – thermal IR SST**

- ❖ Expand the network of buoy SST bulk temperatures to be applied to NPP and NPOESS satellite
- ❖ Coordinate with the MCSST working group on modeled correction factors
- ❖ Integrate skin temperature/radiometric measurements into calibration and validation when available

➢ **Establish and adopt a protocol for ocean observing instruments**
- ❖ Integrate ocean measurement protocols that have been recognized by the SIMBIOS program into the NPP and NPOESS Cal/Val effort
- ❖ Develop a rigorous inter-calibration effort of the primary sensors for radiometric calibration among Cal/Val sites and agencies
- ❖ Initiate 'measurement' consistency checks to assure high quality field data
- ❖ Ensure measurements meet Cal/Val needs of RDR, SDR, EDR, and expansion product lines for the Navy

➢ **Provide an infra - structure that meets requirements of a database of** *in situ* **data and satellite match-ups that can be performed in real-time**
- ❖ Integrate satellite image data and in situ observations so that the products generated from the RRS, and the optical properties, be continually validated and optimized in near real-time.
- ❖ Automate real-time calibration of SST using thermal IR channels and buoy network
- ❖ Update calibration and validation methods and coefficients regularly (a goal of two weeks versus >6 months which is the current practice) and efficiently to minimize reprocessing and errors associated with sensor drift
- ❖ Streamline configuration management in order to accept calibration and algorithm changes without loss of timely product delivery

➢ **Develop both short-term and long-term coastal calibration monitoring sites for Navy products**
- ❖ Calibration should be performed in both coastal and off-shore waters using long-term monitoring (years) and short-term (4-8 weeks) capabilities
- ❖ Calibration should be performed at 3 levels. Level one is radiance and RRS (RDR and SDR); level 2 is optical properties (SDR to EDR) and level 3 Navy products (Navy EDRs)
- ❖ Establish a coastal monitoring site in the Northern Gulf of Mexico as a joint NAVO/NRL /NASA/ NOAA calibration effort [This will serve as a preliminary site to begin a Navy Cal/Val activities for RRS, the most important time critical Cal/Val property]
- ❖ Using Northern Gulf of Mexico technology and Cal/Val experience, establish Cal/Val sites in foreign areas
- ❖ Add calibration sites from those selected as part of the US IOOP program which meet Cal/Val criteria critical to Navy interests
- ❖ Implement new instrumentation and measurement capabilities in the form of short-term moorings as available that can be positioned in time-critical areas to maximize Cal/Val efforts

These suggestions are aimed at providing guidance for new and emerging programs that can and will contribute and participate in future calibration and validation exercises. These suggestions are designed to provide direction to Navy resource sponsors such as ONR, IOOS, SPAWARS, the Oceanographer of the Navy, and NRL basic research to extend their efforts and future programs to include calibration and validation efforts. It is with such forethought that the Navy will be prepared to meet the challenges of NPP and NPOESS VIIRS calibration and validation of operational products. These recommendations are also directed at other agencies in order to coordinate, participate, and leverage from Navy calibration and validation efforts; these include NOAA (NDBO, NESDIS, IOOS, USGS), EPA, Oceans US, and NSF, in addition to a close partnership with the NASA NPP Science team. Furthermore, these recommendations are aimed at providing emerging US coastal observatory networks and real-time coastal laboratories a planning document on coordinated efforts in NPP and NPOESS satellite calibration and validation opportunities.

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Table 3 –Appendix A: MODIS Technical Specifications

Orbit:	**705 km, 10:30 a.m. descending node or 1:30 p.m.**
	ascending node, sun-synchronous, near-polar, circular
Scan Rate:	**20.3 rpm, cross track**
Swath Dimensions:	**2330 km (cross track) by 10 km (along track at nadir)**
Telescope:	**17.78 cm diam. off-axis, afocal (collimated), with**
	intermediate field stop
Size:	**1.0 x 1.6 x 1.0 m**
Weight:	**250 kg**
Power:	**225 W (orbital average)**
Data Rate:	**11 Mbps (peak daytime)** **Design Life:** **5 years**
Quantization:	**12 bits**
Spatial Resolution:	**250 m (bands 1-2)**
	500 m (bands 3-7)
	1000 m (bands 8-36)

Primary Use	Band	Bandwidth	Spectral Radiance	Required SNR
Land/Cloud	**1**	**620 - 670**	**21.8**	**128**
Boundaries	**2**	**841 - 876**	**24.7**	**201**
--				
Land/Cloud	**3**	**459 - 479**	**35.3**	**243**
Properties	**4**	**545 - 565**	**29.0**	**228**
	5	**1230 - 1250**	**5.4**	**74**
	6	**1628 - 1652**	**7.3**	**275**
	7	**2105 - 2155**	**1.0**	**110**
--				
Ocean Color/	**8**	**405 - 420**	**44.9**	**880**
Phytoplankton/	**9**	**438 - 448**	**41.9**	**838**
Biogeochemistry	**10**	**483 - 493**	**32.1**	**802**
	11	**526 - 536**	**27.9**	**754**
	12	**546 - 556**	**21.0**	**750**
	13	**662 - 672**	**9.5**	**910**
	14	**673 - 683**	**8.7**	**1087**
	15	**743 - 753**	**10.2**	**586**
	16	**862 - 877**	**6.2**	**516**
--				
Atmospheric	**17**	**890 - 920**	**10.0**	**167**
Water Vapor	**18**	**931 - 941**	**3.6**	**57**
	19	**915 - 965**	**15.0**	**250**

Primary Use	Band	Bandwidth	Spectral Radiance	Required NE(Delta-T)
Surface/Cloud	**20**	**3.660 - 3.840**	**0.45**	**0.05**

Temperature	21	3.929 - 3.989	2.38	2.00
	22	3.929 - 3.989	0.67	0.07
	23	4.020 - 4.080	0.79	0.07

Atmospheric	24	4.433 - 4.498	0.17	0.25
Temperature	25	4.482 - 4.549	0.59	0.25

Cirrus Clouds	26	1.360 - 1.390	6.00	150 SNR
Water Vapor	27	6.535 - 6.895	1.16	0.25
	28	7.175 - 7.475	2.18	0.25
	29	8.400 - 8.700	9.58	0.05

Ozone	30	9.580 - 9.880	3.69	0.25

Surface/Cloud	31	10.780 - 11.280	9.55	0.05
Temperature	32	11.770 - 12.270	8.94	0.05

Cloud Top	33	13.185 - 13.485	4.52	0.25
Altitude	34	13.485 - 13.785	3.76	0.25
	35	13.785 - 14.085	3.11	0.25
	36	14.085 - 14.385	2.08	0.35

Bands 1 to 19 are in nm Bands 20 to 36 are in um				
Spectral Radiance values are in W/m^2-um-sr				
SNR = Signal-to-noise ratio				
NE(Delta -T) = Noise-equivalent temperature difference				

APPENDIX B. Emerging Ocean Observatory Programs Available for Potential Collaboration in Calibration/Validation Efforts.

1. Alaska –

- Deep Ocean Assessment and Reporting of Tsunamis (DART) Project
- Physical Oceanographic Real-Time System (PORTS)
- Gulf of Alaska Global Ocean Ecosystem Dynamics Monitoring Program (GLOBEC Alaska)
- National Water Level Observation Network (NWLON)
- National Data Buoy Center (NDBC) Moored Buoys and C-MAN Stations
- Prince William Sound Nowcast-Forecast System (PWS NFS)
- Kachemak Bay National Estuarine Research Reserve (NERR)
- Gulf of Alaska Ecosystem Monitoring and Research Program (GEM)
- U.S. Geological Survey Stream Gauge Network

2. North West

- Columbia River Estuary Real-Time Observation and Forecasting System (CORIE)
- National Water Level Observation Network (NWLON)
- National Data Buoy Center (NDBC) Moored Buoys and C-MAN Stations
- Padilla Bay National Estuarine Research Reserve (NERR)
- US Army Corps of Engineers (COE) Wave Data Sites
- South Slough National Estuarine Research Reserve (NERR)
- Oregon State University Coastal Observations
- U.S. Geological Survey Stream Gauge Network

3. South West

- Monterey Bay Aquarium Research Institute (MBARI) Ocean Observing System (MOOS)
- Monterey Inner Shelf Observatory (MISO)
- Physical Oceanographic Real-Time System (PORTS)
- Coastal Data Information Program (CDIP)
- California Cooperative Oceanic Fisheries Investigations (CalCOFI)
- National Data Buoy Center (NDBC) Moored Buoys and C-MAN Stations
- California Center for Integrative Coastal Ocean Research (CI-CORE)
- Center for Integrated Marine Technologies (CIMT)
- National Water Level Observation Network (NWLON)
- Monterey Bay Innovative Coastal Ocean Observing Network (ICON)
- Elkhorn Slough National Estuarine Research Reserve (NERR)
- Tijuana River National Estuarine Research Reserve (NERR)
- US Army Corps of Engineers (COE) Wave Data Sites
- Southern California Coastal Water Research Project Authority
- U.S. Geological Survey Stream Gauge Network
- Southern California Coastal Ocean Observing System (SCCOOS)

4. Hawaii

- Hawaii Ocean Time-series (HOT) Program
- National Data Buoy Center (NDBC) Moored Buoys and C-MAN Stations
- National Water Level Observation Network (NWLON)
- US Army Corps of Engineers (COE) Wave Data Sites
- U.S. Geological Survey Stream Gauge Network
- Coral Reef Ecosystem Investigation (CREI) Monitoring Network

5. North west Gulf of Mexico

- Wave Current Surge Information System (WAVCIS)
- Texas Automated Buoy System (TABS)
- National Data Buoy Center (NDBC) Moored Buoys and C-MAN Stations
- National Water Level Observation Network (NWLON)
- Physical Oceanographic Real-Time System (PORTS)
- Northern Gulf of Mexico Littoral Initiative (NGLI)
- Weeks Bay National Estuarine Research Reserve (NERR)
- Grand Bay National Estuarine Research Reserve (NERR)
- US Army Corps of Engineers (COE) Wave Data Sites
- Texas Coastal Ocean Observation Network (TCOON)
- Louisiana Universities Marine Consortium Environmental Monitoring (LUMCON)
- U.S. Geological Survey Stream Gauge Network

6. Eastern Gulf of Mexico and Florida Atlantic

- National Water Level Observation Network (NWLON)
- West Florida Coastal Ocean Monitoring and Prediction System (COMPS)
- National Data Buoy Center (NDBC) Moored Buoys and C-MAN Stations
- Physical Oceanographic Real-Time System (PORTS)
- Apalachicola Bay National Estuarine Research Reserve (NERR)
- Rookery Bay National Estuarine Research Reserve (NERR)
- SEAKEYS/C-MAN Project
- US Army Corps of Engineers (COE) Wave Data Sites
- South Florida Ocean Measurement Center
- Florida Inshore Marine Monitoring and Assessment Program (IMAP)
- U.S. Geological Survey Stream Gauge Network

7. Mid Atlantic and Southeast coast

- Southeast Atlantic Coastal Ocean Observing System (SEA-COOS)
- Chesapeake Bay Observing System (CBOS)
- Physical Oceanographic Real-Time System (PORTS)
- National Water Level Observation Network (NWLON)
- National Data Buoy Center (NDBC) Moored Buoys and C-MAN Stations
- North Carolina National Estuarine Research Reserve (NERR)
- Chesapeake Bay National Estuarine Research Reserve (NERR) Virginia
- Chesapeake Bay National Estuarine Research Reserve (NERR) Maryland
- US Army Corps of Engineers Field Research Facility (COE FRF) Data Program
- US Army Corps of Engineers (COE) Wave

- [South Atlantic Bight Synoptic Offshore Observational Network (SABSOON)](#)
- [Chesapeake Bay Mouth Monthly](#)
- [Sapelo Island National Estuarine Research Reserve (NERR)](#)
- [ACE Basin National Estuarine Research Reserve (NERR)](#)
- [North Inlet-Winyah Bay National Estuarine Research Reserve (NERR)](#)
- [Carolinas Coastal Ocean Observing and Prediction System (Caro-COOPS)](#)

- [Data Sites](#)
- [Coastal Ocean Research and Monitoring Program (CORMP)](#)
- [Neuse River Remote Monitoring and Data Acquisition Project](#)
- [Alliance for Chesapeake Bay Citizen Monitoring Program](#)
- [U.S. Geological Survey Stream Gauge Network](#)
- [FerryMon](#)
- [Maryland Department of Natural Resources - Eyes on the Bay](#)

8. North East Atlantic

- [Coastal Ocean Observation Laboratory (COOL)](#)
- [New Jersey Coastal Monitoring Network (NJ CMN)](#)
- [National Data Buoy Center (NDBC) Moored Buoys and C-MAN Stations](#)
- [National Water Level Observation Network (NWLON)](#)
- [Physical Oceanographic Real-Time System (PORTS)](#)
- [Gulf of Maine Ocean Observing System (GoMOOS)](#)
- [Delaware National Estuarine Research Reserve (NERR)](#)
- [Jacques Cousteau/Mullica River National Estuarine Research Reserve (NERR)](#)
- [Coastal Ocean Observing and Analysis (COOA)](#)

- [Hudson River National Estuarine Research Reserve (NERR)](#)
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- [Martha's Vineyard Coastal Observatory](#)
- [Waquoit Bay National Estuarine Research Reserve (NERR)](#)
- [Great Bay National Estuarine Research Reserve (NERR)](#)
- [Wells National Estuarine Research Reserve (NERR)](#)
- [US Army Corps of Engineers (COE) Wave Data Sites](#)
- [U.S. Geological Survey Stream Gauge Network](#)
- [Monitoring Your Sound (MYSound](#)

9. Great Lakes

- [NOAA CoastWatch Great Lakes Program](#)
- [Physical Oceanographic Real-Time System (PORTS)](#)
- [National Water Level Observation Network (NWLON)](#)
- [National Data Buoy Center (NDBC) Moored Buoys and C-MAN Stations](#)

- [Old Woman Creek National Estuarine Research Reserve (NERR)](#)
- [US Army Corps of Engineers (COE) Wave Data Sites](#)
- [U.S. Geological Survey Stream](#)